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RESEARCH ARTICLE

What Does it Mean to Mimic Nature? A Typology for Biomimetic Design

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Abstract

In an effort to produce new and more sustainable technologies, designers have turned to nature in search of inspiration and innovation. Biomimetic design (from the Greek *bios*, life, *mimesis*, imitation) is the conscious imitation of biological models to solve today's technical and ecological challenges. Nowadays numerous different approaches exist that take inspiration from nature as a model for design, such as biomimicry, biomimetics, bionics, permaculture, ecological engineering, etc. This variety of practices comes in turn with a wide range of different promises, including sustainability, increased resilience, multi-functionality, and a lower degree of risk. How are we to make sense of this heterogeneous amalgam of existing practices and technologies, and of the numerous promises attached to them? We suggest that a typology of biomimetic approaches would provide a useful hermeneutic framework to understand the different tensions that pull this variegated landscape in different directions. This is achieved through a critical analysis of the literature in different fields of biomimetic design and the philosophy of biomimicry, in order to derive conceptual and normative assumptions concerning the meaning and value of the imitation of nature. These two dimensions are then intersected to derive an analytical grid composed of six different biomimetic types, which enable the classification of existing and possible biomimetic approaches, practices, and technologies according to their specific conceptual assumptions and guiding norms.

Keywords *Biomimetics · Typology · Sustainability · Bioinspired design · Biomimicry · Conceptual and normative assumptions*

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1 Introduction

In an effort to produce new and more sustainable technologies, designers have turned to nature in search of inspiration and innovation (Gerbaud et al., 2022; Palombini & Muthu, 2022). Various approaches to the technical imitation of nature such as biomimicry, biomimetics (both from the Greek *bios*, life, *mimesis*, imitation), bionics, permaculture, and ecological engineering consciously emulate biological models to solve today's technical and ecological challenges (Gremmen, 2022; ISO, 2015; Pedersen Zari et al., 2020; Speck et al., 2017). For example, the water-repellent properties of lotus leaves have inspired self-cleaning materials and paints. As with other solutions to develop more sustainable forms of living and manufacturing, such as the bio-based economy (McCormick & Kautto, 2013) and the cradle-to-cradle approach (McDonough & Braungart, 2002), design approaches that take inspiration from nature are enjoying increasing popularity. This is due to various promises attached to nature-inspired design, including sustainability, increased resilience, multi-functionality, and a lower degree of risk (Gleich et al., 2010; Hashemi Farzaneh & Lindemann, 2019).

This variety of promises, however, is also a source of ambiguity about how to evaluate current biomimetic projects. Existing design approaches that study and emulate nature form a landscape of partial overlaps and occasional contrasts concerning their scopes, methods, and goals. This is clearly visible in relation to sustainability. It is generally agreed upon that within certain biomimetic design strands the link to sustainability is tenuous and that more effort is required to ensure the sustainability of biomimetic solutions (Bensaude-Vincent, 2019; Cohen & Reich, 2016; Hashemi Farzaneh & Lindemann, 2019). While biomimicry, promoted by American consultant Janine Benyus, makes ecological sustainability the core value with nature being taken as "model, measure, and mentor" for sustainable development (Benyus, 2002), other approaches such as biomimetics and bionics do not explicitly aim at sustainable innovations, focusing on the reproduction of innovative functions, e.g. self-assembly and self-organization, modularity, multifunctionality, adaptability and resource-efficiency (Nachtigall & Wisser, 2014). Biomimetics for example focuses on "the function analysis of biological systems, their abstraction into models, and the transfer into and application of these models to the solution" (ISO, 2015). These differences are reflected by the abundant and often inconsistent nomenclature employed to designate different design approaches that take nature as a source of inspiration, of which biomimicry, biomimetics, bionics, bioinspired design, permaculture, and ecological engineering are some of the labels most often employed.

How are we to make sense of this heterogeneous amalgam of existing practices and technologies, and of the numerous promises attached to them? We suggest that a typology of biomimetic approaches that highlights their conceptual and normative differences would provide a useful hermeneutic framework to understand the different tensions that pull this variegated landscape in different directions. To do this, we look at how conceptual and normative assumptions change across different biomimetic disciplines, considering conceptual differences in what is meant by mimicking nature, and normative differences in the reasons why mimicking nature is considered valuable. This is achieved through a critical analysis of the literature in different fields of biomimetic design and the philosophy of biomimicry, to derive conceptual and normative distinctions that enable us to capture more nuanced differences between approaches compared to existing typologies (Iouguina et al., 2014; Jacobs, 2014; Landrum & Mead, 2022; Lenau et al., 2018; Speck et al., 2017). These two dimensions are then intersected to derive an analytical grid composed of six different biomimetic types, which enable the classification of existing and possible biomimetic approaches, practices, and technologies according to their specific conceptual and normative assumptions.

