Narrative Review Article

Inspired by Nature, Made by Industry: The Depth Problem in Biomimicry and the Limits of Copying Form

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ABSTRACT

The interdisciplinary practice of biomimicry, finding design solutions based on living organisms, is often celebrated for its sustainable potential, with nature portrayed as having already solved the problem of building without waste. This narrative review assesses the degree of biological imitation across notable examples from this growing field and the available environmental evidence supporting them. This work involves a structured critical synthesis, where a set of canonical case studies featured repeatedly, including in the field's seminal text, is analyzed for their level of biological imitation, form, process, or ecosystem, with set criteria for which organism feature was imitated and whether the environmental evidence of the biomimicry rested in production or use. The examples of the biomimicry discipline's acclaimed successes cluster almost exclusively at the form level, copying a shape or surface such as a paint inspired by lotus leaves or the nose of a train shaped like a kingfisher, and then employing the same industrial practices that the discipline asserts it seeks to transcend. An acclaimed example of the process level, the Eastgate Centre in Harare, uses passive cooling design without conventional air conditioning, but the mechanisms for what was purportedly a mimicry of a termite mound have since been reworked by biologists. Ultimately, it is clear that biological inspiration is simply that, and not necessarily linked to life-cycle environmental costs. Accounts of these cases often conflate the two, and any sustainability claims must instead focus on life-cycle evidence.

Keywords: biomimicry; biomimetics; sustainable design; biomimetic architecture; Eastgate Centre; design methodology

INTRODUCTION

Biomimicry often gets introduced with a story about a train. In the 1990s, Eiji Nakatsu, a train engineer, redesigned the nose of Japan's 500 Series Shinkansen to resemble the beak of a kingfisher, a bird known for diving into water without a splash. When high-speed trains enter tunnels, they create sonic booms, loud noises caused by micro-pressure waves, a well-known problem in high-speed engineering (1). After adopting the design of the kingfisher's beak, the high-speed train reportedly traveled about ten percent faster than the previous model, used fifteen percent less electricity, and met what are apparently the world's strictest noise regulations (2). Many people love to tell this story because of its moral lesson: the solution to a challenging problem had already been discovered by nature; the engineer simply needed to look.

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This is the emotional appeal behind biomimicry. The concept was popularized by a biologist called Janine Benyus, who wrote a book in 1997 on viewing nature as a mentor rather than a resource pool. The patterns of nature have been refined over billions of years of selection, and are produced without the toxins, high temperatures, and waste of industrial manufacturing (3). Biomimicry therefore offers not only intelligent forms for industry to apply, but also a more sustainable practice. If industry could learn to make things the way a mussel creates its adhesive or a diatom creates its glass, using ambient temperatures and water, then the environmental cost of creating things would drastically decrease.

The higher the environmental stakes, the more the frame's appeal grows. Manufacturing accounts for a major portion of global energy consumption, and the specific energy requirements of industrial processes continue to increase as processing becomes more precise, not less (4). The emergence of a discipline that can diminish the impacts of manufacturing by tapping the low-temperature, water-based, waste-free chemistry of the natural world gets to the core of industrial sustainability. Published papers on biomimetics now run in the thousands per year, up from below one hundred per year in the 1990s (5). Designers and engineers are being taught biomimicry in schools as an approach to improve environmental outcomes, not simply as a source for ideas.

This is a review essay arguing that the promise of biomimicry has diverged from the practice in systematic ways. The environmental argument for biomimicry is that it emulates nature's process and recycling efforts. The more publicized instances of biomimicry, however, have focused on mimicking natural forms. A train nose shaped after a bird's beak is fabricated from metal in a typical manufacturing process; a building paint inspired by a lotus leaf is still made with common solvents. Within this selection of biomimicry examples, the cases upon which the field's reputation for sustainability is based are more efficient in use than sustainable in production. Here, this divergence is called the depth problem: the environmental potential of biomimicry is said to increase with its depth of imitation, and yet, in these cases, the imitation runs only skin deep. The depth problem is a contribution to an existing taxonomy of biomimic approaches, drawing from the layers-of-form-to-process-to-ecosystem framework of Benyus (3) and subsequent design applications (6), as well as critiques raised within the discipline (7, 8). The argument is that this taxonomy speaks distinctly to the evidence behind biomimicry's environmental claims for its public-facing examples.

This review, therefore, aims to assess whether these high-profile, popular examples of biomimicry support the often-assumed sustainable nature of the practice and explore how extensive these examples' imitation of biology is in relation to the environmental evidence available for each. The questions explored are: at what level of imitation are these classic examples of biomimicry operating; what type of environmental benefit are they demonstrating, operational efficiency or reduced production impact; and what would be required for the sustainability claims of biomimicry to be anything but assumed?

SCOPE AND APPROACH

This article is a narrative review based on a conceptual framework and not an original research report. Hence, no new data were collected, and there is no claim for a systematic survey of biomimetics practice. The approach used in this article is a structured critical synthesis of the available literature and cases, with clear criteria for case selection and classification, which can be challenged and analyzed independently.

