Classification criteria and markers for biomimetic building envelope within circular economy principles: a critical review

# Classification criteria and markers for biomimetic building envelope within Circular Economy principles. A critical review

Ernesto Antonini*, Andrea Boeri**, Francesca Giglio ***

**Department of Architecture University of Bologna, Viale del Risorgimento 2, 40136 BOLOGNA, Italy, ORCID: 0000-0001- 9055-6149, ernesto.antonini@unibo.it*

***Department of Architecture University of Bologna, Department of Architecture University of Bologna, Viale del Risorgimento 2, 40136 BOLOGNA, Italy, ORCID: 0000-0003-1390-2030, +39 0547 338349. andrea.boeri@unibo.it*

**** Department of Architecture and Territory, Mediterranea University of Reggio Calabria, Via dell'Università 25, Italy , ORCID: 0000-0002-5047-754X, +39 0965 1697131. francesca.giglio@unirc.it (Corresponding Author)*

# Classification criteria and markers for biomimetic building envelope within Circular Economy principles. A critical review

The responsibilities of the building sector concerning resource consumption and waste generation, as a problem of research, require a transition from a linear to a circular model in order to obtain significant positive effects on the environment. The Biomimicry approach appears to be a promising way to move the sector towards the circular economy, to meet the increasing levels of functional and environmental requirements, which is shifting the research on building materials and products toward biomimetic solutions. Along this path, the building envelope emerges as an interesting application field concerning its adaptive behaviour towards external conditions. In this field of research, the knowledge gap concerns the need for criteria to classify the biomimetic behaviour of building materials under operating conditions and to identify their environmental effects, as well as their compliance with the principles of the circular economy. The study provides a methodology to develop a set of classification criteria applicable to biomimetic materials and products which are suitable for application in the building envelope and a related set of markers of their attitude in integrating circular economy principles. The resulting marker mapping-identifies the strongest environmental relationships and implications related to the aptitude for integrating circular economy principles. The mapping also highlights the absence of some relationships thus highlighting potential limitations of biomimetic materials/products within circular economy principles and thus current research limits. The results obtained may be useful to evaluate and compare biomimetic materials and products for the building envelope, whilst also providing the first step for further research on their environmental implications and their contribution to the dynamics of circular economy processes.

## Highlights

- a classification system for biomimetic devices for building envelopes
- biomimetic device features linked to expected effects provided to envelope
- markers to assess compliance to circular economy principles of biomimetic devices

- there are no previous environmental esteem effects of biomimetic building materials

Keywords: circular economy, Biomimicry, building envelope, classification criteria, markers

## Introduction

The aim is to reduce the pressure on resources and the environment, feed a demand for new technologies, which are alternatives to those developed in the industrial era, with their destructive effects on ecosystems. As a result, the demand for recyclable and biodegradable materials is increasing and it will expand further, as the European Commission expects, stating that “in a world with growing pressures on resources and the environment, the European Commission has no choice but to go for the transition to a resource-efficient and ultimately regenerative circular economy ” (EC 2012). By searching for new technology paradigms, nature appeared as the first inspiring source of knowledge, from which much effective and intrinsically low-impact models can be taken, thus enabling nature-based innovations as alternatives to the current industrial ones (Blok and Gremmen 2016). Being identified as one of the main pillars of Circular Economy (MacArthur Foundation 2016), Biomimicry emerges as a “new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems" (Benyus 1997) and introduces a new ecological approach to nature based on learning and exploration, rather than on domination and exploitation, as in the past. Benyus notes that economies are like ecosystems both systems take energy and materials and transform them into products. The problem is that our economy carries out a linear transformation, while that of nature is cyclical. To try to prevent the current economic system from persisting in the linear model, the Circular Economy advocates a circular system based on the following three key principles: preserve and improve natural capital, controlling finite stocks and balancing the flows of renewable resources; optimise the use of resources; and reveal and eliminating negative externalities ( Mc Arthur Foundation 2019, Lüdeke-Freund et al 2018, Olaizola et al 2020). Following its first applications in several other domains, such as chemistry, medicine, aeronautics, industrial design, textiles, Biomimicry entered the building sector only a few years ago, but has gained significance within the overwhelming global movement for environmentally conscious technologies in building design. This is mainly related to the potential awarded to the nature-inspired responses in developing new features, stimulating creative innovations and exploring unconventional solutions (Oguntona and Aigbavboa 2017) The increasing levels of functional and environmental requirements are thus shifting research on building materials toward biomimetic solutions (Tokuç et al. 2018).

Although environmental issues are one of the drivers pushing Biomimicry development in this sector, a systematic features assessment has not yet been provided for building materials and components with biomimetic behaviour, nor for their related environmental performances and circular economy issues. This is mostly due to the lack of a systematic design methodology by which the relevant principles can be identified to extract suitable and applicable solutions (Badarnah and Kadri 2015).