We refer to such an ensemble of disciplines as "biomimetic design", rather than one of the numerous alternatives such as "nature-inspired design" (Ceschin & Gaziulusoy, 2016), to avoid the confusion with more specific kinds of mimetic relations, such as imitation and inspiration, that we will analyze below. With "mimesis" we thus refer in general to the kind of epistemic operation of "imitation" presupposed by biomimetic design as the attempt to study and replicate nature's functional principles. The proposed typology advances the critical reflection on the assumptions about nature, mimesis, technology, and sustainability in biomimetic design initiated by Mathews (2011), Dicks (2016), and Blok and Gremmen (2016), providing a hermeneutic tool to make sense of this variegated landscape. The articulation of the underlying conceptual and normative assumptions enables us to critically reflect on the impact of implicit meanings and values on technical research and design, contributing to philosophical reflections on design, technology, and our technical relation with nature, as well as to establish a typology relevant to practitioners in biomimetic disciplines.

This approach invites us to understand different biomimetic design approaches not just as isolated units characterized by different methods and aims, but also as forming a whole domain of discourse that brings together heterogeneous sorts of scientific disciplines, technical practices, and societal promises that take nature, natural organisms, and ecosystems as models for better design (Marshall & Lozeva, 2009; Zwart, 2019). Since "nature" is such a normatively loaded and contested concept, different biomimetic approaches and practices tend to focus on, imitate, and value very different aspects of nature. The way in which nature is framed, conceptually and normatively, is revealing of the specific standpoint adopted. Philosopher and historian of science Bernadette Bensaude-Vincent describes these assumptions as a "metaphysical agenda", "a set of tacit and taken for granted presuppositions about nature, life, and about the role of the mind and technology" (2019, p. 3). Contextual factors such as project goals and constraints, study and design methods, cultural assumptions, etc. are related to the specific way in which nature is described and valued. While structural engineers might value self-assembly and other self-organizing biological designs, agroecological farmers might praise ecosystems' resilience and dynamic equilibrium. The situated nature of inquiry and design implies that some aspects, models, and functions of nature will be seen and privileged, while others will be excluded. The investigation of such conceptual details requires opening up the meaning of "biomimetic" and devising a typology that allows for the inclusion of approaches and practices that are broadly inspired by nature as a model for design practice.

The paper will first discuss the existing typologies of biomimetic approaches, finding them lacking an analytic angle that brings to light the underlying conceptual and normative assumptions (§2). To remediate this lack, the paper will offer a framework to analyze conceptual and normative assumptions behind different kinds of biomimetic practices (§3). The intersection of these two dimensions enables the derivation of a qualitative typology that individuates six different biomimetic types, which will be individually characterized through their different assumptions, illustrating them in relation to existing approaches or cases (§4). The potential of such a typology will then be discussed, in particular in relation to sustainability (§5), with the conclusion suggesting potential ways to expand it further (§6).

2 Existing Typologies of Biomimetic Design

Reflection on biomimetic practices has not shied away from trying to re-organize the field into clearer sub-fields. Scholars so far have attempted to provide conceptual classifications to differentiate general approaches based on specific characteristics, such as disciplinary allegiance (Gerbaud et al., 2022), or to propose overarching terms that capture the field as a whole under the banner of some commonly shared feature (Hoeller et al., 2013). The purpose of existing typologies of biomimetic approaches is generally to provide a unified ground by identifying general similarities of the different approaches while acknowledging specific differences, for example in terms of contribution to sustainability. Given the distinctive interdisciplinarity of biomimetic design, according to many practitioners a shared research agenda is needed to bridge specific disciplinary methods and goals, and achieve more clarity in R&D and marketing (Hayes et al., 2020; Hoeller et al., 2013). Existing typologies have tried to provide an overarching term for the field (Iouguina et al., 2014), devise a conceptual classification of different levels of biomimetic design (Jacobs, 2014), classify different kinds of biology-derived products (Speck et al., 2017), describe different paradigms of bio-inspired design (Lenau et al., 2018), and analyze the relation between biomimetic approaches and sustainability (Landrum & Mead, 2022; Montana Hoyos & Fiorentino, 2016). The general agreement is that biomimicry is more concerned with sustainability compared to other approaches such as biomimetics and bionics and that all three, albeit with different goals and methods, attempt to transfer design solutions from nature to technology to solve a particular technical challenge.[1]

The main limitation of existing typologies is the absence of reflection on the conceptual and normative assumptions implicit in different biomimetic approaches and on their role in guiding research agendas. These assumptions concern the meaning behind "nature-" or "bio-" in biomimetic design, what it means to actually mimic nature, and the promises that motivate the development of biomimetic innovations. The way in which nature is conceptualized informs the choice of models to imitate,

[1] It should be observed that the application of biomimicry is not restricted to technology, as it is often applied to business and management strategies as well.

which of their features will be isolated and studied, and what methods will be used to transfer these insights into technical design. These decisions have an influence also on the desired impacts of a biomimetic product, whether its innovative character will lie, for instance, in improved performance or increased sustainability. The growing philosophical literature on biomimicry has begun to devote attention to the problem (Bensaude-Vincent, 2019; Blok & Gremmen, 2016; Dicks, 2016), without however proposing an articulated typology of different kinds of biomimetic approaches based on their specific assumptions about the meaning and value of imitating nature in technology. Philosophical approaches to biomimetic design have treated it as a relatively unified phenomenon that is only distinguished in general subcategories, usually biomimicry, biomimetics, and bionics (e.g., Bensaude-Vincent, 2019), or proposing to distinguish technology-focused approaches from nature-focused ones, such as biomimicry and ecomimicry (Marshall & Lozeva, 2009), or weak and strong biomimicry (Blok & Gremmen, 2016). More conceptual work is necessary to tease out the differences that fragment the field.

