Natural Genius: Approaches and Challenges to Applying Biomimetic Design Principles in Architecture

A thesis submitted in partial fulfillment of the requirements for graduation with Departmental Honors in the Program in Environmental Design
by

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Abstract

This study explores how architects apply biomimetic design processes in their practice. To investigate this phenomenon, eight prominent design professionals from the United States, Canada, and Germany were interviewed to ascertain the opportunities they encounter and the challenges they face when applying biomimetic approaches. Interview data were analyzed according to a hermeneutic coding process to identify emergent themes, such as constraints, common research practices, and gaps in knowledge, as well as the interrelationships between those themes. All synthesized themes were presented as a series of observations, insights, and guidelines to help inform the biomimetic design process for architecture. A set of results were compiled from the collected data in the form of five main themes: the biomimetic design process, systems thinking, resources, opportunities and existing gaps, and constraints. These observations, insights, and guidelines are intended to present biomimetic design to architectural designers as a list of recommendations to allow for biomimicry to become a more widespread design approach.

Study IRB Approval

Approval to conduct the research reported in this thesis was given by The University of Colorado Boulder's Institutional Review Board (IRB) on 11th November 2019. (Protocol Number 19-0569).

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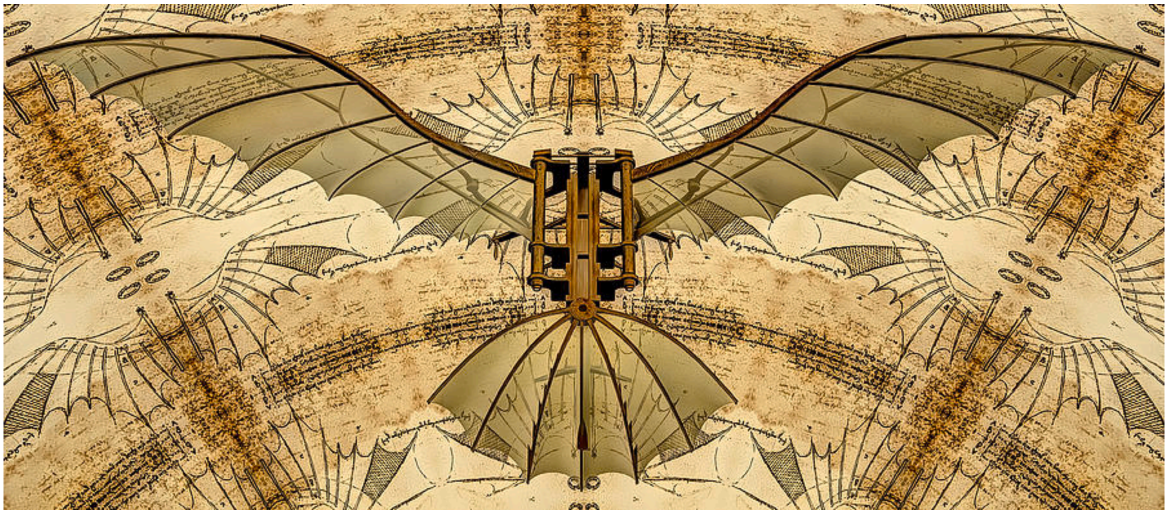
Introduction

Biological processes have shaped the lives of organisms over the last 3.8 billion years. Over the course of history, humans have emulated many biological processes and forms in order to improve their lives. This process of emulating the natural systems that have endured and survived over this period, now known as *biomimicry*, has served to guide design innovation and solutions throughout history.

The term biomimicry comes from the Greek, with *bios* meaning life and *mimesis* meaning imitation (Reed, 2003). Some of the earliest examples of biomimicry date back thousands of years and have served as the foundation of some of our most fundamental inventions. Biomimetic forms inspired architectural elements in ancient Greece and Rome, as many structural details were based on biological systems. For example, the Ancient Greeks applied one major innovation in classical architecture, the structural column, in many of their buildings, a practice that was inspired by the vertical structure of trees and their proportions (Rain & Sassone, 2014). Biological processes also influenced Leonardo da Vinci's design of "flying machines" in 1505, as the artist and inventor based these on the flight processes and anatomy of birds that he observed in nature (Jakab, 2013). While Da Vinci's designs were never realized, they would later influence the work of the Wright Brothers, as they too looked to the anatomy of birds to develop the first airplanes.



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Biological processes would go on to inspire the work of some of the most prominent designers of the last century, such as Catalan architect Antoni Gaudí i Cornet. Gaudi often drew his inspiration from nature, and many of his most well-known buildings, such as La Sagrada Familia cathedral in Barcelona, feature flowing lines that freed themselves from the more geometric design styles of the period. Gaudi was not only inspired by biological forms, but also by the processes and forces defined by nature (Strautman, 2017). If Gaudi were working today, many would consider him as employing biomimetic processes on both a functional and aesthetic level (Strautman, 2017).

Figure 2: Antoni Gaudi's La Sagrada Familia, Barcelona, Spain (Source: Andriotis, M. https://www.architecturaldigest.com/story/incomplete-la-sagrada-familia-barcelona-construction-permits)

In the latter half of the 20th century, biomimicry continued to influence design innovation. For example, in 1955 the Swiss electrical engineer George de Mestral developed Velcro after he observed how the seeds of burdock plants (*Arctium lappa*) adhered to his clothes after a walk in the woods. Mestral noticed that these seeds featured burrs that could attach to loops and used this biological form to create a material to bind plastic strips that are widely used today.