Case selection

These examples were selected purposively and not systematically. This review looks at the canon of examples through which biomimicry is commonly taught and promoted: the cases mentioned repeatedly in the cornerstone text of the field (3), their educational and promotional materials (2, 9), and in the critical literature that responds to them (7, 8, 10). Six cases meet the repetition criterion: Velcro, 500 Series Shinkansen nose, Lotusan exterior paint, Sharklet antibacterial surface, gecko dry adhesives, and Eastgate Centre Harare. Employing a purposive sample is appropriate because these examples have been adopted to build the public image of this field. But this selection cannot reflect the spread of work within the field overall. All conclusions drawn from this review are specific to this question. Whether form-level work is prevalent across the field, as the design literature suggests, is also an empirical question to be explored separately.

Classification criteria

The cases are further categorized by how they imitate biology, answering the question "What does the design imitate from biology?": geometry, structure, or surface texture (form); manufacturing process or functioning principle (process); or material and energy cycles in biological systems (ecosystem). If the case is reported in one category but can be analyzed in another, both categories are used and differentiated. These cases are also categorized by where the positive environmental impact of the design is reported: in use (lower energy use) or in production (manufacturing). These categorizations of each example are the author's interpretation of the respective cases, applying a consistent rubric to the sources for each, and are presented in Tables 1 and 2, with the basis for each categorization noted in the text. The terms biomimetics, bio-inspired, and biomimicry distinguish the varying applications of the concept: biomimetics as the abstraction and application of a biological concept, bio-inspired as the creative application of a biological concept in a general sense, and biomimicry as the general topic of the movement in relation to its sustainable claims (11).

THE THREE LEVELS OF BIOMIMICRY

Biomimicry encompasses several practices, and the discipline has coined terms to distinguish between them. The most common model describes three levels at which designs can imitate nature: natural form, natural process, and natural ecosystem (3). Natural form mimicry copies an appearance or structure, such as how Velcro was invented by reproducing the barbed hooks of a burr. Natural process mimicry copies the method of creation or how something functions, such as the growing of a material without solvents at room temperature, like an abalone does with its shell. Natural ecosystem mimicry copies how components fit together to create a self-sustaining system, such as an industrial park where the waste of one process would be the raw materials for another, imitating a food web (3, 7). The natural ecosystem is the most ambitious and least executed of the three levels, but it is where biomimicry's sustainability claims lie. A developed ecosystem can sustain itself with only sunlight and recycled materials. Similar multiple-level systems exist in other design fields: Pedersen Zari's framework for biomimetic architecture includes natural ecosystem, natural organism, and natural behavior levels, which can be imitated in form, material, construction, process, or function (6). The three-tiered system described here is, therefore, a common tool in the discipline of biomimicry, not merely an original concept of this review.

Each of these three levels has a different degree of claimed environmental benefit, and Benyus posits the largest sustainability improvements come from the third level. Though a design may perfectly replicate an owl feather, for instance, it may still require heat and toxins to create. If the design replicated the feather's waste-free self-assembly, that would improve the production footprint. If the design replicated the nutrient cycles of the surrounding ecosystem, that is what would make the design truly sustainable, at the scale of an economy (3). The three levels create a ladder, each rung harder to reach than the last, but purportedly more worthwhile. This hierarchy is a theoretical construct of the discipline, not an empirical finding. Whether deeper imitation is truly more environmentally beneficial is discussed at the end of this review.

This nuanced definition was formalized. In 2015, the International Organization for Standardization published ISO 18458, which provides a common language and approach for biomimetics and explains its potential and limitations as a sustainable strategy (11). The standard distinguishes authentic biomimetics, the abstraction of a biological concept and its application to a technical solution, from bio-inspired concepts, in which nature provides imagination but not a transfer of mechanisms (11). This distinction is important because much of what is considered to be biomimicry is actually, by the ISO definition, only bio-inspired.

The three levels, along with a representative example and the environmental benefit each is alleged to provide, are summarized in Table 1. This table predicts the pattern traced throughout the rest of this review: the examples that made biomimicry famous sit in the top row, where the benefit is efficiency of use, while the sustainability promise sits in the lower rows, where examples are few.

WHERE THE CANONICAL EXAMPLES OPERATE: THE DOMINANCE OF FORM

If the sustainability argument for biomimicry is at the level of process or ecosystem, then the examples by which the discipline presents itself would be expected to have these characteristics. This is not the case in the canon cited here. Each celebrated case is reviewed below and classified according to the criteria in the Scope and Approach section. In every case, the feature mimicked from the biological model is one of geometry or surface structure.