Several criticisms are recorded in literature about the lack of a unified evaluation system for estimating the sustainability of Biomimicry solutions (De Pauw and Karana 2014, Kennedy and Marting 2016). In fact, many of the Biomimicry inspired products lack an integration within the larger (eco) systems they are part of. As a result, it is therefore hard to assess whether they contribute to sustainability on the larger scale (Marshall and Lozeva 2009). This means that an evaluation framework is still needed to assess the environmental sustainability implications of Biomimicry approaches (Ohlander et al. 2018). A direct link of these indicators with the Circular Economy principles could be very suitable, as it would provide the means for a wide and comprehensive vision of the issue, even if the boundaries of Circular Economy definition are still quite blurred (EASAC[1] 2016, Geng et al. 2012). As the variety of open paths is still very heterogeneous, this prevents a clear perception of the different readiness levels of the deployable technologies.

This paper is part of a study on the application of biomimetic technologies to the building sector and particularly to the building envelope, in relation to its adaptive and responsive behaviour regarding the internal and external environment. The need for new technologies responding to the emerging environmental issues related to resource consumption and waste production fully involves the building sector. Reducing all impacts for which it is responsible leads indeed in innovating the sector, to allow its transition to circular economy models.

The paper is organised in two sections, namely:1) the problem framework, through a review of current literature; 2) the methodology and the final results.

[1]EASAC: European Academies' Science Advisory Council

The first part is a literature review addressing two specific aspects: the evolution of biomimetic approach and the field definition and boundaries of biomimetic design topic in architecture.As the topic is still quite unsettled, establishing some preliminary definitions is the first step needed. This includes an updated terminology and a map of the available biomimetic technologies and materials, pointing back to the principles and bio-behaviours to which each of them is inspired by. A further field limitation is lastly carried out through a literature review about Biomimetic approach and circular economy. This allows identifying of certain basic criteria, by which the assessment of the environmental performance of biomimetic building material can be performed. Finally, linking these criteria to circular economy principles provides a helpful key for quickly estimating the level and degree of Biomimicry reached by a specific device.

The second section of the paper explains how the study methodology was built on the basis of the reviewed literature, adopting and reinterpreting the "solution based approach" model (Badarnah 2012). The methodology is structured in three steps:
I step (Biological domain + Transfer phase): establishing the classification system on Biomimetic behaviour; II step: retrieving from the Asknature database a selection of biomimetic product/prototypes (case studies) suitable for application in the building envelope; III step: establishing the Expected Effects (Technological domain) on the environmental sustainability performances relating each biomimetic behaviour of products/prototypes.

The final phase, regards the application of methodology to case studies (products/prototypes retrieved from Asknature) and relates to the need to estimate the environmental profile of each biomimetic products/prototypes in terms of how its application can integrate the circular economy principles.

The result is a set of markers that is supplied for assessing the compliance to circular economy principles of building envelopes equipped with biomimetic products/prototypes. The study has achieved to identify the expected environmental performance of using biomimetic materials on the building envelope, while the environmental issues of the manufacturing device process are not yet considered. The estimation of the environmental effects of biomimetic materials in building has not been previously documented and is therefore an original element of research, together with the whole classification and expected effects.

## Background: a definitory review of literature

### *The evolution of the Biomimetic approach: a brief terminology review*

The first relevant step concerns the evolution of the concept of biomimicry and its current definition based on the references found in literature. A set of classification criteria can be established on this framework, to apply to biomimetic materials. According to the definitions provided by several authors (Bar Cohen 2005, Vincent et al. 2006,Pietroni, 2015, Hu 2017) a plurality of new concepts appeared, along with new words that aim to identify the stages of the evolution of scientific approaches in the field. Starting from the case of the term "Bionics" (from Greek βιος: life, and the suffix nics for electronics), along with the synonyms "Biomimesis" and "Biomimetic" (from Greek βιος: life and μιμησις: imitation) and also "Biomimicry", which literally means 'imitating nature' which evokes an adaptation or derivation from biology. As Bionics – coined by Jack Steele (Vincent et al 2006) of the US Air Force in 1960 [2] - refers to a technical approach which develops new technologies by applying biological methods, so Biomimesis draws inspiration from the biological systems strategies, processes, functioning logics and organisation models (Pietroni, 2015, Colombo 2010, Gallo 2018). The term Biomimetics was first used in 1969 by Otto Schmitt to define "a discipline that simulates biological structures to make more efficient products" (Schmitt 1969). The same etymology and meaning of Biomimetics are those of the term Biomimicry, which, after first appearing in 1980 was reintroduced by J. Benyus herself, who is still the main scientific reference for the discipline (Benyus 1997).