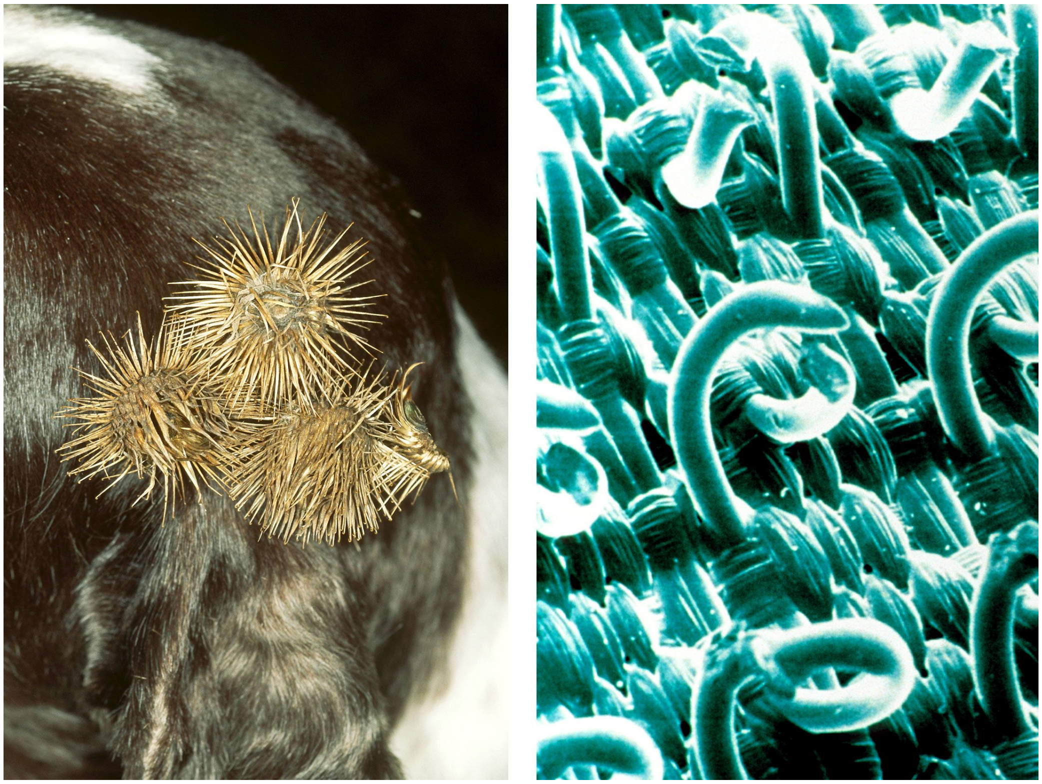
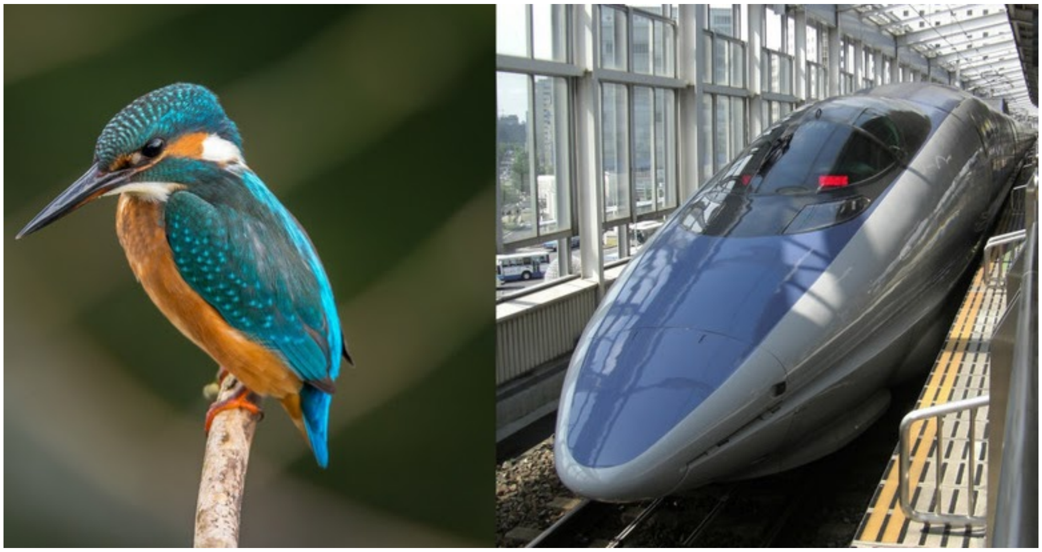


Figure 3: Closeup of burdock seed (*Arctium lappa)* [left]) and structure of Velcro [right] that shows the influence of biomimetic design. (Source: Edwards, L. https://abundary.com/nature-develop-advanced-tech/)

The development of Japan's Shinkansen trains is another example of biomimetic design. These trains, commonly referred to as bullet trains, can travel up to 200 mph. Due to their high rates of speed, early versions of these trains caused sonic booms as they exited tunnels. To address this issue, the trains were redesigned to emulate the beak of a kingfisher (*Alcedines)*, a bird with the aerodynamic ability to allow it to travel efficiently from air to water with little friction. The application of this biological process to the design of these trains eliminated the issue of sonic booms and resulted in a faster and more efficient design (Environment & Ecology, 2019).