The genesis of the entire field, Velcro, imitates the tiny hooks of the burr to function as a mechanical fastener; what is imitated is a hook shape, so it is at the

Table 1. *The three levels of biomimicry in the field's standard taxonomy, with a representative example and the environmental reach claimed for each. Level definitions follow Benyus (3) and Kennedy et al. (7); the example assignments and the right-hand column are the author's summary of those sources and describe claimed potential, not measured outcomes.*

Level	What is copied	Representative example	Claimed environmental reach
Form	A shape, structure, or surface	Velcro hooks; kingfisher-shaped train nose	Efficiency in use; manufacturing unchanged
Process	How a thing is made or functions	Shell-like assembly at ambient temperature	Lower-impact production, if achieved
Ecosystem	How components form a self-sustaining whole	Industrial park run as a closed nutrient loop	System-wide sustainability

level of form (3). The nose of the Shinkansen imitates the shape of a kingfisher's beak and the redesign of the pantograph imitates the serrations on an owl's wing feathers; both are shape, thus form, under the stated criterion (1, 2). The self-cleaning paint, Lotusan, imitates the micro- and nanoscale surface roughness of the lotus leaf that was originally characterized by Barthlott and Neinhuis, with the effect that water beads up and rolls off, carrying dirt with it; what is imitated is a surface texture (12). The antibacterial surface, Sharklet, imitates the microscopic riblet pattern of shark skin; what is imitated is a surface texture that has been shown to inhibit bacterial colonization (13). Climbing adhesive tapes modeled on the foot hairs of the gecko are highly effective, dry adhesives that use the same van der Waals adhesion as the actual gecko foot, with no glue; what is imitated is the geometry of the foot hairs (14). These imitations reproduce the appearance of the organism (at some scale), not the construction of the organism, and are therefore assigned to the level of form in Table 2. Figure 1 depicts the distribution of the examined cases across the three levels.

The example of the lotus shows that even a sophisticated, nanoscale imitation remains an imitation of form. What Barthlott and Neinhuis discovered was the physical structure of the lotus leaf, a hierarchy of microscopic bumps and still finer wax crystals that hold a drop of water on a cushioned layer of air so that the water will roll off and the dirt with it (12). Reproducing that hierarchy of forms in a paint is an impressive technical achievement with an important functional application; here is a wall that will clean itself whenever it rains. But the functional application here is confined to the use phase of the paint; the paint is produced, packaged, and

Table 2. *The canonical examples examined in this review, classified by the author under the criteria in the Scope and Approach section: level of imitation from what feature of the biological model is reproduced, type of benefit from where reported gains arise. "Process (claimed)" for the Eastgate Centre records that the case is publicly presented as process-level imitation, a claim the case study examines. The concentration at the form level illustrates the depth problem within this canon; it is not evidence about the distribution of all biomimetic practice.*

Example	Biological model	What is copied	Level (author's classification)	Type of benefit
Velcro	Burdock burr	Hook geometry	Form	Function in use
Shinkansen 500 nose and pantograph	Kingfisher beak; owl wing feather	Nose profile; feather serrations	Form	Operating efficiency
Lotusan paint	Lotus leaf	Micro/nano surface texture	Form	Function in use
Sharklet surface	Shark skin denticles	Surface texture	Form	Function in use
Gecko-inspired adhesive	Gecko foot setae	Hair geometry	Form	Function in use
Eastgate Centre	Termite mound (as popularly understood)	Passive ventilation strategy	Process (claimed)	Operating efficiency

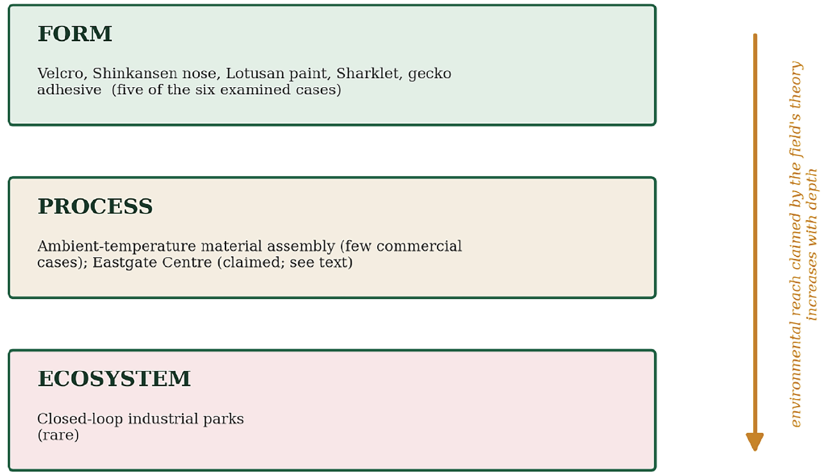

Figure 1. ***Author's classification of the examined canonical biomimicry examples across the three levels of imitation.*** *Each horizontal box represents one level of the taxonomy described in the text (form, process, ecosystem) and lists the examined examples assigned to it by the classification criterion stated in the Scope and Approach section, namely what feature of the biological model each design reproduces: a shape, structure, or surface texture (form); a mechanism of manufacture or functional principle (process); or a closed loop of material and energy (ecosystem). Parenthetical notes describe commercialization at each level within this canon only. The vertical arrow at right shows the direction in which the environmental reach claimed by the field's own theory increases (3, 7); it represents that theoretical claim, not a measured gradient, and no quantitative scale is implied. Figure created by the author; no copyrighted material is reproduced.*

discarded like any other paint. The imitation is deep in terms of nanometers but shallow in the way that matters for the sustainability claims.

