Biomimicry in Building Architecture: *From Theory to Industry-Standard Construction Practice*

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ABSTRACT

Biomimicry— design inspired by the functional genius of nature— is a concept becoming more and more prevalent in fields of material science, architecture, and other sciences. Yet, the construction industry does not understand how to build with biomimetic materials, nor understand their biological precedents. Much of this has to do with the familiar use of traditional, high-carbon materials, and lack of collaboration between contractors and biologists. Thus, this study offers a comprehensive exploration of how well biomimetics is translated into the material and structural qualities of buildings. Furthermore, this study aims to provide insight on how to fill the gap between novel technologies and commercial building development. As a result of this effort, architects and engineers will understand how to leverage nature to make buildings more sustainable. In the first part of this document, biomimicry is contextualized and the scope of this investigation is explained. The second part transitions into a detailed exploration of biological models, processes, and their material feasibility in today's industry. Lastly, this study evaluates evidence from part two to compare how well biomimetic precedents are optimized based on available research. Evidence suggests that a paradigm shift towards system thinking is paramount to the integration of nature's genius into a sustainable built environment.

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1. INTRODUCTION

1.1 Buildings and Climate Change

Buildings contribute to climate change. Globally, construction and building operations accounted for 36% of final energy use and 39% of CO2 emissions, as per the UN Environment, IEA, and GABC report of 2016.[1] Steel and concrete are among the heaviest hitters of embodied carbon emissions, as the concrete industry comprises 50% of all raw material use and 50% of all waste due via aggregate and cement production.[2] Similarly, the steel industry alone accounts for 7-12% of all anthropogenic GHG emissions whilst also being the most energy-consumptive sector.[3] In terms of operations, commercial and residential buildings drive energy-related effects on climate. Across Europe, Australia, and the US, absolute emissions have increased from 6.7 $kgCO^2/m^2$ for existing buildings to 6.7 and 11.2 $kgCO^2/m^2$ in new and advanced residential buildings (post-2005).[1] These statistics encapsulate a massive body of substituent literature about the negative effect of buildings on the environment.

Yet the relationship between buildings and climate goes both ways, and scientists are increasing studies into how climate will affect buildings in the coming years. Operational energy emissions will continue to increase overall as cooling load energy predominates the decrease in heating loads for residential and commercial buildings. A TRNSYS simulation by Li et al. ran an hour-by-hour energy analysis showing an increase of 10.3 $x10^6$kJ per ten years for the next 90 years in Tianjin, Northern China.[4] Zhai et. al tested climate models for US ASHRAE zones 1-7, and found a total increase of 2%-40% of energy-based emission of HVAC systems between 2010 and 2099.[5] The dynamic relationship between building and climate is still being explored, and despite policy changes, this understanding struggles to reach people at the ground level of this issue.

Despite this, new construction projects are still met with the status-quo. Building more sustainably adds to construction costs, complexity, and scheduling pressure. The prevailing convenience of "gut it and go" results in 145 million tonnes of waste annually in the US due to demolition, at $55 per ton.[6] Distance between contractor and architect-client is enabling this waste; there is an underlying need for a more integrated design approach between client, designer, and construction teams to ensure consistent greening of a project from start to finish.[7] Lack of integrative design has meant less effective communication, resulting in an annual loss of $8 billion by dumped waste for new builds in the US.[6]

Lastly, the fruitfulness to many approaches to green design— from discrete programs like LEED to broad systematic thinking— hasn't been fully realized in the blue-collar world due to perceived feasibility and insufficient production methods. Ironically though, the state of architecture is responding to increasingly complex modern building tasks through specialization rather than collaboration, evident throughout the profession and in architectural education.[8] Specialization discourages interaction with scientists in order to aid transition from theoretical experiments into industry-standard practice. In effect scientists and builders struggle to mass produce biomaterials, encourage interdisciplinary discourse, and incentivize construction to stray from traditional building methods.[9] In an era where sustainability metrics are more pertinent than ever, significant investment needs to be made to provide builders with the skills they need to implement biomimicry in architecture.

1.2 Goal and Scope of Investigation

Biomimicry is in its nascent stages. And while there are a growing number of novel building designs to prove this, the industry has a long road before reaching an optimal state. On one hand, technology and climate change will keep pushing radically sustainable projects to new heights. But this does not translate to everyday residential and commercial builds. By addressing this division, scientists and designers will be able to identify opportunities to expand biomimetic construction for climate change mitigation. This study therefore proposes a framework to rate how well existing biomimetic precedents can be translated into common practice right now [Table 1]. Specifically, this Biomimetic Optimization Scorecard organizes data from twelve different biological precedents described in this document, and scores them on a 1-5 scale across nine Optimal Performance Standards (OPS) derived from recurring themes found in the literature. For reference, executing a project with a “5” score for all 9 OPS would indicate that this precedent is highly viable in construction practice. This framework will then be reintroduced at the end of the document to summarize findings. It is hypothesized that most precedents fall short of biomimetic optimization because literature does not present research thorough enough to address all nine OPS.

Literature consulted in this study will provide clues to *how* and *why* biomimicry should be optimized in buildings— including discussions about efficient structures, material manufacturing, and their dissemination into functional built environments. Scope will be limited to material- and structure-related application of biomimicry to prioritize opportunity to replace traditional steel and concrete; precedent applications related to energy and water will be mostly excluded during the fourth section, “BIOMIMETIC MATERIAL TECHNOLOGIES”. Databases including Web of Science, Avery Index to Architectural Periodicals, and BuildingGreen Suite will be used with search terms like “biomimetic design” and “sustainable architecture”. Examples of specific buildings will periodically be introduced to elucidate the biological precedent, but the literature will focus more on the viability of biomimetic theory. Document types assessed will include scientific journal articles, trade journals, and primary sources. Ultimately, this investigation will rely on existing research to predict the future of nature’s role in sustainable architecture.

BIOMIMETIC OPTIMIZATION

	BIOLOGICAL SYSTEM PRECEDENT			MIMICRY OF PRECEDENT			MANIFESTATION OF PRECEDENT			
OPS	A	B	C	D	E	F	G	H	I	AVERAGE SCORE
MATERIAL TECHNOLOGY										
SILKWORMS										
BAMBOO										
WATER LILY										
TREE ROOTS										
BONE										
ECHINODERMS										
MOLLUSCS										
WEAVERBIRDS										
SPIDERS										
MYCELIUM										
GRANULAR										
CHITIN										

BIOLOGICAL SYSTEM PRECEDENT		MIMICRY OF PRECEDENT		MANIFESTATION OF PRECEDENT	
A	IS SYSTEM PRECEDENT, OR MODEL, CLEARLY DEFINED?	D	HAVE FABRICATION METHODS BEEN IDENTIFIED?	G	CAN RESULTING PRODUCT BE DESCRIBED AT ALL THREE SCALES?
B	IS PRECEDENT RELEVANT TO A PROJECT'S HUMAN NEEDS?	E	CAN MATERIAL BE MASS-PRODUCED?	H	IS PRECEDENT APPLIED IN A CONTEXT-SPECIFIC WAY?
C	ARE ALL PROJECT TEAMS EDUCATED ABOUT THE SYSTEM PRECEDENT?	F	IS EVERY MIMICKABLE COMPONENT OF THE PRECEDENT CONSIDERED?	I	IS THE RESULTING PRODUCT REGENERATIVE, AND CONTRIBUTE TO CIRCULAR ECONOMY?

Table 1: Biomimetic Optimization Scorecard. In this case, "optimized" is defined by Optimal Performance Standards (OPS) covered under Biological System Precedent, Mimicry of Precedent, and Manifestation of Precedent. Case studies projects are given a 1-5 score for each OPS, then an unweighted average is used to calculate a cumulative numeric score, compared against other precedents.

2. DEFINITION AND FEATURES OF BIOMIMICRY

2.1 What is Biomimicry

Designers and scientists are in pursuit of climate change solutions through the method of biomimicry—design inspired by the way functional challenges have been solved in nature. In the context of architecture, biomimicry aims to "measure and shape space", as well as define synergistic relationships between structure and environment.[10] Since the 1990's, biomimicry has been a framework studied in architecture, product design, biomedical engineering, and more. And although our fascination with nature goes back thousands of years, emerging technology allows us to revisit nature's refinements with a wider base of scientific knowledge and visualization tools than ever before. Simultaneously, scientists and architects struggle to mass produce biomaterials, encourage interdisciplinary discourse, and incentivize construction to stray from traditional building methods.[11] In an era where sustainability metrics are more pertinent than ever, significant investment needs to be made to shift the paradigm of traditional construction towards nature's functional genius.

In the context of architecture, three goals of biomimicry include 1) resource efficiency 2) solar economy 3) and becoming a closed-loop system.[12] The first goal, resource efficiency, considers the building process of plants and animals. Examples range from wind turbines modeled after humpback whales, which maximize energy generation by increasing fin surface area, to light gridshell framing modeled after molluscs.[13] Evolutionary pressures like these have designed organisms to make the most out of the least amount of material, whose production is energy-intensive. This has prompted algorithmic geometries that optimize structural integrity with the smallest possible footprint. The "heat, beat, and treat" approach to industrial materials are also becoming antiquated as we mimic nature's biodegradable use of carbon, hydrogen, and a few minerals.[14] Adopting the efficiencies of nature into construction practice can make dramatic shifts to the shape, structural, and chemical properties of the built environment.

2.2 Biomimicry vs. Biophilia

In defining biomimicry, it is crucial to distinguish biomimicry from terminology like *biophilia*— the "innate human inclination to affiliate with the natural world".[15] Biophilia represents people's evolved response to nature, rather than adaptive evolution in non-human species to pressures in the environment. Moreover, biophilia is aimed at minimizing physiological effects of the disconnect between natural and industrialized settings.[16] According to Djebbara et al., this disconnect is driven by neurological impulses, including the desire to resonate with environmental features which trigger pleasurable sensorimotor responses.[17] In short, this differs from biomimicry because of the prioritization of human experience, rather than functional biology in industrialized settings.

However, the space between human experience and functional biology in architecture can be incredibly gray. Anoti Gaudi, an icon of the eccentric Art Nouveau movement, aimed to evoke the "splendor of nature" in his renowned design of the Sagrada Familia, located in the heart of Barcelona.[16] This church drew from Gothic and Art Nouveau styles, but distinguishes its form using an equilibrated structure. Gaudi avoided the use of rectilinear internal and external supports by thickening the "stems" of the building in a similar way that a tree buttresses to compensate for gravity loads and outward thrust. The result is an enticing arboresque interior which imbues spirituality for the user. In recent cases, architects have been applying biophilia through the use of greenskins (green walls and roofs), which provide regenerative cultural pleasure, apply ecological principles, and combat effects of climate change in dense urban spaces.[18] Furthermore, Wang estimates that greenskins can alleviate urban heat island effect by reducing average ambient city temperature between 0.3 and 3K, such as that of Westgate Mall in Adelaide.[19] This mall, along with other Fremont Greenskin Projects of Australia, have become urban symbols of biophilia, a vernacular to pacify the human fear of a changing climate.

One more example of biophilia in urban life is through the use of Restorative Healthcare Environmental Design (RHED), derived from 20th-century theories like Attention Restoration Theory (ART) and Psycho-Evolutionary Theory (PET).[20] RHED was applied in the renovation of the Royal Children's Hospital in Melbourne, from which positive physical, emotional, mental, and spiritual impacts were linked to biophilic patterns. These patterns were then associated with benefits, like "reduced occurrence of illness" as a result of visual connection with nature, and incorporated into the hospital's renovation.[21]

Evidence such as this suggests that biophilia does not necessarily *emulate* natural systems like biomimicry does. Rather, the derivation of spiritual, ecological, and health-related qualities of nature is used to satisfy immaterial human needs, which justifies its use in its design. Despite this, critics argue that exclusive application of biophilic qualities does not guarantee better building performance or habitability so long as it remains "apathetic for ecological issues" in favor of visual indulgence.[16] Biophilia often does serve an environmental purpose, though not always. On the other hand, however, biomimicry is defined by the notion of nature for nature's sake, making it the converse of biophilia in this respect. Modeling architecture after a comprehensive biological system puts environmental responsiveness first, and human satisfaction second.

Lastly, it is worth noting the term *bionics,* which emerged in the 1960's, and has also been used interchangeably by architects to describe nature's role in design. Historically, it differs from biomimicry and biophilia because bionics is a technically rigorous field that strays from ecological concerns, creative exercise, and psycho-evolutionary wellbeing.[15] It is grounded in classical physics, with applications including aero- and fluid-dynamics, sonar, manufacturing, and other applications related to adhesion, propulsion, and locomotion.[22] Yet, some scholars argue that biomimicry and bionics have become more integrated through efforts to become energy efficient. Wahl, for instance, notes ten distinct principles of bionics, including 2)

Optimization, 5) Energy saving, and 6) Direct and indirect use of solar energy.[23] These objectives and others speak to biomimicry's inclination towards passive processes for low energy consumption, adaptive thermal environments, and other building climactic concerns.[22] Furthermore, energy efficient buildings are measured through their metabolic processes and flow patterns, which is essential for the survival of biologically-derived models.

