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Research Paper

Biogeneration: Bio-Inspired Architecture for Regenerative Built Environments[1]

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Research Highlights:
The authors introduce a new concept termed "biogeneration," a reflection of bio-inspired architecture, including biomimicry and biophilia, in regenerative built environments.
In elucidating the field's interdisciplinary span, the authors present how biogenerative approaches to architectural design can assist with the identification, ideation, innovation, iteration, and implementation (i^5) design thinking methodology.
The authors expound on the need for and relevance of biogeneration in three major fields of design: development engineering, additive manufacturing (AM), and climate change adaptation and mitigation.
By integrating human urban habitats into the living world, biogeneration can help development engineers find solutions that benefit the poor to bring about substantial change; design thinkers and professionals develop additively manufacturable artifacts and structures that create new AM-enabled opportunities, enriched design processes, new business models, and new technologies with AM; and urban planners transform the built environment to counter the human-caused climate crisis. T
The research examines the mutualistic relationships between people and the environment that ensure the psychological well-being of the former and the ecological health of the latter.

Abstract: *The number of applications of bio-inspired architecture has grown significantly in the past decades, but design professionals lack a framework with which to best employ its principles. We introduce a new concept termed "biogeneration," a reflection of bio-inspired architecture, including biomimicry and biophilia, in regenerative built environments. In elucidating the field's interdisciplinary span, we present how biogenerative approaches to architectural design can assist with the identification, ideation, innovation, iteration, and implementation (i^5) design thinking methodology. We expound on the need for and relevance of biogeneration in three major fields of design: development engineering, additive manufacturing (AM), and climate change adaptation and mitigation. By integrating human urban habitats into the living world, biogeneration can help development engineers find solutions that benefit the poor to bring about substantial change; design thinkers and professionals develop additively manufacturable artifacts and structures that create new AM-enabled opportunities, enriched design processes, new business models, and new technologies with AM; and urban planners transform the built environment to counter the human-caused climate crisis. The research examines the mutualistic relationships between people and the environment that ensure the psychological well-being of the former and the ecological health of the latter.*
Keywords: *biogeneration; bio-inspired; regenerative architecture; i^5 design thinking methodology; development engineering; additive manufacturing; climate change*

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I. INTRODUCTION

Architecture has evolved to encompass a variety of principles from a wide range of fields of study, especially those in science, technology, engineering, and mathematics (STEM). One such emanating discipline, sustainable architecture, seeks to hinder or prevent a given artifact, module, or structure from negatively affecting the living world through greater performance and regulation [1,2]. There are three forms of sustainable architecture: 1) restorative architecture, in which humans help heal natural systems; 2) reconciliatory architecture, which combines humans and ecosystems; and 3) regenerative architecture, in which humans and the living system mutually benefit [3,4].

This article focuses on bio-inspired and regenerative architecture and reviews the growing body of research being conducted in each field while analyzing their ramifications on diverse aspects of design. Bio-inspired architecture emphasizes biomimetic and biophilic strategies to design built environments in which a mutualism between their human inhabitants and the living world secures their individual and collective physical and psychological health, especially in the ongoing coronavirus (COVID-19) pandemic. The turbulent COVID-19 situation has highlighted the adverse effects of urban habitats on human health, especially due to poor indoor air quality. In a normal built environment prior to the novel coronavirus pandemic, the heating, ventilation, and air conditioning (HVAC) systems are integrated into the later stages of the design process for controlling and characterizing qualities of indoor air and prioritizing thermal comfort over human health [5]. The current COVID situation has proven that commonly and popularly used design systems and principles are flawed and insufficient for sustainability and human well-being. Hence, there is a strong need to integrate healthy design strategies (e.g., indoor air quality, and sustainable built environment approaches and principles) into the entire design process and to completely revamp the design thinking approach. We strive to overcome these shortcomings related to sustainable design and architecture in the built environment; propose and conceptualize 'biogeneration' or 'biogenerative architecture' as a mix of bio-inspired and regenerative architectures and as a strategy for sustainable and positive impact architecture; and provide insights into design thinking and design principles for biogeneration.

Before discussing 'biogeneration' in the next section, the article examines bio-inspired architecture through two interrelated concepts that aid in the development of human urban habitats in different ways: biomimicry and biophilia. Biomimicry refers to, "the emulation of strategies seen in biology as a basis for design" [4], (p. 295), [6], so it can mimic a given organism, an organism function, or a whole ecosystem. Similarly, biophilia means, "the innate tendency to focus on life and lifelike processes" [7], (p. 1), so it highlights the need for the link between the human psyche and the observable living world. In a nutshell, biomimetic design serves as a foundation for regenerative building by blending in with its natural surroundings; and biophilic design helps create an environment in which humans grow physically and psychologically.

We further investigate regenerative architecture, which highlights the living world in the built environment, allowing urban planners to use the natural systems at their disposal as "building blocks" [8]. It seeks to yield measurable socioecological results instead of merely curtailing the use of energy or water or the emission of pollutants. In this context, regenerative architecture involves, "human-made interventions and systems… that contribute to ecological, social, and cultural health in various holistic and interconnected ways" [3], (p. 2). To that end, it has two primary objectives: a) deploying and improving maintenance and productivity through the reduction of adverse environmental effects of a building and its materials; and b) perceiving the living world as an equal contributor to the design, creation, construction, bidding, and administration of the built environment [8]. While the first purpose takes into account decreased energy consumption, material assignment, and innovative design; the second, more ambitious one, calls for a more overarching and thorough judgment of natural systems in the scheme of structural design [9]. Therefore, regenerative architecture is founded on the premise that everything that humans develop in the built environment can be coupled with the living world [8].

Figure 1 exhibits different kinds of sustainable architecture. Bio-inspired and regenerative architecture are interdependent such that they can be implemented together in three major fields of design concerning human urban habitats: development engineering, additive manufacturing, and climate change adaptation and mitigation. Through a four-part human-centered design thinking model [10], development engineers can synthesize natural elements in their designs to create biomimetic or biophilic structures that ensure not only the socioemotional well-being of the poor, but also, the biological health of the environment. Engaged in the construction of three-dimensional objects, additive manufacturing (AM) can utilize biomimicry to develop products that benefit not only their customers but also the environment, giving way for more environmentally friendly products, business models, advanced design processes, and technologies with AM [11]. Bio-inspired architecture can also help adapt buildings to mitigate the ongoing climate crisis, directly caused by humans' excessive release of greenhouse gases through knowledge assimilation and transfer from biology to ecology, and the observation of the living world [12].