Existing typologies also share a specific perspective on the field, whose positionality is not reflected upon. For one, they focus primarily on the NBIC side (Nano-, Bio-, Information technologies, and Cognitive science) of science and technology, where disciplines such as materials science, computer science, electrical engineering, biomedical engineering, chemistry, robotics, etc. form the majority of the landscape of contemporary bio-inspired R&D under the labels of biomimetics, bionics and, to a lesser extent, biomimicry. What this bias overlooks are other kinds of bio-inspired and nature-based disciplines such as permaculture, agroforestry and agroecology, ecological restoration, ecological design and industrial ecology, as well as indigenous practices of landscape management which imitate natural patterns and rhythms to grow crops, restore ecosystems and organize productive activities in more sustainable ways (Dicks, 2017b; Gremmen, 2022; Mathews, 2019).[2]

To summarize, the main limitations of existing typologies of biomimetic approaches are the lack of reflection on assumptions about nature and mimesis, and a narrow understanding of biomimetic design. On the other hand, philosophical reflections on biomimetic design have yet to provide articulated typologies that go beyond simple dichotomies. To fill these gaps, we will devise a typology of biomimetic practices based on their specific conceptual and normative assumptions.

[2] We acknowledge that biomimicry tends to be, in general, less NBIC-focused than biomimetics or bionics. Our aim is to point out that the available typologies of bioinspired disciplines tend to focus mainly on the developments in high tech, industrialized, and highly scientific sectors, marginalizing those applications, more widespread within biomimicry and similar disciplines, that focus on less technology- and knowledge-intensive sectors such as agroecology and ecological design.

3 A Framework for a Typology of Biomimetic Design

3.1 Conceptual and Normative Dimensions in Biomimetic Design

Philosophical reflections on biomimetic design have tried to distinguish between different kinds of approaches, usually split into two versions, an innovation-focused, not always sustainable approach, attributed to bionics and biomimetics, and an ecological and sustainability-focused one, attributed to biomimicry (Blok & Gremmen, 2016; Landrum & Mead, 2022; Marshall & Lozeva, 2009). Blok and Gremmen (2016) formulated a concise proposal by distinguishing between a "weak" and "strong" version of biomimicry, based on an Aristotelian distinction between different conceptions of mimesis. Strong biomimicry is based on an ecological ethos that demands close imitation of nature, while weak biomimicry is based on a looser form of inspiration that prioritizes technical functionality. This distinction problematically conflates two distinct levels of assumptions. Conceptual assumptions concern the meaning of "mimesis of nature" implied by biomimetic design, including epistemic assumptions about the methods and forms of knowledge required to understand nature, the required level of abstraction, whether it concerns just the transfer of knowledge, etc. Normative assumptions concern instead the reasons why mimicking nature is considered valuable, what goals biomimetic design should be employed for, and so on.

Blok and Gremmen's (2016) proposal encounters two problems. First, it confuses these two dimensions by conflating two different distinctions in one. In their view, the normative demand for ecological appropriateness implies the need to imitate nature as faithfully as possible, a conceptual assumption. "In order to adhere to natural principles as a normative standard of technology and design, however, mimicry has to be understood in the strict sense of a copying or a reproduction of nature" (Blok & Gremmen, 2016, p. 208). Their proposal conflates the conceptual level of the degree of similitude with the natural model (perfect copy or mere inspiration), and the normative role that nature plays in the imitation (nature as technical model or as ecological standard). Blok and Gremmen thus point out the problems of what are speculative extremes within an actual broader range of different conceptions of biomimetic design, failing to accurately represent existing biomimetic practices.

Second, it depicts a rather strict dichotomy between different degrees of similitude, between perfect copy and mere inspiration, which does not correspond with actual design practices. Biomimetic technologies are rarely the perfect reproduction of the original biological models since the latter are "not always optimal, ideal, elegant or perfect" (Cohen & Reich, 2016, p. 15).[3] Natural designs are rarely optimized for a single function, they are usually multifunctional and adapted to a particular ecosystem, requiring a process of abstraction and translation in order to be effectively transferred into working biomimetic prototypes in different

[3] Bioreplication is perhaps a notable exception in which biological nanostructures are faithfully copied. However such "copies" do not include the entire organism and employ different materials (Pulsifer & Lakhtakia, 2011).

functional contexts and at different orders of magnitude (Vincent et al., 2006). This means that nature's design solutions are often partial and incomplete for many technical purposes, and even biomimicry designers recognize as much when following nature not only as an ecological measure but also a as technical model (cf. Cohen & Reich, 2016; Hayes et al., 2020).[4]

In the remainder of the section, we elaborate on these two dimensions, the normative and the conceptual, of biomimetic design.

3.2 The Normative Dimension of Biomimetic Design

Most, if not all, biomimetic practices consider nature a source of technical insight, a large repository of biological models to learn from and imitate in technical design. Natural organisms have overcome evolutionary challenges by developing particular strategies that were key to ensuring their survival – such as mussels finding a way to remain firmly attached to a rock. Such design solutions can provide design shortcuts to create innovative technologies, improve performance and achieve new functions such as self-healing capabilities. By describing nature as a repository of clever technical designs, "an enormous pool of inventions that passed the harsh test of practicality and durability in changing environment" (Bar-Cohen, 2006, p. 2), designers highlight its epistemic value as an "innovation engine" (Cohen & Reich, 2016, p. 7).