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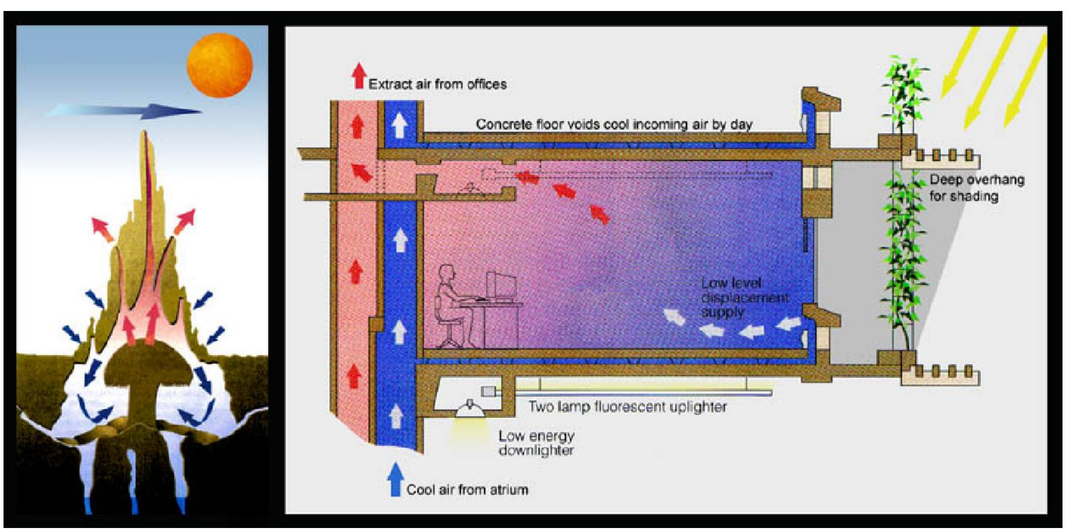
The term *biomimetic* first appeared in 1957 when American inventor Otto Schmitt developed a device during his doctoral research that mimicked the electrical activity of a human nerve (Environment and Ecology, 2019). Schmitt coined the term to define the translation of biological to technical systems (Bhushan, 2009), and it was officially entered into Webster's Dictionary in 1974 (Environment & Ecology, 2019). The term *biomimicry* was first used by biologist and author Janine Benyus in her 1997 book *Biomimicry: Innovation Inspired by Nature.* In her book, Benyus discussed *biomimicry* as a design approach that draws from three factors:

1. *Biology as a model.* A study of biological models that then imitates or takes inspiration from these models to address human problems;
2. *Biology as a measure.* The use of ecological standards to judge the ethics of design innovations; and

3. *Biology as a mentor.* A new way of valuing biological processes that can guide design approaches based not on what we can *extract* from the natural world, but on what we can *learn* from it (Benyus, 1997).

In recent decades, both *biomimetics and biomimicry* have influenced the structural work of many designers, particularly 20th and 21st-century architects. For instance, architect Mick Pearce based the design of his Eastgate Centre (1996), a shopping center and office building in Harare, Zimbabwe, on the structure of macrotermes termite *(Macrotermitinae sp.)* hills. These African termite species construct their hills to facilitate passive internal airflow to maintain consistent internal temperature despite drastically changing external conditions (AskNature, 2016). The Eastgate Centre's design employs a high thermal capacity structure, limited glazing, and deep overhangs in conjunction with an interior atrium, which allows it to passively ventilate airflow and balance interior temperatures, allowing the structure to consume only 10% of the energy of a comparable traditional building (McKeag, 2009).



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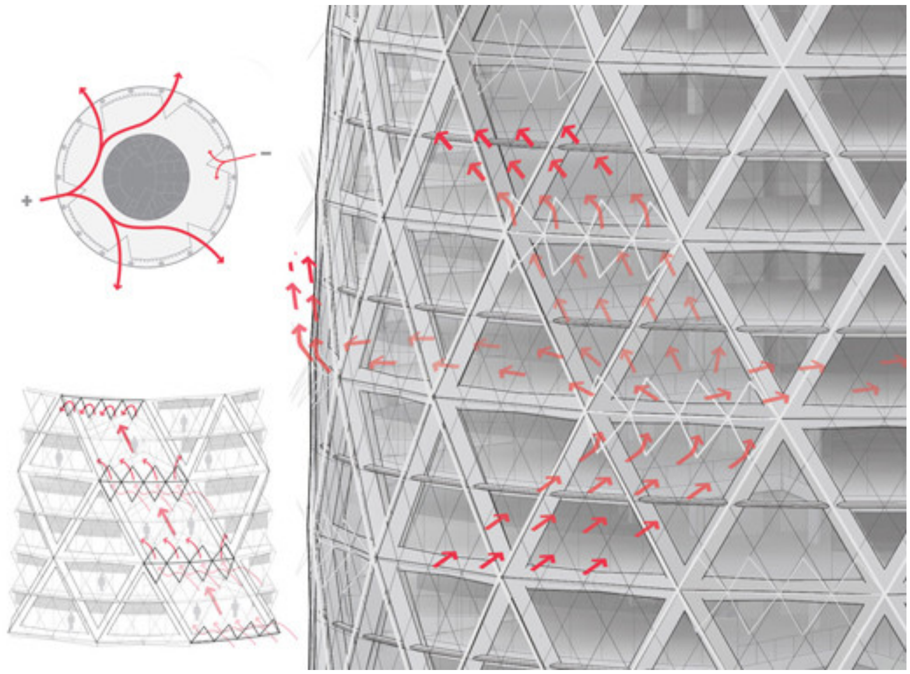
30 St. Mary Axe, a commercial skyscraper located in London, UK, often referred to as the Gherkin, is also considered to be a biomimetic design. Architect Norman Foster based this 2003 structure on a species of Pacific marine sponge, the Venus' flower basket *(Euplectella aspergillum)*.

Figure 6: Venus' flower basket *(Euplectella aspergillum)* influenced the design of 30 St. Mary London, United Kingdom. Venus' flower basket *(Euplectella aspergillum)* [left]) and 30 St. Mary [right]. (Sources: https://asknature.org/strategy/silica-skeleton-is-tough-and-stable/ & http://www.harvarddesignmagazine.org/issues/35/30-st-mary-axe)

The building was designed to emulate the shape of this sponge to deflect wind and passively ventilate the structure through open shafts below each floor. These shafts also release warm air during the summer months, absorb solar insolation to partially heat the structure, and provide light for many interior spaces (Moussavi, 2020).



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Today, while an interest in biomimetic approaches has increasingly shaped how designers look to biological systems for inspiration and innovation, this method requires design guidelines and recommendations for architects for implementation.