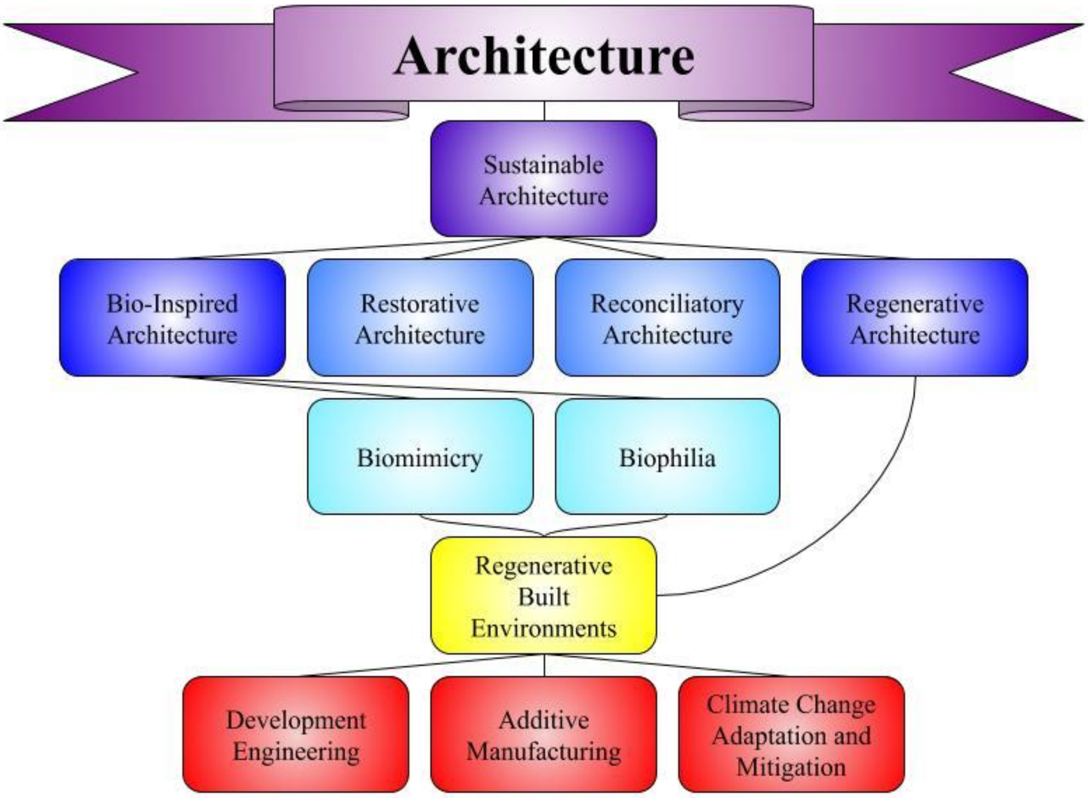

Figure 1. Hierarchical organization of the domains of sustainable architecture concerning development engineering, additive manufacturing, and climate change adaptation and mitigation in regenerative built environments.

The overall goal of this research is to comprehend and implement biogeneration as a mix of bio-inspired and regenerative architectures in the built environment through i5 design thinking methodology. The research addresses the following objectives: (a) define 'biogeneration' by investigating bio-inspired and regenerative architectures and exploring their positive environmental impact interrelationships in the built environment; (b) examine biogeneration and its relationships with development engineering (DE), AM and climate change adaptation and mitigation; and (c) provide real life case examples that investigate biogeneration through the lenses of DE, AM, and climate change adaptation and mitigation. We make the following research contributions. First, we conceptualize and define "biogeneration" in today's turbulent times for the greater good of humanity and environment, and examines interdependencies of biogeneration with development engineering (DE), additive manufacturing (AM), climate change adaptation and mitigation. Second, the study investigates the interrelationships between biogeneration and DE, biogeneration and AM, and biogeneration and climate change adaptation and mitigation. Finally, given the dearth of literature in examining interrelationships among bio-inspired and regenerative architectures with reference to DE, AM, and climate change adaptation and mitigation, we strive to examine these interrelationships and interdependencies through real-life examples.

In the following sections, we begin with a review of bio-inspired and regenerative architectures. Thereafter, we introduce the construct of 'biogeneration', propose a conceptual definition of the construct, and introduce a conceptual framework that offers insights into biogeneration through i5 design thinking methodology. The article concludes with a discussion of biogeneration applications in DM, AM, and climate change through the real life examples, along with a focus on future research and policymaking.

II. THEORETICAL BACKGROUND

Bio-inspired and regenerative architectures share one major commonality in transcending conventional practice and green architecture. Both not only have "positive net environmental benefits" [4], (p. 293), [3] but also promote the coexistence of humans and the living world, setting in motion an "upward spiral of environmental health" [8], (p. 4) that heals both parties. In the following subsections, we delineate the interrelationships between the two fields, deriving mutualisms between design that nurtures the well-being of humans and ecosystems, and depicts how basic elements of bio-inspired architecture lead to regenerative built environments. These interrelationships help design professionals create built environments that glean as much potential from bio-inspired and regenerative designs as possible.

2.1. Bio-inspired Architecture

Biomimicry is derived from the Ancient Greek prefix βίο- (bío-, "life") and root word -μῑ́μησις (-mī́mēsis, "imitation"), so it mimics living nature. It simulates an organism, organism conduct, or a full ecosystem in its materials, forms, functions, construction methods, or process strategies, directing designers towards the living world in their architecture [4]. Biomimetic design requires an understanding of biological functions, principles, and structures in various natural objects known in biology, chemistry, materials science, and physics. Given its application in engineering, it can also be more appropriately termed "biodesign" or "bioinspiration". Integrating several disciplines, biomimicry considers many properties found in both plants and animals [13] and is of interest to researchers and designers alike (refer to Figures 2a and 2b).