However, nature can also constitute a source of normative principles. According to Benyus, nature is not only an unsurpassable model for better technologies, but it also offers a measure of the ecological appropriateness of our technologies. "Biomimicry uses an ecological standard to judge the "rightness" of our innovation. After 3.8 million years of evolution, nature has learned: What works. What is appropriate. What lasts" (Benyus, 2002, p. xi). In other words, the organisms and ecosystems that survived in nature are the ones that managed to do so in ways "appropriate" to their context, that is in ways that, for example, were conducive to the existence of other lifeforms or that did not deplete the resources that guaranteed their survival. According to this view, nature can indicate the ecological limits that we should respect if we are to live sustainably and also provides a blueprint for how to do so. The most emblematic example are the studies conducted at the Land Institute by American agroecologist Wes Jackson. The attempts by Jackson and colleagues to "farm in nature's image" (Soule & Piper, 1992) led them to follow the lessons hidden in native ecosystems, finding inspiration in the suggestion of English poet Alexander Pope to "consult the genius of place in all" (Jackson, 2011, p. 78). Jackson offers the example of two different natural ecosystems, the North American

[4] Henry Dicks has recently proposed a similar distinction based on degrees of similitude, distinguishing different processes through which a model is transferred from biology to technology, namely transposition, translation, and transformation (Dicks, 2023). Dicks avoids the objection that biomimetic technologies are rarely perfect copies of the original by distinguishing different degrees of abstraction at which these processes take place. In our approach we find it less important to focus on how *accurately* nature is copied compared to *how* and *why* nature is copied, namely on the kinds of conceptual and normative assumptions at play in the design process. A fuller discussion of these issues requires more space and lies outside of the scope of the present article.

prairie and the tropical rainforest of Costa Rica, describing how they are differently "designed" to manage water in ways that surpass intensive agricultural attempts in the same regions (ibid., pp. 72–73). Native ecosystems display ecological relations that are uniquely adapted to the local conditions and tend to ensure their general stability. By consulting the ingenuity of ecological relations, agroecologists try to farm in ways that preserve soil health and do not negatively affect local ecosystems. Similarly, Biomimicry Institute's "Life's Principles" capture general strategies found in nature that ensure ecologically beneficial outcomes, for example by closing material loops and fitting form to function (Baumeister et al., 2014).

The idea that nature can be a source of normative principles does not mean that nature can answer all sorts of ethical questions (Jackson, 2011, p. 78), but rather that when we ask questions of ecology and sustainability, nature can offer invaluable lessons and indicate ways to make technology more compatible with life on Earth. This might well require that such lessons are adequately abstracted and translated to apply to human activities (Dicks, 2017a), which would imply that the idea of nature as a normative measure of sustainability does not require that nature is perfectly copied, as Blok and Gremmen (2016) instead presuppose. It is in such a way that nature can be a normative source of ecological standards, enabling us to evaluate the appropriateness of our technologies.[5]

To summarize, there are two general roles that nature can play in biomimetic design. The first is as a technical model which provides insight into functional principles that can be abstracted and translated into technology. The second is as a normative source of ecological principles that enable us to evaluate the ecological appropriateness of our technologies. These two senses can but do not necessarily exclude each other, and in biomimicry they are often seen as complementary. Valuing nature as a model for technical innovation does not exclude following ecological principles to ensure sustainability (Cohen & Reich, 2016; Pedersen Zari et al., 2020).

3.3 The Conceptual Dimension of Biomimetic Design

The concept of mimesis refers to the general idea of "imitation" at the basis of biomimetic design, and is itself a term with a rich history in aesthetics and literary theory (Gebauer & Wulf, 1995). In biomimetic design, ideas associated with mimesis, such as imitation, inspiration, and so on, are used quite liberally and this is part of the reason for the flourishing of numerous alternative names that do not always

[5] The view of nature as a source of normative principles raises the question of whether doing so constitutes a case of the naturalistic fallacy. This point has been observed (Blok & Gremmen 2016; Dicks 2016; Dicks 2017a) and merits further attention but it is beyond the scope of this paper. Here we limit ourselves to observing that biomimicry comprises multiple levels of "normativity", including a technical sense. If the goal is to create, say, a highspeed train that does not produce a sonic boom when coming out of a tunnel, then the beak of the kingfisher offers a solution that should be followed to avoid the problem (Fayemi et al., 2014). However, this kind of normativity is restricted to the particular design goal sought by the engineers. The kind of ecological normativity that nature can offer for Jackson and Benyus, on the other hand, is to be applied to our technological innovation in general (Dicks, 2019). When we refer to the idea that nature can be a source of normative principles, therefore, we mean ecological standards in particular, but without thereby denying the fact that nature can potentially offer other kinds of norms.

individuate clearly identifiable types. However, it is crucial to distinguish between ways in which original and copy, nature and technology, can be related. We propose to distinguish between inspiration, imitation, and integration.