Biomimetic and Traditional Design Approaches Defined

To investigate the advantages and challenges of biomimetic design approaches, this research employed the definition provided by Janine Benyus, one of the world's leading authorities on biomimicry and the founder of the Biomimicry Institute based in Missoula, Montana:

> *Biomimicry is learning from and then emulating nature's forms, processes, and ecosystems to create more sustainable designs* (Biomimicry 3.8, 2005).

The researcher chose this definition for its simplicity and precision in describing the extensive application of biomimicry, as well as based on the Biomimicry Institute's reputation as a leading authority in the field. The Institute further identifies biomimicry as involving three approaches (Hargroves & Smith, 2007):

1. The structure, or *form*, of ecology;
2. The *processes* of ecology;
3. The natural *ecosystems* of ecology.

This thesis explores the use of biomimicry as a design tool along with all three of these approaches: form, processes, and ecosystems. Based on the Institute's method, each approach embodies five dimensions that can be applied to determine the extent to which biomimetic processes have been applied to architectural design: form, material, construction, process, and function (Aziz & El Sherif, 2015).

One component of this research is to understand how the biomimetic design process relates to and contrasts with the traditional architectural design process. The latter process is often linear and moves from one stage to the next in a sequential manner, with the architect signing off on the completion of each stage (HMH Architects, 2017). This approach, which is recognized by architecture accreditation boards such as the American Institute of Architects (AIA) and the National Council of Architectural Registration Boards (NCARB), typically follows a seven-phase process: conceptual design (CD), schematic design (SD), design development (DD), construction documents (CD), construction bidding, and construction administration (CA) (American Institute of Architects 2020; National Council of Architectural Registration Boards 2020).

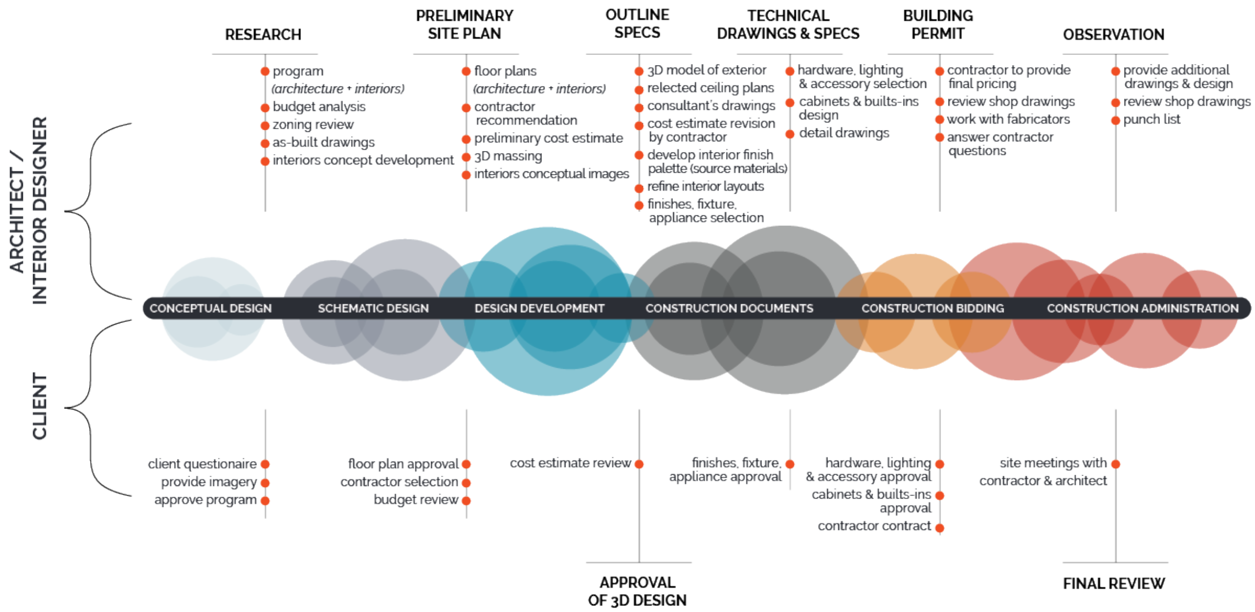
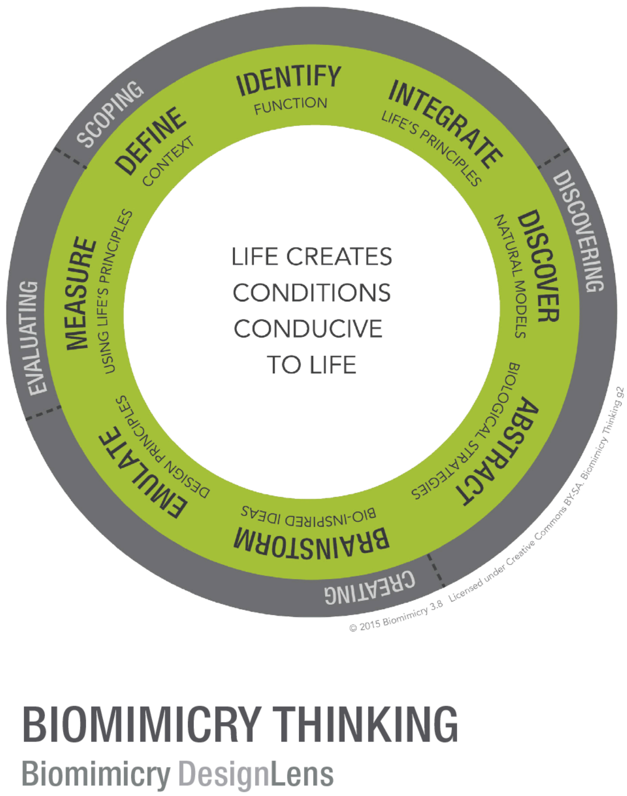


Figure 8: Diagram of the conventional architectural design process recognized by AIA and NCARB depicting the linear process of architectural design (Source: HMH Architects https://hmhai.com/design-phases/)

By contrast, biomimetic design processes supplement the traditional architectural design process by encouraging a more circular and reiterative approach to design. The Biomimicry Institute groups the biomimetic design process into four categories: scoping, discovering, creating, and evaluating (Biomimicry DesignLens, 2015).

