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Research Article

Biology and architecture: An ongoing hybridization of scientific knowledge and design practice by six architectural offices in France

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Abstract As a highly interdisciplinary field, architecture is being influenced by many subjects of natural and social sciences. Biology despite being apparently distant from architecture is currently a scientific field blending into design practices, which have evolved and shifted towards a new hybrid framework. In this article, we present an emerging design field of what we categorize as *biomimetic architecture* pioneering by six architectural offices in France. We observe the impact of scientific researches on design processes and practices through six case studies led by these offices, which can be seen through the actors who involved in various types of interdisciplinary collaborations, through the competencies of the architect himself, and through new sources of ideas coming from biological sciences and related fields. We propose to use a classification of theoretical uses in modeling practice to better understand the role that biological knowledge plays in architectural design practices. Finally, the result of this analysis shows that the use of biology taking place in a design space has external purposes, which transform it to produce engineering devices or urban schemes rather than architectural projects. It also shows that biology in architectural design induces other kinds of non-biological knowledge, is not strictly theoretical and could be obsolete or approximate. These findings lead to an epistemological discussion concerning the confusion between biological 'knowledge' and architectural design 'know-how'.

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1. Introduction

Architecture is a complex negotiated culture practices, which includes all of the aesthetics, technical, economic, political issues of social production itself. For architects, integration of scientific knowledge and design practice can be a difficult activity to define but it can be the intellectual fuel for the engine of innovation and growth in architects' practices.

There are multiple historical examples of bio-inspired architecture but recently a movement of *biomimetic architecture* is trying to push this design practice further by integrating a scientific approach, involving the contemporary biological sciences in order to respond to actual environmental challenges.

Biomimetic architecture is a young discipline that takes part in this inspiration, moves from nature itself to biology, thus integrating a scientific point of view in design. It still remains known mainly in research and academic groups rather than architectural offices. Real-world architectural practice is developed in different layers and has to meet often contradictory requirements that make the transfer from cross-disciplines difficult. In order to get hold of transferable information, research and interdisciplinary collaboration from another perspective in life sciences or biological sciences might be needed.

Willing to investigate this supposed ongoing innovation, we have selected six architectural offices in France that are trying to make use of the biological sciences and not only to work with their own understanding of nature. We are thus trying to catch a hybrid phenomenon and to make a distinction of why we refer these offices pioneering biomimetic design activities. Note that this is an empirical study and not a general speculation on what *biomimetic architecture* could or should be. Moreover, because we assume that the impact of biology is more important if it is not marginal in the architectural world, we decide to focus on the architectural offices close to the regular practice of architecture in the sense that they really build relatively complex architectural design. This choice made us set aside so called 'experimental' practices that are mostly exposed in art shows or small pavilions (Brayer and Migayrou, 2013). We argue, if some architects work with biological knowledge, there must be some specificity of biology that interests these architects. We will approach this specificity with an *internalist* point of view (Raynaud, 2001), trying to tackle the knowledge and expertise of the actors of this biomimetic scene: architects and biologists.

This study is part of our on-going research project *BiomimArchD*[1] funded by Mission for transversal and interdisciplinary initiatives of French national center for scientific research (MITI CNRS) within the framework of Biomimicry challenge 2019.

[1] BiomimArchD: Building a knowledge base for sustainable biomimetic architecture.

2. Bio-inspiration, biomimetic and biology in architecture

2.1. From bio-inspiration to biomimetic framework

Architecture has long considered nature as a source of inspiration. There are numerous movements that can be grouped under the generic term of bio-inspired. Most refers to imitate nature by carrying out aesthetic forms and symbolic associations without taking into account biological knowledge or necessarily sustainable development (Chayaamor-Heil et al., 2018). We must distinguish a primarily formal inspiration of nature with an aesthetic or symbolic aim to a scientific approach of biological knowledge, which attempts to raise a closer relationship between biology and architecture referring as a new movement called *biomimetic architecture*.

Biomimetic architecture is a subdomain of a larger field called *Biomimicry*. Janine Benyus, author of the book *Biomimicry: Innovation Inspired by Nature* (Benyus, 1997), has defined biomimicry as a new science that studied nature in order to draw inspiration to design our innovations from a perspective of sustainability.

In the international standard *ISO 18458:2015 Biomimetics — Terminology, concepts and methodology* describes how biomimetic method differ from classic forms of research and development. Biomimetic design process is a type of analogical thinking based on an association of 'similar relationships between parameters' that links biological systems to technical systems (ISO 18458, 2015).

Biomimetic approach has been recently taken into account in architectural research and practice for the past 10 years, by investigating nature through sciences (e.g. life sciences, biological sciences). Today, technical advances in observation on a very small scale allow to have a deeper knowledge of the functioning of nature and offer a new source of knowledge and inspiration for architecture. Despite a numerous research on biomimetic architecture (Gruber, 2011; Badarnah, 2012; Mazzoleni, 2013; Knippers et al., 2016; Zari, 2018; Knippers, 2019), the examples in the real-world practice are still rare (Cruz, 2016). In this section, we will firstly provide an overview of a few existing biomimetic architectural designs in real-world practice and then of the relation between the two fields of knowledge: architecture and biology.

2.2. Biomimetic approach in real-world architectural design practices

In the period of modern architecture, Frei Otto in collaboration with biologist J.G. Helmke, started studying *Radiolaria*[2] micro-organisms, within the field of biomimetics, looking for a structural design medium that could account for the state of natural equilibrium for lightweight

[2] Radiolaria are marine single-celled (protozoa) animals that belong to the Actinopod superclass.

structures. From this emerged his theory, so-called 'From-Finding', which led to his analogic models, like hanging chains or nets of cables (Thomas, 2017). His project, the roof of the Munich Olympic stadium is known for his tensile architectural designs—lightweight tent-like structures. Otto scrutinized the properties of soap film. The surfaces of bubbles are efficient natural machines; balancing strength and lightness, they find the largest possible shape using the smallest amount of material. He literally calculated the degrees of change along the surface of soap film, and used those figures to understand the same structural dynamic in the curvature of his roof. Frei Otto was one of the pioneers that utilized mathematical and structural qualities of minimal surfaces in large scale projects such as German pavilion for EXPO 1968 and Munich Olympic stadium. Many other architects and engineers also attracted by surfaces of soap bubbles and used them for the design of light weight structures, such as a postwar Italian engineer Sergio Musmeci. His theoretical propositions focus on structure, statics, or the encounter of architecture and engineering; what is more, soap film and rubber sheets do not share the same physics of matter.[3] Bridge over the Basento is one example of his works using soap membrane mathematical and physical modeling technique towards material efficiency of a reinforce concrete bridge design application (Canestrini, 1975).

Other architects have pursue this path. Patrick Schumacher for exemple claims that he and his team at Zaha Hadid Architects "have absorbed the lessons of Frei Otto" (Schumacher, 2018.). Despite this claim, it must be noted that Zaha Hadid's architecture was criticized for its claim to biomimicry as a bare justification for biomorphic form. This approach of fluid forms is seen as not respectuous of the environnement, but only a formal spectacular gesture (Buchanan, 2015). However, Schumacher's assertion is subtler since he indicates that biomimicry tend to be limited to engineering solutions rather than architectural solutions for two reasons: First, the scale of a building's macro-morphology is so large in comparison to most organic structures that the performative effectiveness of analogical transference often breaks down. Second, the performance criteria that buildings or building components share with organic structures are technical rather than social (Schumacher, 2018). There are other theories related to computational approaches towards performative design with biology, such as (Hensel et al., 2010) but this work does not show real building results.

A strong Interdisciplinary collaboration between Architect Göran Pohl and biologist Werner Nachtigall is presented in the book *Biomimetics for architecture and design* (Pohl and Nachtigall, 2015). A result of a combined effort by the two disciplines describes the principles how biology can be used as a source of inspiration and 'translated' in building and architectural solutions along. Pohl and Nachtigall emphasized that nature cannot be directly copied to be able to provide architects with a wealth of analogues and inspirations to achieve a true objective of a creative interdisciplinary design process. Inspirations from nature for architecture will not function if they do not well abstract within the context of an interdisciplinary analogue. By observing a cognitive biomimetic design process within the context of an interdisciplinary, the authors defined the biomimetic design methodology as a three-step process: *Research* → *Abstraction* → *Implementation* as shown in Fig. 1.

Speaking about abstraction it is useful to consider the work of the mathematician and architect Christopher Alexander. By using a mathematical and systemic approach, he developed a framework for interpreting nature's features and transfer them to architectural space. He considers architecture as a part of the natural environment in which patterns it should be integrated (Alexander, C., 2002). In this sense it is not exactly a standard biological approach, but it relies on abstract disciplines (Mehaffy and Alexander, 2016). This way of studying nature with mathematical eyes is not new but can recall D'Arcy Thomson (Thompson, 1992) or even Galileo and his belief that nature is written in a mathematical language. We can note that the architectural language resulting, as for example in the Eishin Campus by Alexander, has nothing to do with a formal biomorphism, as Zaha Hadid developed.

Eastgate Center in Harare is considered as the most well-known biomimetic built case because of such an achievement of building energy performance. Architect Mick Pearce is fascinated by *autoregulation*[4] system of African termite mounds. He has spent years to study by himself passive techniques of the termite mound for inventing new ventilation system for buildings. His biomimetic ventilation system is first applied in the Eastgate Center, which efficiently respond to external air movements and humidity in order to keep the building interior stable. The result shows 90% reduction of energy required for air-conditioning compared to building of the same size (Chayaamor-Heil and Hannachi-Belkadi, 2017). His biomimetic invention has also been applied in other several buildings, including Council House 2 in Melbourne and Portcullis House in London. This example also opens the question of its architectural language since the result can be seen as relatively poor and repetitive from the formal point of view (see Fig. 2).