2.3 Dynamism in Biomimicry

Biomimicry is among the most advanced architectural concepts of combating climate change. It pushes past net-zero— an end goal held by many green building programs like LEED— towards an inherently net-positive ideal. Zari argues this by stating that biomimicry is *regenerative*. By transferring knowledge from biology and ecology into architectural design, architects embrace a "resilient and adaptable built environment" that can regenerate ecosystems.[24] An net-positive example includes technology modeled after sea kelp mobility against oscillating waves. BioPower, an Australian company, is currently testing oscillating power generators as an alternative to rotating turbines. But biomimicry's regenerative characteristic also applies to built structure and program, in addition to energy. An example of this is Chrysler's Bionic car prototype, whose sturdiness and aerodynamism mimic the plate structure of a boxfish. This design possessed a drag coefficient of 0.19 while having 40% more rigidity in panels.[24,25] The synthesis of a variety of biocomposites, from artificial nacre to 3D-printed mycelium, also fall into the category of net-positive structure. In essence, biomimicry's ability to heal, restore, and regenerate is at the root of its innovation, leading to the birth of technologies that would not otherwise be created.

Biomimicry is as complex as it is regenerative, resulting in organization across three scales: organismal (imitate nature), behavioral (imitate processes), and ecosystem (imitate macro principles).[12] Form, shape, and structure are examples of organismal-scale biomimicry, while interaction between building and site are considered behavioral scale. Ecosystem scale involves focus on how different parts of the building weave into a large urban context. For example, buildings modeled after ecosystem-level biomimicry consider the "location, posture, positive and negative" reciprocities between an organism and its environment.[11] If a termite mound were used as a biomimetic building model, achieving the ecosystem scale would entail the building being constructed using the accumulative succession of organic materials, convert energy from the sun, and participate in nutrient cycling.[12] One project which exemplifies this is the Eastgate Center in Harare, Zimbabwe, where passive cooling is implemented via both thermosiphoning and induced flow mechanics.[26] Induced flows permeate tall stacks with voluminous air spaces, as a product of heat-driven siphoning from occupied spaces and thermal mass. However, while the process of energy efficiency in this project optimizes the termite model, construction and material-related components of the termite model are lacking in the Eastgate Center.[12] Concrete bays were constructed via traditional slab methods, and do not use the saliva, soil, and dung mixture used in natural termite mounds. Furthermore, the building does not produce the same byproducts as termites do for rich, erosion-resistant soils in the surrounding area.

Therefore, mobilizing all simultaneous processes of the biological model, rather than isolating one facet of the system, will enable the fullest extent of dynamism— and integrity— of a biomimetic model.

On the other hand, this isn't to say that a non-fully optimized model is useless. Isolating equivalencies between the architectural and biomimetic models can be critical towards establishing similar feedback structures at the ecosystem level, and therefore optimizing the system.[27] For instance, Sanga et al. launched an investigation into the fabrication of mud bricks with a similar chemical composition of a termite mound.[28] Methods included the collection of termite mound soil samples (TMSS) via excavation at 1m depth in the Chunya district of Tanzania (latitude 8°28`31.70`` and longitude 33°23`09.23``), followed by oven-drying at 105°C every 12 hours until no change in mass was observed due to water loss. Simultaneously, soil samples from sites away from the subject termite mounds (noted as OCSS) were mixed with cassava paste and distilled water to create a synthetic mound mud to compare physical characterizations via ANOVA. Mechanical tests were performed according to BS-EN 12390-3: Testing hardened Concrete – Part 3: Compressive Strength of Test Specimens. Results revealed that TMSS samples had a compressive strength of 0.76MPa, while OCSS samples managed a maximum average of 4.28MPa at 1.5% cassava paste; for comparison, the average universal sun-dried brick yields an average of 2.0MPa of compressive strength.[28]

Sanga et al.'s study represents organismal-level biomimicry, rather than ecosystem-level, because it focuses on the simulation of a natural material devoid of its natural construction methods.[12] It also represents Garcia et al.'s description of Stage 3: Abstraction, Stage 4: Correlation, and Stage 5: Transference of an isolated system in the ecosystem approach.[27] If the fabrication method for OCSS was taken into an urban context, successfully executing a large-scale commercial project would be a feat in and of itself. Yet, pushing this precedent to an optimal level would include devising a mounding method to successively accumulate mud, self-cycle nutrients within the site, and mimic passive energy processes for heating and cooling within the structure. This is why ecosystem-level biomimicry is also closely tied to behavioral and organismal-level scales. Each mimicked facet, from chemical composition to processes, to morphology of the building, is what collectively builds a model system to the ecosystem level. This is the inherent dynamism of bringing nature into architecture.

2.4 Top-Down vs. Bottom-Up

When discussing the application of biomimetic concepts, problem-solving is often framed as a "bottom-up" or "top-down" approach.[29] Both approaches are adept at meeting key biomimetic goals and can encourage biological research to find its way into built environments. In a top-down approach, designers identify a human need or design problem and seek the solutions in nature, whereas in bottom-up, designers employ a known biological model— a solution— to human needs rather than first determine the design problem.[8] A top-down example is the Dragonfly Vertical Farm concept by Vincent Callebout, which models durable, yet lightweight dragonfly wing facades to fit wind load capacities and provide mixed-use programming. Wind load resistance was the human need, and a dragonfly was subsequently selected to fit this need.[12] Conversely, Neri Oxman's Silk Pavilion Project illustrates an example of a bottom-up approach to biomimetic design, and subsequently the essential role of biological instruments in developing an application for silkworms in construction. It required the examination of *B. mori* silkworm behavior at the organism-structure level using a magnetometer, high resolution imaging, and electron microscopes to determine the logic of cocoon weaving as a design solution.[30] Perricone et al. frames this as a bottom up approach in the field of mechanical engineering, which includes (1) identification, (2) investigation, (3) abstraction, (4) modeling, and (5) application.[31] In this case, silkworms were first selected as a model, and a solution to a human need, shelter, was selected based on the capabilities of that model.

More bottom up examples include the Pearl River Tower (2011) in Goungzhou, which adopted the sea sponge as a porous structure used to generate building energy via wind. Additionally, recent nacre studies are trending towards bottom-up logic by harnessing self-assembled biomineralization; under mild temperature and pH, elementary mineral units are accredited as a solution then applied to materials.[30] Lastly, leaf-inspired thermal exchangers are considered an exploration of a biological solution despite generally addressing the issue of evaporative thermal devices.[32] Arguably, cited evidence suggests that starting with a rigorous biological mechanism may provide the fullest integration of biology into architecture, as such projects tend to uncover novel fabrication and manufacturing tactics along the whole course of implementation.

2.5 The Value of Prototyping

Unlike semantic-based approaches, prototyping is a way in which biomimetics can be understood without hindrance of different field's mechanistic understandings. McCardle et al. recalls four main themes in the use of prototypes: (1) Approximation, (2) Principle, (3) Synthesis and Testing, and (4) Validation.[13] Internalizing these themes can help to disseminate common mechanistic understanding between fields of architecture, biology, and structural engineering. In Hilbertz's proposal for *sea-autopia ampere*, for instance, electric currents are proposed to be used to produce magnesium chloride, CaCO3 crystals, oxygen, and chlorine, causing dissolved minerals to crystallize into white limestone structures similar to coral reefs.[30] This proposal addresses themes (1) and (2), but has yet to enter phase (3) Synthesis and Testing. It's considered a 'prototyping principle' currently in need of assumption checking for functional efficacy.[8,13] In the Silk Pavilion Project, aluminum scaffolding was created via CNC machine that fabricated silk-based threads as a base structure.[30] In the resulting pavilion, completed in 2013, loadbearing paths were constructed by 3D printing and then filled by biological fabrication. Without prototyping, stage (4) of the bottom up approach couldn't have been satisfied.[7] In this case, stage (4) required a 3D-model of the shell inspired by the silkworm cocoon-spinning precedent.

Despite successes like the Silk Pavilion Project, however, prototyping is still relatively underused. McCardle et al. conducted a survey of 270 members from such fields, which indicated that 74% used illustration and text as communication modality in daily work, while 21% of respondents indicated that physical prototyping was commonplace work practice.[13] But that percentage was only 2% higher for those with a self-declared design/architecture background. In a field where visualization is critical to design ideation, architects apparently underutilize prototyping as practitioners of biomimicry. Nonetheless, cross-domain collaboration seems to benefit from prototyping, which increases the odds of a project reaching implementation.[33]

Prototyping is also a critical educational tool. Students in UC Berkeley's Studio One post-professional program used prototyping to fabricate insect-inspired lightweight facade models using PETG.[8] Venation was modeled in two ways. First, by thermoforming two sheets of plastic onto a 3D-printed cellular core, and second, by laser-cutting thin sheets of plywood used to thermaform a layer of plastic from one side. The first approach was limited by the size of the 3D print bed, however, layering plastic with a core provided higher rigidity than anticipated This project demonstrated another key value of prototyping, which is pointing out needs for improvement in the manufacturing process. All of these examples show the value of prototyping— of building and disseminating tangible ideas— can be applied to close the learning gap between architects and scientists, thereby encouraging viable building projects.

3. SUSTAINABLE BUILDING TODAY

3.1 Overview of Building Regulations & Incentives

Fully understanding the three goals of biomimicry listed earlier requires a greater understanding of how these goals integrate themselves into the broader context of the green building industry. These goals include provisions for energy efficiency, water, site design, carbon, and/or air quality, all of which are in sync with the optimization of adaptive processes in nature. Wednt categorize green building into two types of frameworks: *regulations* and *incentives* [Fig. 1].[34] Regulations, which include International Code Council (ICC) codes and ordinances, are considered a prescriptive approach that is easy for both builder and code officials to implement.[35] ICC codes can be further broken down into International Building Codes (IBC), International Residential Codes (IRC), International Performance Codes (IPC), International Green Construction Codes (IGCC), as well as geography-specific adaptations of Mechanical, Plumbing, Fire, and Energy Conservation Codes. In the US, all fifty states follow the IBC with amendments added per state and local jurisdiction. Colorado, for example, follows I-codes for all buildings state-wide, but those under the jurisdiction of the City of Boulder must also follow the Boulder Revised Code. This includes extra provisions for land use (Title 9-6-1, & 9-11-16), and the 2020 edition of the NFPA 70 National Electrical Code.[36] Local amendments like these generally provide more red tape for builders, but also contribute to more than $5 billion in consumer savings, according to the US Department of Energy.[37]

Historically, codes derived authority from a societal expectation that the public must be protected from threats of building failure.[38] This has diverted attention away from health and safety-related impacts as it pertains to the environment. Up until the last two decades, IBC codes were devised with little concern for impacts away from the actual site, and predicted climate effects of buildings. These conflicts oppose the three goals of biomimicry described earlier because they neglect the sentiment of system-thinking in biomimetic architecture. For example, human suffering brought by climate extremes— whether it be re-occupying a mold-infested home after a flood, or homelessness due to wildfire— are not addressed beyond the fact that a building must operate for a certain amount of time for people to evacuate.[37] Environmental responsiveness reflects biological resilience, and as events such as these become more common, resilience is gaining headway in the reform of building codes. Therefore, although downstream code amendments allow for context-specific changes to local site conditions, codes are far too stiff, and should reflect the dynamic nature of biomimicry to optimize resilience and sustainability.