In this process, designers identify design challenges, investigate natural models and biological processes that can address these challenges, and then create bio-inspired designs from natural models (Biomimicry DesignLens, 2015). Thus, the biomimetic design process becomes more iterative than the traditional architectural design process and allows designers not only to move from one stage to the next in a linear fashion but also to move back and forth between stages when finding and implementing successful biomimetic design solutions (Cohen & Reich, 2016).



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Research Problem

As discussed above, biomimicry is an emerging design approach that models the design of materials, structures, and systems on biological processes. To date, most research on biomimetic design has focused on design outcomes, but few studies have explored how architects who employ biomimetic processes arrive at these outcomes or investigated the challenges that they face in employing these processes. Further, the current literature often relies heavily on the use of precedent research and case study analyses as main sources of information without any considerations of the processes of architects themselves. As architects begin to explore the use of biomimicry in their work, there is the need for knowledge on how to apply the guidelines and principles associated with this design tool.

Moreover, one of the main challenges to architects who wish to apply biomimetic design approaches concerns the lack of information available as it pertains to navigating the biomimetic process. While a few methods exist to guide architects in creating biomimetic designs, such as Biomimicry 3.8’s Design Lens (2015) and BioTRIZ (2008), they remain in the early stages of development and do not serve as an all-encompassing methodology that architects can rely on. In addition, many definitions of biomimicry and biomimetic design appear in the existing literature, often leaving ambiguity in its definition and application.

There is also the challenge that relatively few examples of built biomimetic architectural design exist, and while these examples have served to support the push for biomimetic design, their relatively low numbers do not allow architects to apply their insights to a variety of design solutions. Without existing biomimetic designs, designers can encounter difficulties in understanding what made these designs a success, how they may have failed, and most importantly their methodology for arriving to those biomimetic design solutions.

Research Objectives

To address this gap in the literature, this study explored how architects incorporate biomimicry in their design process and the challenges associated with implementing this design method. This study gathered insights of architects who follow biomimetic design processes in order to document their approaches. Specifically, this thesis investigated the opportunities specific architects identified when incorporating biomimetic principles in the design process as well as the challenges they face in pursuing biomimetic design. This research also explores how architects inform themselves about biomimetic design processes as well as what their research process entails. It is the researcher's hope that documenting these insights can help to inform and guide architects in applying biomimetic design approaches in their work.

Research Question

How do designers employ principles of biomimicry and what challenges do they face in implementing those principles in biomimetic design processes?

Literature Review

As discussed above, biomimicry concerns an approach to design that involves studying and applying biological principles and systems to address design challenges through the creation of materials, products, or processes (Biomimicry Primer, 2009). Zari (2010) concluded that biomimetic approaches can be applied to architectural design in two broad ways: *design looking to biology* and *biology influencing design*. The first approach begins with the identification of a design problem or human need and then looking to biological systems to address this problem. The second category involves the general identification of biological characteristics and then finding a way to implement them into design (Zari, 2010).