Figure 2a. A wondrous group of Venus' flower baskets [51] (left); and Gherkin Tower [52] (right). One of the first environmentally progressive buildings in London, UK, Gherkin takes inspiration from sea sponges and anemones. These creatures feed by directing sea water to flow through their bodies. Gherkin is supported by an exoskeleton structure, and is designed so ventilation flows through the entire building.

Figure 2b. Germany's extraordinary "algae house" or BIQ building in Wilhelmsburg, Hamburg incorporates microalgae into its design [53]. One side of the green-hued tower's transparent surface contains growing algae that controls light entering the building and provides shade when needed.

Biophilia, too, originates from the Ancient Greek βίο- and -φιλία (-philía, "love"), and it symbolizes the love of nature. It engages evidence and theories from neuroscience, psychology, and the biophilia hypothesis to facilitate the connection between the human psyche and natural systems. The biophilia hypothesis is the idea that humans' "urge to affiliate with other forms of life is to some degree innate" [7], (p. 85), given circumstantial and qualitative evidence that humankind is genetically attracted to the environment [14]. Since the human mind evolved with the living world, survival behaviors and reactions linked to specific landscapes, natural forms, or organisms are hereditary and, in turn, influence humans' sense of belonging and well-being in the natural world. Consequently, the living world is the biological realm of the most intricate aspect of the human spirit, exponentially increasing humans' curiosity about faraway lands and exotic flora and fauna that draws them ever closer to nature [7]. Overall, biophilic design not only invites elements of the living world (for example, plants) into building interiors and urban landscapes, but also mimics the configuration or groundwork of organic form to promote psychological well-being [4].

2.2. Regenerative Architecture

The other dominant sphere of sustainable architecture is regenerative architecture, which is emerging as a mediator between humans and the living world but whose adaptation to the built environment has been lagging. Without concrete regenerative design concepts, symbioses in bio-inspired architecture, which aspires to make the built environment ecologically and psychologically healthier, could prove critical to regenerative architecture [4]. By embodying the natural world and building its foundation on millions of years of natural engineering and evolution, it guarantees the operation of human urban habitats that brings about positive biological outcomes. Figures 3a and 3b show real life examples of regenerative architecture. One way to devise this is to provide, regulate, and support ecosystem services, granting built environment professionals the freedom to experiment with biomimicry while enabling them to produce structures that best take advantage of blue and green spaces. Because the biosphere is the epitome of ecological organization, it is most logical to learn about and emulate organisms and their ecosystems under the development of regenerative human urban habitats [3]. Architecture can only be regenerative if and when it assimilates the building to the energy, plants and animals, place, site, systems, etc., enhancing its environment and production [8].

Figure 3a. Portola High School in Irvine, California [54], has regenerative design, whereby the green roof is connected to the HVAC system so that on hot days when the air conditioning kicks in, the water generated from it is used to irrigate the green roof. Once the roof is saturated, it passively cools the building, and reduces reliance on the air conditioning system.

Figure 3b. The VanDusen Botanical Garden Visitor Centre [55] in Vancouver, Canada, utilizes regenerative architecture by generating its own electricity through geothermal boreholes and solar photovoltaics and hot water tubes. Over 50 such boreholes store heat underground during the summer for winter application.

2.3. Conceptualizing 'Biogeneration' in the Built Environment

Guided by bio-inspired and regenerative architectures, and their mutualisms that manifest themselves psychologically in built environments; ecologically in the living world through building components, buildings, or cities; and to generate a consistent definition for the construct of Biogeneration, we propose the following definition as below:

Biogeneration or Biogenerative architecture*, refers to philosophies, attributes and activities related to ideation, innovation, iteration and implementation of biomimetic, biophilic and regenerative architectures in built environments. It confronts the dynamic intersections between bio-inspired and regenerative architectures that enable architects, designers, engineers, design thinkers, government officials, planners, and urban habitat professionals to define, design, and develop bio-inspired (biomimetic and biophilic) structures in regenerative built environments.*

Biogeneration and the i^5 Design Thinking Methodology Design thinking is an umbrella term encompassing the logics, tools and practices of design [15], and "uses the designer's sensibility and methods to match people's needs with what is technologically feasible and what a viable business strategy can convert into customer value and market opportunity" [16], (p. 86). The turbulence of the ongoing COVID-19 pandemic has triggered the strategic retooling of the built environment whereby design thinking will be helpful for local and global suppliers to create organizational resilience, manage contingencies and risks, and redesign existing human urban habitats to strike a balance between society and nature. Due to the current unprecedented circumstances, biogeneration requires a framework that introduces a new design thinking paradigm in which sustainability will inherently be embraced into the design process at all levels of design thinking [17]. Thus, we integrate this newly designated form of architecture (a.k.a., biogeneration or biogenerative architecture) with the identification, ideation, innovation, iteration, and implementation (i^5) design thinking methodology.

First, the design professional must identify with the problem she or he is aiming to solve, understand the inhabitants' needs, observe the design surroundings, and gain perspective on present design solutions. Second, the design professional must ideate certain design models that appropriately settle the problem, brainstorm ways to decrease or remove design limitations, prototype possible versions that analyze specific ideas, and test those versions / solutions to make additions or eliminate alternative solutions. Third, she or he must innovate select models that solve the problem, utilize new processes, products, services, and/or technologies, improvise previous models with an expanded design toolkit, and revolutionize past ideas to tinker with better features. Fourth, the design professional must iterate the process to come up with models that incrementally develop themselves until she or he reaches the final stage. Lastly, the design professional must implement the final version in the built environment, inform the inhabitants of the new design, pilot it, and launch its operation. This i^5 design thinking approach adapts to the design professional's logical reasoning and pace, where the stages do not adhere to a particular order and can occur simultaneously, similar to a systems thinking initiative [15, 17]. Figure 4 exhibits the five building blocks, or dimensions, of biogeneration with the i^5 design thinking methodology. The five building blocks of biogeneration (as shown in Figure 4) address: (a) interdependence between the built environment and the living world, (b) biological equity and ethical design in the built environment, (c) coexistence and coevolution of the built environment and the living world, (d) ecological accountability in the built environment, and (e) sustainable rehabilitation of human industry in the built environment.