Code-based regulations can also hinder innovation desperately needed to meet today's climate targets. Over 40% of material resources in the global economy belong to the building industry, and of that, modern buildings in the US alone account for 10% of global energy use.[39] Reconciling these statistics with necessary innovation is where incentives become useful. A tax deduction for energy-efficient commercial buildings was created in the Energy Policy Act of 2005, which is an early example of incentives that range from tax benefits to expedited permitting, low-interest loans, and rebates.[34] This particular deduction was worth up to $1.80/ft^2 and covered lighting systems, mechanical systems, and the building envelope. Developmental incentives (density bonuses and fast permitting) is another type of incentive program that became popular in Chicago in the early 2000's; for a tall office building, for example, financial rewards were provided after a project team reached LEED certified silver status, devoted half of the roof area to a green roof, and choose from a specified list of green strategies intended to reduce operational carbon.[40]

Relevant incentive frameworks can be further broken down into standards and guidelines, neither of which are required by law, but are becoming more popular as climate targets become more lucrative [Fig. 1]. Standards like LEED prioritize sustainability in site footprint, water efficiency, and energy, and more in exchange for tax credits, rebates, and low interest loans.[7] Other examples of standards are the HERS rating system, PassiveHouse, BREEAM and Green Globes, and the LBC. Guidelines are typically less streamlined, like the Residential Environmental Guidelines, Sustainable Sites Initiative, and the 2030 Challenge.[38] Ultimately, the case for integrating these green incentives into mainstream practice is growing with industry's slow awakening to the scope and magnitude of the environmental impacts of the building industry.[41] Effects that occur away from the actual building site, require cumulative observation, or are generally hard to measure, are now becoming more visible due to these incentives; Eisenberg and David note that exceptions for alternative building designs, materials, and systems are laid out in the IBC; builders can work with local code officials to test and implement technologies that support above-code sustainability on a local level.[38]

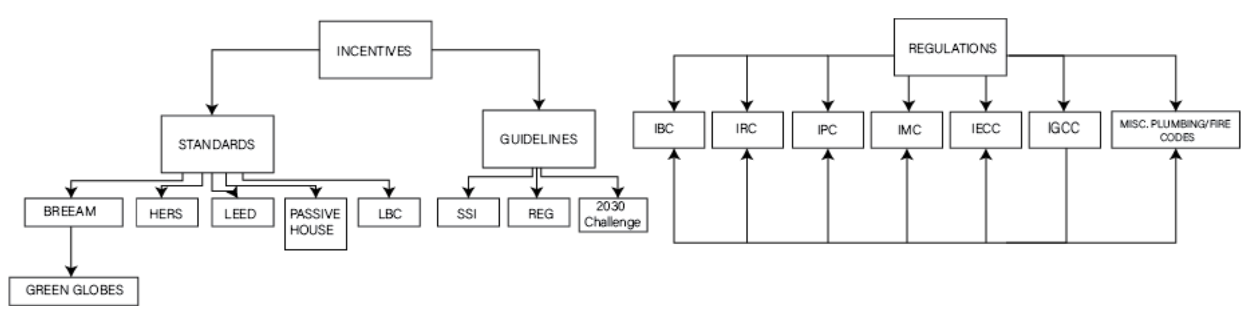

***Figure 1**: Green Framework Organization: Incentives vs. Regulations. Regulations are legally-binding, while Incentives are voluntary green frameworks.*

In the Living Building Challenge, arguably the most "biomimetic" of all incentive programs, there are seven impacts designated as "petals".[42] To achieve Imperative 05. (Net-Positive Water) under the Water petal, most LBC projects utilize composting toilets. At the Hitchcock Center for the Environment (2015), an LBC-certified construction in Amherst, MA, the use of composting toilets presented cultural and regulatory barriers, as well as different bathroom fixtures to meet 100% close-looped water capture.[42] This imperative aligns with biomimetic design as net-positive water capture is modeled by desert plants and animals, as well as other organisms. As such, designing a behavioral-scale building after *F. glaucescens* is one example that could lend itself to LBC Water petal imperatives. In this light, biomimicry isn't necessarily a singular framework, but akin to a sort of prerequisite, or corequisite, whose values are inherent in standards like the LBC and the broader scope of sustainable construction.[43]

3.2 Renewable Materials in Green Building Programs

In 2006, Architecture 2030 published the 2030 Palette, which outlines five carbon-smart materials: bamboo, wood, wool, straw, and hemp.[44] These materials represent a shift away from consumptive construction materials towards those that are regenerative— that is, they can be grown, harvested, and applied without irreversibly depleting earth's resources.[45] This returns to the notion of biomimicry as regenerative and dynamic. However, these materials don't fit cleanly into any scale of biomimetic modeling, nor are they codified into construction in the US. Bamboo, for example, has the capacity to replace traditional timber construction thanks to its wind resilience, lightweight construction, load-bearing behavior, and repairability. A building Life Cycle Assessment (LCA) by Escamilla et al. also indicates that traditional pole construction yields a negative CO^2 balance of 10%, accounting for CO^2 captured, stored, and emitted in the manufacturing of materials.[46] Despite these advantages, Jayanetti et al. notes that difficulties in joining, lack of structural design data, and exclusion from building codes restrict its application.[47]

As per the US, bamboo is regulated under ASTM D5456, which is also referenced in the IBC 2303.1.10 and IRC R502.1.5. All of these codes classify bamboo into the Structural Composite Lumber (SCL) product category which does not differentiate between physical characteristics of wood and bamboo. Whereas, in other geographic regions, there are more specific codes governing the performance of bamboo products. This could reflect little effort or understanding in testing bamboo products in commercial and residential construction in the US.[46] As a result, green building programs, like LEED or LBC, which award points for the use of renewable materials, fall short in acknowledging the viability of actually implementing such materials in sustainable projects.

Key considerations that should be detailed in green programs for bamboo include material availability in local conditions, climate-related weathering, engineered vs. full or half-culm application, and the lack of mechanical research into bamboo-reinforced concrete or fiber reinforced concrete.[48] There also exists a socio-economic dimension, in which Asian-Pacific vernacular can be preserved. This includes fostering traditional joinery techniques, as well as the reduction of poverty and urban migration from deforested communities.[49] Other considerations vary per renewable material, but each must have a distinct regimine for builders to understand their lucrative impact in modern building. To put this in context, LEED v4.1 addresses bio-based materials under Material Resource (*MR) Credit: Sourcing of Raw Material*. This section indicates that bio-based products “must be tested using ASTM Test Method D6866 or equivalent method ISO 16620-2”, with points calculated by mass of material used.[50] Moreover, *MR Credit: Building Life-Cycle Impact Reduction* Option 2 states that users are to conduct a life cycle assessment on a building’s structure, without setting a framework for *how* to conduct the assessment. Fortunately, however, such a framework for an LCA is set out in the AIA Guide to Building LCAs in Practice, which outlines LCA stages, steps, and impact categories, but does not address variant calculations pertaining to renewable materials.[7] Ultimately, as green building programs iterate to keep up with industry demands, renewable material specs need to be thoroughly documented based on novel performance research. Builders must know how, why, and to what extent these materials can be utilized for a given project. On an even deeper level, this will begin to shift builders towards a regenerative mindset, and leave the industry more adept at understanding biomimicry’s role in design.

3.3 Green Building Examples

It should be noted that green building, and by extension biomimicry, is difficult to implement in projects because it can add to construction costs, complexity, and scheduling pressure. Salvaging existing materials of a project instead of fully demolishing existing buildings can thus be an easy place to start addressing the resource efficiency proponent of biomimicry by reducing embodied carbon by the production of new materials. This is important in the building sector, where 90% of carbon emissions are due to new construction while only 10% is operational.[12] This statistic prevails due to the “gut it and go” mentality in the world of salvaging, and it contributes to 145 million tonnes of waste annually in the US due to demolition, at $55 per ton.[51] The distance between contractor and architect-client could be the link to understanding wastefulness in a construction project, and potentially encouraging the incorporation of biomimetic concepts into salvage projects.

The case for salvage projects points towards an underlying need for a more integrated design approach between client, designer, and construction teams to ensure consistent greening of a project from start to finish.[7] Integrated design results in more effective communication in any construction project, and it can resolve the distance between the architect-client and construction team resulting in an annual loss of $8 billion by dumped waste for new builds.[6] One such example of integrated design in salvage projects is the case of the Ford Foundation for Social Justice, located in Manhattan. A two-year renovation between Gensler, Henegan Construction Co., the Ford Foundation President and Trustees, and the City of NYC led to an 85% reuse of building material by volume, or 91% of the original building’s embodied carbon.[51] More specifically, this project included a consistent relationship between Gensler’s Sustainability Director, public relations specialist, city inspectors, and Henegan’s subcontractors to ensure maximum care in reusing original Dakota granite, Corten steel, and glass facade. Cross-hierarchical communications were a key distinguishing factor that earned this project the Civil/Institutional Design Award of Excellence.[51] Another example of the importance of the integrated design process comes in the form of voluntary standards themselves, like Passive House. Successful performance hinges on the ability of the construction team to assemble an envelope system precisely the way it was designed. The larger and more complex a system becomes, the more subcontractors are needed, and thus the more essential integrated communication becomes the delivery of an energy efficient build. An example is the certified Orchards at Orenco project in Hillsboro Oregon. In this construction, the design team worked heavily with contracts in application of the PHPP modeling tool after co-creating provisional insulation values of different assemblies.[35] Iterations were informed by constant contractor-designer feedback until an R-40 wall value was reached and solidified in the design. This level of intentionality might suggest that biomimetic design could benefit from an integrated approach, in which iteration isn't strictly controlled by the designer but rather designer, contractor, client, and scientists.

Ironically, some elements of green building frameworks also pose obstacles to incorporating biomimetics into builds. The previous example of PassiveHouse can also be seen in this light, whose premise is to use an airtight envelope with low surface-area-to-volume ratio to minimize thermal bridging.[52] Premises in thermal bridging are already abundant in nature, such as the heat and mass exchange of vascular tissue in plants.[32] Yet, PassiveHouse deters clients because of the 2.4% increase in initial cost due to the design and construction of a complex facade and general envelope system.[43] There are very few window types that are Passive House certified, and the U.S. also lacks options for fiber-reinforced biocomposites and high-strength polyurethane materials to provide structural thermal breaks. This raises an issue for advancing research in the heat exchange of plant tissues, as clients don't yet see it as lucrative to achieving a more energy efficient building. But to make it more lucrative, people need to invest in the development. Such is the challenge of embracing technologies required for biomimetic designs.

3.4 Computational Tools for Green Building

Computational design relies on a combination of definitions, like algorithms and parameters, to solve design problems with advanced computer processing. This is helpful for green building because creative problem-solving can be negatively affected by human cognition, including qualitative factors like mood, intelligence, and biases.[53] As a result, automated design generation can overcome cognitive barriers when teams are unable to generate ideas. Whole Building Life Cycle Assessments (WBLCAs) are a noteworthy example of computational design in the green building world. WBLCAs are used as energy modeling tools that quantify and disseminate information about a system's energy use. Benefits include tax credits or rebates, and recognition via green standards and guidelines.[7] In any shape or form, having contractors, clients, and architects learn about the energy flow between products and their environment is core to understanding ecological processes; LCAs could bolster confidence builders have with testing new building technologies, which could pave a path for embracing biomimicry technologies. The scope of these assessments have included any of the following: site visits and client meetings, land disturbance, installed materials, construction, site transportation, building operations, maintenance, repairs and renovations, demolition, use, or material service life.[33] A study of 16 WBLCA tools across North America, Europe, and Australia attempts to organize a catalog of 650 of these scope parameters for the Goal & Scope phase (G&S).[43] Results from this study proposed a new taxonomy of 54 parameters classified as either "LCA descriptors" or "Building Descriptors". The practical importance of streamlining these parameters means that engineers, architects, and contractors can all contribute to WBLCAs efficiently, and without an organized and quantifiable way to go about WBLCAs, resource efficient biomimetic designs don't have teeth to justify their existence.[9]

Regardless of the benefits of WBLCAs, skeptics are quick to point out the inconsistency in the model, as it isn't a "one size fits all" approach. According to Rodriguez et al., an Embodied Benchmark Study reveals that WLBCA tools inhibit consistent parameters necessary for the G&S phase, based on a survey of 1,191 buildings.[43] Specific parameters include functional units, building definitions, and standardized reporting systems. The USGBC is also still grappling with how to incorporate the net-zero aspect of LCAs into the IGCC and standards like LEED. This puts LCAs between a rock and a hard place, since tightening the scope of LCAs would prohibit user manipulation from suiting unique needs to a project.[51] This is echoed by Rodriguez et al., who excluded national codes in their study because codes don't exclusively address how to perform WBLCAs, but rather provide guidance on various other environmental assessments such as building performance or water efficiency.[43] Lastly, another drawback is that WBLCAs can be costly, up to $50k for large, comprehensive commercial projects, and thus tailoring the scope of the LCA depends on the values of designer and client teams. This price varies even more due to the complexity of parameters involved in specific projects.

Other computation tools, like BioTRIZ, exist to support design teams during the ideation phase of the project lifecycle. BioTRIZ is based on Theory of Inventive Problem-Solving (TRIZ) software, which is used as both a computational method, and a database. Drawing from 40 embedded design principles (*Inventive Principles*, IP), TRIZ defines design problems in pairs of contradictions linked to at least one design principle [Fig. 3].[54,55] As described by Abdala et al., contradictions between EPs occur when improving one would negatively affect another.[53] Two examples of EPs are *illumination intensity*, and *ease of operation*. The "Bio-" aspect of BioTRIZ comes from the integration of 500 biological phenomena related to 270 natural functions to address more than 2,500 contradictions in respect to their biological solutions.[53] It also reorganizes the same 39 EPs into six operational fields: substance, structure, time, space, information, and energy, which compose the biological scope of the design problem being asked.[54,56,57] Parameterized phenomena originally came from a combination of scientific publications, patents, and research studies, as per BioTRIZ Ltd who own the software.