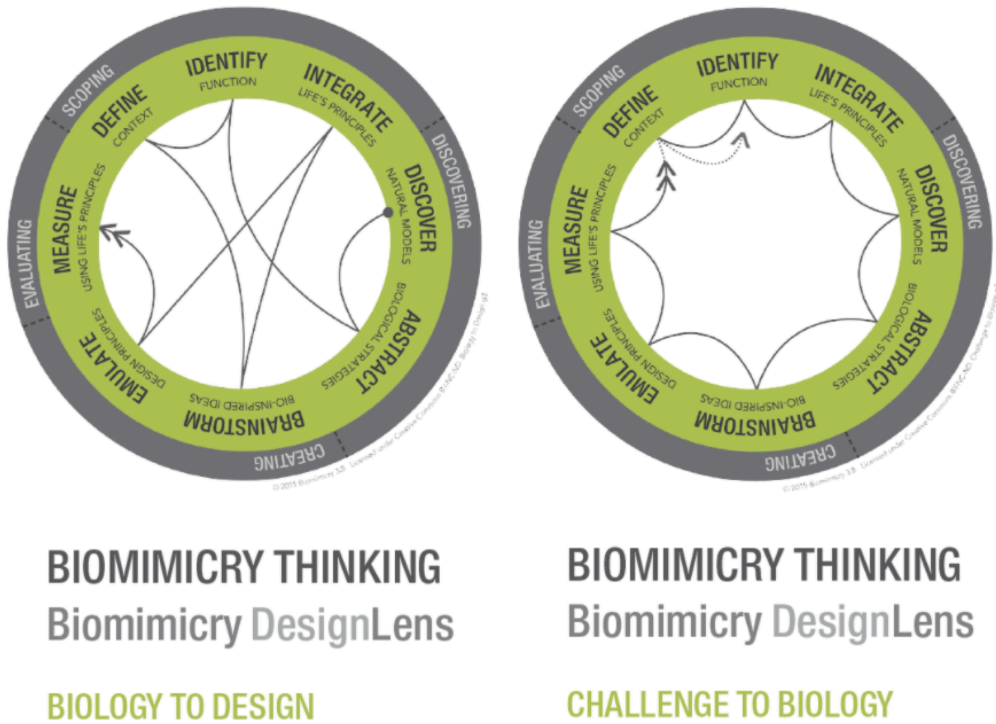
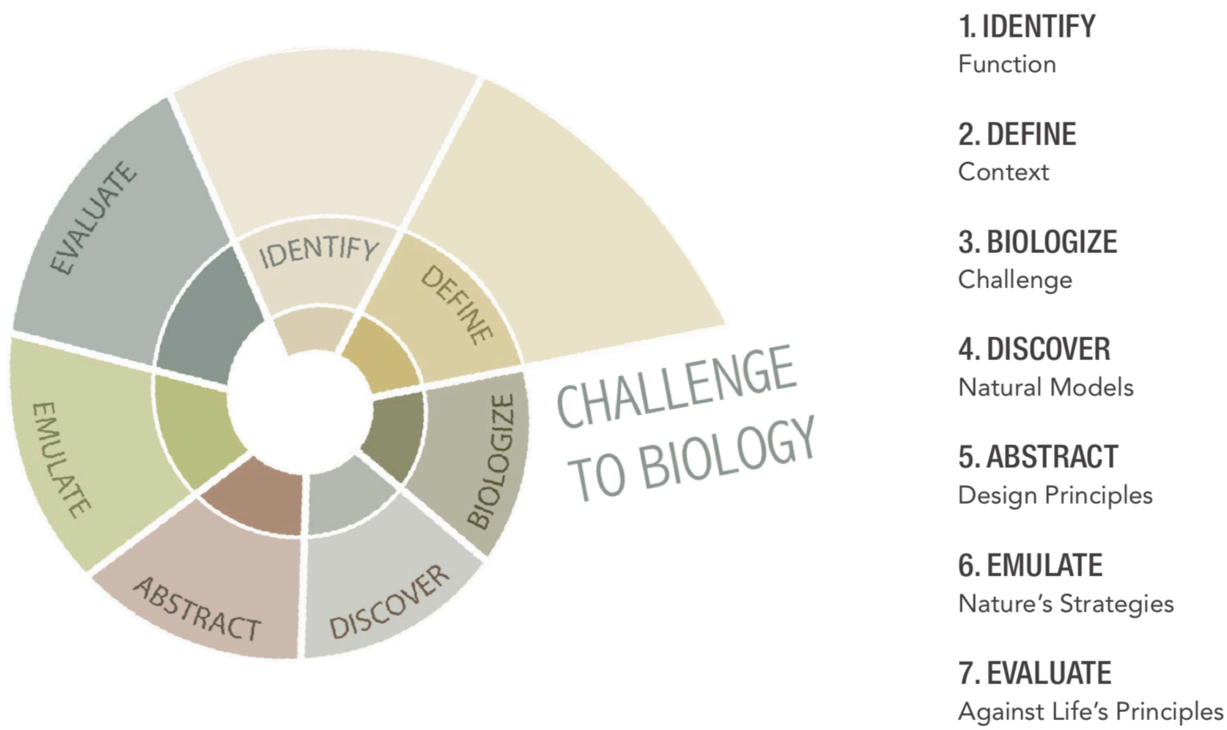


Figure 10: Diagrams of two applications of biomimetic design to architecture as developed by the Biomimicry Institute. Design looking to biology design depicting design challenges being solved by biological solutions [left] and biology influencing design in which biological characteristics are applied to design [right] (Source: Biomimicry Institute https://biomimicry.net/thebuzz/resources/biomimicry-designlens/)

Some biomimetic strategies exist to inform architects about biomimetic design processes. One such strategy is Hastrich's Biomimicry Design Spiral (2014), which was modeled on the Biomimicry 3.8 Toolbox (2006), that is intended to guide architects as they explore the reiterative process of biomimetic design (Rossin, 2010).



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Another application that bridges the gap between biomimicry theory and practice is BioTRIZ (Altshuller & Shapiro, 2008), a collection of tools and techniques based on an algorithm that can be used to transfer functions and solutions present in biological systems into applications for engineering projects (Vincent et al., 2006). This algorithm is used to define engineering problems and then match potential solutions to these problems from natural systems (Vincent et al., 2006). An additional biomimetic design tool used by some architects is Life's Principles (Biomimicry 3.8, 2013), a set of twenty-six principles derived from the natural realm that have, over the course of 3.8 billion years, allowed biological systems to thrive. These principles can serve as guidelines for architects to employ biomimetic strategies throughout the design process.