At this stage, four properties of any biomimetic design must be distinguished: the depth of biological imitation (which feature of the organism is imitated), the functional performance (of the artifact regarding its purpose), the manufacturing impact (the environmental cost of its production), and the life-cycle sustainability (the net account of production, use, and end of life). The theory of the field claims that deeper imitation allows a lower manufacturing impact, but depth in itself does not guarantee better sustainability; a deeper imitation is only sustainable if its environmental performance across the life cycle is superior. Depth tells where environmental gains can be expected; it is not a measure of these gains, and the four properties are independent of one another.

This distinction is significant because the benefits of the form-level imitation are limited. Each time a streamlined train runs, there is the real impact of using less energy; this is a saving in operation, however, not in manufacturing, for the train is still built in an energy-intensive manufacturing facility from mined and smelted metal. The project's own claims for the 500 Series are ten percent higher speed and fifteen percent reduced electricity consumption compared with previous trains on the same service (2). They are cited here as reported operational improvements, as opposed to independently reviewed life-cycle results. The environmental improvements arrive downstream of the manufacturing costs, which biomimicry at this level does not address. Research within the field points to the same issue: Kennedy et al. caution that biomimicry is not by definition sustainable, citing organism-level imitation as the most frequently employed in the research they review, and noting that to increase the likelihood of a sustainable outcome, the manufacturing process must be considered and not just the form that is imitated (7). The frequency of this level of imitation is consistent with the pattern in the canon here, but proving this would require a systematic sample, which was included neither in their study nor in this review.

This does not mean the famous examples are failures; they are engineering successes, and efficient engineering is valuable. The problem is one of misattribution. When a success at the level of the form is used as evidence that biomimicry is a sustainable design approach, it is credited with a virtue it has not earned, because the form replicated is produced by the very tools that advocates say biomimicry should supplant. The problem of depth is this discordance between the level at which the examined canon is successful and that at which the field claims significance.

CASE STUDY: THE EASTGATE CENTRE AND THE TERMITE-MOUND ANALOGY

To find the clearest example of the depth problem at work, one must turn to architecture, because a building is costly, long-term, and conspicuous, and because a single building has been used as a prime example of biomimicry's sustainability claims. In studying it, one must distinguish between the building's actual passive cooling design, its reported performance, the architect's stated sources of inspiration, and the mythologized narrative that emerged around the building. The case is instructive because all of these have been confused.

The building is the Eastgate Centre, a shopping and office complex in Harare, Zimbabwe, designed by architect Mick Pearce and engineered by Arup (15, 16). Eastgate was occupied in 1996 and was one of the first large-scale modern buildings in southern Africa to use no conventional air conditioning (16, 17). Its cooling strategy is night-purge ventilation (Figure 2). Fans on a day-night cycle push air through voids within the building's concrete floors; the large thermal mass of brick and concrete soaks up heat during the day and dumps it after dark through banks of rooftop brick chimneys (16, 17). The verifiable public record on performance is slimmer than Eastgate's fame would suggest. Eastgate clearly uses no conventional air conditioning (16), and skipping the air-conditioning plant reportedly saved about ten percent of the building's capital cost (9). Beyond that, the claim that Eastgate uses less than ten percent of the energy of comparable conventional buildings is oft-repeated in project documents and engineering community papers where the specifics of the comparison, whether whole building energy or just cooling and ventilation energy of the two buildings, are not consistently outlined (17). To the author's knowledge, no independent, full life cycle audit of these numbers exists and these claims are used here as reported, rather than proven.

But the architect's stated inspiration did include termites: the written accounts of the project also state that Pearce was inspired by the self-regulating mounds of African termites, which controlled climate not by machines, but by cleverly designed structures (9, 10). From that starting point, a somewhat different narrative developed, and it turned Eastgate into the field's favorite classroom example. The story, repeated again and again in the educational texts of the field, described how the tall mounds of *Macrotermes* termites maintain the interior temperature through convection: hot air inside the mound rises up and out, drawing in cooler air at ground level, and the Eastgate building is simply a large-scale model of this termite air-conditioning (9). The field's educational materials have only recently acknowledged the research updates (9). The story is that a biomimicry of natural processes, not of natural form, yields the energy savings.