Garcia et al. mentions a counterpoint to the use of BioTRIZ for green building, that is, the "tool might not be able to take into consideration the multiple interactions among building components".[55] However, Bai et al. has since established a multi-contradiction resolution by creating a green factor matrix, evaluating correlations between green factors and NEPs (EPs based on natural principles), then running a statistical analysis to determine which green factor is most correlated with a given NEP.[58] Green factors include (A) energy efficiency, (B) materials, (C) disassembly, (D) life, (E) emission of harmful substances, (F) product disposal, (G) efficiency, (H) reliability, and (I) cost.[59] To evaluate correlations, BioTRIZ experts filled out questionnaires, ranking the strength of correlation between a given factor and an NEP on a 1-10 scale. Average correlation scores were subsequently calculated using Statistical Package for the Social Sciences (SPSS).[58]

By assigning green factors to specific NEP parameters, BioTRIZ computational applications are more inclined to support problem-solving in green building. However, green building programs do not sufficiently acknowledge the use of computational tools in their guidelines. This gap can be bridged by adapting program language to fit green factors and their corresponding NEPs into program guidelines, or explicitly prescribing the use of BioTRIZ for generating green solutions in a given credit area. Program points should also be awarded by how well a team's solution responds to multiple contradictory parameters, which would incentivize multi-variable problem-solving. Lastly, using computational tools in green building can facilitate the integration of biomimetics in projects by offering unbiased, consistent IPs and NEPs that result in unbiased solutions. This will help teams keep sight of a whole building system while solving interconnected problems without unintentionally prioritizing one system over another.

4. BIOMIMETIC MATERIAL TECHNOLOGIES

4.1 Vascular Plant Tissue

One structural application of biomimetics in building systems is to model foundations after tree roots. The premise of using branched structures in construction is based on solid mechanical calculations, which confirm that hollow circular cross-sections are optimal for members subjected to axial, bending, and torsional combined stresses.[60] Roots also branch into a multitude of progressively smaller segments resulting in higher surface area to volume ratio, unlike pile columns, which extend into soil in a linear fashion.[2] In a comparative study of tree root foundations, effort was made to expand knowledge on architecture and force-displacement of traditional concrete foundation systems. One experiment shows that tensile capacity per volume of root systems are 43 and 70 times more efficient than shallow footing foundations, and 8 and 13 times more efficient than micropiles.[60] Methods included the extraction of Lovell, Marianna, and Myrobalan rootstocks from the UC Davis Plant Science Department teaching orchard. Moreover, Stachew et al. describes steps to employing root adaptation algorithms to specific building loads, including (1) collect data via computer algorithms for foundation design, (2) populate a database with load data and simulate root system reactions, and (3) develop a branch morphology to specific building load conditions.[61] Similar to in nature, if loading direction is known, the foundation can thus be fortified to resist combine stressors with even higher capacity. These applications extend to a broad range of structural engineering and architecture projects, and are particularly useful in the engineering of coastal infrastructure. Stachew et al. noted a concept application for *Root-Inspired Patterning of Multifunctional Seawalls*, which outlines large-scale undulations as a solution to reduce wave reflection and toe score as compared to a recurved seawall.[61] This concept would employ algorithmic load calculations to determine differences in wind, wave, and compression loads at different points along the wall surface. Together, these findings suggest that higher load efficiency can reduce material demand in foundation systems, namely concrete.

The Amazon water lily leaf (genus *Victoria*) represents another example of nature's iterative refinement of minimal material for maximum area, with leaves spanning up to 6ft in diameter. It pioneers a network of stiff, hollow-tube ribs with a proportional mass of roughly 15% of an equivalent solid section, enabling the plant to quickly outcompete other photosynthetic species in fast-drying ephemeral pools.[62] And, even with a relatively low leaf biomass, the Amazon water lily achieves equal bending resistance to that of a 100% solid section by shaving away mass from the neutral axis and placing it where the leaf faces the most resistance.[29] Box et al. later tested this mechanic by conducting a series of load-bearing experiments on a mature leaf surface; results indicated that the vascular profile of *Victoria* represented a maximum vascular thickness to lamina thickness (h_{vein}/h_{lamina}) of ~ 50.[62] This creates a much stiffer surface than other aquatic plants like Nymphaea, whose ratio is roughly 2.7.[63] Yet, the novel structure of the Amazon water lily was recognized long before biomimicry was established. Joseph Paxton's Crystal Palace, an 18-acre glass and iron construction, was a seminal work of the early industrial revolution in which he configured iron support members in a hierarchy modeled after *Victoria's* vascular tubes.[64] Today, such principles inspire the use of rigid tubes to create lightweight steel trusses and other common construction members.

Another biomimetic example of vascular architecture is the use of bamboo, which is already well-integrated into construction thanks to its lightness and high compressive strength. In a mechanical test, Chen et al. predicted that bamboo fiber composites could inspire the structural design of artificial composites.[65] His experiment consisted of a bending deflection setup using micro-CT to analyze deformation of parenchyma cells, fiber bundles, and vessels under different bending behaviors. Results suggested a span buckling reduction of roughly 2000μm between inner and outer layers. This is due to a higher volume fraction of FCs in the outer layer, which doubles force needed to induce buckling.[66] Results are significant because the layered assembly of fibers allows for easy and strong deformation to achieve structural elements with a tight radii yet high axial strength and stiffness.[65] Chen et al. suggested further that larger-scale experiments are necessary to validate these mechanical properties and explore tissue-cell deformation interactions for larger and more deformed construction. Findings such as these are critical towards previous discussion about renewables in green building programs. In other words, this experimentation will allow for improved bamboo products and biomimetic applications— especially space frames, winding composite pipes, and curvilinear builds that are outlined in building regulations and incentives.

4.2 Calcified Structures

Bones are a more complex example of hollow tube stiffness, unlike the relatively simple configurations of vascular plant tissues. Vertebrate skeletons contend with asymmetrical forces that create intricate lines of stress visible in X-ray imaging. Electromagnetic radiation has allowed scientists to observe dense bone filament in areas of greater stress that yields smaller void space, whereas the opposite is true in areas of low stress.[29] Extreme examples include the magpie skull, whose effective thickness rises while weight decreases due to "strut and tie" filament comprising the void space between layers. Andres Harris of Foxlin Architects applied this novelty to a skeletal dome structure, showcasing the function of non-directional spongiosa cells that create mineralized bone modules.[10]

Fracture resistance of bone material depends on the quality of the bone structure, particularly the compositional, microstructural, and cellular tissue properties.[67] Teleosts follow this logic, similar to that of human and bird skeletal composition despite wide taxonomic variation. For example, cross sections of a swordfish's 0.82m-long rostral bill, explored by Schimdt et al., showed a porosity gradient and base-to-tip-wise aging of the sword via increased mineralization towards the tip.[68] The study also showed a dense, outer bony layer encasing longitudinal osteons (void spaces) created by osteocytes. Osteocyte cells play a vital role in the remodeling of fractured bone, and also enable the swordfish to resist high bending forces while slashing and stabbing prey.[69] This ability to resist asymmetrical load fracture through gradients of calcium-phosphate mineralization is a key biomimetic takeaway; similar to that of vascular tubes, the presence of homologous bone structures across the natural world warrant deeper mechanical assessments of mineralized structure for lightweight construction.

There are also ways in which biomimetic structures are well-understood, but scientists have differing levels of knowledge on how to employ them. Echinoid eco-physiology is one such example of this. According to Perricone et al., echinoid strength, flexibility, lightness, stability, and stress-resistance applications require collaboration between biology, architecture, and other disciplines, while also requiring the use of diverse tools like CAD, computer-aided optimization, and algorithmic technologies.[31] Furthermore, different load conditions, such as self-weight, snow loads, wind and hydrostatic loads, which can generate over- or under-pressure, can be calculated adapting constructions to specific mechanical needs and functions.[31] One example of this is demonstrated in the 2011 ICE/ITKE Research Pavilion, which illustrates a hollow mosaic module, and interconnection via comb joints.

Sea urchin skeletons are composed of plates called ossicles, which are near-hexagonal members of calcite crystals. These plates are porous, lightweight, and stiff, whose double-layers create high effective performance.[29] They also offer architects and engineers five distinctive structural techniques: (1) mosaic-arranged plates (three plates meet in the middle to avoid straight edges, as demonstrated in Figure 3 above, (2) clypseasteroid-type plates, interconnected by skeletal protrusions leading to secure plate interlocking; (3) light-weight constructions; (4) double-wall constructions as found in *C. rosaceus*, and (5) fiber-connected plates.[70,71] IDC professor Achim Menges, who oversaw the Landesgartenschau Exhibition Hall project, noted that these joinery techniques require the use of parametric design softwares to resolve the precise complexity of such structures, echoing the previous discussion about a lack of computation in current green building programs.

Other components of echinoderms have been biomimetically utilized to varying degrees. For instance, sea urchins evolved spines for protection, locomotion, and sensing and as such they face intense axial loading forces.[29] Similar to bones, spines are not monolithically composed of calcium carbonate, else they would be extremely brittle. Instead, they possess a porous blend of calcite and proteins stacked together.[31] Previously, Pawlyn suggested that this resistant and flexible structure had not yet been employed in an architectural project. More recently, however, Perricone et al. noted that the calcitic microstructure has been applied to macroporous copper and functionally graded concrete for greater shearing strength.[72,73] Another component, the urchin's water vascular system, consists of a water vessel passing along each the radius of each appendage that unite at their proximal ends by a circumoral water vessel.[74] These vessels enable movement of arms via hydraulic pressure, and have not yet been credibly applied to mechanical building systems.

4.3 Reciprocated and Woven Structures

Reciprocated structures are another example of structural efficiency in nature, and they are reflected in buildings through cable tension and lattice structures. They are used to represent long spans where individual members are too short and thus rely on each other for support, such as distance between two tree branches or a gap spanned by a bridge.[75] They also symbolize the optimization of a system to achieve qualities unobtainable on the individual level. Biomimetically speaking, the natural precedent of woven forms is derived from nesting species such as the village weaverbird (*P. cucullatus*), who use knots including hitches, binding, loops, and overhand knots to create lightweight dwellings suspended on tree branches.[29] Assembly methods vary as some nests are crude masses of twigs held by only friction and gravity, while other avian species use natural adhesives to bind components together. Members can include wool, animal hair, spider silk and fine plant fibers. On a similar note, spider silk has already been studied as a model polymer due to its ability to absorb massive kinetic energy before breaking.[76] There are roughly 41,000 species of spiders producing some 200,000 different silks with slightly different biomechanical properties. Agnarrson et al. deduced that the Darwin's Bark Spider (*C. darwini*) produces the greatest elasticity and tensile strength at 350-520 MJ/m^3 necessary to anchor threads across riverbanks of 25 meters.[77] Further mechanical testing confirmed that *C darwini* silk outperformed the strength of Kevlar, a synthetic fabric used in bulletproof vests, by nearly 300%. Yet this remarkable biopolymer has yet to be synthesized at a scale conducive to replace steel cables in buildings despite lucrative biomaterial research opportunities. Both spider silk and woven nests therefore represent biomimetic methods that have been partially mobilized in building systems. However, a direct transfer of naturally reciprocated structures can only be achieved when both methods and material properties are harnessed in architectural projects.

4.4 Scale of Manufacturing

Given the acceleration of climate change, there is growing pressure to lessen steel, concrete, and other high-footprint materials in favor of composite, flexible, and force-adaptive biomaterials capable of non-rectilinear design.[10] One obstacle to achieving this is the issue of mass production of biomaterials with excellent mechanical properties, and therefore, improving manufacturing and durability of biomaterials has become today's most important research priority for engineers in biomimetics.[78] Such a challenge exists in the use of mycelium-based composites (MBC) in additive manufacturing. Structural mycelium prototypes are most often employed in modular bricks or acoustic panels, but are reinforced with traditional wood or metal connectors. This is due to mycelium's low compressive strength of 0.2MPa compared to traditional brick's minimum 28MPa.[79] However, mycelium is nearly sixty times lighter with a weight of 43kg/m^3, reducing the need for heavy foundations and supporting members.[80] The 2014 Hy-Fi tower by The Living

Studio and Arup is one example of brick application noted above.[81] Almpani-Lekka et al. also outlined the emergence of monolithic mycelium prototypes via a review of six recent MCB projects, including the Hy-Fi Tower, Shell Mycelium, Mycotree, Monolito Micelio, Growing Pavillion, and My-Co Space.[81] Monolito Micelio by Georgia Institute of Technology's School of Architecture exemplifies a monolithic mycelium project, which boasts a less controllable, but more morphologically free-form design frequently achieved by concrete. Biocoating was also used to enhance water resistance and durability in this project.[82] Another monolithic study by Modanloo et al. used *B. corium* and Gloeophyllum crust fungi to 3D-print a prototype for the Pulp-Faction project, whose greatest challenge was creating viable geometries for compression-only members.[41] Overall, literature suggest that there may be a future for continued refinement of discrete mycelium members, but also monolithic forms. More research is necessary to test the viability of 3D-printing for monolithic structures, which can then be reinforced with compression-based geometries.