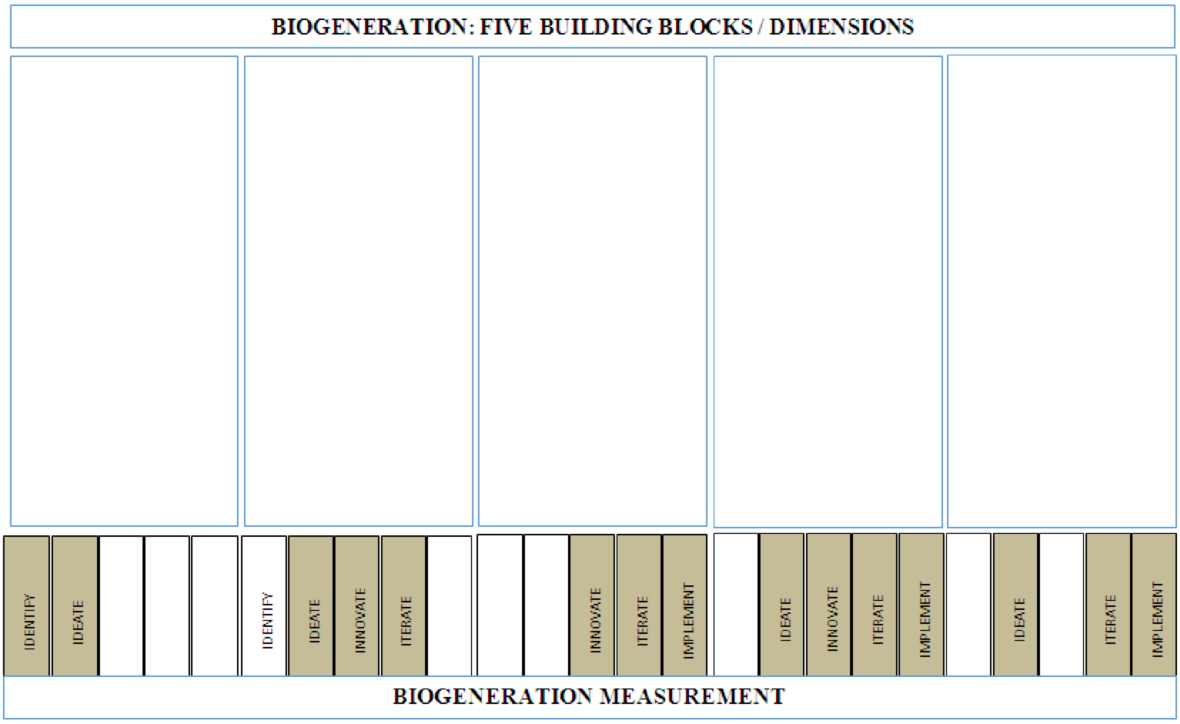

Figure 4. The five building blocks, or dimensions, of biogeneration, integrated with the i^5 design thinking methodology.

The first dimension - Interdependence between the Built Environment and the Living World - contends with the interrelationships between humans and nature that reinforce the psychological well-being of the former and the ecological health of the latter. These connections help design professionals identify and ideate sustainable architectural solutions and develop design principles through different outlooks and in various ways: environmental impact identification, a solution-based view, architectural form and structures, similarity in design, internal communications, knowledge sharing, and informal networks. The second building block - Biological Equity and Ethical Design in the Built Environment - involves balancing equity and ethics in the built environment' designs within and across human urban habitats, both of which keep urban planners' architecture in check. This regulation helps design professionals ideate, innovate, and iterate solutions that fulfill both distinctive genres of design and intelligence shift, bioregionalism, ecological design, information assimilation, dissemination, and trading, and knowledge transfer.

The third dimension - Coexistence and Coevolution of the Built Environment and the Living World - relates to the built environment coexisting and coevolving with the living world, allowing both ecosystems to mutually benefit each other in more progressive ways. This reciprocity helps design professionals innovate, iterate, and implement solutions, leading to such unexplored benefits and relations as mutualisms, interdependencies and interrelationships, environmental capabilities and consciousness, economies of scale, and knowledge transformation and transfer. The fourth building block - Ecological Accountability in the Built Environment - refers to ecological responsibility and accountability within and across built environments, which affirms the sustainability of urban planners' architecture while tracing its environmental impact. This record and verification helps design professionals ideate, innovate, iterate, and implement solutions that consider multiple perspectives and communicative approaches, including a solution-based view, environmental responsibility, collective content creation and knowledge sharing, and information trading and knowledge exchange and transfer.

The final dimension - Sustainable Rehabilitation of Human Industry in the Built Environment - deals with the sustainable rebuilding of human industry in the built environment, in which resources are formed into products that eventually go to waste when they could have otherwise gone through a more biological cycle. This natural undertaking helps design professionals ideate, iterate, and implement solutions that can be viable in

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architecture, especially in cradle-to-cradle design patterns; ecological design and responsibility; overall environmental impact; and an ethical compromise between materials by humans and in nature.

2.4. Biogeneration and the Guiding Principles in the Built Environment

As the chief subdivisions of sustainable architecture, biogeneration is particularly important during turbulent times (e.g., the current COVID-19 pandemic situation) interdependent on bio-inspired and regenerative architectures through an array of approaches and principles [17]. The first step towards biogenerative design is not to build the structure in mind, but rather for the urban planner to deeply familiarize herself or himself with the current energies, forces, and patterns on its site. To aid this assessment and investigation, the designer/planner can use a set of guiding criteria and questions to best analyze, document, and understand the place as palpable data for the architecture. The questions to inquire about respective flows and their connection overstep those of composition or form to those of qualities the building displays due to its fundamental nature [18].