The problem, however, is that subsequent biology has radically modified the mechanism at the heart of that popular account. J. Scott Turner, a physiologist who measured gas flow within *Macrotermes* mounds, concluded that the mound is not a constant-temperature convective chimney. Rather, respiratory function dominates: the mound acts not like a chimney but like a lung. External wind and temperature fluctuations induce a tidal breathing mechanism that flushes carbon dioxide from the colony and its fungus gardens (10). More recent measurements and modeling of Indian *Odontotermes*

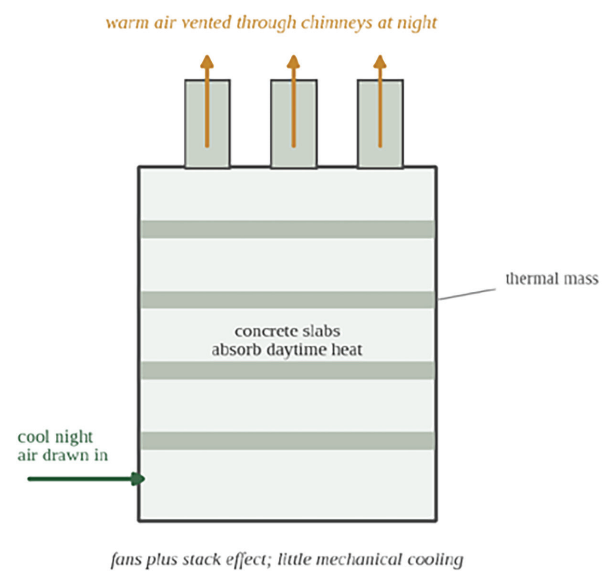

***Figure 2.* Passive night-cooling strategy of the Eastgate Centre, Harare, as described in published accounts of the project.** *The diagram is a simplified author's schematic, not an architectural drawing. The green arrow (lower left) marks cool night air drawn in by fans; the shaded horizontal bands represent the concrete floor slabs, incorporating ventilation voids, and the high-thermal-capacity fabric that absorb interior heat during the day; the orange arrows (top) mark warm air vented through rooftop brick chimneys at night. The strategy, fan-driven night ventilation plus high thermal mass and stack-effect venting, is sound passive building physics independent of any biological analogy. Drawn by the author from published descriptions of the building (16, 17); no copyrighted material is reproduced.*

mounds conclude a similar thing: daily temperature fluctuations induce a gentle internal circulation that ventilates the nest (18). Later fieldwork on African mounds concludes that ventilation is driven primarily by solar heating of the mound's flanks, with different mechanisms dominating for different species, mound morphologies, and conditions (19). Figure 3 compares the two interpretations. These papers do not show that the termite-inspired Eastgate mechanism is incorrect; they do show, though, that the thermosiphon cooling mechanism attributed to these mounds is only one part of a complex and somewhat controversial picture in which gas exchange seems central, more so than temperature control (10, 18, 19). It is not the termite mound that the revised biology calls into question; rather it is the reduction of the mound to a cooling chimney, and of Eastgate to a scaled-up mound (10, 18, 19).

Turner and his colleague, the engineer Rupert Soar, drew a lesson from this. They wanted to push biomimicry further. What termites offer architects, they argue, is not a small model to be enlarged into a building shaped like a termite mound, but an example of how buildings can become an extension of the self-regulating action of the organisms they house (10). To copy the shape or chimney feature, Turner and Soar argue, is to confuse the appearance of the solution with its principle. This critique is all the more surprising because it is directed against the biomimetic example used as a case for going deeper.

The interesting thing about Eastgate is that it does work. The building runs without conventional air conditioning in a climate like Harare's (16), its strategy of purging the building with cold air at night is good passive building physics whether or not the termite mounds do the same, and the saving in capital expenditure by leaving out an air-conditioning plant is considerable (9). The particular biological technique used to achieve this, at least as popularized, is to some extent a story that has