Benyus deems that inspiration from nature can be deployed by three modes, or levels:

- Nature as a model, which consists of studying the models of nature and in emulating their forms, processes, systems and strategies to solve human problems. This "organisational level" has inspired biomimetic techniques that imitate either the entire observed model, or just some of its elements.

- Nature as measure: this mode can be designated as the "behaviour level": we learn from a natural mechanism and we reproduce the principles that provide

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[2] Steele coined the term Bionics at a meeting at Wright-Patterson Air Force Base in Dayton, Ohio

effectiveness for the device i.e.: the pine cones opening mechanism, which is enabled by the different shrinkage rate of the cone's scales, can be assumed as suitable reference for responsive façade design.

- Nature as a mentor: this mode presupposes nature not as a resource from which to extract, but from which we can learn. This 'system level' is the most challenging innovation path, since the functionalities on which it is focused are often the most difficult feature to mimic.

However, long before the modern concept of Biomimicry was introduced, history records many functional performances, product concepts or solutions, reproducing those observed in nature, that have been transferred to artefacts, through selection and abstraction processes. As it potently appears in the anticipatory "Code on the Flight of Birds" published by Leonardo da Vinci in 1505 (Colombo 2010).

A literature review on the structure-form-function approach of different authors (Pietroni 2015, Hu 2017, Zari 2007, Pagani et al. 2015, Persiani 2019) integrates and deepens the main classification of Benyus, still valid today, with respect to nature-inspired models. In parallel, the approach called Technical biology by Nachtigall provides inspiration for much research on biomimetics, investigating the structure-form-function relationships in living organisms, through physics and engineering methods (Pohl 2010, Pohl and Nachtigall 2015). This trend has seen a powerful acceleration within the last decades, when the characteristics and properties of living organisms as well as the biology of functional processes have been greatly investigated and interpreted by various disciplines, forging strong advances in knowledge (Pietroni, 2015, Colombo 2010, Gallo 2018).

Biomimicry, from the point of view of a solution-driven approach, or biology push (ISO 2015) applies biological knowledge obtained by examining principles in biological functions and focuses on the activities of biological and ecological resources that promote the value of biodiversity. Applying Biomimicry means finding and mimicking a biological and ecological model to solve the problems of integrated sustainable development in society, the environment, and the economy (Bae and Lee 2019). Biomimicry is considered to be a new approach for achieving sustainable architecture, but there is still not enough access for architects to make use of it, especially to implement biomimetic design strategy in architectural project (Heil and Belkadi 2017). For this reason it has also become of great interest for the building sector and its possible fields of application, as highlighted in the following paragraph.

***A framework for biomimetic design in architecture***

By defining the application of Biomimicry that has evolved as an architectural design method, this framework may allow designers who wish to employ Biomimicry as a methodology for improving the sustainability of the built environment to identify an effective approach to take.

Biomimicry has been looking at advanced technologies derived from bio-inspired engineering at different levels and in diverse fields, including architecture, where it has recently had a significant impact, especially as a driver for sustainability (Hu 2017, Ricard 2015).

.Approaches to Biomimicry as a design process typically fall into two categories:

- biology influencing design: identifying a particular characteristic, behaviour or function in an organism or ecosystem and translating that into human designs
- design looking to biology: Defining a human need or design problem and looking to the ways other organisms or ecosystems solve this (Biomimicry Guild 2007).

More recently, Badarnah integrated these concepts referring respectively to:

- solution-based approaches: the steps adapted by the investigated biomimetic methodologies are categorized by biological and technological domains and the transfer phase between the domains.
- problem-based approach : the steps adapted by the investigated biomimetic methodologies are categorized based on the three general phases of the design process: problem definition, exploration & investigation, and solution development (Badarnah 2012).

In this general scenario, although various forms of Biomimicry or bio-inspired design are discussed by researchers and professionals in the field of sustainable architecture (Reed 2006), the widespread and practical application of Biomimicry as an architectural design method remains largely unrealised, as demonstrated by the small number of built case-studies (Faludi 2005). One barrier of particular note is the lack of a clearly defined approach to Biomimicry that architectural designers can initially employ (Vincent 2006).

One of the first approaches to architectural design is Bionic Design, proposed and conducted by Nachtigall (Nachtigall 2003), a cross-disciplinary approach between biology and architecture which strictly relates to the Biomimicry approach . The principles which can be used in integrating nature, design and technology are described as a result of a combined effort by the two disciplines, where biology can provide the inspiration that has then to be "translated" into architectural and building design solutions by means of the available technologies. The main assumption of the method is that nature cannot be simply copied to provide architects with inspiration to achieve eco-innovative design goals. This is because the transition from nature to architecture is a logical process, sharpening the best adaptation of natural models, over years, under a variety of conditions, (Mirniazmandan and Rahimianzarif 2017). The theme of Bionic Design is currently also intended as a tool for the design and development of new industrial products that are inspired by nature, according to the principles of efficiency, effectiveness, sufficiency (Colombo 2010).