Concerning inspiration, terms such as bio-inspiration and bio-inspired design (BID) have been broadly defined as the attempt to create innovative designs by transferring biological knowledge to the technical domain (Fayemi et al., 2014; Hashemi Farzaneh & Lindemann, 2019). In this general sense "bio-inspired design" is the generic term that encompasses all the different design approaches that generate new ideas from nature and living systems (Montana Hoyos & Fiorentino, 2016).[6] To distinguish inspiration from more detailed processes, Cohen and Reich define it as the "transferring of ideas or general design principles" from nature to technology (2016, p. 5). For example, the idea for "liquid robots" has been inspired by sea cucumbers, organisms that can reversibly adjust the stiffness of their tissues (Wang et al., 2023). In this case, the organism provided just the idea for the technical function, a reversible liquid–solid transition, the implementation of which did not occur by studying the biological details of the model, but through engineering methods.

Concerning imitation, disciplines such as biomimetics go a step further than bio-inspiration when studying nature as a technical model. We argue that they constitute a case of imitation, which involves "transferring more detailed knowledge including models and exact parameters" (Cohen & Reich, 2016, p. 5). Imitation requires the abstraction of functional principles found in the model and their translation into functional requirements for a technological application (Hashemi Farzaneh & Lindemann, 2019; Lenau et al., 2018). For example, by understanding the physical principle behind the form of the humpback whale's fins, it was possible to improve the efficiency of wind rotor blades (Nachtigall & Wisser, 2014, p. 103). Imitation thus includes the most common approaches in biomimetic design such as biomimicry, biomimetics, and bionics. The Venn diagram provided by Fayemi et al. (2014) illustrates well the idea that all cases of bio-imitation are also cases of bio-inspiration since the abstraction and translation of the functional principles of a natural model imply the latter being the inspiration for the design.

Yet integration goes a step further than imitation. Biomimetic designers sometimes integrate nature into design for functional reasons, as well as integrating design into nature (Dicks, 2016; Holy-Luczaj & Blok, 2019). The first strand comprises all those practices that do not limit themselves to transferring abstract principles from biology to technology but employ biological organisms and materials by incorporating them in biomimetic design. Bio-design argues for the need to go "beyond mimicry" and harness biological processes and their "near perfect economies of energy and materials" (Myers & Antonelli, 2014, p. 10) to address environmental degradation. Such bio-integrated projects can include biotechnological hybrids (Rijssenbeek et al., 2022) and bio-hybrid robots (Froese, 2013; Ricotti et al., 2017) as well as ecological designs by the likes of John and

[6] Often non-biological models are employed as well. For example, spiral flows have inspired more efficient water and material mixing systems.

Nancy Todd (Todd, 1994; Todd & Todd, 1994), who designed wastewater treatment plants that imitate filtration processes occurring in natural wetlands.[7] However, the ambition of ecodesigners is not only to design with nature but also to integrate design into nature. The second strand thus integrates human designs and ecology to "restore biodiversity or the health of ecosystems" (Pedersen Zari et al., 2020, p. 5). Ecological approaches such as regenerative design (Reed, 2007; Wahl, 2006, 2016) and permaculture (Gremmen, 2022) are inspired by, imitate and integrate the lessons of biology and ecology looking beyond form and process at the level of ecosystem (Kennedy et al., 2015) in order to make human designs less impactful on the environment and an integral and functional part of the ecosystems they are part of.[8] There are of course many bio-integrated approaches that do not aim at imitating nature, manipulating biological materials to fit particular purposes or creating novel biomaterials; "integration" here is meant to capture only those approaches that employ biological materials and organisms or embed technical designs in ecosystems with the aim of reproducing some of the functional principles of the natural models.

To summarize, we distinguish three different conceptual levels of mimesis, that represent three different ways in which nature comes into play in technology. Inspiration is the most general and refers to designs in which nature simply provided the initial idea. Imitation further requires the study, abstraction, and translation of functional principles from biology to technology. Lastly, integration involves the effective incorporation of biological materials into the design, harnessing their properties for functional but also for ecological purposes.

It is important to emphasize that these distinctions do not constitute opposites, but rather a continuous range in which the new level is often built upon the former. This means, for example, that a design practice that considers nature a normative source of ecological standards does not exclude the possibility that it may also employ nature's design solutions as inspiration for solving technical challenges. Likewise, modeling an organism's function to abstract a particular principle does not exclude – rather it implies – that the organism also provided the initial inspiration. This is an insight that becomes visible when looking at the blurry world of biomimetic design in practice rather than by just pondering the clear-cut categorizations of philosophy.

4 A Typology of Biomimetic Approaches

The intersection of the two dimensions of biomimetic design described above enables us to describe six different biomimetic types, illustrated in Fig. 1 and described below. Again, it is crucial to keep in mind that generally each subsequent row and column, from left to right and from bottom to top, represents a more specific type, which

[7] Interestingly enough, both synthetic biological organisms and the ecological design projects by John and Nancy Todd have been called "living machines", in spite of the clear differences in focus.

[8] Some authors have proposed to name these approaches ecomimetic (Blok, 2017; Marshall & Lozeva, 2009).