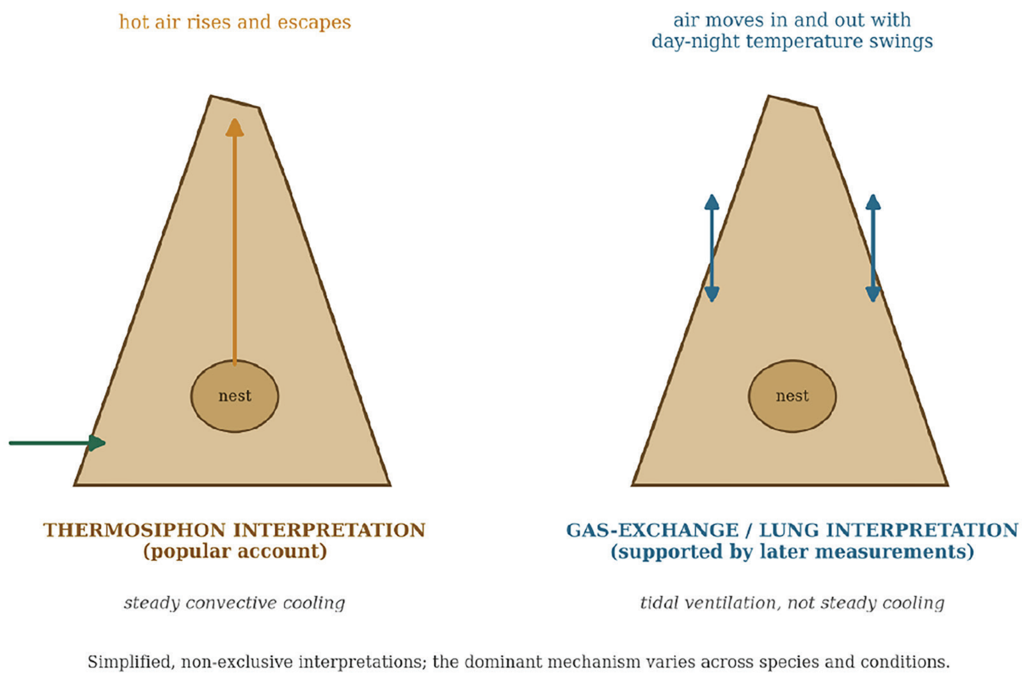

Figure 3. ***Two published interpretations of how large termite mounds ventilate.*** *Both panels are simplified author's schematics drawn for contrast, not anatomical diagrams. Left: the thermosiphon interpretation underlying the popular Eastgate account, in which metabolic heat drives a steady one-way convective flow (orange arrow) venting warm air at the top while cooler air enters below (green arrow), keeping the nest cool. Right: the gas-exchange interpretation supported by later measurements, in which daily temperature swings and solar heating drive an oscillating, tidal movement of air (blue double-headed arrows) that exchanges respiratory gases with little steady cooling. The two interpretations are not strictly mutually exclusive, and field work indicates the dominant mechanism varies across termite species, mound forms, and conditions; the binary contrast is a simplification for exposition. Drawn by the author from the cited findings (10, 18, 19); no copyrighted material is reproduced.*

been told after the fact. Eastgate is used as evidence that mimicking a natural process results in sustainability. What the building shows is that its performance derives from sound passive design principles on one hand, while its claims of termite ancestry, in the strong version of the story, rest on a model that biologists have since revised on the other. That the premier example in this field should owe its performance to sound engineering considerably weakens the claim of a linear relationship between the depth of mimicry and sustainability implicit in the general narrative, and argues for the need to show this claim in every case.

THE INSTITUTIONAL RESPONSE

Such tensions have not escaped the field's attention. The response from within has taken two forms: a formal standard and sustained philosophical criticism.

An official standard, ISO 18458, was published in 2015, providing biomimetics with accepted terminology and approach. This standard specifies steps in abstracting a biological principle and applying it to a technical problem. It also establishes the distinction discussed above between strict biomimetics and more general bio-inspired design (11). The standard's requirement that biomimetics must involve some form of transfer of a functional principle is, in part, an answer to the depth issue: a design that simply references the outline or shape of a natural model would not qualify. But the standard cannot police the use of terms, and no product claiming nature inspiration would have to comply with ISO 18458 before making that claim.

Vincent Blok and Bart Gremmen provide the harshest criticism. They define strong and weak biomimicry (8). Nature in the weak form is a huge library of mechanisms waiting to be borrowed, cut out, and sewn into human technology; biomimicry is simply a more creative form of R&D, not specifically ecological. Nature in the strong version is a model that sets the standard for correct technology; an economy truly inspired by biomimicry would be based on ecological principles. Blok and Gremmen point out that almost all actual biomimicry is weak, and that the strong biomimicry claimed by marketers rests on ultimately questionable ideas about whether nature can be used as a standard of morality at all (8). Their criticisms could almost be a response to the depth problem: the marketing uses the idea of strong, ecosystem biomimicry while the products are delivering weak, form-only biomimicry.

What evidence design scholars can muster has reinforced the point. Literature reviewing biomimetic work notes that the predominant level of biological imitation is the organism, and that biomimetic products are not necessarily more sustainable than other products; the more sustainable biomimetic products are found at the level of the process and the system, which are more difficult to achieve and less frequent (7). The picture, then, is of a field whose own standard and critics have rightly noted the gap that now has to be filled. There is, for example, no commonly used certification process that verifies the life-cycle footprint of biomimetic products, nor is there a requirement that the sustainable nature of the product's biomimetic label be proved.

This leaves a vocabulary problem with commercial implications. As the marketing aspect of the nature-inspired term lends pressure to use it liberally, neither a concept applied to a highly abstracted material strategy nor a loosely referenced visual cue can communicate much about its sustainable contribution. Unconnected to any type of testing or certification, there is nothing to prevent this loose definition from occupying the space that belongs to the strict one in general usage (11). The field expresses its depth problem well both in its standard and in its literature; what is missing is a way to make this diagnosis apply to the products that use the term. Looking at the chronology of the examples in Figure 4, the accomplishments at the form level arrived and accumulated for decades before the critique and standard; the field's most famous exemplar of deep imitation was constructed before the biology it referenced was established.