These last principles structurally integrate the biomimetic approach, providing architects with a rich set of inspiring means to explore new synthesis between form and function, opening a wide range of possible biomimetic features and devices as well as the growing demand for sustainability and energy efficiency (Tokuç et al. 2018, Kennedy and Niewiarowski 2018). This concept is closely connected to the three biomimetic levels - form, process and ecosystem (Biomimicry Guild 2007). These are integrated by Zari (Zari 2007) in her research for understanding the application of Biomimicry, through three levels of mimicry: the organism, the behaviour, the ecosystem:

- The first level refers to a specific organism like a plant or animal and may involve mimicking part of or the whole organism.

- The second level refers to mimicking behaviour, and may include translating an aspect of how an organism behaves, or relates to a larger context.
- The third level is the mimicking of whole ecosystems and the common principles that allow them to successfully function.

Within each of these levels, a further five possible dimensions to the mimicry exist. The design may be biomimetic for example in terms of what it looks like (form), what it is made out of (material), how it is made (construction), how it works (process) or what it is able to do (function) (Zari 2007).

By virtue of this, the application of Biomimicry devices thus drives a relevant change in building design, due to the envelope a new concept of skin is able to assure multiple functions (RadwanandOsama 2016). This requires a performance-driven design approach, helping to systematically  integrate the performative capacities of its different components (Hensel 2013).

According to Imani (Imani et al. 2018), integrating this Biomimicry strategy into the design process generates benefits for both designers and the natural environment, as bio-inspired designs can contribute to sustainability. Their literature review demonstrates that researchers and designers are significantly inspired by animals', plants', or microorganisms' innovative biological systems (functions, structures, and processes) in order to design bio-inspired materials for increasing energy efficiency of the buildings. However, the literature shows a gap in the very first step where designers search nature to find inspirations to improve mechanical or functional aspects of materials (Imani et al. 2018).

The aim of this paper, therefore, is relevant to further highlight those studies that deepen the relationship between the biomimetic approach and envelope performance, to enhance ecologically sustainable design.

Among the various studies, we highlight an ecological model BTM (Biomimicry Theoretical Model) that helps outline a BTF (Biomimicry Theoretical Framework), which is most applicable to architecture. This model proposes two ways of emulating nature: the direct approach – in which various aspects of biology are major determinants in the design and are specifically applied, and the indirect approach – in which the application is found at any scale or level of an organisation in architecture. The greatest potential of the BTF resides in its application for problem solving as a process rather than by directly mimicking biological shapes and forms. This approach can be transformed into an ecological design thinking process for built systems by identifying how built systems can be categorised by how their function is, and used, and how best the functions can be integrated; what the microenvironment is, what it sits in and how best the building can be adapted to the local climate (Gamage and Hyde 2012). In addition to this method, we would like to highlight, for their relevance in the development of biomimetic strategies for the building envelope, other frameworks useful for the study.

When they are transposed from natural to built systems, the adaptation properties must still assure the same peculiar effect, making the organism better suited to its habitat. This means that building must be designed according to the adaptation strategies of the applied devices, but also that the integrated Biomimicry feature choice depends on the design options. This is especially relevant for those features related to orientation, light and ventilation, volume shape and spatial organising. In fact, Biomimicry provides a wide range of smart guides for structural efficiency, zero-waste processes, thermal comfort and energy supply, which are the key-reference for sustainable building design (Singh and Nayyar 2015). Due to their relevance to developing biomimetic strategies for the building envelope, we wish to highlight other frameworks useful for the aim of the study that concern Biomimetic Principles derived from micro and macro adaptations of plants for the design of adaptive architectural envelopes (López et al. 2017); BioGen is a methodology for the generation of biomimetic design concept that creates an exploration model mapping functional aspects, relevant processes and influencing factors (Kuru et al. 2020). The biological entities called pinnacles are presented as examples for a specific function or process; BioMAPS, a database developed at the University of Toronto (Shu 2010) ; this database is to be used at the beginning of the biomimetic design process, and it helps to connect engineering terms with biological ones (Garcia et al. 2016); DANE (Design by Analogy to Nature Engine) provides access to a design case library containing Structure- Behaviour-Function (SBF) models of biological and engineering system (Goel et al. 2009); BioTRIZ a systematic technology transfer from biology to engineering using TRIZ (translated as Theory of Inventive Problem Solving) (Vincent et al. 2007) .The database's purpose is to make biological information available in a language specific to engineering. However, the process is out of biological context, meaning the strategies do not exist in nature, but as theoretical ideas (Kuruet al.2020). Despite this promising scenario, the building sector is a field of application still in evolution for biomimetics. The technology-push dynamic is easy to identify as the prominent innovation driver for Biomimicry applications, due to the large contents of basic and applied research which are needed for material development. However, a demand-pull-process can also play a relevant, additional role in building, in terms of both speeding the spread of the already available biomimetic devices and identifying new targets for further technological developments (Gleich et al. 2010). The construction process actors, namely the architects, could more effectively integrate this process if they could more easily classify biomimetic devices and the effects that their application can bring to the building, including those concerning its environmental sustainability.