Other scaling challenges exist in the engineering of granular building materials, which use repulsive contact forces rather than mechanical or chemical bonding to stack together.[83] A research group at ETH Zurich created a project titled, "Jammed Architectural Structures", to explore the reinforcement of granular materials with a string. Methods included using a six-axis robot to assemble wood dowel and velcro assemblages into amorphous columns and arches. However, this research focused on the fabrication of the particles, rather than the simulation of particles necessary for addressing architectural applications. In the case of the Pulp-Faction Project, a mixture of wood, paper pulp, and clay was combined with natural glue and inoculated with the fungus before and after printing via a Vormvrij Lutum v4 printer.[41] Similar to aforementioned granular material studies, the Pulp-Faction Project was heavily focused on the fabrication, i.e. the growth conditions of the fungal biomass, rather than testing its physical performance under load conditions. Studies into both MBCs and granular material show that novel biofabrication methods are project-specific— echoing nature's context-specific adaptive characteristics— but need to be broadened and assessed if they are to make their way into architectural designs. This challenge could be due to the difficulty of creating universal parametric models and additive processes, where biomaterial characteristics could be adjusted to fit needs of different structural performances.

4.5 Stress Resistance

Scientists have also been examining the stress capacities of nacre, in which it is known that extensive hierarchical organization in cross-lamellar structure results in superior crack arrest and other mechanical advantages.[84] This is a similar scheme to the fracture-resistance of mineralized bone, where large aspect ratios and staggered mineral platelets are key for strong biological nanocomposites.[85] Furthermore, Slesarenko et al. conclude that the strength of nacreous nanocomposites is dependent on the deformation and failure of soft phase in tension and shear under uniaxial tension.[86,87] These properties are showcased in the Guastavino vaulting of the Mapungubwe Interpretation Center by Peter Rich Architects. Guastavino vaulting is a method of building out units from a circular concrete ring beam, employed in this project to achieve a long and curvaceous roof span of sun-baked bricks, albeit with industrial construction materials.[29]

When it comes to recreating nacre's stress-resistance, scientists aim to optimize mechanical properties like self-healing. Electron microscopy shows that mollusc shells, like that of the abalone (genus *Haliotis*), consists of hexagonal aragonite platelets separated by elastic bipolymer sheets— a flexible "mortar" 3,000 times tougher than calcium carbonate chalk.[29,88] This structure is manifested via biomineralization, involving the deposition of the inorganic component in a very well-organized three-dimensional organic template, made of macromolecules, proteins or polysaccharides, typically rich in carboxylate groups and, in many cases, phosphate or sulfate groups.[78] The lamellar structure retains the ability to self-heal as staggered plates interrupt cracking, and restore themselves via hydrogen bonding over time.[89] The polymer mortar also aids in spreading concentrated loads over a larger surface area, further reducing cracking.[84]

In the past two decades, previous studies into the mechanical properties of nacre have uncovered it's nanoscale structural character, created multiobjective models to reconcile stiffness and toughness, and undergone a variety of stress tests.[78] For instance, macroscopic beam-bending tests have been extensively used to study the resistance of nacre to catastrophic fracture, and several fracture models have been proposed.[88] Yet, there is still a gap between nacre-inspired nanocomposites and the ability to self-heal due to their inherent durability. For instance, complex multi-scale structure prohibits the inclusion of encapsulated agents for extrinsic healing.[56] Therefore, there is a need for research into developing self-healing polymeric materials whose long-chain, chemical structure, and glass transition temperature (Tg) can be modified through designed chemistries.[90]

In light of thorough biomechanical knowledge, nacre represents a recurring theme in biomimicry: the gap between bio-inspired assembly, and understanding biomaterial characteristics.[14] Molluscs, along with fungi, echinoderms, and spider silks, are among the most viable models for biomimetic construction. This is because scientists and architects have access to a knowledge base of nuanced biomaterial characteristics established through research, like how nacre is synthesized by shelled organisms. Yet, in the Mapungubwe Interpretation Center, architects and engineers mimicked nacre's assembly without addressing nacre's lamellar materiality. This was likely due to a combination of financial, time-related, or technological constraints, but in order to optimize a biomimetic system as thoroughly as possible, every facet of the system must be addressed. In future studies, nacreous material ought to be explored in construction prototypes to reach the level of viability of technologies like mycelium, which is already being used in real buildings.

4.6 Additive Manufacturing

Adaptive accretion and additive manufacturing are vast concepts in nature, as they describe the self-assembly of molecules in an "ordered arrangement" without external guidance to shape emergent, macroscopic assemblies.[29] Chitin and cellulose are two classic examples of the additive manufacturing phenomenon. Specifically, these biomaterials are formed naturally through glycosidic bonding of glucose monomers to form linear polymer chains. Macro-assembly of these chains are what form increments of structural tissue in plant walls and skeletal components of lower animals like insects.[91] In the industry, biomedical and material engineers use chitin material sourced from marine organisms for wound dressing, artificial skin, and sutures, but are trying to synthesize their own biopolymers for wider applications.[92] Although, commercialization has been slow because isolating chitin from animals involves treating proteins with basic solutions and demineralizing the exoskeleton with acids. Further challenges arise in mechanical and optimal properties of the resulting product.[93] Despite this, however, Scolucka-Scarzy et al. have invented a novel biopolymer, chitin pentanoate (DVCH), in efforts to create a "technology friendly" biomaterial.[94] Filmogenic qualities make DVCH suitable for the manufacturing of threads, foils, foams, and non-woven materials, all of which can be referenced in the replacement of conventional materials like steel and concrete. In turn, these advancements are allowing architects and engineers to incorporate additive manufacturing processes into the design process through 3D-printing, which entails the bottom-up layering of resinous or plastic filament in the exact position intended by a digital prototype.[8] For instance, Neri Oxman and peers at the MIT Media Lab have established a water-based chitosan material that can be used to 3D-print rigid forms with renewable materials.[95] The printing platform consists of a multi-nozzle extrusion system and multi-axis robot arm that is capable of fabricating small-scale recyclable components out of gel. From a biomimetic perspective, the ability of 3D-printing to reflect organic growth of self-assembled materials will be vital towards optimizing additive manufacturing in buildings.

4.7 Circular Economies

Circular economies are important to consider when discussing nature's zero-waste policy. As opposed to a linear economy, which converts product to residual waste, circular economies strive to convert product to waste and back to product.[96] They seek to extend product life cycles, reduce waste, and manage natural assets in a way that can support mass consumption.[97] McDonough and Braungart's "Cradle-to-Cradle" concept is perhaps the most recognized model of this.[98] Under this concept, waste falls into two cycles: biological, and technical waste. In a biological cycle, materials are metabolized with sunlight as the only input. Organic matter is degraded and incorporated into other organisms, setting a standard for biodegradable and ecologically-safe materials that can be reused endlessly. The Cardboard to Caviar project by Green Business Network (GBN) is one example of a close-looped biological metabolism, where waste cardboard from restaurants is shredded for equestrian bedding, used in vermiculture, and eventually converted to sturgeon caviar.[14] A technical cycle acknowledges the inevitability of artificial products, but that these "nutrients" should pose zero hazard to the biological metabolism.[97] An example of this is the Mobius Project by Exploration Architecture, in which flue gasses from methane combustion is sequestered by accelerated carbonation and transformed into building materials.[99] Ongoing improvements to the technical metabolism include the elimination of heavy metals like lead in car batteries; lead can be substituted for minerals like zinc which offers equal performance without poisoning a biological cycle.

Literature suggests that cradle to cradle ideology and biomimicry are closely linked, but there is no consensus on an exact relationship. One prevailing perspective is that biomimicry and cradle to cradle are different tools towards creating a circular economy.[96] This line of reasoning views biomimicry as a mode to solve problems by imitating natural processes, while a cradle to cradle ideology is described as waste reduction using knowledge obtained by nature. The distinction here is subtle, but arises from whether or not we should copy nature, or be inspired by nature. A second perspective can be summarized as claiming that cradle to cradle *is* a biomimetic approach, as nature does not possess waste in the first place.[100] Either way, both perspectives hinge on total elimination of waste in construction.

Earthen architecture is a well-studied precedent that demonstrates the difficulty in shifting from a linear economy model to a circular economy model. This encompasses a wide variety of empirical practices ranging from rammed earth, to adobe masonry, cob, termite mounds, and other vernacular building techniques.[101] Earth materials are almost always excavated from subsoil horizons, alterites, or soft rock deposits because the spongier topsoils are prone to shrinkage and decay.[102,103] They are also classified as a granular material, which was discussed earlier. Mechanical cohesion is created by colloidal particles, like clay, while friction arises from contact between silts and sand.[101] Strength of cohesion varies by water content and clay type, with surface area of particles ranging from $20m^2g^{-1}$ to $850m^2g^{-1}$. Therefore, two different earthen walls in two different geographies can exhibit unique mechanical properties, in which suitability thresholds must be determined by a skilled mason upon performance-based tests.[104] In terms of circular economy benefits, lack of waste is earth building's greatest appeal, since ruins can simply be reabsorbed by the earth without any external aid. There are also no volatile organic compounds (VOCs) that pose occupant health risks through the building's lifespan, making it excellent fodder for biological metabolism.[105]

Morel et al. lists five main barriers for earthen materials in the circular economy: economical, organizational, sociological, political, and technical-related topics.[101] Technically speaking, heterogeneity in composition and water content make it hard to link lab tests to performance on the site. Walls also require less finishing work, but more performance-specific technical design in the arrangement of components. Organizationally, fragmented construction processes must become more streamlined due to the mason's key role in both construction and design. In addition, contracts must reflect guidance in line with the circular economy model. Lack of local codes and incentives on renewable materials, as well as near-sighted real-estate development, suppresses circular behavior from a political and socio-economic perspective; stimulating market demand for earthen architecture will therefore require strong advocacy on the financial merit of a circular model.[86] These limitations are important because they mirror those of biomimicry, in which circular processes are inherent. Optimizing earthen models in the built environment can thereby be a tool to steer the global economy away from linear consumption, and towards the nature-driven promise of biomimicry.

5. ANALYSIS: RESULTS & DISCUSSION

5.1 Summary of Results

BIOMIMETIC OPTIMIZATION

	BIOLOGICAL SYSTEM PRECEDENT			MIMICRY OF PRECEDENT			MANIFESTATION OF PRECEDENT			
OPS / MATERIAL TECHNOLOGY	A	B	C	D	E	F	G	H	I	AVERAGE SCORE
SILKWORMS	2	3	5	4	2	4	3	3	5	3.4
BAMBOO	4	4	2	5	4	5	5	5	5	4.3
WATER LILY	5	3	3	2	3	2	3	4	1	2.9
TREE ROOTS	3	3	4	2	1	1	1	5	1	2.3
BONE	4	3	3	2	1	2	3	4	4	2.9
ECHINODERMS	3	5	4	3	3	4	3	2	4	3.4
MOLLUSCS	3	3	3	1	2	1	1	5	4	2.6
WEAVERBIRDS	2	1	3	1	3	1	2	5	4	2.6
SPIDERS	2	1	2	1	2	1	3	1	4	1.9
MYCELIUM	3	2	2	5	4	3	3	5	5	3.6
GRANULAR	1	1	4	3	3	5	3	3	2	2.3
CHITIN	5	1	3	2	2	1	1	2	4	2.3

BIOLOGICAL SYSTEM PRECEDENT		MIMICRY OF PRECEDENT		MANIFESTATION OF PRECEDENT	
A	IS SYSTEM PRECEDENT, OR MODEL, CLEARLY DEFINED?	D	HAVE FABRICATION METHODS BEEN IDENTIFIED?	G	CAN RESULTING PRODUCT BE DESCRIBED AT ALL THREE SCALES?
B	IS PRECEDENT RELEVANT TO A PROJECT'S HUMAN NEEDS?	E	CAN MATERIAL BE MASS-PRODUCED?	H	IS PRECEDENT APPLIED IN A CONTEXT-SPECIFIC WAY?
C	ARE ALL PROJECT TEAMS EDUCATED ABOUT THE SYSTEM PRECEDENT?	F	IS EVERY MIMICKABLE COMPONENT OF THE PRECEDENT CONSIDERED?	I	IS THE RESULTING PRODUCT REGENERATIVE, AND CONTRIBUTE TO CIRCULAR ECONOMY?