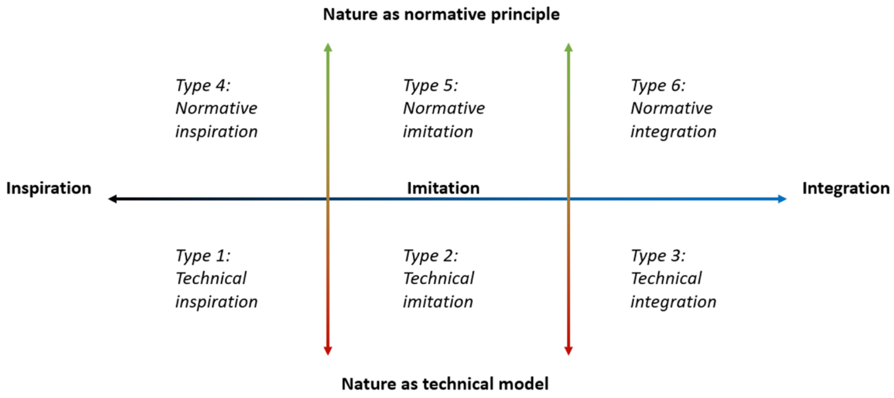

Fig. 1 Typology of biomimetic design

usually includes some aspects of the more general as well. Table 1 summarizes the findings in terms of the assumptions of the different biomimetic types about nature, mimesis, technology, and implicit ideas of sustainability. The latter will be further discussed in §5.2.

Biomimetic type 1 – Technical Inspiration

The first biomimetic type is the most general and comprises all those practices that have natural models as idea generators. Sometimes "bioinspiration", "bio-inspired design" (BID) or "biologically inspired design" are used as general labels for all biomimetic design. However, projects and practices that limit themselves to considering abstract ideas and principles instead of modeling and abstracting precise functional principles of biology, remain at the general level of inspiration. Technical inspiration looks at nature as a repository of clever ideas that offer inspiration to create innovative technologies but does not seek to replicate the details of how nature achieves such results. The "liquid robot" case we mentioned in §3.2 provides the perfect example (Wang et al., 2023). The sea cucumber's ability to alter the stiffness of its tissues suggested the idea of a robot able to change between a solid and a fluid state. The engineers did not, however, study the functional characteristics of the sea cucumber's skin to realize their invention; the sea cucumber inspired the idea but did not offer the precise functional model for its realization, in contrast to the smart material created by Zhao et al. (2022) which actually imitates its skin structure.

Biomimetic type 2 – Technical Imitation

When engineers model, abstract, and translate functional principles from nature to technology, we are in the realm of imitation. Biomimetic designers employ this design method to implement precise functional principles found in nature in technology. Famous examples such as the Japanese bullet train inspired by the beak of the kingfisher bird, self-cleaning paint that imitates the surface of lotus leaves, or

Table 1 Assumptions of Biomimetic Types

	Nature	Mimesis	Technology	Idea of sustainability[a]	Example
Type 1 – Technical inspiration	Source of ideas for innovative functions	Inspiration from broad functional principles	Focus on innovation	Very weak to weak, increased efficiency can reduce energy and material cost	Liquid robot
Type 2 – Technical imitation	R&D lab, repository of innovative designs to study	Abstraction and translation of precise functional principles for technical purposes	Focus on innovation and learning functional ideas from nature	Very weak to weak, increased efficiency can reduce energy and material cost	Bullet train, self-cleaning paint
Type 3 – Technical integration	Realm offering unique properties that can be harnessed	Functional incorporation of biology and technology to replicate and enhance biological capabilities	Focus on hybrid technologies that provide innovative functions	Very weak to intermediate, possibility to replace artificial products with hybrid alternatives	Biohybrid robots
Type 4 – Normative inspiration	Source of ideas for sustainability	Inspiration from broad functional principles for ecological sustainability	Focus on sustainable ideas	Intermediate, Life Cycle Analysis and other general principles to reduce environmental impact	Recycling
Type 5 – Normative imitation	Model and measure for sustainable innovation	Abstraction and translation of precise functional principles for ecological sustainability	Focus on innovative and sustainable design	Intermediate to very strong, Life Cycle Analysis and functional principles that reduce resource consumption	Shading façades
Type 6 – Normative integration	Instrumental and intrinsic value of ecosystems	Functional integration of biology and technology to obtain services and regenerate ecosystems	Focus on remediation and restoration	Strong to very strong, focus on maintenance and regeneration of landscapes	Todd's "living machines", regenerative agriculture

[a]The classification of sustainability from (very) weak to (very) strong is by Landrum and Mead (2022). See §5.2 for a more detailed discussion

wind rotor blades modeled after whales' fins, all fall in this category (Nachtigall & Wisser, 2014). In technical imitation nature is framed as a repository of refined design ideas developed through the extensive "R&D" process of evolution, whose optimization and resilience humans can study, learn from, and imitate.

Biomimetic type 3 – Technical Integration

Technical integration is biomimetic design that employs biological organisms directly. Practices such as bio-design (Myers & Antonelli, 2014) and bio-hybrid robotics (Mestre et al., 2021) employ, modify, and integrate biological material into technology to harness the unique properties of living organisms, imitating their natural counterparts. For example, biohybrid actuators integrate artificial structures with living cells and tissues to create biohybrid robots that overcome the limitations of small-scale fully artificial robots and could be used for drug delivery (Ricotti et al., 2017). The direct use and modification of organisms enable the leverage of processes (metabolism, movement, substance production, etc.) that are otherwise difficult to reproduce through non-biological processes.