The biogenerative architecture observations relate to biomimicry and biophilia in that they help the design professional recognize the diverse ways in which the building interacts with its surroundings. Through this guide, she or he could then implement natural components and systems into the structure to best amalgamate it and its residents with the environment. The Hannover Principles, used by designers, planners, and built environment professionals involved in establishing priorities for the built environment strengthen the proposed biogenerative framework. American architect McDonough and German chemist Braungart [19] created them for World Expo 2000 in Hannover, Germany, to advise international design contests and, overall, conceive a design philosophy to navigate the future of planned construction and systems for the city, its state, its country, and its foreign neighbors and Expo partners. While current means, procedures, and technologies are prone to segregate the ecological, material, and spiritual elements of society, the Principles facilitate in the adaptation and development of humans' understanding of their relationship with nature:

1. Insist on rights of humanity and nature to co-exist as cooperative, strong, sustainable, and versatile partners.
2. Recognize interdependence. Elements of human design communicate with and draw on the environment, with broader and more various ramifications across any aspect. Extend design judgment to acknowledge even remote impacts.
3. Respect relationships between spirit and matter. In the context of existing and evolving connections between material and spiritual conscience, take all elements of human civilization into account, such as community, housing, industry, and trade.
4. Accept responsibility for the consequences of design considerations on human well-being and the sustainability of natural systems and their freedom to coexist.
5. Create safe objects of long-term value. Do not overwhelm future generations with repair needs or wary management of implicit risks due to the reckless production of goods, practices, or processes.
6. Eliminate the concept of waste. Assess and maximize the entire life cycle of goods and procedures to address the status of natural systems, in which no waste exists.
7. Rely on natural energy flows. Like the living world, human creations should reap their innovative capabilities from constant solar revenue. Cautiously and efficiently consolidate this energy for sustainable use.
8. Understand the limitations of design. There is no enduring human structure, and design does not solve every problem. Those who build and prepare should be respectful towards the environment. Treat nature as an instructor of and an asset for design, not as a liability that must be avoided or restrained.
9. Seek constant improvement by the sharing of knowledge. Prompt explicit and overt discussion among consumers, colleagues, employers, and operators to connect long-term environmental aspects to moral responsibility and to reinforce the essential relationship between human activity and natural processes.

These Principles, to be collectively considered a living document that may metamorphose with our evolving knowledge of nature, apply to biogenerative architecture through its five building blocks or dimensions and i5 design thinking methodology. They are connected to biomimicry and biophilia wherein they reveal humans' inherent reliance on the natural world, and to regenerative design in that they expose the effects of human design on the feasibility of ecosystems [8]. Additionally, McDonough and Braungart [20] introduced cradle-to-cradle design, a framework for the manufacture of products and the formation of systems that rebuilds human industry on the foundation of living procedures. Elements of natural matter circulate through biogeochemical cycles, through which nutrients continuously flow from abiotic (nonliving) to biotic (living) segments of the biosphere through healthy, safe metabolisms that yield no waste [21]. Although this biological system has served life ever since it first emerged 3.8 billion years ago [13], the Industrial Revolution soon gave rise to cradle-to-grave design patterns that overrode the planet's living equilibrium of materials. McDonough and Braungart [20] remark that humans extort resources from the Earth's crust; condense, fuse, and modify them into products; and ultimately dispose of the wastes. Some such products come with "planned obsolescence," This linear, one-way process has developed an industrial infrastructure that not only pours millions of dollars' worth of material goods down the drain but also ignores the biodegradable value of many articles that could have otherwise nourished the soil.

Two other sets of design criteria critical to and prominent in biogenerative architecture include the Five Principles of Ecological Design, designed by architects Van Der Ryn and Cowan [22], and the Todds' Principles of Ecological Design, developed by writer and environmental activist Todd and biologist Todd [23]. The Five Principles relate to ecological design and biogeneration that reduces environmentally damaging effects through integration with living procedures. They underscore the significance of knowing place and creating architecture that conforms to the environment. Van Der Ryn and Cowan [22] find that the more easily applicable natural processes and systems are in the built environment, the less will human activity harm the health of the living world:

1. Solutions grow from place. Ecological design starts with a deep understanding of a given place. Therefore, it is scaled down and simple, sensitive to both local people and circumstances. Humans can live without ruining the nuances of place if they are thoughtful of them.
2. Ecological accounting informs design. Track the environmental impacts of existing or future designs. Utilize this information to ascertain the most ecologically conscious design option.
3. Design with nature. In collaborating with life processes, humans recognize the demands of all species while fulfilling their own. They are rejuvenated when they invest in systems that regenerate as opposed to deplete.
4. Everyone is a designer. Heed to all advice in the design procedure. No one is either a designer or a participant; everyone is a designer-participant. Commend every person's unique knowledge. People heal themselves in working to heal the places they inhabit.
5. Make nature visible. Degrading environments dismiss humans' learning needs and potential. Making natural cycles and procedures perceptible enkindles the built environment. Efficient architecture allows us to learn more about the living world.

The Todds' Principles openly and unequivocally illuminate nature throughout the design process, deeming it the engine and tutor of architecture. Todd and Todd [23] embrace design, food production, and waste management in the Principles, which can be considered as the most imperative measures to undertake in biogenerative architecture, whereby the focus is on the natural world as the groundwork for all architecture, design should obey the laws of life rather than defy them, biological equity must influence architecture, design should emulate bioregionalism, renewable energy sources should be the basis of any project, architecture should be sustainable through the incorporation of natural systems, design should coevolve with the living world, the built environment should revive the planet, and all (sustainable) architecture should pursue a hallowed ecology.

Both the Five Principles and the Todds' Principles of Ecological Design can be implemented within biogenerative architecture. The Five Principles are related to biogeneration wherein they help identify and merge the singularities of place with urban human habitats, such as the animals, climate, soils, topography, vegetation, water flows, and people who afford its consistency ([22]. The Todds' Principles are also connected to biogeneration through biomimicry and biophilia in that they encourage the use of living procedures and systems in the built environment while treating the well-being of humans equally as important as the health of the natural world. Both these guiding principles regard biogeneration as an architectural design that acts in response to bioregionalism and the consequent positive environmental impact on the built environment [8, 15, 17]. Both biogeneration and bioregionalism fit into design and systems thinking perspective and has wide applications.

Biogeneration can be applied across numerous branches of knowledge in which architecture and science actively take shape, especially in economics, environmentalism, public health, neurology, policy, product design, psychology, and regional planning. This research centers on three fields of design in which this form of architecture can utilize concepts and processes from bio-inspired and regenerative design together: development engineering, additive manufacturing (AM), and climate change adaptation and mitigation. Each discipline entails the programming, schematic design, design development, construction documentation, bidding or procurement, and construction administration of the built environment with individual products, procedures, services, and technologies. In the next section, we explore the applications of biogeneration in development engineering (DE), additive manufacturing (AM), and climate change adaptation and mitigation.