Table 1: Biomimetic Optimization Scorecard. In this case, "optimized" is defined by Optimal Performance Standards (OPS) covered under Biological System Precedent, Mimicry of Precedent, and Manifestation of Precedent. Case studies projects are given a 1-5 score for each OPS, then an unweighted average is used to calculate a cumulative numeric score, compared against other precedents.

The Biomimetic Optimization Scorecard above demonstrates optimization results from twelve distinct biological precedents discussed throughout this document [Table 1]. Literature from which these scores were derived reflect investigation of material mimicry to focus the scope on innovative alternatives to industrial building materials. These twelve precedents were derived from key searches including phrases like "biomimetic design" and "sustainable architecture", and scores reflect knowledge presented strictly from sources cited in this document. Furthermore, the three headers dividing OPS into three groups ("A"-"C", "D"-"F", and "G"-"I"), represent the layers of implementing biomimicry in a project. In other words, mimicry is the intermediary between a biological system precedent, and manifesting the system into a tangible, built form. Scores were given for OPS A-I, corresponding to columns below each letter. Immediate observation of the scorecard indicates that "Bamboo" received the highest cumulative optimization score of 4.3, while "Spiders" was given the lowest score of 1.9. Bamboo received maximum scores in OPS "D", "F", "G", "H" and "I" with a low of 2 in OPS "C".

"Spiders" will be used as an example to elucidate the scoring process. "Spider" symbolizes the application of spider silk, which has attracted attention as an engineered biomaterial. For OPS "A", spider silk received a score of 2 because the scope of the system is too narrow. Extensive research has been published on the mechanical and molecular properties of a spider's web-spinning, yet it appears that little is published on the use of the whole organism. In essence, an organismal-level trait is extracted without more studies into web-building behavior, or the arachnid's services to the ecosystem around it. In OPS "B", a score of 1 was awarded because *structural* applications are lacking. Silk has been widely utilized as a biomaterial for tougher fabrics like Kevlar, but this level of inquiry is not reflected in more defined building uses other than general tensile structures. In OPS "C" a 2 was awarded because biomimetic knowledge is predominantly fostered by expert material scientists, arachnologists have an expert knowledge about the behavior- and ecosystem-scale characteristics of the whole organism. In a spider-inspired design, both groups must exchange knowledge, and introduce it to structural engineers, contracts, and clients. OPS "D" was awarded a 1 on the same premise as OPS "A". For clarification, this is not because silk biomaterials haven't been fabricated, but they have not yet been applied to an architectural setting. For OPS "E", the score of 2 is due to the synthesis of silk material being too miniscule for the amount required to use in any building setting. Mass methods of production ought to be planned before larger prototyping can occur. OPS "F" follows a similar line of reasoning as OPS "A", whereas the literature emphasis on the silk production may be diverting effort away from other mimickable traits of a spider at different scales. "G" was awarded a 3 because the widespread integration of cable tension represents a critical behavioral trait of a spider's silk. "H" received a 1 because there is no consensus on what optimal conditions a spider's holistic precedent should be applied to a building, indicative of a lack of research. Lastly, "I" received a 4 because arachnoid mediums, such as the silk, chitinous exoskeleton, and venoms can all be biologically metabolized with ease.

Involving general trends, it appears that the highest quartile of scores, including "Bamboo", "Mycelium", and "Silkworm"/"Echinoderms" have one common derivative, that is, they have already been used to create structures [Fig. 2]. Bamboo is a renewable material that has been harvested and used since prehistory, and represents the vernacular of East Asian constituents like India, China, and Malaysia. It has also been implemented in some South American and South African communities. Scaffolding and joinery techniques have already been discovered, and it is usually applied in full- or half-culm forms. A decent body of tension and compression tests, like that of Chen et al., has also been pushing structural bamboo structures closer and closer to its potential. Similarly, mycelium appears to be in the prototyping phase, with even more diverse experimentation into panel and brick forms, as well as monolithic or "grown" structures. Projects like the Hy-Fi Tower, MYCO-SPACE, and El Monolito Micelio are drawing attention to spectacular morphologies that can be created by organisms lowest on the food chain. The endoskeleton of echinoderms is reinventing the technique of building with panels, and enables modular units to create organic shapes. Lastly, Oxman's Silkworm Pavilion demonstrates the value of novel fabrication techniques, combining robotics and silkworms to apply materials manufactured directly by nature. Based on this evidence, direct application of a biomaterial is more optimal than "mimicking" it; if scientists can cultivate ways to harvest such materials from nature in a sustainable way, they can avoid the lengthy process of synthesizing it in a lab setting.

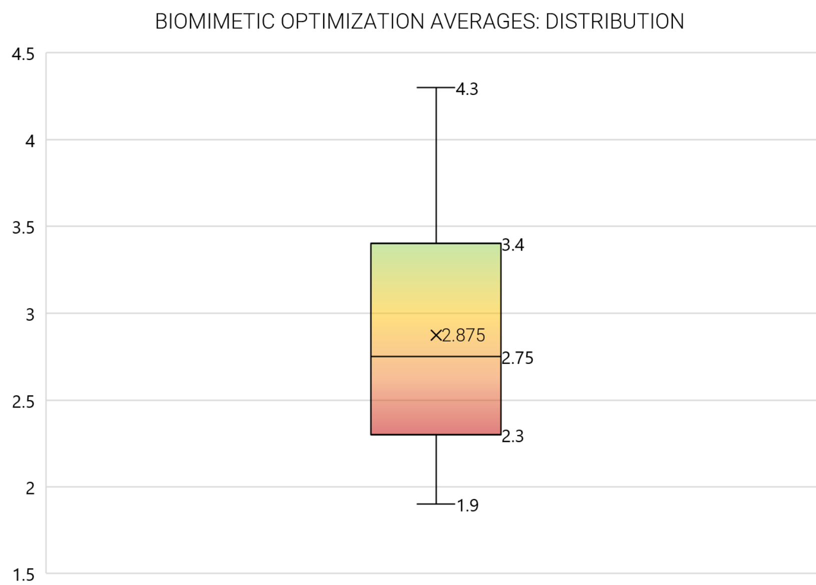

Figure 2: Biomimetic Optimization Averages: Distribution. A box-and-whisker plot reveals variation between average scores. Middle line represents median score of 2.75 represents median OPS average score, while "x" represents the mean of OPS average scores. Gradient from green to red represents trends from precedents most integrated (green) into industry, towards precedents least integrated (red) into industry at present day.

Although biological precedents noted above represent the highest scores, room for improvement still exists. For instance, the IBC does not sufficiently address codes reflecting the details of bamboo's physical properties, nor does voluntary green building programs. The same is true for every other precedent noted on the scorecard. Additionally, more testing is needed to discover bamboo's use in hybrid technologies like fiber-reinforced concrete, which could replace steel reinforcement. Perhaps as a symptom of little specificity in the IBC, contractors in industrialized geographies may be less likely to understand how to build with bamboo or be intimidated by its physical drawbacks. This may be especially true in climates such as the midwest, where climate may be less suited than its native habitat. There are still barriers regarding strength and durability of bamboo, mycelium, and other renewables. Renewables do not last nearly as long as "heat, beat and treat" materials, as their purpose is to contribute to a circular economy. This dichotomy will be difficult to amend without a collective embrace of nature's temporary state.

5.2 Discussion: Study Limitations & Opportunities

The twelve precedents scored in this investigation do not present an analysis of all organisms that apply to structural biomimetics. As the field of biomimicry is still in its nascency, substantial discoveries are yet to be made. Precedents from new organisms are yet to arise, and more precedents from existing biomimetic models have yet to be tested. Additionally, biomimetics is a highly interconnective concept, and limiting the scope to explore only material technologies was difficult in light of the fact that there are numerous system technologies related to water retention, energy generation, and thermal environments modeled after organisms that have also been used to study structural elements. For example, the vascular structure of *Victoria* was isolated from knowledge about solar energy capture and buoyancy, which could also inform building system designs. In future studies, biological precedents should be scored as a whole organism, ranked with all biomimetic derivatives considered to achieve optimization. Studying material characteristics alone will not ensure optimization, as in nature, form and function are corequisite entities.

The twelve precedents scored in this study were also not at the same scale, causing discrepancies in scoring. For instance, when considering spider silk, OPS "F" was difficult to assign a value to. Spider silk is already a mimicked trait of a larger organism, in which there is a lack of "whole-organism" that could be consulted in this investigation. On the other hand, "Bamboo" may've performed well because it is a complete organism, from which there is literature drawn into this document to substantiate bamboo's score across all nine OPS. Despite limitations, these twelve precedents still provide value because they reflect an authentic slice of the current state. Literature has revealed research priorities for future biomimetic studies, and where there is a lack of attention. For instance, in the case of spiders, research was heavily skewed towards understanding silk, an organismal-level trait rather than behavioral- or ecosystem-mimicry. Low scores in some or all areas therefore indicate that certain biological precedents are not as established as others; a mix of thoroughly studied organisms exists alongside a body of studies of isolated biomimetic traits which aren't conducive towards an optimized model. Future research should reflect biomimicry's inherent interconnectedness in order to sufficiently study a biological model for building application.

6. CONCLUSION

6.1 Biomimicry for People

Biomimic processes addressing energy efficiency, resource efficiency, water, and overall stewardship are, to an extent, already self-evident in the construction world, but by many different names. Scientists on the cutting edge are still grappling with how to scale processes and materials because the reality is that nature is highly differentiated in its approach to each species survival than it is a "one size fits all" adaptation. Embracing these context-specific adaptations of nature has led scientists to embrace context-specific research into material applications. With MBCs, scientists are on the brink of employing a renewable, fully biodegradable alternative building material. But details need to be addressed on how mycelium biomass can be mass-produced on a commercial scale, and tailor mycelium's mechanical properties for different spatial needs. Similarly, designers have yet to discover a universal parametric model for granular materials that can be sculpted into different forms and perform as part of a conditioned system, in addition to exploring the characteristics of the granular material itself. The list of biomimetic material studies necessary to bridge the gap from nature to construction is lengthy, yet each study presents a new opportunity to push green building standards, codes, and fields of knowledge into further alignment with nature's methods.

Substantial technical knowledge is also required to implement biomimetics beyond surface-level mimicking of natural forms, and thus cross-collaboration is required to achieve full-depth applications in construction. An architect lacks knowledge of tools like electron microscopes which limits deeper understanding of species applications, like in the use of *B. mori* for the Silkworm Pavilion. Limitations in biological knowledge and novel tools are thus hindering stakeholders' involvement in biomimetic construction. Professional awareness is needed to bring innovations to light, which could be done most effectively through collaboration between biologists, architects, engineers, contractors, and clients throughout the duration of a project. Thus, reframing how teams work together could be key to more biomimetic research, cross-disciplinary interaction, and deeper technological skills. During the integrated design process, selecting a biological system precedent to express intended values could be more instrumental than conforming a biological system to a human need. This describes the bottom-up approach, as it is a way to start with nature first and work towards solving design problems while maintaining the integrity of nature's methods. Integrated design processes also emphasize collaboration for sustainable solutions, rather than specialization in architectural education and profession. UC Berkeley's Studio One has demonstrated an alternative teaching model aimed at improving collaboration through industrial partnership, constantly refining curriculum, and widening the scope of admitted students beyond architecture alone. Lastly, an interdisciplinary team equates to a wider repertoire of algorithmic technologies and computer-aided optimization for visualization.

In short, biomimicry is for people. Resource constraints we are likely to face in coming years can be addressed by a wealth of adaptations through biomimicry. Evolutionary pressures, which have ferociously induced organisms to optimize themselves over millions of years, can be a means by which humans identify solutions without exacerbating climate change. The extent to which this concept persuades people to adopt greener construction practices hinges on how architects and scientists integrate functional designs of nature into the hands of builders. The faster we follow suit, the faster waste will be designed out in exchange for a sustainable, habitable built environment.