The starchitect like Grimshaw and Norman Foster have also used biological models in some of their projects to solve specific design problems. Grimshaw was observing at the *overlapping assembly* technique of fish's scales for the redevelopment of the Waterloo station's roof. The flexible-hard scale of fish is imitated in the parts that fix the glass panels of the roof so that the changes in the air pressure caused by the trains entering and leaving the terminal do not damage the glass panels because they can flexibly move in response to applied air pressure forces. The Iconic high-rise commercial Swiss Re building of Norman Foster in London is required to be built with a minimum impact on the local wind environment. The architects have observed

[3] Alessando Tursi and Donato Abruzzese provide a thoughtful analysis of the nonlinear process that Musmeci followed during his form-finding tests, including the challenges that forced him to direct these experiments along particular routes (Tursi and Abruzzese, 2003).

[4] Autoregulation is a process within many biological systems, resulting from an internal adaptive mechanism that works to adjust (or mitigate) that system's response to stimuli.

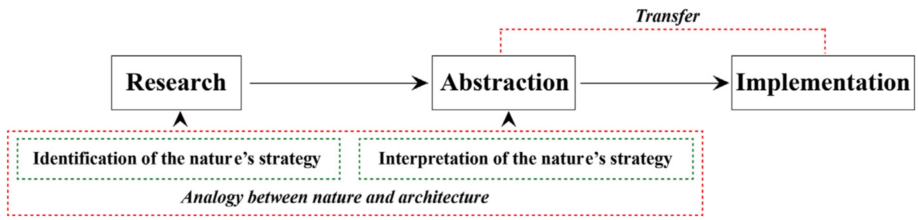


Fig. 1 Three-step cognitive process of biomimetic design (Image source: N. Heil).

Fig. 2 Eastgate Center, Harare (Image source: courtesy Pierre Côté, Université Laval).

hierarchical structure organization of the marine organism *Venus' flower basket* (*Euplectella aspergillum*). The study of this organism's structure has been referenced in (Wester, 2002). The architects have taken this biological principle to design the structure of the building that allows the wind to easily whip around the tower.

Michael Pawlyn, wrote the book *Biomimicry in Architecture* (Pawlyn, 2011) introduce practical guidelines to apply biomimicry in architectural design practices. He referred that interdisciplinary collaboration is one of the ways in which he benefits from research-practice in this young field. Pawlyn has collaborated with several biologists and academicians to study several biological models with digital tools to transfer their principles into the design context (Fig. 3).

As seen, there are several works regarding biology approaches in architecture. There are different levels of integrating biological knowledge in design practice as shown in the examples above. Note that, some of the architectural productions resulting from the integration of biology and architectural design might lack of architectural language quality, some tend to be impressive but superficial and maybe be rather called biomorphic, others are really abstract but seem to rely more on mathematics

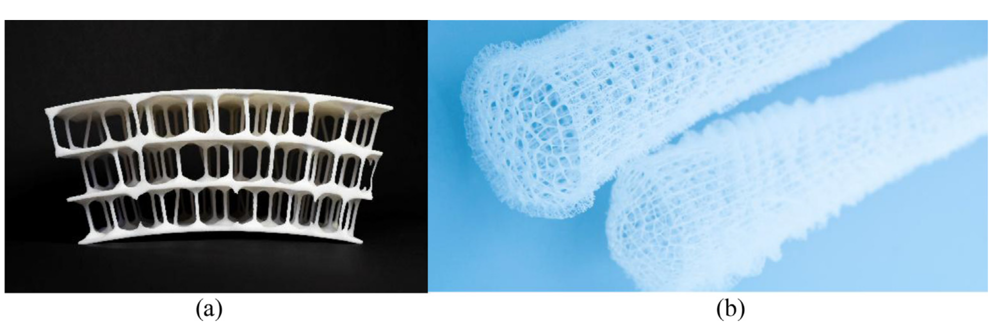


Fig. 3 Observing a bird's skull (a) and Venus' flower basket structure (b) to explore the potential for 3D printing to get closer to the efficiency of biological structures (Image source: Michael Pawlyn).

than on traditional biological science. We will now review the relationship between biology and architecture from knowledge standpoint.

2.3. Knowledge relationship between architecture and biology

Scientific knowledge flows in various practices and so does biology. Architectural design is a practice where it might land. But one could legitimately ask '*what kind of help can science such as biology be for a messy creative architectural design process?*' In a previous study, we similarly asked ourselves '*what can architects do with theories?*' (Vitalis and Guéna, 2019). The answer, to make it short, was: nothing. Doing and theory are heterogeneous, and if we respect them as scientific theories, we need to transform them, at least into models, in order to use them. Models have been regarded as a place where practice meets knowledge and helps a know-how. This work showed how theories, abstract from practices, could be transformed into models to help three types of practices: *design* (what the professional architect commonly does), *analysis* (a practice more closely associated to the researcher) and *simulation* (a practice that both research and designer may use). We showed how these three modeling categories work for natural, social and artificial science by describing how architects could use practically astronomy, sociology of the uses or the scales of architecturology. But we did not tackle the question of biology. Hence, the question of the use of biological theories remains open.

Differently, the relation between architecture and biology among various disciplines can be grasped through the work of Panos Mantziaras who did try to catch architecture as a discipline (Mantziaras, 2014). First he showed that architecture does not appear on the map of scientific disciplines (Fig. 4a) (Rosvall and Bergstrom, 2008). Despite that, the map shows that Biology is somehow too big and thus split in various sub-disciplines (molecular & cell biology, medicine, ecology & evolution ...). After asking the researchers where architecture was on the map, Panos Mantziaras obtained a second map (Fig. 4b) (Mantziaras, 2015). There, we can see that architecture shows no direct link with biology but is part of the arts field and linked to literature, history and classical studies. This reveals that architecture and biology are not only far away, but that they do not have the same status on the scientific map: too big or not visible at first glance.

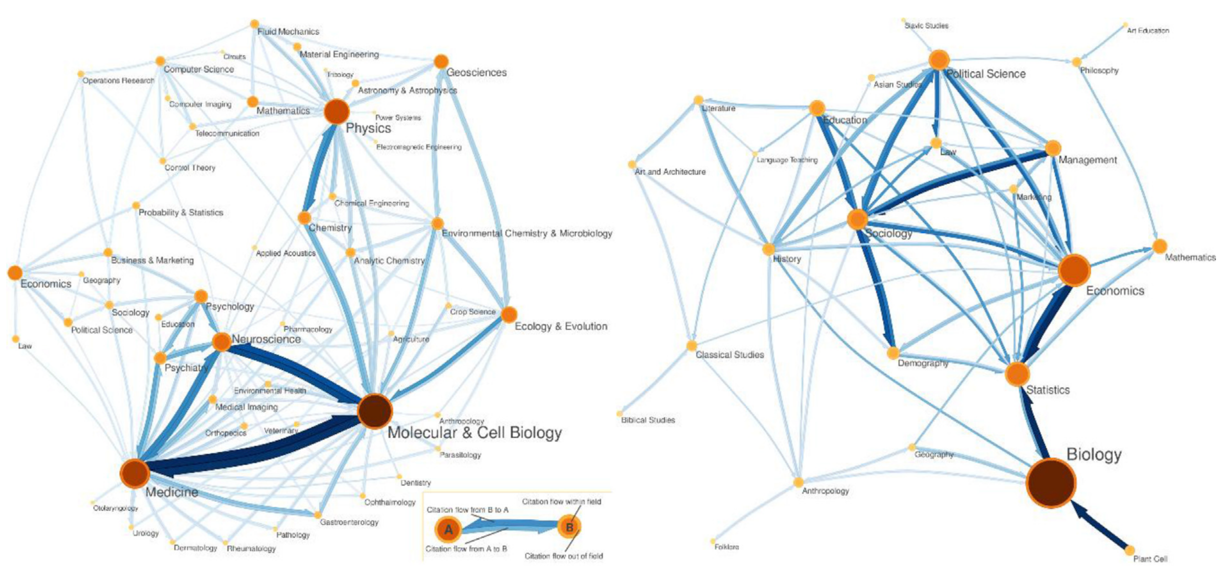
On this basis, we lay that if we try to understand the link between the two fields of knowledge (biology and architecture), then one important requirement is not to mistake the architectural practice (which is more a matter of knowing-how), with the status of knowledge in a strict propositional sense. The latter might be achieved (however rarely) in the field of architectural scientific researches, but architectural practice should not be regarded scientific *per se*.

In Section 3 we will analyse selected case studies in order to understand better hybridization of biology and architecture.

3. Materials, methods and analyses

3.1. Case studies and data collection

In order to investigate the relationship between biological knowledge and design practice, we have selected six case studies of architectural offices base in France pioneering this type of hybridization in their architectural projects according to the criteria of biomimetic design framework in *ISO 18458:2015* (ISO 18458, 2015). Moreover, the interviewees who we have chosen to conduct the interview are actors involved in the investigated hybrid framework. In



(a) (b)

Fig. 4 (a—b) A maps of scientific disciplines based on citation patterns, (b) locating architecture. (Image sources: (a) Rosvall and Bergstrom, 2008, (b) courtesy Martin Rosvall).