III. BIOGENERATION: APPLICATIONS OF DEVELOPMENT ENGINEERING IN THE BUILT ENVIRONMENT

Development engineering is a new versatile field for finding solutions that aid the poor in developing areas that bring about significant change [10]. It is interrelated with biogeneration in that development engineers can create structures that mutually benefit the psychological well-being of the poverty-stricken and the ecological health of their surroundings. They can execute this by fusing the i5 design thinking methodology with the University of California, Berkeley's design thinking model redrafted for DE. Levine et al. [10] define this iterative process these engineers follow:

- making observations of the poor and taking note of the contexts, whether physical or economic, in which they live;
- forming insights from these evaluations to frame the problem(s) they face;
- developing ideas to alleviate their plight by employing creative toolkits and design fundamentals; and
- deriving solutions from their prototyping and testing that best benefit their target audience.

This procedure not only considers the needs of the poverty-stricken but also oversees the use of certain technologies that advance the engineers' goals of public health development [10]. As represented in Figure 4, development engineers 1) start the design project in the observations quadrant; 2) conduct immersive user needs assessments to frame the design problem in the framework quadrant; 3) straighten priorities and take advantage of design principles in the imperatives quadrant; and 4) improve design concepts and create design prototypes in the solutions quadrant. Levine et al. theorize that, by continuously performing this process to test their concepts and prototypes with customers, stakeholders, and users for quick alteration and refinement, these engineers can assimilate design constraints, goals, and opportunities; adjust for impact; and apply original experiments, large datasets, and sensors.

By appraising both socioeconomic and environmental backgrounds, exemplifying popular choice, and involving direct collaboration with operational institutions, development engineers can administer biogeneration to considerably benefit human health and well-being with the aid of sanitation systems and through the secure regulation of water supply [24 – 26]. Muller [24] remarks that such public health interventions can help developing countries lengthen their life expectancy and lower their infant mortality far more than medicine. We present select historic case studies of DE in southern Africa, where there remained a dire need for more appropriate and newer strategies to water-borne hygiene even before decolonization. This owed to the swift development of larger but poorer human urban habitats across the region that demanded a more systematized approach to sanitation than common practice [24]. In fact, solutions to these challenges acted toward the Sustainable Development Goals (SDGs) under the 2030 Agenda for Sustainable Development, an international framework dedicated to the prosperity of people and the planet, which all United Nations Member States ratified in 2015. Goal 6: Clean Water and Sanitation, which is to establish the accessibility and sustainable supervision of sanitation and water for everyone, is of great importance to these case studies and has grown ever more prevalent during the ongoing COVID-19 pandemic. Hand hygiene is among the most productive measures one can take to reduce the spread of pathogens and avoid disease, including severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), but development engineers must resist the lack of safe water sanitation and insufficient funds.

Muller [24] puts forward several key examples of DE in colonial Africa, which gave the impetus for the transformation of housing policies and urban planning throughout the continent. He observes that mineworkers in Northern Rhodesia, or present-day Zambia, originally inhabited single quarters, or "compounds," where sanitation facilities were virtually nonexistent. In 1948, the Colonial Office enacted the Urban African Housing Ordinance due to burgeoning political pressure for improved standards, so landlords had to accommodate their tenants and their families as single-family housing was built in place of the compounds [24]. Still, since the British government never viewed them as permanent residents, Rhodesians lived in transient structures with no more than one to two bedrooms, a small kitchen, and a pit toilet — which today persists as the principal form of sanitation in urban slums across developing built environments — that lacked many essential amenities [27, 28]. As the volume of wastewater from the toilets increased over time, the need for a low-cost alternative treatment technology grew proportionally [24]. Given Northern Rhodesia's suitable climatic conditions, South African technician and eventual academic Gerrit Marais instituted waste stabilization ponds in the region, which he went on to build for Brasília, Brazil [29]. These are broad, shallow reservoirs encompassed by terrain that process raw wastewater through natural processes in which algae and bacteria act as agents [30].

From the discussion pertaining to biogeneration and its applications in DE, it is evident that two building blocks of biogeneration (refer to Figure 4) integrated in DE are the coexistence and coevolution of the built environment and the living world; and ecological accountability in the built environment. By ensuring the well-being of the economically disadvantaged in developing countries with methods that best account for ecological attention, DE can help support the poor in biogenerative structures that benefit them and their natural surroundings. It can further protect the living world by taking advantage of biological resources to avert pollution and gradually improve slums' environmental performance, giving rise to symbiosis between human urban habitats and the living world. Therefore, development engineers can ideate, innovate, iterate, and implement design solutions that mutually benefit the poor and nature. In fact, they can adopt the Five Principles of Ecological Design to design sustainable systems that interweave architecture, city and regional planning, industrial design, and infrastructure development and serve the impoverished and their bioregions [22]. Development engineers can also employ the Todds' Principles of Ecological Design to introduce biological design into their engineering interventions [23]. Design professionals, development engineers, future researchers, and policymakers should take these dimensions of biogeneration, integrated with the i5 design thinking methodology and the sets of principles concerning DE, into consideration to aid in the creation of more dynamic and healthy human urban habitats. Biogenerative considerations in development engineering are necessary to ensure that the past mistakes made during the industrialization of the West, which have consequences on both human and environmental health, are not repeated or exacerbated.

IV. BIOGENERATION: APPLICATIONS OF ADDITIVE MANUFACTURING IN THE BUILT ENVIRONMENT

Additive manufacturing (AM) — three-dimensional (3D) printing — has surfaced as a unifying field for the production of intricate casts — the stereolithography (STL) file — from the digital portrayal of their layered parts — the computer-aided design (CAD) file [11, 31]. Perez et al. [11] find that it can create artifacts from a range of materials with vitally complex element geometries that provide major practical advantages and through the combination of components and functions into a single part. In addressing the need for and relevance of AM in design innovation (DI), they compare and contrast design with additive manufacturing (DwAM) and design for additive manufacturing (DfAM). Although Perez et al. acknowledge the difference between the two is "minor and pedantic" (p. 4), DfAM deals with the fundamentals of product design using AM, while DwAM surrounds greater design possibilities that are closely related to the design process. The latter serves as a better guide for designers and engineers wherein it not only allows more convergent thought but also helps them tweak their products such that it increases their chances of successful manufacture through AM. Through industrial examples, Perez et al. show how DwAM, as opposed to DfAM:

- can be leveraged to create new products, from the formation of their individual components to their fabrication in full;
- develops entirely innovative business models from its limited need for manufacturing parts nearer to the point of consumption, digital part representation, and fixturing;
- improves and accelerates product design processes; and
- fulfils the specific needs of production.