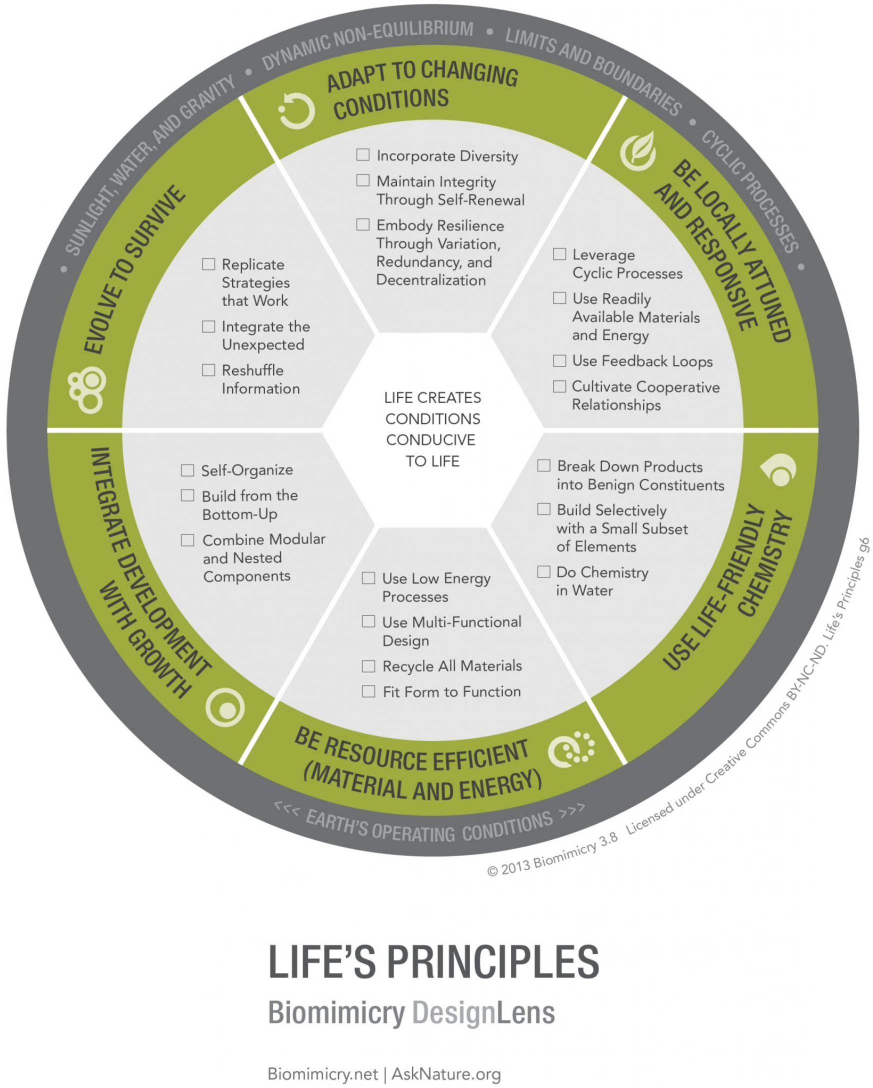

Figure 12: Biomimicry 3.8's Life's Principles which are a set of 26 guidelines made up operating conditions almost all living organisms follow (Source: Biomimicry Institute https://glbiomimicry.org/Education/Lifes_Principles_Handout_FINAL.pdf/)

Some researchers have begun to explore the challenges involved when implementing biomimetic approaches in design. For example, Badarnah and Kadri (2015) detailed three major obstacles to employing biomimetic methods. The first concerns the often-daunting task of finding and selecting appropriate strategies for design solutions given the broad array of knowledge available regarding biological systems and organisms. A second involves the difficulty in scaling and applying natural processes and forms to design, as one desired process may operate at a microscopic level and thus may not translate to the scale of a building. The third pertains to conflict between various biomimetic design concepts, as one concept may eliminate an element upon which another relies, making it a challenge to reconcile various systems and components throughout a design (Badarnah & Kadri, 2015).

In addition, Ohlander et al. (2018) critiqued several biomimetic frameworks, specifically Janine Benyus' Biomimicry Design Toolbox (2006), a resource that is intended to guide architects in applying biomimetic processes, as lacking a sense of human scale and a consideration of social factors in biomimetic design (Ohlander et al., 2018). Papanek (1985) also discussed the concern of 'overromanticizing nature' within the design process, which often leads to a tendency of designers to simply mimic biological features rather than actually emulating natural processes in their work (Papanek, 1985). Further, biomimicry has been criticized for adopting a romanticized view of biological systems and limiting themselves to simply using already implemented solutions that can be easily copied while overlooking the more grotesque side of nature and what it has to offer to the field of innovation in biomimicry (Armstrong, 2015). Further, Collins (2014) stated that limiting oneself to a narrow and romanticized view of natural systems can ignore the darker sides of biological processes that can provide valuable insight into implementing biomimicry at a design scale (Collins, 2014). Moreover, Kaplinsky (2006) identified a sense of over-idolization of ecology in design that can lead to a disregard of human perspectives and result in designs that are not produced for human use and enjoyment. Kaplinsky also maintained that biomimetic design approaches should retain a user-focused ideology throughout the concept and design process so as to not diminish confidence in human's ability to push past incrementalism to adapt to human needs and to further diminish the mindset that we are lesser than or separate from biology (Kaplinsky, 2006).

To successfully implement biomimetic principles in architectural design, many researchers have stated that architects must go beyond the various definitions of biomimicry to consider the many factors that determine this approach. Bay (2010) argued that biomimetic design can only be fully implemented if professionals from a range of disciplines work collaboratively in the design process, as professionals from various backgrounds bring diverse and needed expertise to the process. Only then, the author maintained, can designers arrive at solutions that fully consider built and unbuilt environments in which they are constructed (Bay, 2010). Moreover, Zari (2015) maintained that it is critical that professionals across various allied disciplines, such as architecture, engineering, and planning, understand biological processes in order to ensure that biomimetic designs are not over-simplified and fall short of their intended performance goals. Further, Jones (1998) argued that in order to implement biomimetic design, the entire traditional design process must be changed, rather than pieces of the whole (Jones, 1998).

In response, Mazzoleni (2013) asserted that biomimetic architecture is a means to not only change the traditional architectural design process but to radically alter how buildings are constructed and built. She further argued that biomimicry is an opportunity to consider architectural projects as part of broader ecosystems, rather than isolated forms within the built environment (Mazzoleni, 2013). Author and biomimetic architect Michael Pawlyn went on to maintain that biomimicry does not simply involve the implementation of expensive technologies and materials in buildings but rather the celebration of ingenuity in design and the designer's ability to apply biologically inspired innovations to human problems (Pawlyn, 2016).

Some researchers have begun to address how biomimetic approaches in architecture have been implemented within traditional architectural practice over time. For instance, Zari (2010) and Chayaamor-Heil and Hannachi-Belkadi (2017) reviewed a range of architectural designs in order to identify any common principles they embodied and develop design methodologies. Elmeligy (2016) studied existing biomimetic designs to determine their design objective and how architects reached these objectives (Elmeligy, 2016). Rossin (2010), compared the design process to biological processes by evaluating the work of the Hellmith, Obata + Kassabaum (HOK) architecture firm in terms of biomimetic design in order to define a set of biomimetic principles (Rossin, 2010). Finally, Sarwate and Patil (2016) and Cohen and Reich (2016) evaluated biomimetic literature in their research in order to develop biomimetic design processes. Although these approaches have brought the field of study closer to a better understanding of the biomimetic design process, these various approaches have omitted the voices of the designers themselves and their role within the process.