REFERENCES

1. Roeck M, Saade MRM, Balouktsi M, Rasmussen FN, Birgisdottir H, Frischknecht R, Habert G, Luetzkendorf T, Passer A. Embodied GHG emissions of buildings - The hidden challenge for effective climate change mitigation. Applied Energy. 2020;258:114107. doi:10.1016/j.apenergy.2019.114107

2. Behera M, Bhattacharyya SK, Minocha AK, Deoliya R, Maiti S. Recycled aggregate from C&D waste & its use in concrete - A breakthrough towards sustainability in construction sector: A review. Construction and Building Materials. 2014;68:501–516. doi:10.1016/j.conbuildmat.2014.07.003

3. Rynikiewicz C. The climate change challenge and transitions for radical changes in the European steel industry. Journal of Cleaner Production. 2008;16(7):781–789. doi:10.1016/j.jclepro.2007.03.001

4. Li M, Guo J, Tian Z, Shi J, Xiong M, Xiang C. Future climate change and building energy demand in Tianjin, China. Building Services Engineering Research and Technology. 2014;35(4):362–375. doi:10.1177/0143624413498245

5. Zhai ZJ, Helman JM. Implications of climate changes to building energy and design. Sustainable Cities and Society. 2019;44:511–519. doi:10.1016/j.scs.2018.10.043

6. Logan K. Waste not, want not: case studies of building material reuse. BuildingGreen. 2022 Jan 20 [accessed 2022 Feb 20]. http://www.buildinggreen.com/feature/waste-not-want-not-case-studies-building-material-reuse

7. Joshi S. AIA guide to Building Life Cycle Assessment in practice. :194.

8. Schleicher S, Kontominas G, Makker T, Tatli I, Yavaribajestani Y. Studio one: a new teaching model for exploring bio-inspired design and fabrication. Biomimetics. 2019;4(2):34. doi:10.3390/biomimetics4020034

9. Malin N. Prefabricating green: building environmentally friendly houses off site. Environmental Building News. 2007;16(10):16.

10. Vrcelj Z, Link to external site this link will open in a new window. Biomimicry and the built environment, learning from nature's solutions. Applied Sciences. 2021;11(16):7514. doi:http://dx.doi.org/10.3390/app11167514

11. Bayhan HG, Karaca E. SWOT analysis of biomimicry for sustainable buildings – a literature review of the importance of kinetic architecture applications in sustainable construction projects. IOP Conference Series. Materials Science and Engineering. 2019 [accessed 2022 Feb 7];471(8). https://www.proquest.com/docview/2560830072/abstract/8D3D7AD309194D4BPQ/1. doi:http://dx.doi.org/10.1088/1757-899X/471/8/082047

12. Mirniazmandan S, Rahimianzarif E. Biomimicry, an approach toward sustainability of high-rise buildings. Iranian Journal of Science and Technology: Science, Transaction A. 2018;42(4):1837–1846. doi:http://dx.doi.org/10.1007/s40995-017-0397-4

13. McCardle J, Link to external site this link will open in a new window. Performance based abstraction of biomimicry design principles using prototyping. Designs. 2019;3(3):38. doi:http://dx.doi.org/10.3390/designs3030038

14. Nkandu M, Alibaba H. Biomimicry as an Alternative Approach to Sustainability. Bulletin of the Polytechnic Institute of Jassy, CONSTRUCTIONS. ARCHITECTURE Section. 2018;8. doi:10.5923/j.arch.20180801.01

15. Kellert S. Biophilia and biomimicry: evolutionary adaptation of human versus nonhuman nature. Intelligent Buildings International. 2016;8(2):51–56. doi:10.1080/17508975.2014.902802

16. Ramzy NS. Beyond Sustainability, Design for Well-Being: Gaudí's Monument to Nature, Biomimetic Functions with Biophilic Morphology. Journal of Architectural Engineering. 2022;28(1):05021016. doi:10.1061/(ASCE)AE.1943-5568.0000515

17. Djebbara Z, Jensen OB, Parada FJ, Gramann K. Neuroscience and architecture: Modulating behavior through sensorimotor responses to the built environment. Neuroscience and Biobehavioral Reviews. 2022;138:104715. doi:10.1016/j.neubiorev.2022.104715

18. Revell G, Anda M. Sustainable Urban Biophilia: The Case of Greenskins for Urban Density. Sustainability. 2014;6(8):5423–5438. doi:10.3390/su6085423

19. Wang Y, Bakker F, de Groot R, Wörtche H. Effect of ecosystem services provided by urban green infrastructure on indoor environment: A literature review. Building and Environment. 2014;77:88–100. doi:10.1016/j.buildenv.2014.03.021

20. Full article: Biophilia and Salutogenesis as restorative design approaches in healthcare architecture. [accessed 2022 Oct 6]. https://www-tandfonline-com.colorado.idm.oclc.org/doi/full/10.1080/00038628.2019.1604313?10.1080/00038628.2019.1604313

21. Understanding Knowledge Workers' Interactions With Workplace Greenspace: Open Space Use and Restoration Experiences at Urban-Fringe Business Sites - Kathryn Colley, Caroline Brown, Alicia Montarzino, 2017. [accessed 2022 Oct 25]. https://journals-sagepub-com.colorado.idm.oclc.org/doi/10.1177/0013916516629194

22. Yuan Y, Yu X, Yang X, Xiao Y, Xiang B, Wang Y. Bionic building energy efficiency and bionic green architecture: A review. Renewable and Sustainable Energy Reviews. 2017;74:771–787. doi:10.1016/j.rser.2017.03.004

23. Wahl DC. Bionics vs. biomimicry: from control *of* nature to sustainable participation *in* nature. In: Design and Nature III: Comparing Design in Nature with Science and Engineering. Vol. 1. The New Forest, UK: WIT Press; 2006. p. 289–298. http://library.witpress.com/viewpaper.asp?pcode=DN06-028-1. doi:10.2495/DN060281

24. Zari MP. Biomimetic design for climate change adaptation and mitigation. Architectural Science Review. 2010;53(2):172–183. doi:10.3763/asre.2008.0065

25. Bhushan B. Biomimetics: lessons from nature–an overview. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2009;367(1893):1445–1486. doi:10.1098/rsta.2009.0011

26. Wallis I. Industrialised, integrated, intelligent sustainable construction: I3CON handbook 2. Great Britain: I3CON in collaboration with, BSRIA; 2010.

27. Garcia-Holguera M, Clark OG, Sprecher A, Gaskin S. Ecosystem biomimetics for resource use optimization in buildings. Building Research & Information. 2016;44(3):263–278. doi:10.1080/09613218.2015.1052315

28. Sanga R, Kilumile M, Mohamed F. Alternative clay bricks inspired from termite mound biomimicry. Case Studies in Construction Materials. 2022;16:e00977. doi:10.1016/j.cscm.2022.e00977

29. Pawlyn M. Biomimicry in Architecture. Routledge; 2019.

30. Kırdök O, Altun TD, Dokgöz D, Tokuç A. Biodesign as an innovative tool to decrease construction induced carbon emissions in the environment. :24.

31. Perricone V, Grun TB, Marmo F, Langella C, Candia Carnevali MD. Constructional design of echinoid endoskeleton: main structural components and their potential for biomimetic applications. Bioinspiration & Biomimetics. 2020;16(1):011001. doi:10.1088/1748-3190/abb86b

32. Rupp AIKS, Gruber P. Biomimetic groundwork for thermal exchange structures inspired by plant leaf design. Biomimetics. 2019;4(4):75. doi:10.3390/biomimetics4040075

33. Melton P. Whole-Building Life-Cycle Assessment: taking the measure of a green building. BuildingGreen. 2013 Apr 29 [accessed

2022 Feb 20]. http://www.buildinggreen.com/feature/whole-building-life-cycle-assessment-taking-measure-green-building

34. Wendt A. Prefabricating Green: Building Environmentally Friendly Houses Off Site. BuildingGreen. 2007 Sep 28 [accessed 2022 Feb 20]. http://www.buildinggreen.com/feature/prefabricating-green-building-environmentally-friendly-houses-site

35. Wilson J. When Passive House goes big. 2018:20.

36. Municipal Code | Boulder, CO | Municode Library. [accessed 2022 Oct 8]. https://library.municode.com/co/boulder/codes/municipal_code?nodeId=18020

37. Pearson C. An Advocate's Guide to Resilience Regulations. BuildingGreen. 2021 Jan 20 [accessed 2022 Oct 8]. http://www.buildinggreen.com/feature/advocate-s-guide-resilience-regulations

38. Eisenberg -David, Yost P. Sustainability and building codes. BuildingGreen. 2001 Sep 1 [accessed 2022 Mar 5]. http://www.buildinggreen.com/feature/sustainability-and-building-codes

39. Melton P. The urgency of embodied carbon and what you can do about it. BuildingGreen. 2018 Aug 20 [accessed 2022 Feb 20]. http://www.buildinggreen.com/feature/urgency-embodied-carbon-and-what-you-can-do-about-it

40. Melton P, Roberts T. How to succeed with the living building challenge: 12 teams share tips. 2015:22.

41. Modanloo B, Ghazvinian A, Matini M, Andaroodi E. Tilted arch; implementation of additive manufacturing and bio-welding of mycelium-based composites. Biomimetics. 2021;6(4):68. doi:10.3390/biomimetics6040068

42. living building basics | Living-Future.org. 2016 [accessed 2022 Mar 6]. https://living-future.org/lbc-3_1/basics/

43. Rodriguez BX, Link to external site this link will open in a new window, Simonen K, Huang M, De Wolf C. A taxonomy for Whole Building Life Cycle Assessment (WBLCA). Smart and Sustainable Built Environment. 2019;8(3):190–205. doi:http://dx.doi.org.colorado.idm.oclc.org/10.1108/SASBE-06-2018-0034

44. CARBON SMART MATERIALS PALETTE – Carbon Smart Materials Palette. [accessed 2022 Oct 10]. https://materialspalette.org/palette/

45. Chele E-S, Ricardo M-C, Ana P-M, Teresa M-R. Bamboo, from Traditional Crafts to Contemporary Design and Architecture. Procedia - Social and Behavioral Sciences. 2012;51:777–781. (The World Conference on Design, Arts and Education (DAE-2012), May 1-3 2012, Antalya, Turkey). doi:10.1016/j.sbspro.2012.08.239

46. Zea Escamilla E, Habert G, Correal Daza JF, Archilla HF, Echeverry Fernández JS, Trujillo D. Industrial or Traditional Bamboo Construction? Comparative Life Cycle Assessment (LCA) of Bamboo-Based Buildings. Sustainability. 2018;10(9):3096. doi:10.3390/su10093096

47. Jayanetti DL, Follett PR. Bamboo in construction. In: Xiao Y, Inoue M, Paudel SK, editors. Modern Bamboo Structures. Boca Raton: Crc Press-Taylor & Francis Group; 2008. p. 23–32. http://www.webofscience.com/wos/woscc/full-record/WOS:000265332100002

48. Sharma B, Gatóo A, Bock M, Ramage M. Engineered bamboo for structural applications. Construction and Building Materials. 2015;81:66–73. doi:10.1016/j.conbuildmat.2015.01.077

49. Manandhar R, Kim J-H, Kim J-T. Environmental, social and economic sustainability of bamboo and bamboo-based construction materials in buildings. Journal of Asian Architecture and Building Engineering. 2019;18(2):49–59. doi:10.1080/13467581.2019.1595629

50. LEED v4.1 | U.S. Green Building Council. [accessed 2022 Oct 12]. https://www.usgbc.org/leed/v41#bdc

51. Melton P. Existing buildings are architecture's future. BuildingGreen. 2020 May 20 [accessed 2022 Mar 3]. http://www.buildinggreen.com/feature/existing-buildings-are-architecture-s-future

52. Didari A, Link to external site this link will open in a new window, Mengüç MP, Link to external site this link will open in a new window. A biomimicry design for nanoscale radiative cooling applications inspired by Morpho didius butterfly. Scientific Reports (Nature Publisher Group). 2018;8:1–9. doi:http://dx.doi.org/10.1038/s41598-018-35082-3

53. Abdala LN, Fernandes RB, Ogliari A, Loewer M, Feldhusen J. Creative Contributions of the Methods of Inventive Principles of TRIZ and BioTRIZ to Problem Solving. Journal of Mechanical Design. 2017;139(8):082001. doi:10.1115/1.4036566

54. Biomimetics: its practice and theory | Journal of The Royal Society Interface. [accessed 2022 Oct 16]. https://royalsocietypublishing-org.colorado.idm.oclc.org/doi/10.1098/rsif.2006.0127

55. Garcia-Holguera M, Clark OG, Sprecher A, Gaskin S. Ecosystem biomimetics for resource use optimization in buildings. Building Research & Information. 2016;44(3):263–278. doi:10.1080/09613218.2015.1052315

56. Du G, Mao A, Yu J, Hou J, Zhao N, Han J, Zhao Q, Gao W, Xie T, Bai H. Nacre-mimetic composite with intrinsic self-healing and shape-programming capability. Nature Communications. 2019;10(1):800. doi:10.1038/s41467-019-08643-x