AM is connected to biogeneration in that computer-aided design (CAD) engineers can create additively manufacturable artifacts and structures with synthetic printer filaments that benefit the living world while keeping their users' interests in mind. They can achieve this by utilizing the i5 design thinking methodology (refer to Figure 4) in conjunction with the discovery, definition, development, and delivery (d4) DI process to grasp more environmentally friendly DI with AM processes. Perez et al. [11] categorize exclusive DI and AM methods into d4, to each of which they associate at least one mindset and high-level objective:

- discovery, from which CAD engineers can employ AM opportunities, a business model canvas, and functional models through empathy by
- understanding the market and their users, and
- validating assumptions about their users and functionality;
- definition, from which they can exploit Vaneker's [32] suitability and "how might we" questions through vision, sensing, and mindfulness by
- prioritizing needs and functions, and
- scoping opportunity;
- development, from which CAD engineers can employ seeded mind mapping, design by analogy, Kumke et al. [33 -34] examined AM levers, prototyping strategies, optimization, C-sketch, a knowledge database, and AM part consolidation through cognition and joy by
- ideating potential solutions,
- downselecting the best ones,
- validating them, and
- refining them; and
- delivery, from which they can take advantage of DfAM rules and guidelines through activity and non-attachment with production-ready solutions.

By integrating high-caliber structures that have evolved over millions of years into engineering materials systems, AM can exercise biogeneration to create theoretical compositions that consider biological functions and their relationship with natural and technological limitations [35]. This can give rise to new environmentally friendly business models, design processes, products, and technologies [11]. Yang et al. [35] distinguish three types of 3D-printed bio-inspired structures, each of which utilizes specific categories of AM technology to derive inspiration from the living world: single-material, multi-material, and composite. We present a collection of case studies of AM defined by electrics, interface, mechanics, optics, and shapeshifting that interact with the natural world in a multitude of ways.

Yang et al. [35] offer a variety of central examples of AM, providing insight into the production of additively manufacturable products with biological components across different scales. They begin at the nanoscale, where robust gyroid nanostructures imitate butterfly wings built with the two-beam superresolution lithography. According to Gan, Turner, and Gu [36], the module's controllability, size, and uniformity are better than those of its living equivalents, since Young's modulus of its nanowires was increased by 20 percent. They find this assembly yields an excellent means of gleaning CAD models from the natural world. Next, at the microscale, lattice structures from a recent aerosol jet 3D printer have a strength-to-weight ratio comparable to those of such biological materials as bone and wood. Saleh, Hu, and Panat [37] created the design materials by crushing them and mixing them with a solvent, ethylene glycol, to make an ink, with which a printer precisely built the desired 3D modules. They not only tested the final product's strength but also kept it permeable to maximize surface area, experimenting with shapes like annular pillars, microscaffolds with trusses, spirals, and zigzagged electronic connections. Finally, at the macroscale, Song et al. [38] researched about 3D-printed fish scale armor on account of its flexibility and high-impact resistance, while Martini, Balit, and Barthelat [39] explored the complex configurations and topologies of arrays with contrasting degrees of overlap. Using the ZPrinter® 310 Plus from Z Corporation, the former developed macroscopic prototypes of the three-spined stickleback (Gasterosteus aculeatus), which has peg-and-socket joints for mobility and thick bony plates for protection. The latter discovered that arrays that best combine flexural compliance and puncture resistance have similar arrangements and geometries to those of teleosts, revealing how the living world has augmented this class' flexible protection.

From the analysis of biogeneration and its applications in AM, we can conclude that two building blocks of biogeneration integrated with AM are biological equity and ethical design in the built environment; and the sustainable rehabilitation of human industry in the built environment. By fabricating additively manufacturable artifacts with their environmental impacts throughout their lifecycle in mind, AM can utilize biodegradable materials like polylactic acid (PLA) plastic, which in many cases is superior to traditional plastics that greatly contribute to ocean waste and pollution and pose a threat to ocean life. CAD engineers and future researchers should confirm that AM is derived from renewable sources; otherwise, this defeats the biogenerative purpose of AM. Further, besides taking advantage of bio-inspired models, AM can replace conventional methods of production that rely on the creation of numerous of the same parts in light of the better possibilities of customization. Although any example of mass-production can reduce a given product's environmental impacts using AM (e.g., personalized cars), it is important to avoid consumerism and overproduction by producing goods on-demand (e.g., on-demand book printing). Thus, CAD engineers, future researchers, and policymakers may ideate, innovate, iterate, and implement design solutions that jointly benefit their users and the natural world. Indeed, they can apply Murphy & Marvick's [18] guiding criteria and questions to coalesce all parts of the module into a whole and assess its mutualisms with the environment through an established network of nodes and links. CAD engineers can also implement cradle-to-cradle design to establish a biological and technical process of manufacture in AM involving detritivores, nutrients, and plants to use materials to create products for animal consumption [20]. Design professionals and policymakers should take these dimensions of biogeneration, combined with the i5 design thinking methodology and two sets of principles concerning AM, into account to help develop stronger human urban habitats.

V. BIOGENERATION: APPLICATIONS OF CLIMATE CHANGE ADAPTATION AND MITIGATION IN THE BUILT ENVIRONMENT

Climate change adaptation and mitigation is an emerging tool in the built environment that targets the ongoing climate crisis, directly caused by humans' excess greenhouse gas (GHG) emissions [12]. In outlining the need for and relevance of biomimetic architecture through statistics, she reasons that buildings should overall support the environment rather than have "neutral" or "zero" impact on it. Zari [12] illustrates how a translation of knowledge from biology to ecology and observation of the living world could produce "a resilient and adaptable built environment" that mimics an organism or a system while ensuring the health of its people and surroundings. She continues by reviewing the growing body of research being conducted in the field of design but showing architects' and designers' initial inability to properly apply it. From there, Zari [12] presents the climatic effects the built environment has brought upon itself and describes two accepted responses to climate change:

- alleviating its causes by reducing GHG emissions; and
- adapting current buildings to the predicted impacts of climate change, given all past emissions Earth's atmosphere, oceans, and other carbon sinks have slowly absorbed.