***Biomimetic approach and circular economy***

According to Ellen McArthur Foundation, Biomimicry is identified as one of the pillars which has contributed to the development of the circular economy concept since the 1970s. Together with Regenerative Design (Lyle 1994), Performance economy (Stahel, and Reday-Mulvey 1976), Industrial Ecology (Garner and. Keoleian 1995) , Cradle to Cradle[52] (McDonough and Braungart 2002), Natural Capitalism (Hawken et al. 1999), Blue Economy (Pauli 2010). Even though these concepts have overlapping ideas and similar goals, they also differ from each other regarding certain characteristics (MacArthur Foundation 2015, Geisendorf and Pietrulla 2017).Unlike natural processes which they mime, the industrial production of such materials can be very complex, energy demanding and anything but emission neutral.

Therefore, the features provided to buildings by these devices may not be sufficiently environmental effective to balance their embodied impacts, thus reducing the benefits of these solutions when assessed along their whole life cycle. The computation of embodied impacts and the combined operational elements are especially critical for buildings, due to their long lifespan. Biomimetic materials often aim to improve sustainability and reduce emissions, particularly those concerning energy consumption in operation, but it is still unknown at what global environmental price this can be assured. Indeed, the environmental profiles of these technologies and the overall balance of the impacts associated with their application are still very uncertain, including those products already on the market.

How performance should measure is still one of the critical questions in the circular economy, since this radically different paradigm makes the metrics developed for the traditional linear economy unsuitable or ineffective. In order to remedy this, EU has developed a monitoring framework for the circular economy, that is a tool aimed at checking the state and progress of policies for the circular economy within the Union (COM 2018). The monitoring framework on the circular economy as set up by the European Commission consists of 10 indicators, some of which are broken down into sub-indicators. These indicators were selected in order to capture the main elements of a circular economy. About half of the indicators in this framework come from Eurostat; others are produced by the Joint Research Centre (JRC) and the Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW). The indicator on patents comes from the European Patent Office. The 10 indicators are divided into four thematic areas:

(1) Production and consumption that comprises 4 indicators:

- Self-sufficiency of raw materials for production in the EU
- Green public procurement (as an indicator for financing aspects)
- Waste generation (as an indicator for consumption aspects)
- Food waste

(2) Waste management, that comprises 2 indicators:

- Recycling rates (the share of waste which is recycled)
- Specific waste streams (packaging waste, bio-waste, e-waste)

(3)Secondary raw materials, that comprises 2 indicators:

- Contribution of recycled materials to raw materials demand

- Trade of recyclable raw materials between the EU Member States and with the rest of the world

(4) Competitiveness and innovation, that comprises 2 indicators:

- Private investments, jobs and gross value added
- Patents related to recycling and secondary raw materials as a proxy for innovation (COM 2018).

The framework shows that most of the indicators focus on the preservation of materials, with strategies such as recycling. The application of the framework seems to suggest that not one, but a set of indicators are necessary to perform the assessment (Moraga and Huysveld 2019).

Many indicators related to environment and resources have also been proposed by several organisations. The United Nations Environment Program (UNEP 2013) has a set of key environmental indicators that can serve as a basis for elaborating sustainable development goals and indicators for tracking progress towards environmental sustainability. The United Nations Development Program (UNDP) has developed 17 Sustainable Development Goals (SDGs) - as is now well known - which include goals related to resource use (climate action, responsible consumption and production). In September 2015, the 2030 Agenda for Sustainable Development, with the 17 SDGs as its main target, was adopted (ADB 2019).

A comprehensive set of indicators relevant to corporate sustainability reporting has been assembled by the Global Reporting Initiative (GRI 2020)covering the three pillars of sustainability (economic, environmental, societal). Another set of indicators has been developed in a joint project between Yale and Columbia Universities and the World Economic Forum. This started with an Environmental Sustainability Index (ESI) based on a compilation of 21 indicators, derived from 76 underlying data sets (Daniel 2005). The World Bank has also assembled 50 indicators which can be used to measure progress on sustainable development goals (SDGs) (EASAC 2016).

The estimation of the environmental effects of biomimetic materials in the building sector has no previous documentation. Consequently, what should be measured is however subject for debate, as the definition of circular economy is still ambiguous, so indicators might lead to different or even incoherent conclusions (Moraga and Huysveld 2019). However, it is considered significant to describe the ongoing debate on how to measure performance in the circular economy and on the contribution of various indicators useful for this purpose. A mapping tool designed for this purpose and made available to the architects could help the exploitation of the Biomimicry supplied features in building.