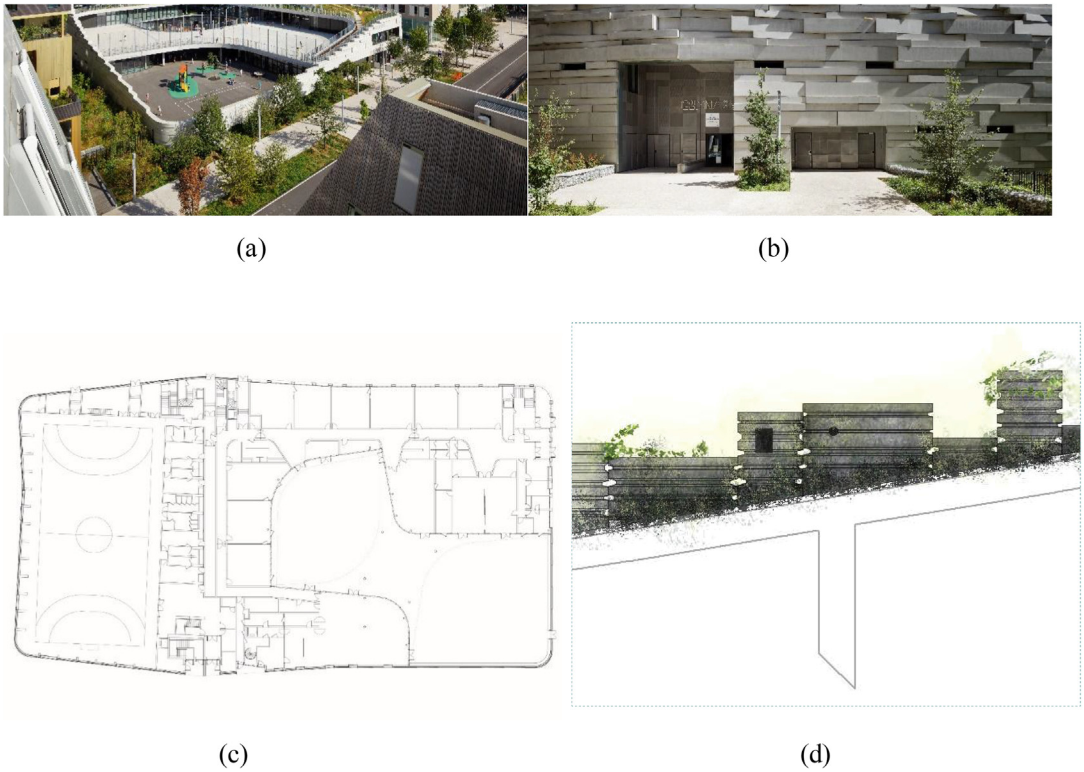


Fig. 5 (a) School and Gymnasium, Boulogne Billancourt. (b) West façade after the delivery of the School in 2014. (c) Master plan. (d) Development of cryptic vegetation on the façade (Image source: ChartierDalix architects).

particular, architects and biological scientists as we are willing to scrutinize biological sciences related knowledge used in architectural design practice. Which are:

No.1 ChartierDalix Architects
No.2 IN SITU Architecture
No.3 Art & Build Architect
No.4 Philippe Rahm Architects
No.5 Tangram Architects
No.6 Bechu & Associates

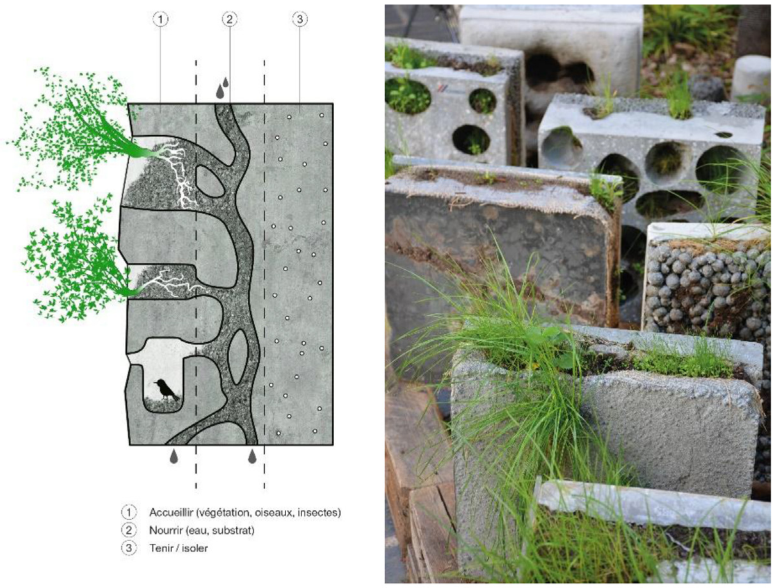
Several methods that we have used to collect the data during the period of 6-month time for different case studies are; corpus (articles, books, journals, etc.), one-on-one semi-structured interviews with open ended questions in person, skype or by phone, following up with several exchanges by e-mails, video conferences and lectures, documents, reports and original images provided by the offices, including the field notes during visiting the offices as shown in Table 1. These data relate to the architectural offices and their design practices as to the integration of biological knowledge (See complete data in Table Appendix 1).

3.1.1. No.1 ChartierDalix architects

For several years, ChartierDalix have conducted work on the integration of biodiversity in architecture Chartier Dalix, 2019. The theme of the competition "School of Science and biodiversity" captured architects' attention on the actual principle of the city, where there is a separation between buildings and their local biodiversity. To answer the theme of the competition, the architects have created a new type of façade system made of concrete blocks that can host local fauna and flora, thus the School group project in Boulogne (Fig. 5) is transformed as part of its local biodiversity, creating ecosystemic network along with nature. The architects have collaborated with two ecologist consultants who accompanied the project phase for the selection of local species to suit the layout of the different environments and the implementation methods to follow the construction site. Note that this hosting biodiversity program had the consequences on the design of the exterior facade that resulted with small proportions of aperture, and that the typology was developped around a courtyard.

For ChartierDalix architects, their interest on research-practice is directly towards application. During the realization of the school group project, the experience feedback from the design process and development of the new façade system, which they found that the separated layers of the façade was too complex for a long-term maintenance. Thus, the architects have pursued R&D project to improve the technical system of the façade. The new concept is to combine all the multi-layers integrating in the façade system as a whole (Fig. 6a). The office has submitted CIR[5] dossier to support their R&D activity. The research framework on *Architecture and Biodiversity-Designing a new urban ecosystem* has started by a call for

[5] The Research Tax Credit, designed to encourage research and company development efforts by deducting from your taxes the research and development expenses in France.



(a) (b)

Fig. 6 (a) New concept of a multi-layer façade system. (b) The first prototype FAIRE (Image source: ChartierDalix architects).

(a) (b)

Fig. 7 (a) Mycelium Workshop 2018. (b) The colonization of mycelium in a façade prototype (Image source: ChartierDalix architects).

projects FAIRE,[6] launched by the *Pavillon de l'Arsenal* in 2017. FAIRE R&D devotes to the studies of new prototypes of façade elements integrating biodiversity and taking into account successful thermal qualities to reconcile external insulation and the use of living organisms. The team has initiated first series of studies and experiments with several types of concrete to understand conditions for growth of various flora and fauna within the façade at the CEMEX Swiss research laboratory in Biel where the first prototype was made in 2017 (Fig. 6b).

Following year 2018, ChartierDalix held two experimental workshops called *Mycelium Workshops* and invited Maurizio Montalti, founder of Officinal Corpuscoli, whose work investigates possible uses of *mycelium*[7] in the fields of art and design (Fig. 7a). The workshops aim to observe mycelium's potential to enrich its environment, especially regarding the sustainability of living wall and their substrate. This experiment allowed the team to observe the mycelium colonization process for further research works on the technical design of the living façade and biodiversity (Fig. 7b).

Further, the architect has submitted a type of research-practice Ph.D. thesis with ANRT[8] launched in October 2019 with the title: *Towards a biodiverse conception of facades: technical proposals and professional recommendations*, proposed by the ChartierDalix office with two academic-research partnerships; Robert Le Roy, thesis director,

[6] FAIRE Paris, calls for innovative urban projects.

[7] Mycelium refers to the fungus' vegetative forms, a root system comprised of filaments producing cells through the decomposition of organic matter.

[8] ANRT is the intersectoral public-private network for French research.

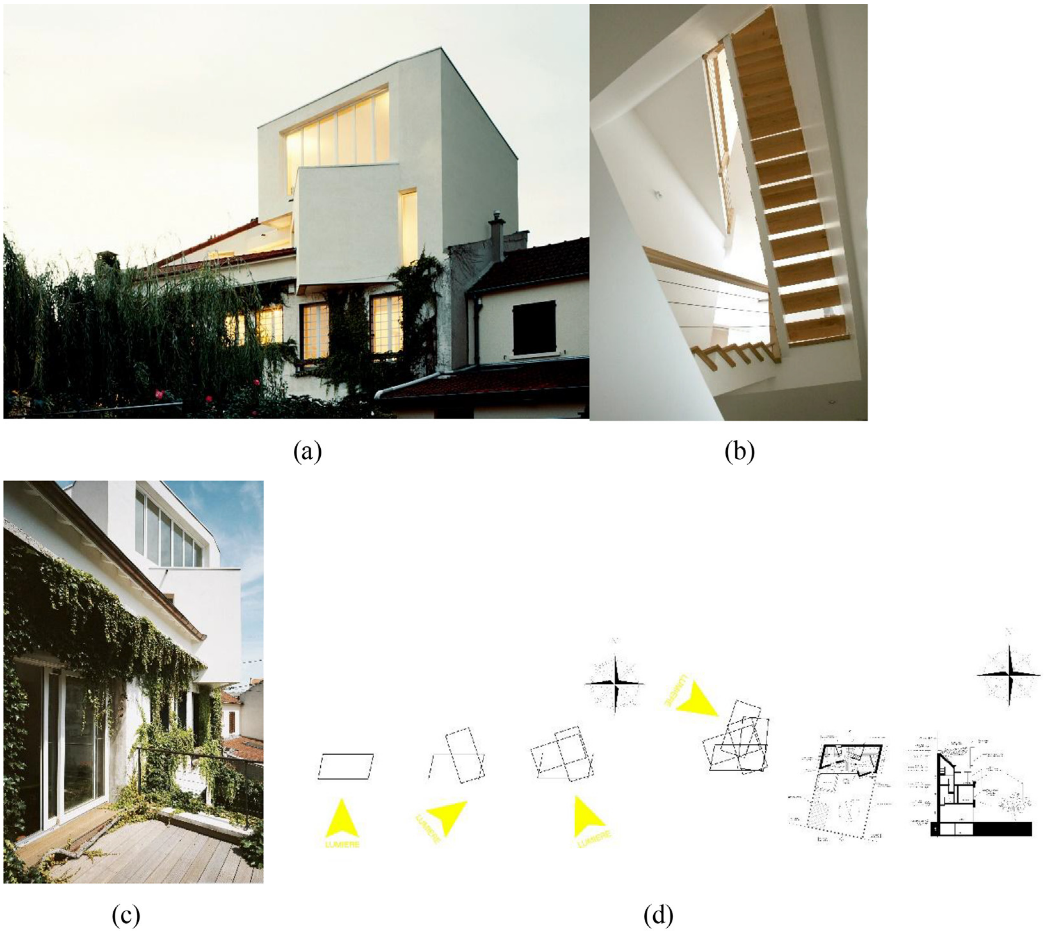


Fig. 8 Spiral house project (a) Exterior building. (b) Interior of the house. (c) Terrace area. (d) Optimization algorithms of sunlight. (Image source: IN SITU architecture).