WHY DEPTH IS HARD AND WHAT WOULD CLOSE THE GAP

If the depth problem is indeed real in these works, the question arises: why does the desire to imitate stop at form, and what would drive it further? The first answer is simply that form is the easiest to imitate. The form of a structure can be observed, measured, and reproduced with existing manufacturing equipment. Natural processes often involve chemistry and physics that industry cannot yet reproduce in large quantities. The abalone builds its shell by a self-assembly process using seawater, an organic production technique that materials scientists can readily describe but not cheaply reproduce; the spider produces silk that is stronger than almost any man-made fiber, at ambient temperature, in water, and from liquid-crystal feedstock (21). It is much easier to replicate the shell itself than the factory that produced

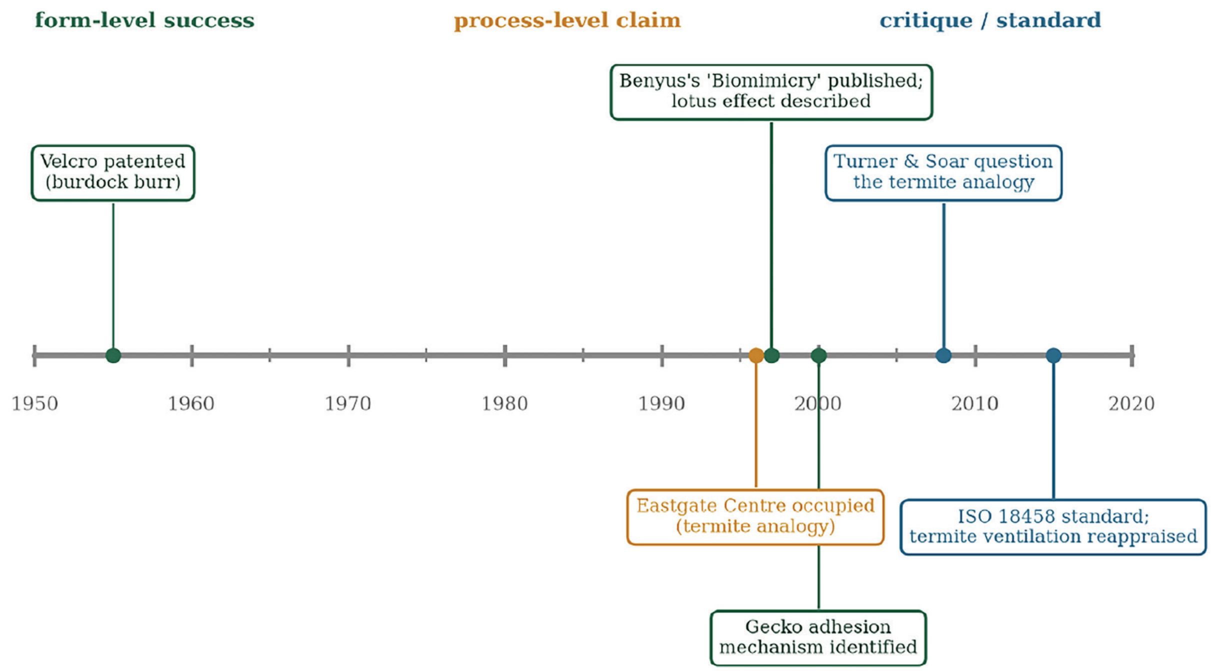

Figure 4. ***Timeline of the milestones discussed in this review, 1950–2020.*** *Each labeled marker is an event discussed in the text, plotted by year on a horizontal time axis; marker colors group events into the three categories named across the top: green for form-level successes within the examined canon (Velcro patented, 1955 (20); Benyus's Biomimicry published and the lotus effect characterized, 1997; gecko adhesion mechanism identified, 2000), orange for the canon's process-level claim (Eastgate Centre occupied, 1996), and blue for critique and standardization (Turner and Soar's reappraisal of the termite analogy, 2008; ISO 18458 and new termite-ventilation measurements, 2015). The selection reflects the cases examined here and is not a comprehensive history of the field. Figure created by the author from the sources cited in the text; no copyrighted material is reproduced.*

it; the shape is an afternoon's work, and the factory is a lifetime's toil.

A second reason is economic. The advantages of form-level imitation are easily incorporated into existing manufacturing processes and industrial systems without the need to rebuild supply chains. Benefits, such as reduced drag or a "self-cleaning" surface, can be directly implemented into a product's performance and marketing strategy. Process- and ecosystem-level imitation would require altering current manufacturing practices and industrial configurations, the returns on which would be realized only over a long-term timeframe. The motivations driving most product development initiatives push strongly toward the shallow end of the pool, where the sustainability claims are most tenuous.

A third challenge, beyond the technical and economic ones, is that biological understanding is provisional and subject to change. To accurately replicate a natural process, designers must understand it soundly. The popular story told about Eastgate linked the building's ventilation processes to a model of termite ventilation that has since been significantly revised (10, 18, 19). Relying on a current biological explanation will leave the design vulnerable when that explanation shifts, which suggests the need for replication to be based on proven principles rather than popular imagery, and applied biology to be viewed as a theory that must be validated against actual design performance rather than certitude.