**Methodology**

The methodology was developed by reviewing literature on defining aspects of the field of Biomimicry, its applications in the building sector and its contribution to the circular economy, analysing critical aspects and open issues. In particular, reference is made to the "solution based approach" methodology with steps defined by Badarnah (Badarnah, 2012), based on Biomimicry3.8(Group, 2014) (Baumeister etal.,2014) and Goel (Helms etal.,2009) and re-proposed by Gomez (Gomez, Ros et al 2019) as summarized in the Fig 1 .
*[Fig 1down here]*

The identification of these still little resolved aspects that mainly concern a particularly growing field; that is, the application of biomimetic technologies to the building envelope, has led to the development of a research methodology with the following aims:

- classifying the functional behaviour of biomimetic materials, based on the biological strategy they perform
- relating the material features with the expected performances of the building envelope on which materials are applied
- providing a set of markers related to the expected environmental effect of the building envelope equipped with biomimetic devices, through the application of the methodology to specific case studies.

To reach these goals, the research adopts a three-step method as described in the flow chart below, adopting the steps of “solution based approach” model (Badarnah 2012).

- First step (Biological Domain+Transfer phase) : establishing the classification system on Biomimetic behaviour, based on two criteria for Biological Domain and two criteria for Transfer phase (Tab1).

- Second step: retrieving from the Asknature database a selection of biomimetic product/prototypes suitable and their technological behaviour for application in the building envelope and classified by the method developed in Step 1 (Tab. 2)

- Third step: establishing the Expected Effects (Technological Domain) on the environmental sustainability performances relating each biomimetic behaviour (functionality) to the performances that supply to the building envelope through selected biomimetic product/prototypes (Tab.3)

*[Fig 2down here]*.

For the *first* step, we refer to the level 2 of Benyus' Biomimicry Classification ( Benyus 1997) also known as the behaviour level that outlines the Biological Domain with the following criteria:

(1) Biological Strategy identification

(2) Behavioural adaptations mechanism by which the product performs the function

and Transfer phase with the following criteria:

(3) Equivalent function in building (Biomimetic replication)

(4) Biomimetic behaviour that synthesises the Functionality for each biological Strategy as summarized in Tab 1.

This criterion looks at the biomimetic behaviour that is possibly replicated by a material, relating the provided functionality and the biological strategy to which it is inspired by. Organisms meet functional needs through Biological Strategies. A biological strategy is a characteristic, mechanism, or process that performs a function for an organism. It is the adaptation the organism has in order to survive. Biological models adapt to tolerate the environmental changes in their natural habitats. These adaptations are categorised into three types - morphological, physiological and behavioural. Morphological adaptations relate to a form, structure or texture;

physiological adaptations refer to a characteristic (trait) or chemical response; behavioural adaptations refer to a kinetic response to a stimulus ( Kuru 2018). For the aim of the study, behavioural adaptations were adopted.
A Function is an essential underpinning of Biomimicry and is one element that distinguishes biomimetic design from biophilic and biomorphic design.

The correlation between Strategy and Functionality helps to detect the kind of natural mimesis which is performed by the material.

The classification system recognises 9 categories of functionalities, obtained through the analysis of existing literature on biomimetic behaviour in building sector, namely:

- Photocatalytic
- Thermoregulation
- Adaptivity
- Optimising shape
- Self repair
- Self cleaning
- Self assembly
- Stimuli responsive
- Anti-reflecting

*[Table 1 down here]*.

The *second* step relates the selection of several biomimetic products/prototypes suitable for application in building envelope, which have been extracted from the Asknature database (https://asknature.org) . The feature of each device is identified as Technological behaviour.

The products/prototypes performing biomimetic feature have been retrieved from Asknature, among those suitable for applications in building envelopes. This selection is useful as case studies to which the methodology can be applied.This experimental application of the classification system was performed by building an inventory of biomimetic materials suitable for application in building envelope. The selection was extract from Asknature, a free, open source, online database developed by the Biomimicry Institute to promote life-inspired innovation and technologies. The circular economy is a biomimetic concept, inspired by the flow of resources and energy within ecosystems and according to this aim, Asknature database maps the world's literature on the topic, providing access to information on biological strategies, bio-inspired products classified by function and living systems, as well as to blueprints, sketches and those designs applying them (Vierra 2016) .

*[Table 2 down here]*.

The *Third step* concerns the estimate of the environmental effects expected , related to the biomimetic products/prototypes to be provided to the building envelope in relation to each functionalities, outlining the Technological Domain .

*[Table 3 down here]*.