National School of Architecture Paris-Malaquais and Philippe Clergeau, thesis co-director, National Natural History Museum of Paris, including the doctoral candidate, Delphine Lewandowski who works full-time on the project in three different locations. In addition, the biologist Clergeau brings his point of view on ecological landscape that he applies to cities (Clergeau, 2010). The thesis focuses on the development of biodiversity in cities through the design of living walls, to support this, the team is going to build an experimental instrumented pavilion, consisting of six large living wall prototypes (panels of 1.5m $\times$ 2.5m), in order to observe the living façade and to pursue experimental research within a full-scale test. Placed in different orientations, the pavilion's façades will develop long enough for the team to observe the evolution of three declinations of the biodiverse wall system along the gradual apparition of fauna and flora and the evolution of the vertical substrate inside the wall. The prototypes will be implemented at *Assistance publique — Hôpitaux de Paris* (ChartierDalix's client) in order to test a biodiverse wall system for a real-world usage.

3.1.2. No.2 in SITU architecture

The architect founder, Nicolas Vernoux claims to be interested in biology since at school, deriving from his family background. After he started his own practice, he tried to integrate the aspects around biology directly in his very first architectural projects.

Not until the project 'a spiral house' in Malakoff (Paris), 2007, when Nicolas has started to officially collaborated with his brother Teva Vernoux, a biologist and director of RDP Laboratory.[9] Inspired by Teva's research work, together, they have designed the house using biomimetic approach of the plant's spiral principle derived from *phyllotaxy*[10] to better optimise natural light income at each levels and avoid shading the lower levels (Vernoux, 2020). The translated principle is highly abstracted and the result is not linked to the shape of leaves (Fig. 8).

The hybrid collaboration between the two brothers has started since then. They have developed several projects on the theme of phyllotaxy and biomimetic architecture until present. Furthermore, Nicolas has taken a botanist training level 1 (2011) and level 2 (2013) at National Natural History Museum of Paris, mentioned that some basic knowledge from the training help him to proper

[9] Plant reproduction and development CNRS.

[10] The study of the arrangement of leaves on a stem (see Vernoux, 2018).

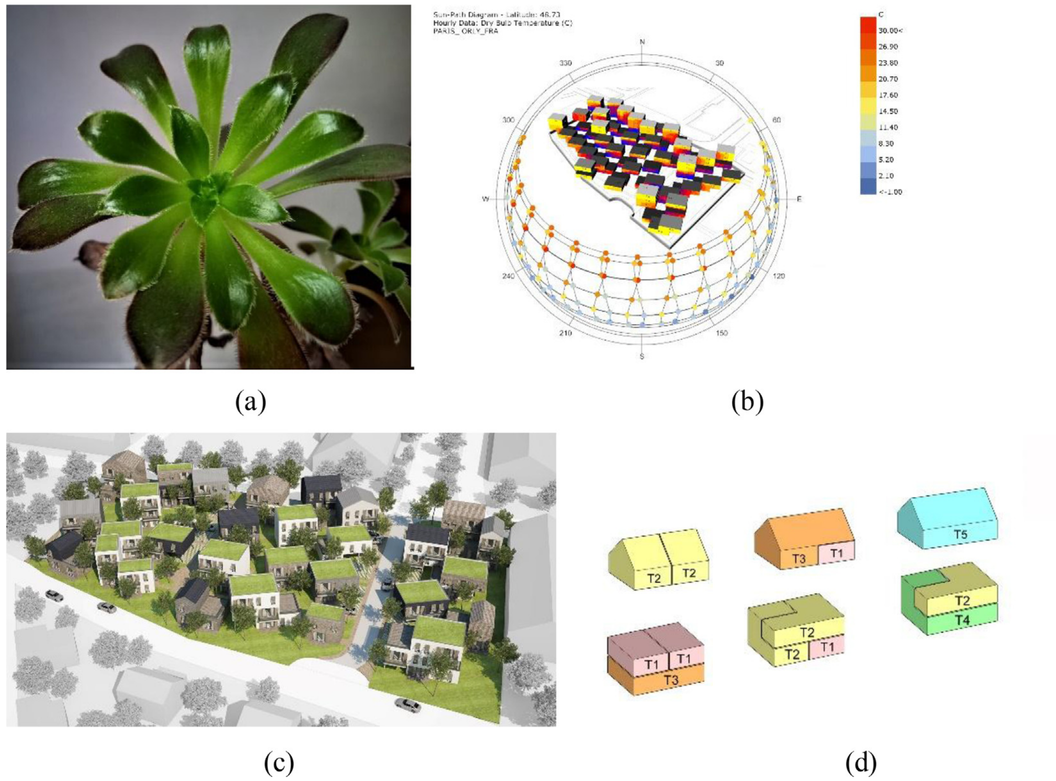


Fig. 9 (a) Phyllotaxy (arrangement of leaves on the stem) (b) Algorithm Phyllotaxy. (c) The arrangement of a 70-unit mixed residence in the Ordener district of Senlis inspired by the principles of phyllotaxy (d) Housing typology (Image source: (a) L. Vitalis, (b, c, d) IN SITU architecture).

communicate with his brother, especially some technical terms in botanical domain.

Since 2016, IN SITU and RDP have become official partnership and have commenced the R&D mainline with a theme of 'an algorithm inspired by phyllotaxy' optimizing the supply of light and solar energy to reduce energy consumption in the buildings. IN SITU has recruited several internships who have highly competences in mathematical and computational modeling to work and develop several algorithm models to suit with project particularities (Fig. 9a and b). The algorithm is initially used in an on-going project 'Senlis Residence Solar 2.0' a creation of 70 housing units in *Caserne d'Ordener*, Senlis, in collaboration with an Institute for Energy Transition NOBATEK for the design study and development of the project in particular on technicality of energetic issues (Fig. 9c and d).

3.1.3. No.3 Art & Build Architect

Steven Ware, one of architect partners, graduated in biology from the University of Western Ontario and in architecture from the Architectural Association in London (AA). As an architect and a biologist, he claims that biology is an important subject that should be integrated into current architectural design schools to be the pursuit of new methods and new construction technique evolves towards more ecologically responsible practices.

In 2017, Steven has initiated R&D project on '*biomimetic kinetic solar shading device for energy efficient building*'. The project focuses on design and development of a self-responsive shading device inspired by flowers' deployment mechanism, which can be observed in certain flowers whose petals close-open as a response to another form of external stimuli, in this case both varying light and temperature (*nyctinasty)*. Steven mentioned that nastic motion of flowers is, for him, alluringly inspirational because flowers have evolved a multitude of mechanisms to actuate organ movement with neither supply or external energy nor any kind of mechanical or electronic control. However, the transformation of these strategies into technical solutions for adaptive architectural envelopes requires a large number of studies and experiments with new technologies, which include smart materials and new capabilities in simulation software. BILAME is the first prototype (Fig. 10a, b), the use of smart materials, SMA as an actuator wire and Thermobimetal as the petals are selected for biomimetic application, so it needs very small amount of activator to move the shading device, because the material react itself to the temperature change. BILAME façade prototype is envisaged to be implemented in the new headquarters for the International Agency for Research on Cancer in Lyon (IARC) with delivery expected in 2022 (Fig. 10c).

Further, Art & Build has developed the second prototype called *Pho'liage*. This developed prototype tries new opportunities to merge energy production with solar shading, with PV sub-elements integrated into the petal-like devices. Renewable solar energy can be used to further reduce cooling loads in buildings. Art& Build has recently tackled the topic of biodiversity in collaboration with biologists and sociologists. Steven Ware claims to increased collaboration to improve biomimetic design processes and applications as ideas continue to emerge from experts from different disciplines and the practice strengthens its

Fig. 10 (a) BILAME shading device. (b) BILAME prototype with human scale. (c) BILAME envisaged to be implemented at IARC (Image source: ArtBuild).

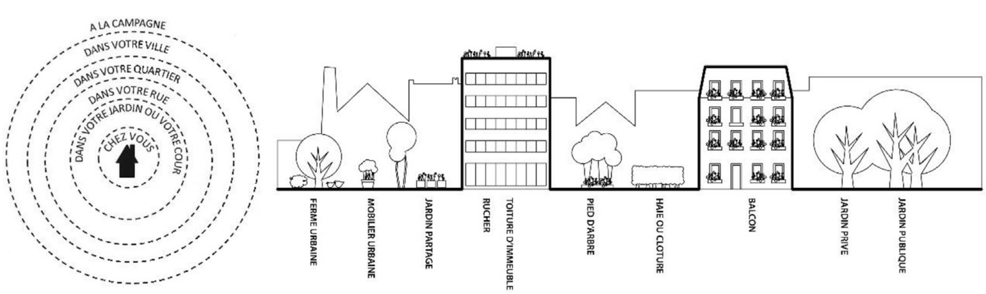
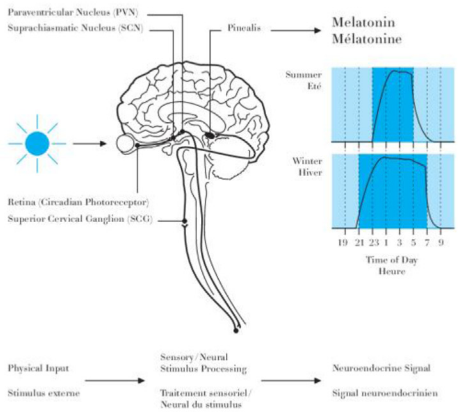


Fig. 11 Research paper #01- Biodiversity: a new element for urban planning (Image source: ArtBuild).