But to be fair to this framework, there are cases to be made on both sides. First, form-level imitation may achieve significant environmental gains even with conventional manufacturing, because small use-phase efficiencies add up when multiplied across a fleet of products and the entire product lifecycle. For example, shark skin-inspired riblet surfaces have been found to reduce drag by just a few percentage points in various experimental and flight-test scenarios (22). Applied to an entire fleet of airplanes for the duration of their useful lifespan, a form-level design like this could drastically reduce fuel consumption and subsequent emissions. In fact, a form-level design that offers sizable use-phase efficiencies could outperform a process-level design that offers only modest use-phase efficiencies in terms of net environmental impact. Second, deeper imitation is not necessarily better; replicating biological nanostructures requires precise manufacturing techniques that may have energy demands several orders of magnitude greater than conventional manufacturing processes (4). A process-level material may also rely on rare materials, or may not be recyclable at the end of product lifespan. The choice of imitation level cannot, then, serve as the sole criterion of environmental superiority between designs. While the depth of imitation uncovers where efficiency gains are likely to be found (production for process-level designs and operation for form-level designs), it is ultimately the net efficiency gains of a particular design that need to be evaluated through measurement; life-cycle assessment provides a rigorous methodology for these tests. The problem with the depth of imitation argument is not that form-level biomimicry is not useful; it is that there are sustainability claims pitched at levels for which, according to the examples studied, the evidence has not been supplied.

There is also a more subtle cultural hurdle. The allure of biomimicry is the story: the narrative of the engineer who looked to a kingfisher, or the architect who analyzed a termite mound, is more memorable than a life-cycle assessment, and that memorability has value in classrooms and public outreach. But the narrative of how a design came to be is easily confused with the evidence of the results, a concept illustrated by the two different accounts of Eastgate, the inspiring one and the accurate one. A discipline that markets itself with narratives of origin must be vigilant against those narratives, which means scrutinizing its favorites as critically as any other product on the market.

What would close the gap is not a reconceptualization of biomimicry, but a change in what the label is allowed to claim. First, the sustainability claim should be based on evidence of production and end of life, not inspiration: a life cycle assessment, not an origin story, demonstrates whether a nature-inspired product really has less impact on the environment. Second, the degree of imitation should be truthfully reported, so a success at form level is rightly celebrated for the efficiency it offers, but not for the sustainability it lacks. Third, the difference between strict biomimetics and loose bio-inspiration, currently articulated in ISO 18458, should be given teeth in the form of a certification so the marketing appeal of the nature-inspired label is tied to a verifiable standard. Certifications that evaluate material health, reuse, and energy footprint are well established in neighboring areas of sustainable design; biomimicry just needs to be expected to pass through them. None of this calls for biomimicry to be less creative or inventive; it calls only for the sustainability claim to be disentangled from the inspiration claim and evaluated on its own merits.

A few caveats are in order. The cases studied are a purposive sample of the best-known cases in the field, as defined by the repetition criterion in the Scope and Approach section. These are well-known cases because they succeeded; a close examination of biomimetic patents and products may reveal far more prototype and process work than these famous examples represent. The analysis and classification of cases used the criteria stated throughout, but remains the author's interpretation of the published descriptions of these projects. The energy data for the Shinkansen and Eastgate are cited in the literature by the respective project teams; to the best of the author's knowledge, neither has been independently audited for its full life cycle energy footprint. The assertion that deeper levels of imitation will yield greater sustainability benefits is, again, a theoretical position of this field that requires the same life cycle evidence this review claims is lacking. The argument is not that biomimicry does not work, but that the canon reviewed here assumes its sustainability credentials where it should prove them.

CONCLUSION

Biomimicry's appeal is well-deserved. Nature boasts an extraordinary collection of solutions, and the discipline that grew from studying this collection has produced quieter trains, cleaner surfaces, and cooler buildings. The problem lies in the gap between the promise biomimicry offers at its deepest level, its processes and ecosystems that build without waste, and how the canonical examples that biomimicry uses to represent itself work at its shallowest level, the level of copied shapes. A kingfisher-shaped nose for a train and a lotus leaf imitation for a building's walls are laudable accomplishments, but they are efficiencies of use added on to conventional, industrial production. Conflating these things with sustainability confuses where a design comes from with what it costs. The popular explanation for the sustainability of the Eastgate Centre, a canonical biomimetic building modeled after a termite mound, has recently been revised by biologists. The building's sustainability can be attributed to sound passive engineering. Being inspired by nature is a claim about origin. Being sustainable is a claim about consequences. In the cases explored in this review, the first claim has often been used in lieu of the second. Biomimicry will garner the reputation it enjoys when it no longer permits this replacement.

CONFLICT OF INTEREST

The author declares that there are no conflicts of interest related to this work.

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