## The results: markers for biomimetic building envelope within Circular Economy principles

This last phase regards the application of methodology to case studies (products/prototypes retrieved from Asknature) and relates to the need to estimate the environmental profile of each biomimetic products/prototypes in terms of how its application can integrate the circular economy principles. For this purpose, the potentially determined effects by each biomimetic feature on the building envelope (Technological domain) have been linked with the six actions for circular economy (Regenerate, Share, Optimise, Loop , Virtualise, Exchange) from the ReSOLVE framework elaborated by Ellen MacArthur Foundation’s research activity (MacArthur Foundation 2015). The six actions concern a large variety of objects, from materials to buildings, neighbourhoods, cities, regions or even entire economies. According to the purposes of this study, we focused our analysis on biomimetic materials and products for applications in buildings façade, intended as elements of the built environment (MacArthur Foundation 2016).

The outcome of this step allow the identification of involved circular processes and the aptitude of the biomimetic products/prototypes to integrate them, in line with the EU circular economy monitoring framework. According to ReSOLVE framework (MacArthur Foundation 2015), the actions and sub-actions are the following:

(1) REGENERATE. Regenerating and restoring natural capital by:

- Safeguarding, restoring and increasing resilience of ecosystems
- Returning valuable biological nutrients safely to the biosphere

(2) SHARE. Maximising product utilisation by:

- Mutualising the usage of assets
- Reusing assets

(3) OPTIMISE. Optimising system performance by:

- Prolonging the life of an asset
- Decreasing resource usage
- Implementing reverse logistics

(4) LOOP. Keeping products and materials in cycles by:

- Remanufacturing and refurbishing products and components
- Recycling materials

(5) VIRTUALISE. Displacing resource use and delivering utility virtually by:

- Replacing physical products with virtual services
- Replacing physical with virtual locations
- Delivering services remotely

(6) EXCHANGE. Selecting resources and technologies wisely by:

- Shifting to renewable energy and material sources
- Using alternative material inputs
- Replacing traditional with advanced technical solutions
- Replacing product-centric delivery models with new service-centric ones

The effects that the biomimetic features are expected to supply the building envelope - as identified in step 3 - have thus been related by way of the six actions, to consider any possible improvements they might produce with respect to the current situation. The contribution of adopting a biomimetic solution makes the building more compliant to circular economy principles. The relationships between the expected effects of biomimetic behaviour related to selected products/prototypes on building envelope (Technological domain) and the ReSOLVE actions are analysed both at the Building scale, considering the effects of products/prototypes application to the building envelope, and at the Material scale, considering the effects of the products/prototypes behaviour regardless of the application context. The circular economy markers have therefore been highlighted for both conditions .
*[Table 4 down here]*

**Findings and discussion**

The overall result of this sorting process is a set of circular economy markers for biomimetic materials, allowing a profile of them through the relevant features they supply the building envelope. The markers within the matrix link the expected effect of the biomimetic device and the action/sub-action is identified by the ReSOLVE system.

The resulting marker mapping identifies the strongest environmental relationships and implications related to the attitude for integrating circular economy principles.The mapping also highlights the absence of some particularly important relationships with respect to circular economy principles.

The relationships were highlighted on both at material scale and building scale. The environmental aptitude of the material according to the circular economy may be different depending on the application conditions on the building envelope, relating to the installation, the contextual conditions, the environment and in relation to the overall behaviour of the building envelope.

In some cases, several markers have also been identified, based on the type of environmental effect of a material. Stronger relationships rank among the *Regenerate, Share, Optimise, Exchange* actions and are the following:

At the Building scale:

- Safeguarding, restoring and increasing resilience of ecosystems
- Mutualising the usage of assets
- Prolonging the life of an asset
- Decreasing resource usage

At the Material scale:

- Using alternative material inputs
- Replacing traditional with advanced technical solutions
- Shifting to renewable energy and material sources

The framework that is achieved highlights two aspects of particular relevance:

(1) at the Building scale, in the Optimise action, with reference to the decrease in the use of resources for all the expected effects in building envelope biomimetic behaviour of case studies;

(2) at the Materials scale, in the Exchange action, with reference to the exchange processes in technologies, especially through the use of alternative material inputs and the shift to renewable energy sources and materials.

The *Share, Virtualise, Loop,* actions, with respect to the case studies analyzed, have no relation to the expected effects of the same. The *Share* and *Virtualise* actions because they are not specifically coherent with the products/prototypes analysed and therefore with the building context; the Loop action because, referring to the possibility of recovery/reuse/recycling, the biomimetic products/prototypes, being mainly made up of nanotechnologies, do not have characteristics of "circularity" . Although Biomimicry, as stated in the introduction, is one of the schools of thought of the circular economy, this last aspect makes biomimetic products/prototypes poorly connected to the circular economy principles, at least as far as their reusability or recyclability is concerned. This represents also the limit of the research.