Biomimetic type 4 – Normative Inspiration

Normative inspiration occurs when designers look to nature for sustainable design ideas, being inspired by abstract principles and not looking into the functionality of specific models. The goal is to achieve functions similar to nature to replace less sustainable alternatives, such as using the sun as an energy source, without relying on the same mechanisms of nature to achieve them. For example, recycling practices are inspired by the closed-loop circles found in nature, but the relation with existing material cycles is often very loose and based more on general ideas rather than close imitation (McCormick & Kautto, 2013; Zwier et al., 2015).

Biomimetic type 5 – Normative Imitation

Biomimetic design that studies nature to transfer functional principles and does so to improve the sustainability of innovations falls within normative imitation. Many designs in biomimicry emulate particular life-sustaining principles, evaluating the compliance of the final design with "Life's Principles" as the last step of a "design spiral" methodology (Baumeister et al., 2014). In this way, the biomimicry approach "creates conditions conducive to life" by trying to ensure that the idea of nature as a measure of ecological sustainability is considered. Sustainable architecture has developed numerous solutions by modeling and adapting design solutions from nature, such as shading façades for thermal regulation that imitate the *strelitzia* or Bird of Paradise flower (Pawlyn, 2016, pp. 96–97).

Biomimetic type 6 – Normative Integration

Normative integration comprises biomimetic practices that try to connect human interventions with the environment in order to create innovations that are not only sustainable but also support, remediate, and restore existing ecosystems. Bio-integrated innovations that focus on reconnecting with the ecological structure of a landscape integrate nature into design and design into nature in order employ nature's capacities in the service of humans while also ensuring that such projects benefit the surrounding ecological community. It comprises approaches such as regenerative design (Reed, 2007; Wahl, 2016), Todd's eco-designs and "living machines" (Todd & Todd, 1994), and practices such as regenerative agriculture (Gremmen, 2022; Jackson, 2011).

5 Discussion

5.1 Making Sense of Biomimetic Design

The six biomimetic types identified above provide a framework that can help make sense of the variety of biomimetic design practices, based on their conceptual and normative assumptions. The paper brings together insights from different discourses, with the distinction between inspiration and imitation being fundamental in biomimetics and its focus on technological innovation, and the dimensions of ecosystem integration and nature as normative principle that feature prominently in the sustainability discourses of biomimicry. These insights made it possible to distinguish two different dimensions of biomimetic design, conceptual and normative, which previous typologies and classifications often conflated. The conceptual dimension captures the assumptions behind the meaning of "mimesis" of nature in the context of design, in which ways the copy resembles the original, and what aspects of the original the design focuses on. The normative dimension adds a further layer that is sensitive to value considerations in design, which in the case of biomimicry are often values of resilience and ecological sustainability. By bringing these dimensions together, the framework organizes the range of existing assumptions about the meaning and value involved in the technical imitation of living nature. In this way, the typology reflects the existing diversity of discourses around and about biomimetic design and weaves them together to provide a way to make sense of its current landscape.

The types distinguish clearly between different conceptual and normative senses in which a natural organism or ecosystem can be a model in biomimetic design. Types 1, 2, and 3 are typically broader than 4, 5, and 6, as both consider the technical value of natural organisms as sources of inspiration, while the latter three tend to go a step further and consider ecological criteria as well. This step in biomimicry is called the "evaluation" step, which makes it possible to compare the proposed design with sets of normative criteria of ecological sustainability inspired by nature (Baumeister et al., 2014). Approaches that follow nature as a normative ideal do not only employ design ideas suggested by natural organisms; they also make space for ecological considerations to inform design goals and possibilities. In this, they follow Freya Mathews' call for "allowing nature to "redesign" not only our commodities but also our own desires" (2011, p. 19).

5.2 Biomimetic Design and Sustainability

It may seem that the framework fails to capture a dimension originally captured by the strong–weak distinction, namely that between more or less sustainable approaches in biomimetic design. Drawing this distinction accurately is important if we are to reflect critically on biomimetic design, given its ambiguous character in relation to its promises of sustainability and to harmonize human innovation and nature (Mathews, 2011). There is in fact the risk that the "bio-inspired" or "biomimetic" labels are perceived as inherently supporting sustainability (Kohsaka et al., 2018), while sustainability promises vary greatly among different approaches. In the framework, most approaches and practices focused on ecological sustainability would be found among types 4 to 6, while types 1 to 3 would represent those approaches that do not consider sustainability or do so only secondarily.