(a)

(b)

Fig. 12 (a) Melatonine activation principle. (b) Hormonorium spatial experimentation (Images source: Philippe Rahm Architects).

discourse alongside urban ecologist Philippe Clergeau. New projects include mapping the urban microbiome, better understanding biodiversity (Fig. 11).

3.1.4. No.4 Philippe Rahm Architects

Philippe Rahm's works aim to extends the field of architecture from the physiological to the meteorological approach creating synergetic relationships between climate-architecture-habitant. Rahm personally has interest in medicine, in its certain sciences like *biochemistry, physiology* and *thermoregulation*. This scientific knowledge is presented in his architectural design works, which shifts architecture radically from a notion of purely solid object to invisible atmosphere composition. During several years of his architectural practices, Rahm has been exploring with various phenomena shaping the atmosphere as exhibited in his six main architectural phenomenology; *radiation — conduction — convection — pressure —evaporation — digestion*, explored methodologies of architectural spatial design as the environmental with certain meteorological parameters.

Rahm and Décosterd presented the project *Hormonorium* in 2002 at the 8th Venice Architecture Biennale, which aims to establish a continuity between living and non-living through the concept of physiological architecture. In collaboration with two scientific actors, Prof. Urs Scherrer, Department of Internal Medicine, CHUV Lausanne and Dr. Anna Wirz-Justice, Center for Chronobiology, University of Basel. The result is not about the architectural formal language that is quite absent as we can see in Fig. 12b. Beyond its almost high-tech style, this architecture is about the sensory experience of the space.

Philippe Rahm's work had remained largely conceptual until the Taichung Park competition in 2012. *Central Park* project (Fig. 13), which gave him the opportunity to explore climate ideas on an urban scale maintaining his point of view in human experience. This project represents a new type of 'thermodynamic architecture[11]'based on energy and climate criteria rather than on the current financial or economic criteria shifting architectural production towards the microscopic and the atmospheric, the biological and the meteorological space. In this project, Rahm has collaborated with multi-disciplinary actors from landscape designers, climatic engineer and Dr. Anna Wirz-Justice.

3.1.5. No.5 Tangram Architects

Since 2013, Tangram Lab has been created for research and development on the theme of bioinspired materials, led by Olivier Bocquet. The first conceptual project is *Parramatta Tower project*. The purpose of this tower was to develop a concept of glass towers in blue-green tones, recalling the color and appearance of the local eels. To succeed in restoring this color, Olivier Bocquet turned to the moon jellyfish (Fig. 14a) and their naturally luminescent properties providing this singular shade, this particular biological property becomes the starting point for the R&D mainline on bioluminescence material for architecture and construction since. Although for this conceptual project, the form of the tower is not itself affected by the biological data. The language remains one of international styles with the additional material of bioluminescence glow (Fig. 14b).

In somehow, the characteristics of the project drove the team to combine on multiple and complementary skills, in architecture and science, which allowed them to develop the research subject entitled *BIOLUMARCHI: Bioluminescence research for potential applications in architectural projects*. Tangram has established a research collaboration contract[12] in 2016 to support BIOLUMARCHI, which is a scientific research project, taking the form of a doctoral thesis collaborated with a scientific research laboratory MIO (Mediterranean Institute of Oceanography CNRS) along with Christian Tamburini, research director and the PhD candidate, Lisa Tanet. The research project aims to understand the environmental conditions and the

[11] Philippe Rahm speaks about 'Thermodynamic architecture' in (Rahm, 2008).

[12] The research collaboration contract is negotiated by the Research Department and the SAIC in partnership with the researcher and the industrial partner.

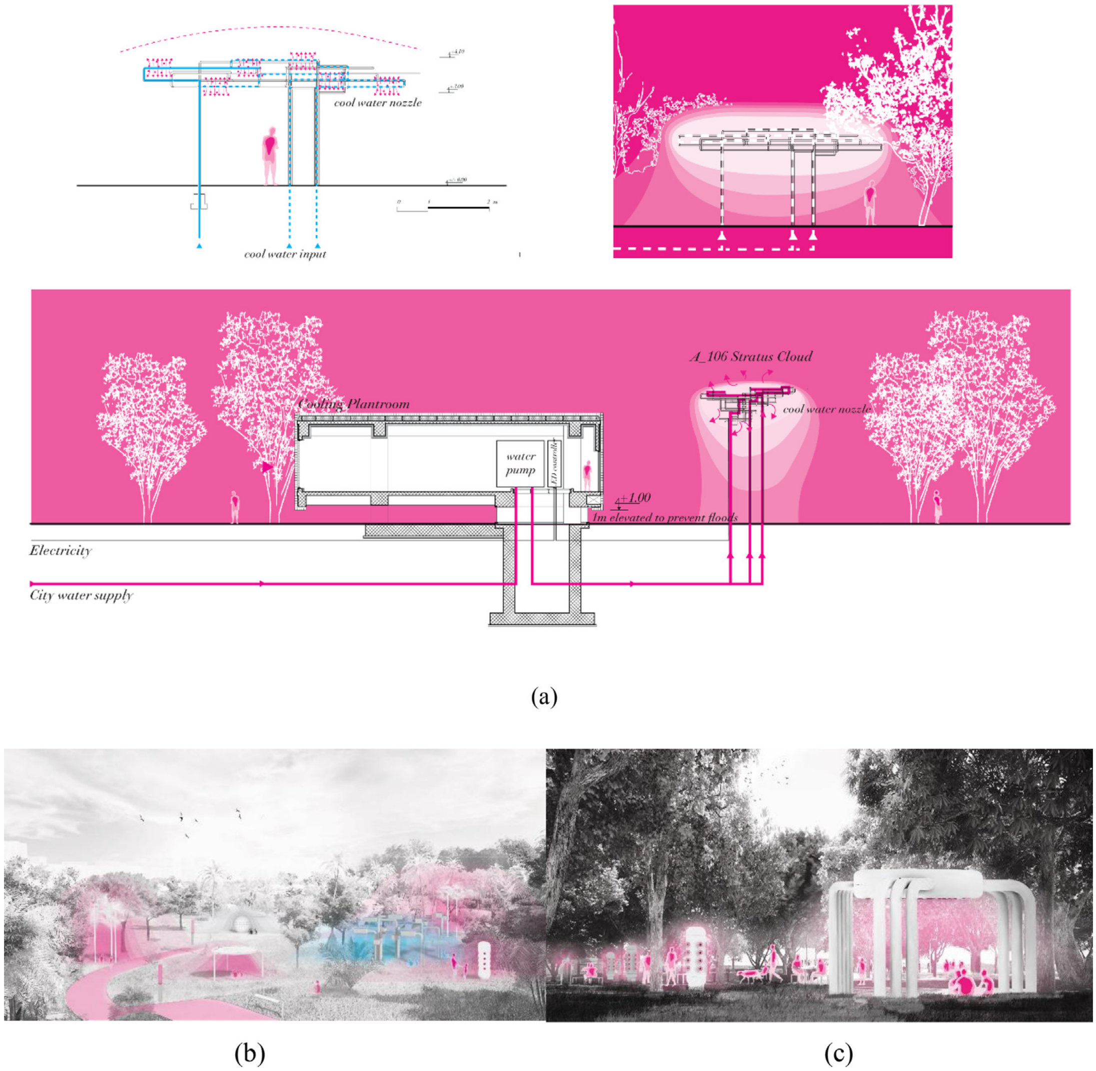


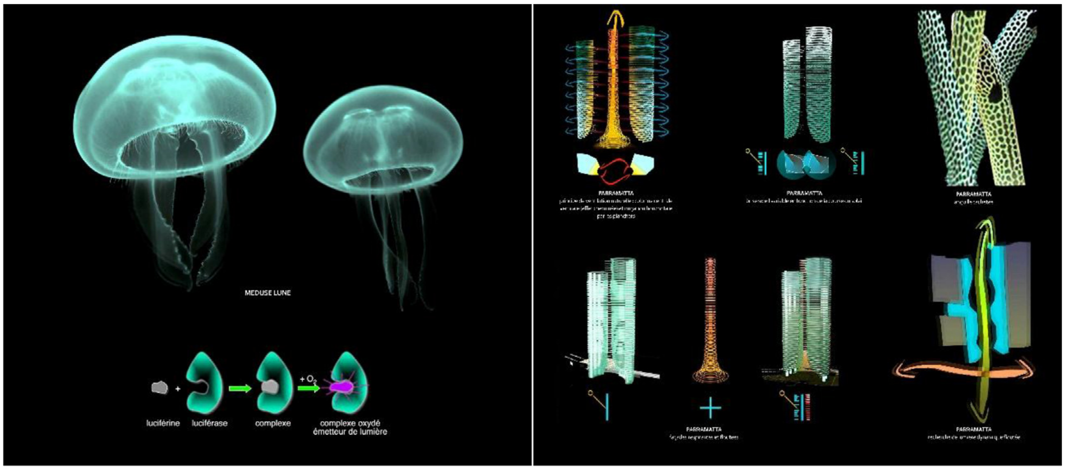
Fig. 13 Central park project. (a) The natural cooling device by evaporation. (b) Climatic variations in the park mapped by computational fluid dynamics simulation (CFD). (c) Visitors' body temperature relating to different climatic devices. (Image source: Philippe Rahm Architects, Mosbach paysagistes, Ricky Liu & Associates).

development parameters of bioluminescent bacteria for developing autonomous lighting materials for architecture (Tanet, 2020).

Within the same research framework, Tangram lab collaborate with Laboratory MIO to pursue a research on prototype of bacterial cultures and microalgae towards different types of bioluminescence materials (Fig. 15a), the on-going project has initiated in 2018 called *BiolumReef* (Fig. 15b and c).