57. Systematic technology transfer from biology to engineering. [accessed 2022 Oct 16]. http://royalsocietypublishing.org/doi/epdf/10.1098/rsta.2001.0923. doi:10.1098/rsta.2001.0923

58. Bai Z, Mu L, Lin H-C. Green Product Design Based on the BioTRIZ Multi-Contradiction Resolution Method. Sustainability. 2020;12(10):4276. doi:10.3390/su12104276

59. Cherifi A, Dubois M, Gardoni M, Tairi A. Methodology for innovative eco-design based on TRIZ. International Journal on Interactive Design and Manufacturing (IJIDeM). 2015;9(3):167–175. doi:10.1007/s12008-014-0255-y

60. Burrall M, DeJong JT, Martinez A, Wilson DW. Vertical pullout tests of orchard trees for bio-inspired engineering of anchorage and foundation systems. Bioinspiration & Biomimetics. 2020;16(1):016009. doi:10.1088/1748-3190/abb414

61. Stachew E, Houette T, Gruber P. Root systems research for bioinspired resilient design: A concept framework for foundation and coastal engineering. Frontiers in Robotics and AI. 2021 [accessed 2022 Mar 2];8. https://www.frontiersin.org/article/10.3389/frobt.2021.548444

62. Box F, Erlich A, Guan JH, Thorogood C. Gigantic floating leaves occupy a large surface area at an economical material cost. Science Advances. 8(6):eabg3790. doi:10.1126/sciadv.abg3790

63. Wunnenberg J, Rjosk A, Neinhuis C, Lautenschläger T. Strengthening Structures in the Petiole–Lamina Junction of Peltate Leaves. Biomimetics. 2021;6(2):25. doi:10.3390/biomimetics6020025

64. Carpi A, Brebbia CA. Design & Nature V: Comparing Design in Nature with Science and Engineering. WIT Press; 2010.

65. Chen Q, Razi H, Schlepütz CM, Fang C, Ma X, Fei B, Burgert I. Bamboo's tissue structure facilitates large bending deflections. Bioinspiration & Biomimetics. 2021;16(6):065005. doi:10.1088/1748-3190/ac253b

66. Wang Y, Chun Q. BAMBOO CANOPY: TOWARDS A LIGHT CONSTRUCTION OF BAMBOO. Journal of Green Building. 2020;15(3):215–234. doi:10.3992/jgb.15.3.215

67. Milovanovic P, Zimmermann EA, vom Scheidt A, Hoffmann B, Sarau G, Yorgan T, Schweizer M, Amling M, Christiansen S, Busse B. The Formation of Calcified Nanospherites during Micropetrosis Represents a Unique Mineralization Mechanism in Aged Human Bone. Small. 2017;13(3):1602215. doi:10.1002/smll.201602215

68. Schmidt FN, Zimmermann EA, Walsh F, Plumeyer C, Schaible E, Fiedler IAK, Milovanovic P, Rößle M, Amling M, Blanchet C, et al. On the Origins of Fracture Toughness in Advanced Teleosts: How the Swordfish Sword's Bone Structure and Composition Allow for Slashing under Water to Kill or Stun Prey. Advanced Science. 2019;6(12):1900287. doi:10.1002/advs.201900287

69. Li Z, Chu D, Gao Y, Jin L, Zhang X, Cui W, Li J. Biomimicry, biomineralization, and bioregeneration of bone using advanced three-dimensional fibrous hydroxyapatite scaffold. Materials Today Advances. 2019;3:100014. doi:10.1016/j.mtadv.2019.100014

70. Grun TB, Koohi Fayegh Dehkordi L, Schwinn T, Sonntag D, von Scheven M, Bischoff M, Knippers J, Menges A, Nebelsick JH. The Skeleton of the Sand Dollar as a Biological Role Model for Segmented Shells in Building Construction: A Research Review. In: Knippers J, Nickel KG, Speck T, editors. Biomimetic Research for Architecture and Building Construction: Biological Design and Integrative Structures. Cham: Springer International Publishing; 2016. p. 217–242. (Biologically-Inspired Systems). https://doi.org/10.1007/978-3-319-46374-2_11. doi:10.1007/978-3-319-46374-2_11

71. Nebelsick JH, Dynowski JF, Grossmann JN, Tötzke C. Echinoderms: Hierarchically Organized Light Weight Skeletons. Springer; 2015. p. 141–155. https://pub.h-brs.de/frontdoor/index/index/docId/4175

72. Lai M, Kulak AN, Law D, Zhang Z, Meldrum FC, Riley DJ. Profiting from nature: macroporous copper with superior mechanical properties. Chemical Communications. 2007;(34):3547–3549. doi:10.1039/B707469G

73. (PDF) Energy Absorption in Functionally Graded Concrete Bioinspired by Sea Urchin Spines | ResearchGate. [accessed 2022 Oct 22]. https://www.researchgate.net/publication/315956912_Energy_Absorption_in_Functionally_Graded_Concrete_Bioinspired_by_Sea_Urchin_Spines

74. Binyon J. CHAPTER 8 - PHYSIOLOGY OF THE WATER VASCULAR SYSTEM AND THE NEURAL CONTROL OF LOCOMOTION. In: Binyon J, editor. Physiology of Echinoderms. Pergamon; 1972. p. 124–146. (International Series of Monographs in Pure and Applied Biology. Division: Zoology). https://www.sciencedirect.com/science/article/pii/B9780080169910500155. doi:10.1016/B978-0-08-016991-0.50015-5

75. Sindhu Nachiar S, Satyanarayanan KS, Lakshmipathy M. Study on the behaviour of tension member based on the concept of biomimics. Materials Today: Proceedings. 2021;34:371–378. (3rd International Conference on Recent Advances in Material Chemistry, ICRAMC 2019, February 13-15, 2019, Kattankulathur, India). doi:10.1016/j.matpr.2020.02.194

76. Jane G, Kuria KP. Spider silk: A natural marvel of mechanical and structural strength. African Journal of Biological Sciences. 2021;3(4):1–16. doi:10.33472/AFJBS.3.4.2021.1-16

77. Bioprospecting Finds the Toughest Biological Material: Extraordinary Silk from a Giant Riverine Orb Spider. - EBSCO. [accessed 2022 Oct 22]. https://discovery.ebsco.com/c/3czfwv/viewer/pdf/f222h7vfdj

78. Luz GM, Mano JF. Biomimetic design of materials and biomaterials inspired by the structure of nacre. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2009;367(1893):1587–1605. doi:10.1098/rsta.2009.0007

79. Jones MS. Birthright Citizens: A History of Race and Rights in Antebellum America. Cambridge University Press; 2018.

80. Hoeven D van der. Mycelium as a construction material. Bio Based Press. 2020 Apr 7 [accessed 2022 Oct 23]. https://www.biobasedpress.eu/2020/04/mycelium-as-a-construction-material/

81. Almpani-Lekka D, Pfeiffer S, Schmidts C, Seo S. A review on architecture with fungal biomaterials: the desired and the feasible. Fungal Biology and Biotechnology. 2021;8(1):17. doi:10.1186/s40694-021-00124-5

82. About The Growing Pavilion. The Growing Pavilion. [accessed 2022 Oct 23]. https://thegrowingpavilion.com/about/

83. Dierichs K, Menges A. Designing architectural materials: from granular form to functional granular material. Bioinspiration & Biomimetics. 2021;16(6):065010. doi:10.1088/1748-3190/ac2987

84. Al-Maskari NS, McAdams DA, Reddy JN. Modeling of a biological material nacre: Multi-objective optimization model. Mechanics of Advanced Materials and Structures. 2021;28(4):430–439. doi:10.1080/15376494.2019.1568649

85. Ji B, Gao H. Mechanical properties of nanostructure of biological materials. Journal of the Mechanics and Physics of Solids. 2004;52(9):1963–1990. doi:10.1016/j.jmps.2004.03.006

86. Slesarenko V, Rudykh S. Towards mechanical characterization of soft digital materials for multimaterial 3D-printing. International Journal of Engineering Science. 2018;123:62–72. doi:10.1016/j.ijengsci.2017.11.011

87. Slesarenko V, Volokh KY, Aboudi J, Rudykh S. Understanding the strength of bioinspired soft composites. International Journal of Mechanical Sciences. 2017;131–132:171–178. doi:10.1016/j.ijmecsci.2017.06.054

88. Li X, Chang W-C, Chao YJ, Wang R, Chang M. Nanoscale Structural and Mechanical Characterization of a Natural Nanocomposite Material: The Shell of Red Abalone. Nano Letters. 2004;4(4):613–617. doi:10.1021/nl049962k

89. Zhu B, Jasinski N, Benitez A, Noack M, Park D, Goldmann AS, Barner-Kowollik C, Walther A. Hierarchical Nacre Mimetics with Synergistic Mechanical Properties by Control of Molecular Interactions in Self-Healing Polymers. Angewandte Chemie International Edition. 2015;54(30):8653–8657. doi:10.1002/anie.201502323

90. Reddy KR, El-Zein A, Airey DW, Alonso-Marroquin F, Schubel P, Manalo A. Self-healing polymers: Synthesis methods and applications. Nano-Structures & Nano-Objects. 2020;23:100500. doi:10.1016/j.nanoso.2020.100500

91. Merzendorfer H, Zimoch L. Chitin metabolism in insects: structure, function and regulation of chitin synthases and chitinases. Journal of Experimental Biology. 2003;206(24):4393–4412. doi:10.1242/jeb.00709

92. Shiwei N, Dritsas S, Fernandez JG. Martian biolith: A bioinspired regolith composite for closed-loop extraterrestrial manufacturing. PLOS ONE. 2020;15(9):e0238606. doi:10.1371/journal.pone.0238606

93. Hou J, Aydemir BE, Dumanli AG. Understanding the structural diversity of chitins as a versatile biomaterial. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2021;379(2206):20200331. doi:10.1098/rsta.2020.0331

94. Skołucka-Szary K, Ramięga A, Piaskowska W, Janicki B, Grala M, Rieske P, Stoczyńska-Fidelus E, Piaskowski S. Chitin dipentanoate as the new technologically usable biomaterial. Materials Science and Engineering: C. 2015;55:50–60. doi:10.1016/j.msec.2015.05.051

95. Mogas-Soldevila L, Oxman N. Water-based Engineering & Fabrication: Large-Scale Additive Manufacturing of Biomaterials. MRS Online Proceedings Library (OPL). 2015;1800:mrss15. doi:10.1557/opl.2015.659

96. Ghisellini P, Cialani C, Ulgiati S. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner Production. 2016;114:11–32. (Towards Post Fossil Carbon Societies: Regenerative and Preventative Eco-Industrial Development). doi:10.1016/j.jclepro.2015.09.007

97. NATURE-INSPIRED DESIGN: BIOMIMICRY AND CRADLE TO CRADLE. - EBSCO. [accessed 2022 Oct 24].

https://discovery.ebsco.com/c/3czfwv/viewer/pdf/kvfzqqkuon

98. McDonough W, Braungart M. Cradle to Cradle: Remaking the Way We Make Things. Farrar, Straus and Giroux; 2010.

99. Taylor Buck N. The art of imitating life: The potential contribution of biomimicry in shaping the future of our cities. Environment and Planning B: Urban Analytics and City Science. 2017;44(1):120–140. doi:10.1177/0265813515611417

100. Bruel A, Kronenberg J, Troussier N, Guillaume B. Linking Industrial Ecology and Ecological Economics: A Theoretical and Empirical Foundation for the Circular Economy. Journal of Industrial Ecology. 2019;23(1):12–21. doi:10.1111/jiec.12745

101. Morel J-C, Charef R, Hamard E, Fabbri A, Beckett C, Bui Q-B. Earth as construction material in the circular economy context: practitioner perspectives on barriers to overcome. Philosophical Transactions of the Royal Society B: Biological Sciences. 2021;376(1834):20200182. doi:10.1098/rstb.2020.0182

102. Maniatidis V, Walker P. A Review of Rammed Earth Construction: DTI Project Report. 2003.

103. (PDF) Rediscovering of vernacular adaptative construction strategies for sustainable modern building : application to cob and rammed earth | ResearchGate. [accessed 2022 Oct 24]. https://www.researchgate.net/publication/323387530_Rediscovering_of_vernacular_adaptative_construction_strategies_for_sustainable_modern_building_application_to_cob_and_rammed_earth

104. Kouakou CH, Morel JC. Strength and elasto-plastic properties of non-industrial building materials manufactured with clay as a natural binder. Applied Clay Science. 2009;44(1):27–34. doi:10.1016/j.clay.2008.12.019

105. Guo M. Assessment of the Impact of Higher Education on Environmental Quality in BRICS Economies Based on Sustainable Development Pathways. Journal of Environmental and Public Health. 2022;2022:6447763. doi:10.1155/2022/6447763