Although these implications are "numerous and… difficult to quantify" (p. 173), Zari [12] lists a few potential direct climate change effects and their consequences for the built environment:

- changes in temperatures, which could increase overheating and air conditioning load;
- increased intense weather events, which could damage buildings and the infrastructure;
- changes in precipitation patterns, which could harm foundations, underground cables and pipes, etc. while increasing surface runoff and leaching pollutants into aquifers and waterways;
- thermal expansion of oceans and changes in the cryosphere, which could increase coastal flooding;
- changes in wind patterns and intensities, which could affect wind loading on buildings; and
- increased air pollution, which could raise needed ventilation.

An array of recent technologies can also aid in mitigating GHG emissions through three methods:

- simulating the energy effectiveness or efficiency of living organisms and systems, resulting in less fossil fuel burning;
- determining new ways to produce energy that decreases human dependence on fossil fuels; and
- studying ecosystems or organisms to find examples or processes that can sequester or store carbon.

While the former two are the most widespread approaches, the final one prevents emitted GHGs from entering the atmosphere, arguably making it the most innovative.

Climate change adaptation and mitigation are related to biogeneration in that urban planners can resort to discrete design techniques and technologies to alleviate the causes of global warming, founding the basis for flexible and volatile built environments [12]. They can realize this by uniting the i5 design thinking methodology with the assimilation of biological concepts into ecological solutions, encouraging collaboration between two fields that sporadically cofunction. Design professionals can draw on biomimetic and biophilic knowledge to best exploit ecosystem process strategies, with which they can contrive the inner workings and modus operandi of human urban habitats [40]. While the emerging economic situation in built environments throughout the world presents a challenge to this strategy [41], stimulating greater independence as well as knowledge transfer and resource pooling can change the attitudinal, financial, and legal status quo. Zari [12] suggests that authorities and landowners could share their understanding of how to create or evolve systems needed in cultural, climatic, and economic aspects of society, regardless of their bioregion's development of said systems. These systems will vary significantly with place, but cooperation and coordination between the right officials can provoke sweeping sustainable progress. Zari [12, 42] concludes that only once ecology is paired with systems design can design teams decisively and fully utilize biogeneration to adapt cities to and mitigate the current climate crisis.

By curbing anthropogenic GHG emissions, making human urban habitats more climatically resilient, and diagnosing the plight the built environment faces today, climate change adaptation and mitigation can implement biogeneration to find bio-inspired solutions that improve humans' ability to heal ecosystems rather than harm them [12, 43]. This can advance a favorable response to climate change through design that emulates nature at different scales and best takes advantage of synergies between adaptation and mitigation process strategies in global warming [42]. We present an assortment of case studies from human urban habitats in which building components and buildings can adapt to and mitigate global warming.

Zari [12, 42] defines a range of examples of climate change adaptation and mitigation in the built environment, illuminating how design professionals and lawmakers are quickly strengthening human urban habitats through actions and policies that decrease GHG emission [44]. She examines Mick Pearce's Eastgate Centre in Harare, Zimbabwe, possibly the most cited model of bio-inspired architecture [45, 46]. Imitating the construction of southern Africa's termite (Macrotermes michaelseni) mounds, it boasts a moderately stable thermal interior with minimum mechanical cooling. Although the science behind it is debated [47], Pearce developed his design with induced flow concepts and by leveraging kinetic resources for temperature control. As a result, this decreased energy consumption by 17 to 52 percent as compared to other buildings in the African country's capital [48]. Since careful orientation, passive ventilation techniques, and spatial organization help control temperatures in their mounds, Eastgate does not mimic the termites but rather their building behaviors [42]. Zari [42] notes that biomimicry at the behavior level is not as common as that at the organism level.

From the discussion pertaining to biogeneration and its applications in climate change adaptation and mitigation, it is evident that three building blocks of biogeneration (refer to Figure 4) integrated in climate change adaptation and mitigation are the interdependence between the built environment and the living world; the coexistence and coevolution of the built environment and the living world; and ecological accountability in the built environment. Rapid industrialization across the globe has led to increased use of hydrocarbons and rising levels of GHG emissions. Comprehensive ecological accountability of harmful impacts is imperative if the ultimate goal of the built environment is to have a positive impact rather than a negative one [49]. Actions taken to limit emissions, and to cope with negative impacts of the built environment must be friendly to the living world. In order to achieve this, design engineers must innovate, iterate and finally implement their ideas keeping in mind an environmentally sound transition to a society having a positive impact on nature. Increased climate disruption will have a profound impact across the world and will affect both economically advanced as well as less developed regions. Less economically developed regions will be more susceptible to harmful effects of climate change as compared to economically stronger regions [50]. Coupled with the COVID-19 pandemic, climate change will likely have a profound economic impact on developing countries. Design professionals, future researchers, and policymakers should examine these dimensions of biogeneration, along with the i^5 design thinking methodology, to design adaptable human urban habitats concerning climate change adaptation and mitigation.

VI. CONCLUSION

This article conceptualizes and focuses on biogeneration, a mix of bio-inspired and regenerative architectures in the built environment. The main goal of biogeneration is to actively support the environment rather than have 'neutral' or 'zero' impact on it. Through this research, we comprehend and implement biogeneration through i5 design thinking methodology. Our research centers on biogeneration and its applications on three fields of design: development engineering (DE), additive manufacturing (AM), and climate change adaptation and mitigation. Further, we examine these interrelationships between biogeneration and development engineering (DE), biogeneration and additive manufacturing (AM), and biogeneration and climate change adaptation and mitigation through five building blocks of biogeneration and i5 methodology. Finally, we provide case examples and avenues for future research for design professionals and policymakers with regard to biogeneration and its applications in DE, AM, and climate change adaptation and mitigation.

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