3.1.6. No.6 bechu & associates

Bechu architects has recently developed R&D on biomimicry. In the article *Using architecture to reconnect cities with nature* (Bechu and Bechu, 2019) presents their on-going projects and architectural design concepts within Bio-inspiration and biomimicry framework aiming towards synergetic relationship of architecture and nature. The architects turn to biomimicry claiming that this new approach has enabled them to construct buildings with outstanding energy performance in parts of the world with severe climate constraints, as presenting in one of their projects *Skolkovo, district 11*. The architects were asked to design a group of housings for researchers and their families in an extreme cold location. The initial idea was the master plan arranging numbers of housing in circle form. Lead architect, Pablo Lorenzino was interested to observe emperor penguins as a role model for architecture and urban design in such extreme cold climate. The master plan and the arrangement of the group of housings (Fig. 16b) are inspired by a social organization of emperor penguin (Fig. 16a). Lorenzino mentioned that he has learnt this biological principle



(a) (b)

Fig. 14 (a) Concepts for the tour of Parramatta-bioluminescence applied to architecture, (b) Moon Jelly fish with luminescent properties (Image source: Tangram Architects + TREEX).

from nature documentaries and particularly from two scientific articles (Gerum et al., 2013; Zitterbart et al., 2011). The intention is to create micro-communities organized around a central space that provides the atmosphere of a village square in order to create a social link between residents. At the same time the architect says that he used a calculation algorithm to transpose this principle of thermal regulation to an urban complex, which is capable of protecting a hundred individual houses from the extreme cold and ultimately saving 5 °C

(a)

(b) (c)

Fig. 15 (a) Prototypes of bacterial cultures and microalgae. (b) *BiolumReef* project. (c) Bioluminescence material prototype (Image source: (b) Tangram Architects, (a, c) Tangram Architects + M.I.O. (Mediterranean Institute of Oceanology)).

Table 1 Six case studies and methods for the data collection (Table by N. Heil and L. Vitalis).

Architectural offices	Interviewees	Types and numbers of Interview	Offices visit(s)	Documents provided by the offices	Other types of data by researchers
ChartierDalix Paris	Interviewer: Natasha Heil **Frédéric Chartier** **Pascale Dalix** **Sophie Deramond** (Architects, partners) Interviewer: Louis Vitalis **Philippe Clergeau** (Biologist)	Face to face: 1 Telephone: 1 Email exchanges Telephone:1	1	Original images	Books, Video conferences
IN SITU Paris	Interviewer: Natasha Heil **Nicolas Vernoux** (Architect, founder) Interviewer: Louis Vitalis **Teva Vernoux** (Biologist)	Face to face: 3 Email exchanges Skype: 1 Email exchanges	3	Original images, A book of IN SITU projects	Video conferences, scientific articles
Art & Build Paris	Interviewer: Natasha Heil **Steven Ware** (Associate architect)	Face to face: 1 Skype: 1 Email exchanges	2	Original images, a report on biomimetic framework in PDF	Scientific articles
Philippe Rahm Paris	Interviewer: Natasha Heil **Philippe Rahm** (Architect, founder)	Face to face: 1 Email exchanges	1	Original images, websites linked to projects	Video lectures, press articles
Tangram Marseille	Interviewer: Natasha Heil **Olivier Bocquet** (Architect, director of Tangram Lab) Interviewer: Louis Vitalis **Lisa Tanet** (Biologist, PhD MIO)	Skype: 1 Email exchanges Email exchanges	—	Original images, a presentation of biomimetic projects in PDF	Video conferences, scientific articles
Bechu Paris	Interviewer: Natasha Heil **Pablo Lorenzino** (Associate architect) **Clémence Bechu** (R&D associate partner, business developer)	Telephone: 1 Email exchanges	—	Original images, a report on biomimetic projects in PDF	Video conferences, scientific articles

Table 2 Summary table of the design decision framework applied to the case studies (Table by L. Vitalis and N. Heil).

Case study - Selected projects	Main purposes and guidelines (with which biology is concerned)	Affiliated scientific fields involved in the design practice (biology and related)	Type of structure produced (result concerned with the use of biology)
1. Chartier Dalix — Faire Pavilion (Paris)	> Pedagogic ends (observing long term natural colonization, the idea first came in the project of a school in Boulogne Billancourt) > Sustainable construction process (panels should be able to be assemble and disassemble) > Subnature (instead of the classic clean hygienic façade, acceptance and value-creation of uncontrolled weeds) > Aesthetic (random composition)	> Biodiversity > Landscape ecology (systemic holistic approach)	Component (Inhabited facade system)
2. In SITU — Ordener District (Senlis)	> Sustainable energy consumption (using passive income) > Human comfort (the daylight should be a factor of healthy habitat)	> Phyllotaxy > Geometry > Physics (solar model heliodon like, implemented in Grasshopper plugin Ladybug)	Urban district (70 housings) *note: other projects of the office are bioinspired architectural spaces
3. Art&Build — IARC headquarters with BILAME panels (Lyon)	> Human comfort (providing shadow, avoiding overheated interiors) > Sustainable energy consumption (passive moving actuators and cooling systems) > Aesthetic (changing aspect, petal shape)	> Nyctinasty (Day/night nastic motions of flowers) > Smart materials (shape memory alloy and Thermobimetal)	Component (BILAME shading façade system)
4. Philippe Rahm — Central Park (Taiwan)	> Human comfort (enjoying outdoor spaces despite summer despite heat humidity and pollution)	> Climate science (physical geography study of atmosphere: heat, humidity, pollution variations)	Urban district (urban park with facilities and towers) *note: other projects of the office are bioinspired architectural spaces

	> Aesthetic (creating diverse sensual experiences) > Subnature (replacing the idealistic clean, cool and dry space by accepting continuous variations of this parameters)	> Fluid dynamics (physical flow models) > Human physiology (sensations and thermoregulation)	
5. Tangram — Parramatta towers (Sydney area)	> Sustainable energy consumption (reducing lighting energy needs) > Human comfort (the light should be sufficient to allow certain activities) > Aesthetic (link with the cultural symbol of the eels, aquatic bluish hue) > Economical challenge (it should be a competitive technological innovation)	> Oceanography > Bacteriology (bioluminescent bacteria) > Genetics (*lux* gene) > Biochemistry > Bioinformatics (metagenomics)	Component (material)
6. Bechu + Associés — Skolkovo district 11 (Moscow area)	> Sustainable energy consumption (reduce heating energy needs) > Human comfort (small neighborhood unit for social life, resisting extreme cold) > Aesthetic (avoid the repetitive grid ground-plane)	> Social behavior (animal huddles) > Physics (colloidal jam and solar model heliodon type, implemented in Grasshopper environmental plugins Ladybug/Honeybee) > Mathematics (model of traffic jam dynamics)	Urban district (90 housings)

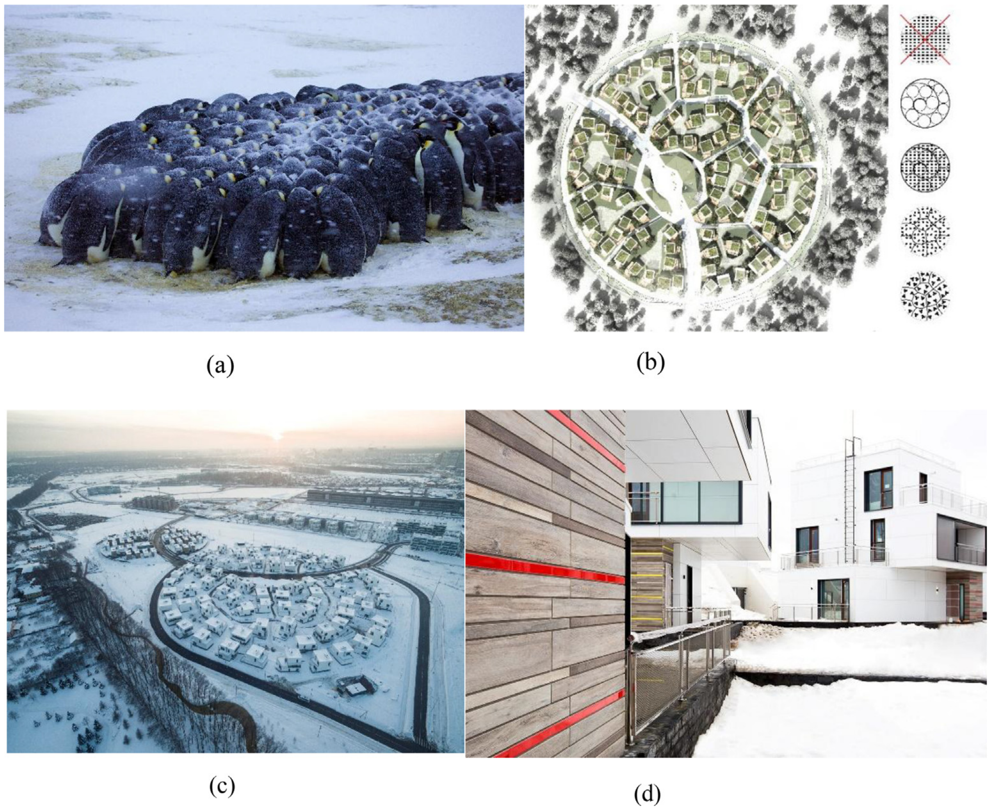


Fig. 16 (a) Social huddling phenomenon of emperor penguins. (b) Concept master plan. (c) Skolkovo village district 11. (d) Skolkovo's housings (Image source: (a) Fred Olivier, Nature Picture Library, Science Photo Library, (b, c, d) Bechu architects).