The main results achieved are:

- a classification method, identified by a set of classification criteria of biomimetic characteristics (functionality) according to 9 categories of behaviour
- a matrix linking the biological mechanism (functionality) to its Biomimicry replication (biomimetic behaviour)
- the identification of the expected environmental effects from biomimetic devices applied within building envelopes
- the assignment of a set of markers to the Biomimicry equipped building envelopes, which identifies its compliance to circular economy principles; that is its attitude to integrate circular economy processes.

The outcome of the developed classification system are:

- a taxonomy of biomimetic behaviours of materials suitable for applications within building envelopes. This classification currently consists of nine categories of biomimetic behaviour, that could be opened to further implementation, depending on the research progress.
- a set of markers identifying the aptitude of a building-applied-biomimetic-device in integrating circular economy principles. This may be useful for a comparative assessment of the environmental performance of different devices or applications of them.

The building envelope has become a very fertile research field for adaptive technologies, which make it an active filter between the inner and the surrounding environment, as well as a testing ground for innovation. The wider dissemination of the promising Biomimetic material features needs more information, evaluation criteria, sustainability assessments and indicators able to lean towards circular economy principles.

## Conclusions

The study provides a methodology to develop a set of classification criteria applicable to biomimetic materials and products which are suitable for application in the building envelope and a related set of markers of their attitude for the integration of circular economy principles.

The set of markers related the expected environmental effects of biomimetic materials and products with the six actions of ReSOLVE Framework identifying the strongest environmental relationships and the implications relating to the ability to integrate the principles of the circular economy. These relationships were highlighted both at the material scale, with respect to the operation of the material/product, and at the building scale, with reference to the operation when the product is applied, and therefore, with respect to the different environmental and technical construction conditions.

The set of markers show particularly strong relationships between the expected effects of the case studies analyzed and the actions *Regenerate, Share, Optimise, Exchange* both at the scale of the material/product analyzed(material scale) and with respect to their application to the building envelope (building scale). Differently, the *Share, Virtualise, Loop* actions show any relationship with the expected effects, so any circular economy markers are present. This absence, especially with respect to the *Loop* action, demonstrates the main limit of the research, namely the difficulty in identifying, at present, the potential for recoverability, reusability, recyclability of these biomimetic materials/products in the building sector, despite the expected environmental effects on the building envelope with respect to their performance.

The results obtained, in fact, may be useful to evaluate and compare biomimetic materials/products for the building envelope, whilst also providing a first step for further research on their environmental implications and their contribution to the dynamics of circular economy processes.

Biomimetic applications in the building sector are a growing field, which stimulates multidisciplinary research and production practices on both the material and building sides.

The innovative aspects involve multiple scales:

- at the material scale, by identifying the performance improvement that can be reached through nature-inspired solutions, especially when using constituents of biological origin and favouring cyclical circularity matter
- on building components and construction scale systems, to which biomimetic devices provide adaptive dynamisms able to enhance their ability to respond to the changing requirements of both users and environmental conditions, with little or no external energy supply.
- in production, use and maintenance processes of buildings, by providing models inspired by living organisms, metabolism and mechanics, with positive effects in lowering impact and improving efficiency. On this path, promising steps forward are also expected from the application of Biomimicry approaches on a wider scale, such as defining functional and structural operations in settlements.

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Conceptualization, investigation, and data curation F.G.; methodology and formal analysis E.A.; validation and supervision, A.B.

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Fig 1 Solution based approach methodology. Steps defined by Badarnah (Badarnah, 2012), based on Biomimicry3.8(Group, 2014) (Baumeister et al.,2014), Goel (Helms et al., 2009) and re-proposed by Gomez (Gomez, Ros, et al, 2019).

Fig. 2 Methodology flow chart

Tab1: Biological Domain+Transfer phase: Establishing the classification system on Biomimetic behaviour, based on two criteria for Biological Domain (Biological strategies, Behavioural adaptations) and two criteria for Transfer phase (Equivalent function in building: Biomimetic replication, Biomimetic Behaviour). Elaboration by the Authors.

Tab 2:  Selection of biomimetic product/prototypes and their technological behaviour from the Asknature database (https://asknature.org) as case studies, suitable for application in the building envelope corresponding to the Biomimetic behaviour classification. Elaboration by the Authors.

Tab 3: Technological Domain: Expected Effects on the environmental sustainability performances relating each biomimetic behaviour and to the performances that supply to the building envelope through selected biomimetic product/prototypes. Elaboration by the Authors.

Tab 4: Circular economy markers for Biomimetic materials/products for building envelope as environmental relationship between the effects at the building and material scale of case studies (Technological domain) and the six actions of ReSOLVE Framework, Ellen MacArthur Foundation 2016. Elaboration by the Authors.