However, it is also important to avoid simplistic distinctions, assuming that sustainability is only possible for approaches within types 4 to 6, which value nature as a source of sustainable ideas. In principle, sustainable innovations can also be found in other types. The meaning of "sustainability", for a start, is not unique and is hard to pin down precisely, being more often considered a matter of degrees (Ceschin & Gaziulusoy, 2016; Landrum & Mead, 2022; Mead & Jeanrenaud, 2017). Each type may suggest different ideas of sustainability and different paths to sustainable biomimetic design, which provides a more nuanced account compared to typologies that only present a sustainable-non sustainable range. In types 1 and 2 the efficiency of certain organic structures can inspire technologies that require less material or less energy to function, which could be considered a weak kind of sustainability. Type 3 may replace artificial materials whose production requires high environmental costs with biological components that are less harmful to the environment. Types 4, 5, and 6 consider the ways in which nature preserves and regenerates itself and try to implement these ideas in biomimetic technologies, striving for stronger forms of sustainability. Type 4 and 5 can include Life Cycle Analysis, such as in the Cradle-to-Cradle approach (McDonough & Braungart, 2002), as a further step to ensure greater sustainability of new technologies. Type 6 also adds a restorative and regenerative dimension that promotes the positive impact of biomimetic designs on the rest of the ecological community, promoting a strong to very strong idea of sustainability (Cf. Landrum & Mead, 2022).

The framework enables a more accurate understanding of the ways in which individual cases of biomimetic design relate to their original model and sustainability. The idea for passive ventilation inspired by termite mounds in the Eastgate Center in Harare, Zimbabwe, is one of the most famous examples of biomimetic design. The case has been described as a practical success, consuming only 10% of the energy required by buildings with traditional ventilation, but also as a theoretical failure (Fayemi et al., 2014; Turner & Soar, 2008). Further studies seem to have proved that termite mounds are less thermally stable than previously thought and that the main cooling factor is the soil they are embedded in rather than the induced airflow (Pawlyn, 2016). In this regard, the Eastgate Center might be better understood as a case of inspiration rather than imitation. Be it as it may, the case does raise a question about the extent to which we need to actually "get nature right" to design sustainable solutions. In this sense, not only biomimetic solutions may not always be sustainable, but biomimetic design may also not be the only way to create more sustainable solutions. This suggests that the relationship between biomimetic design and sustainability is not a straightforward one.

6 Conclusion

In order to make sense of the heterogeneous field of biomimetic design, the paper provided an analytical typology based on existing assumptions about the conceptual and normative dimensions of biomimetic design. Their intersection generated six different biomimetic types, which represent the conceptual and normative tensions that are driving different research trends in the field. These types can help characterize different kinds of approaches, practices, and technologies that draw inspiration from, imitate, or integrate nature into technological design. The typology categorizes the assumptions that a particular approach adopts concerning how the mimicking of nature is achieved and with what goals and values, enabling the comparison and contrast with other biomimetic practices and technologies. In this way, the typology offers a hermeneutic tool to interpret the current variegated landscape of biomimetic design that can be useful to philosophers reflecting on nature-based technologies and to practitioners involved in biomimetic disciplines.

The typology reveals that different biomimetic approaches may disagree on what they consider "mimicking nature" to imply conceptually, not only and not so much just in terms of degrees of similarity, like the strong–weak distinction presupposed, but more concretely in terms of what a biomimetic copy consists of in relation to the original biological model. A biomimetic technology can incorporate general functional principles inspired by nature, or it can imitate more precise functions that have been accurately modeled. Sometimes a biomimetic product also requires the integration of artificial and biological elements. Besides such conceptual disagreements, normative differences separate approaches that value the mimicking of nature for reasons of functionality and performance from those that may value it also for reasons of ecological sustainability, seeing biomimetic design as a crucial path in the development of more environmentally friendly technologies.

This framework contributes to a broader and more nuanced picture of biomimetic design as a field traversed by numerous conceptual and normative assumptions about nature and its technical imitation. Such assumptions are likely to influence design practice, informing project methods and goals. Further studies could test the framework empirically by looking at the role played by conceptual and normative assumptions within particular biomimetic approaches. It might be the case that more general approaches such as biomimetics comprise different technologies that fall within different types. The typology could also be enriched further, for example by adding the levels at which mimicking can take place, namely form, process, and (eco)system (Hayes et al., 2020; Jacobs, 2014; Kennedy et al., 2015).[9]

[9] The reader might wonder whether the (eco)system level is already captured by the idea of integration. There is certainly a relation between integration and (eco)system level, but the two concepts do not capture quite the same idea. First, integration of biological material into technology does not always fit the system level, but rather form or process; it is mainly the integration of technology into nature that tends to consider ecosystem relations. Second, the system level as defined by Jacobs (2014) does not consist only of ecosystem relations, but of any "systemic" kind of relations. In this sense, swarm robotics could also be said to operate at the system level. This suggests that there are indeed similarities between integration and system level, but the two are not the same; this difference is precisely the reason why adding the different levels to the typology could offer a substantial extension.

Critical reflection on such assumptions can contribute to bring more awareness and reflexivity to a field that has generated numerous promises and is nowadays often featured in mainstream media, but that is commonly depicted as more homogenous than how the field actually is. As a fast-growing trend, biomimetic design sits at the intersection between promises of innovation and sustainability, providing a unique case to study how conceptual and normative assumptions about nature and technology overlap and influence each other in research and development. Do biomimetic technologies invite us to rethink human material, epistemic, and moral relations with nature? Is biomimetic design mediating how human beings perceive and value nature, non-human entities, and the natural environment? What role do conceptual and normative assumptions play in shaping the values that biomimetic technologies embody? These and other questions point to the increasing need for philosophy of technology and environmental philosophy to join forces and reflect on the ways in which emerging technologies such as biomimetic design are shaping the interface between nature, technology, and human beings.

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