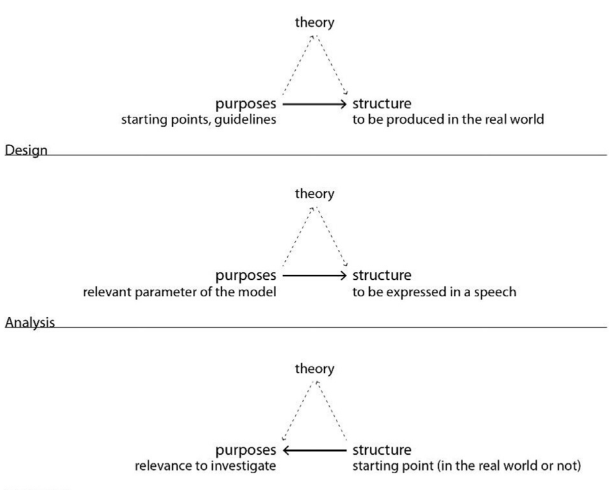


Fig. 17 Types of 'theory usage decisions' (Diagram by L. Vitalis, translated from *Que peut-on faire des théories?* Vitalis and Guéna, 2019).

in temperature. Note that although the penguins regulate temperature through their movements, the buildings are motionless. Thus one could argue the result of the transfer from biology is based more on formal resemblance rather than on process (Fig. 16b and c).

Currently, Bechu office is engaging in the design of a large scale on-going project of 2900 m^2, *Estran: Center of Excellence in Marine biomimicry of Biarritz* integrating biomimicry in ecosystem level, interfacing between climate and ocean. In collaboration with specialists; François Gaill, Oceanologist, scientific director of the Institute of Ecology and Environment of CNRS and Pr. Yves Tourre, Climatologist, researcher at Columbia University.

Next chapter, we will focus on the analysis of selected projects of each office to scrutinize how the architects understand and use biological sciences in their architectural design practices related to final applications.

3.2. Biological knowledge used in the design practice: case studies

In order to now better understand the role that biological knowledge plays in design practice of these architectural offices, we will attempt to reuse the classification of theoretical uses in modeling practice we proposed previously: this framework, distinguishes three modeling types (design, analysis and simulation) to understand the use of a scientific theory (Vitalis and Guéna, 2019). We showed that it corresponds to three types of decisions of using a scientific theory, each one involves different purposes (ends in a teleological system) and some structure[13] (whether real or ideal). This is synthetically express by the Fig. 17. We will use it as an analytical framework for our case studies.

[13] One should not be misled by its architectural background, 'structure' is intended in the sense of systemic theory: a system has a structure (stable form) that is active and evolves in an environment according to some ends (Le Moigne, 2006).

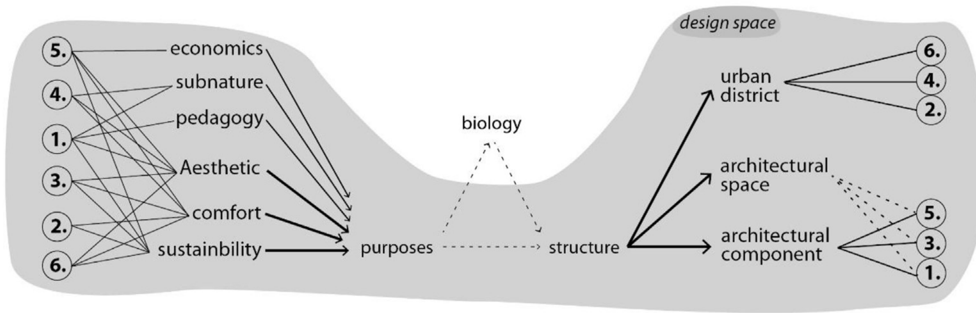


Fig. 18 Design modeling decision framework applied to the case studies' design space (Diagram by L. Vitalis).

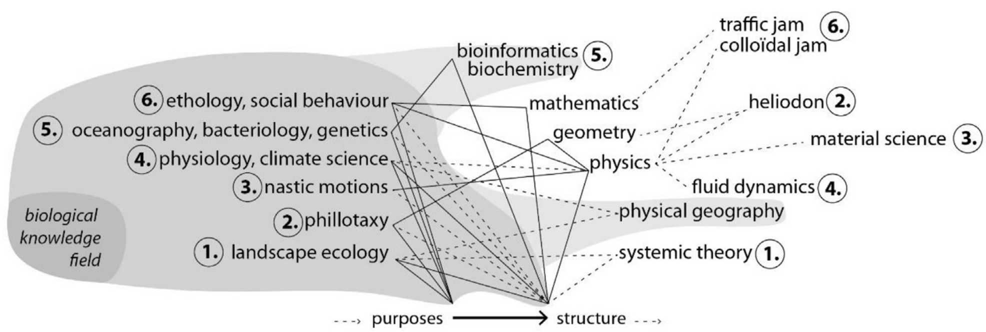


Fig. 19 Design modeling decision framework applied to the case studies' knowledge space (Diagram by L. Vitalis).

For the feasibility of the study, we here focus on one project for each office as detailed in Table 2. We will focus only on the 'design' type of decision as the cases mainly match with it. If we first focus on the inputs and outputs, we see that the six offices used biology in a design space that has purposes external to biology and produced structures that are smaller (component) or bigger (urban) than architecture.

As seen in Fig. 18, architects used ingredient from biology in order to produce a real structure: whether building component or urban district. They were intending to produce some physical modification (they did not aim to produce concepts neither discourse even if they might be a tool). The first observation at this step is that the architects used biology not exactly to produce architectural spaces, but tended more to produce components (that are intended to be used in various architectures) or urban schemes.[14] For example, in the IARC headquarters, the façade panels of BILAME represent just a small part of the architectural complexity and there are not specific to it since they are made to be reused elsewhere. This was predictable if we acknowledge the stranglehold of engineering on the biomimicry field, leading to a latent difficulty to design a genuine biomimetic architecture (that one should be able to conceptually distinguish from urban-planning or engineering biomimetics).

When biology is introduced in architecture, the design space is not neutral, but already oriented by values, intentions and guidelines, which alter or lean the pure biological knowledge. These purposes have been grouped in common categories. We try to only list values concerning the use of biology that are still external to it. Three core purposes for calling on biology are sustainability, human comfort and aesthetics. Each varies in its exact content. Some other secondary purposes were also identified with economics, pedagogy and what we called 'subnature'. With reference to David Gissen, subnature means a reversal of classic values: the ideal of clean hygienic architecture and its rejection of 'dirt' is replaced by acceptance and value-creation (Gissen, 2009).[15] This list of purposes might not be exhaustive, since it is based on the gathered data, freely communicated by architects,[16] they are still the most prominent. For example, Tangram architects call on bioluminescence, which is a light phenomenon produced diversely by bacteria (Tanet et al., 2019) and relying on a genetic diversity (Vannier et al., 2020). But when the architects catch it, they add to it a value: at least implying the idea that it is better for architecture and urban systems to reduce carbon energy consumption, and that light should have a certain intensity to be comfortable enough at certain moments of the day … we might agree with those values, the point is, they are exterior to nature itself (nature doesn't switch the light off because she wants to pay

[14] However, this result should be tempered since it is partly due to the chosen projects. Some offices with an older relation with biology, as Philippe Rahm and IN SITU, seem to use biology also at the architectural scale.

[15] Philippe Rahm is explicitly mentioned in this book (p.109).

[16] Tangram office might be transparent on the economical innovative target, but this doesn't mean that other architects don't.

less charges at the end of the month[17]). Likewise, before the inspiration of the emperor penguin's social huddling ends up in the Skolkovo project (case No. 6), the architects had already decided to group the buildings in small subgroups which was not a feature of the penguin huddles. But since they granted value to this sub-groups organization, they adapted the biological knowledge to a set of values already presented in the design space (Lorenzino, 2018).

With a second look focusing on the biological ingredient, we see that the use of biological knowledge is more complex than it seemed. There are three reasons for this: often the knowledge involved has non-biological aspects, is not strictly theoretical and it could be obsolete or approximate.

Even though architects called on biology, we have observed that the scientific field involved is multiple, and moreover that through biologies other sciences appear (Fig. 19). This is due to a known interplay of sciences which are sometimes historically constructed one with the help of others. Thereby, non-biological disciplines may be not involved directly neither intentionally by architects. The fact remains that biology acts as a mediation between more sciences. For example, by calling on Phyllotaxy, *In Situ Architecture* is led to use models from physics (like heliodons). This leads sometimes to simulations; there, it is not biology that is simulated, but the physics phenomena. The relation to biology is even more scattered with the tool taken from the study of the emperor penguin's huddling that *Bechu + Associés* used. We can observe that the architects resorted to a study published in a journal of *physics* (mentioned in Lorenzino, 2018), from which they took a *mathematical* model first made for the understanding of *traffic jams*[18] ... this should make us wonder about the specificity of biological knowledge implied here and its implicitly associated sustainability. But, not to simplify the situation, mathematics should neither *a priori* be regarded as non-biological. Its role could also be regarded as the one of a tool, just as it is for physics.[19] Some projects seem to involve more directly biological knowledge as cases No. 1 and 4, this might be because they use human biology, or a biology studying human phenomenon (human physiology, urban ecology). This is why their approaches are less mimicking than utilizing biological phenomena concerning humans. The same tendency is seen in case n°5 but the reason is that there is a direct use of living beings (rather than an abstract application of knowledge).

Also, the status of the biological ingredient cannot be strictly defined as theoretical. As seen with the example of the penguin huddles, it may be already a model. Ingredients taken from biology oscillate between models, general concepts, forecasting ideas, even livings themselves ... One of the latest book of Philippe Clergeau, the biologist collaborating in ChartierDalix's project among others, is a manifesto (Clergeau, 2015). Yet manifestoes use to be an architect's hobby. By invading the ball park of artists and politicians, the scientist is found where he is not expected. Clergeau has an atypical career history, as part of the scientific committee of the PUCA (an inter-ministerial service conducting action research, and encouraging innovation), supervising architects PhD, working as a consultant, etc.... he has moved from his first naturalist attitude to invest an emerging field where research blurs with action, getting away from the classical observational scientific attitude.

Ultimately, we should also stress the degree of precision and depth of the biology involved. Biologist Teva Vernoux gave us the hint of this idea, when he told us that useful biological concepts for architecture are intended in a really general sense. The details of the natural model could be of no use because they have to be rebuilt in the architectural field. Following this trail, we see that Philippe Rahm, for example, declares that the source of his biological knowledge is taken in two books (Koolman and Henrich Röhm, 2004; Silbernagl and Despopoulos, 2001) and mentions Google scholar and *Nature* in general (rather than a specific publication). The fact that the books are student textbooks published several years before the competition *Central Park* (and even more before its opening) should lead us to doubt on scientific agenda of this knowledge. Whereas the databases he uses show that these scientific fields are very productive[20]. This great amount of publication indicates on the other hand a rather imprecise reference: aren't they any progress, contradiction, refutation in such a productive discipline? In the same vein, *Art & Build* office takes interest in the nastic motions of plants which, depending on species, react to various stimuli as light temperature and are due to a cell *growth* (Doorn and Meeteren, 2003). But then, after going through material sciences, the *BILAME* project reacts only to temperature (brought by sun, but works in the dark) and is due to an *expansion*. *BILAME* doesn't adapt to the seasonal variation. While the flowers open to increase exchange with their environment and enabling reproduction, the brise-soleil provides more shadow and reduces the exchange with the outside. All this should not be seen as a critique neither of the *Art & build's* prototype neither of Philippe Rahm's erudition which both certainly required a big amount of work. It just indicates us that the link between biology and architecture can be based on very approximate or general links, and that it does not prevent architect's design practices.[21] This is not to say that the specificity of biosciences should be rejected, but that we need to catch this vagueness in its very process since it seems to be a characteristic of designing with biology. It also opens up

[17] It is in the name of what humans call « nature » that they sometimes do.

[18] The model makes the researchers assume that the penguins 'are oriented all time in the same direction' (as cars are) despite the observations. This doesn't mean that the model is wrong, only that it implies a specific point of view. (Gerum et al., 2013).

[19] As, biologist Philippe de Reffye argues for example in (Coutellec, 2014).

[20] 920,000 results on Google scholar and 8966 on Nature between 2001 and 2011 with the keyword 'physiology'.

[21] This result is consistent with other observations we made where a bird nest could be seen by the designers equivalent to a Mikado game or a spaghetti plate (Vitalis, 2020).

to a wider discussion because science is sometimes used as the criterion to depart biomimicry from a simple bioinspiration: should we then understand that the same architecture, today regarded biomimicry, might become, even though unchanged, bioinspired with the progress of biological sciences?

4. Findings and discussion

4.1. Interdisciplinary collaboration and hybridization of knowledge

Main reason that the architects of our case studies turn their interest to biomimicry is sustainable related aspects. Spoken of responding to actual environmental problems, energetic concerns and material used for construction, but personal interests, competitions and office images are also main drives that mobilize biomimicry in their works. Architects claim that they turn to biology as new knowledge and inspiration for new design ideas and strategies, involving the optimization of resources and materials, new type of facade systems, and the use of renewable energies, but perhaps not just all. Also to mention: innovation might play a role in the economic competition of the offices. This external factor falls out of our scopes but could be later studied.

There are different forms of interdisciplinary collaboration and integrate biological knowledge in the design practice (see Table Appendix 1). For example, S. Ware (case No. 3) has graduated in biology before pursuing architecture, having two combined degrees, as a trained biologist and architect help facilitate the integration of biological knowledge into architectural practices. N. Vernoux (case No. 2) has close collaboration with his botanist brother T. Vernoux on Phyllotaxy model, and he also has done some basic course in botany at the National Natural History Museum of Paris. Other cases (No. 1, No. 4, No. 5, No. 6), all the architects have developed interdisciplinary collaborations with biological science experts. There are only 2 cases (No. 1, No. 5) that have established a research-practice contract in a form of PhD thesis, one is CIFRE system and another is Research collaboration contract. ChartierDalix has mentioned that they need someone who can work on the research subject full-time and for Tangram, they need somebody with a particular competence to work on bioluminescence of different bacteria species.

P. Rahm (case No. 4) also learns about biology through self-taught. He has intrinsically integrated biological sciences since his early works without having a segregation between scientific research and architectural design practices. On the other hand, a biologist like Philippe Clergeau now sees himself as an urban planner (Clergeau, 2019) The role of clients is also as important as main collaborators. As seen, in ChartierDalix and Art&Build have chosen to implement (case No. 1) or to test (case No. 3) their biomimetic design applications and prototypes with the clients who they design and construct the building for.

Biomimetic is an ambiguous concept because it is not clear what "bio" refers to: nature or its scientific study? In the end, we should ask ourselves what does the use of biological sciences provide to the field of biomimetic architecture? The use of biology does not seem to be a sufficient criterion for biomimetic architectural design since some cases might be called bioinspired. But the question should be answered keeping in mind that our cases show that the hybridization affects both domain: biology losses some rigor and is not an architectural cure-all.

4.2. Biological knowledge and architectural know-how: an epistemological opening

It should be said here that the analysis and the findings from Section 3.2 are somehow not completely satisfying. The fact that all cases are in the same category (design decision) is correct in a sense but doesn't provide us a unified understanding of what happens to biological knowledge in the architectural design practice. Because of the aforesaid hybridization, the meanings 'theory', 'model' or 'biology', etc., tends to vary. Thus, we find out concepts where we would not classically expect them (like a scientist writing manifestoes). Our classification only helps us situating these architectural practices in a general manner, but is limited to precisely address its diverse types. Regarding the biomimetic architecture field, our cases tend to corroborate the opposite views of both Ch. Alexander and P. Schumacher: for the first view, because the abstraction from biology leads to other fields of knowledge such as mathematics and systemic theory (here it has been pushed further to other disciplines), for the second, because biomimetic results tend to be limited to engineering components and hardly find a specific architectural language (here we point to urban schemes as another limit).

One important question opened to our view is the problem coined as a displacement between architecture, science and biology. To find a way out of this fuzziness, we suggest to consider two different kinds of objects. The difference is not only one of content, but also, and more epistemologically fundamental, a formal difference. One refers to a scientific object, the other to one or more empirical objects.[22] If we are speaking about only empirical objects — *a duck and a specific house* (both seen as givens) — or only scientific objects — *the homeostasis process and the architectural design operation of scaling* (both in a specific theoretical frame) — everything would have been more simple. We suggest that the study of this displacement could lead to understand the confusion between science and technology, between propositional knowledge and know-how (see Vitalis and Heil, forthcoming article, Forcing Biological Sciences into Architectural Design).

[22] On the difference between given (empirical) objects and constructed (scientific) objects, and architecture as an empirical object that can be taken from the view of various scientific objects, see (Boudon, 2001).

Appendix 1 The table shows different collaborated actors, types of organization, external activities, biological and sciences related knowledge that each office has implemented for their hybridization framework.

Case N°	Hybridization Framework "source(s) of inspiration"	Internal actors (inside office)		External actors/structures (outside office)		Collaborations		Subside(s)	Other activities to support the framework
		Profession(s)/ training skills	New recruitment	Biological science related Professions	Other professions	Established framework	Client(s)		
1	Architecture as an ecosystem	F. Chartier P. Dalix Architect dplg, founders S. Deramond Architect dplg, PhD, partner, Head of R&D	Delphine Lewandowski PhD candidate CIFRE	P. Clergeau (FAIRE + CIFRE) A. Huguet JL. Ducreux (School project) N. Bel F. Madre M. Barra G. Lecuir (FAIRE) All Ecologists	P. Le Roy Professor at ENSAPM (CIFRE) M. Montalti, designer (FAIRE) CBC Vinci construction group (FAIRE)	FAIRE R&D CIFRE	Public (APHP, Saem Val de Seine)	CIR CIFRE contract	Book Hosting life: Architecture as an ecosystem, 2019
2	Architecture inspired by phyllotaxy	N. Vernoux, Architect dplg, founder, Training botanic course level 1 and 2 at MNHN	Several temporary internships	T. Vernoux, Botanist JP Vernoux, micro-biologist (Terre d'algues)	G. Mortier, recycling consultant (Terre d'algues) Olivier Scheffer BIP consultant NOBATEK	Informal collaboration for Phyllotaxy and biomimetic architecture framework	Public (Mairie de Senlis) and privates	BIP	CEEBIOS Biomim'expo Biomim'city Lab
3	Shading system inspired by nastic motions of plants Biodiversity	Steven Ware Architect dplg, trained biologist, partner Art & build Paris	—	P. Clergeau, ecologist PJ. Lopez, biologist V. Hervé, micro-biologist	R. Raymond, sociologist UCL ULB	—	Public (IARC and public competitions)	Horizon SME	Guideline Tarik Chechak's lectures
4	Physiological/ meteorological architecture	Philippe Rahm Architect dplg, PhD, founder, Teaching at ENSA Versailles	—	A. Wirz-Justice, medicine U. Scherrer, chronobiology	Mosbach paysagistes Ricky liu & associates Transpolar Munich, climatic engineers	—	Public (Taichung City Government)	—	Several books on physiology and meteorology architecture

5	Building material incorporating bioluminescence	Oliver Bocquet, Architect dplg, director of Tangram Lab	Lisa Tanet PhD candidate Research collaboration contract	Lisa Tanet C. Tamburini L. Cassalot MIO	VICAT SoLiquid SEA BOOST Fondation Rougerie	Research collaboration contract	First public (City of Parramatta Council) and ideas competitions	Co-fund PACA	CEEBIOS Biomim'expo Biomim'city Lab
6	Several concepts depending on projects Ex. Social organization of emperor penguin Skolkovo, Russia	Pablo Lorenzino, architect dplg, partner associate Clémence Bechu, business developer	—	F. Gaille, biologist, BOREA Y. Tourre, climatologist, Columbia University	—	—	Public (LLC UDAS Skolkovo)	—	CEEBIOS Biomim'expo Biomim'city Lab

Declaration of competing interest

None.

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