By contrast, Gamage (2015) is one of the few researchers who took a novel approach to generating a biomimetic design method by conducting surveys with architects and non-designers as well as combining her analysis with other social research approaches, such as precedent design, in order to establish a biomimetic design method. Her work suggests the need for design indicators, a design matrix, and the use of vernacular architectural strategies to further biomimetic design in architecture. Also, McCardle and Rovalo (2019) used interview and survey techniques to offer a performance-based approach to guide designers through the process of prototyping. Researchers Husukić and Zejnilović (2015) offered insight into how biomimetic design could impact environmental, economic, and social development through a series of interviews and surveys with design professionals. In addition, Helms et al (2009) took a more human-centric approach to biomimetic design by investigating how engineering students implemented biomimicry in their design work.

The work of this study will build upon the existing literature to further understand the perspective of the designer and will elaborate on the work of Gamage (2015) by providing a more in-depth understanding of the designer's perspective with the use of interviews, rather than surveys, to allow participants to speak for themselves and share their experiences. This work will also build on the work of McCardle and Rovalo (2019) and Husukić and Zejnilović (2015) by continuing the use of qualitative interviews with design professionals to learn about their biomimetic design process, research processes, and constraints to which a set of observations, insights, and guidelines can be garnered that future designers could apply to their biomimicry work.

Thus, a review of the literature suggests that researchers have not yet taken the necessary next step in identifying insights that practicing architects can use to guide biomimetic design and reveals a gap in current biomimetic knowledge in that existing research has relied on the use of existing precedent work without incorporating the architect's perspectives. Further, although architects are beginning to test biomimetic approaches, no unified methodology exists to guide architects unfamiliar with the process of implementing this design process While biomimetic design tools such as the Design Spiral (2014), BioTRIZ (2008), and Life's Principles (2013) exist to assist designers in this process, they do not serve as a method that can be applied to all project scales. Gamage (2015) and Helms (2009) have worked to fill this gap in the literature by providing a more human-centric approach to biomimetic design, but much work remains in distilling and understanding the biomimetic design processes of architects. This study addresses this gap by interviewing architects in order to better understand their processes and challenges in implementing biomimetic design.

Method

To address the research question, the researcher employed a qualitative research method by conducting semi-structured interviews with design professionals. Qualitative research methods are often used in social science research and are well-suited for research that requires an in-depth exploration of human behavior and beliefs (Patton, 1990). As a social science research method, collecting data through interviews allows for a greater depth of understanding when it comes to the necessity of gaining first-hand accounts in order to investigate a given research phenomenon (Arksey & Knight, 1999). This qualitative approach was used to collect, interpret, and analyze data collected throughout the research process to understand the perspective of architects with respect to biomimetic design processes. As Patton (1990) stated, "The purpose of interviewing is to find out what is in and on a person's mind … to access the perspective of the person being interviewed … to find out from them things that we cannot directly observe."

Data were collected through a standardized semi-structured interview process that allowed the researcher to investigate the biomimetic design processes of participants. The researcher interviewed eight architects who were selected based on their qualifications and expertise in the field of biomimetic design (see Appendix B). The architects and practitioners selected as research participants are notable authors and award-winning individuals considered experts in the field of biomimicry and were thus representative of the broader majority due to their professional expertise and experience. The researcher began with a series of internet searches to find designers with the expertise to speak to the research question based on a set of three criteria: geographic distribution, diversity of job title (i.e. academics, architects and consultants), and relevant experience. These preliminary internet searches yielded 15 potential participants. The researcher then contacted all 15 of these potential participants, a process that yielded three interviews. After these the three interviews were complete, the designer then conducted another internet search that yielded an additional two interviews. The researcher then employed the snowballing sampling technique (Wilson, 2014), in which the first five interviewees were asked at the end of each of their respective interviews to recommend other potential participants. This technique yielded an additional three interviews.

The interviews were semi-structured in order to direct the conversations and to allow participants to discuss topics they deemed relevant at any point in the interview process. Rubin and Rubin (2005) discussed the semi-structured interview process and how it can elicit depth, richness, and vividness through a mix of questions structured as main questions, follow-ups, and probes. All interviews took place over a one-hour meeting either in person or via telephone with the researcher recording and taking handwritten notes throughout the interviews.

Although conducting semi-structured interviews as a social research technique is often relied upon by researchers, there are still challenges involved with implementing this technique. Choosing a sample method is often an area of dispute with most research proposals and can determine the credibility of the researcher's work. Methods exist to determine if the sample relied upon throughout the interview process is representative of a studied phenomenon. Purposive sampling involves identifying and selecting individuals that are knowledgeable about or experienced in the researcher's area of interest (Cresswell & Plano Clark, 2011). The use of this technique allows researchers to choose respondents based on their qualifications and experience within that particular field, making a sampled group a strong representative of the whole (Wilson, 2014). This technique was used in the research as the researcher chose the interview participants based on their level of expertise and experience within the field of biomimicry with respect to architecture. Wilson also accounted for the use of 'snowball sampling' techniques within purposive sampling, in that chosen interviewees may be able to identify other experts in the field worth interviewing, ensuring that these potential future candidates are considered reliable for sampling amongst their colleagues and peers (Wilson, 2014). This technique was used in the research at the end of each interview when the researcher would ask the interviewee to identify and recommend additional architects to interview for the purpose of this research.

After all interviews were conducted and data were collected, the interview recordings were transcribed and organized and then coded using a hermeneutic process. Hermeneutic coding involves a process of identifying relevant results that are then connected and grouped in order to identify themes in the research data (Medelyan, 2019). As Kennedy (2016) stated, hermeneutics is the art of interpretation. Hermeneutic coding processes are used as a research method when conducting interviews or surveys in order to better understand an individual's thoughts or experiences. Hermeneutic coding allows for the interpretation of research data by including the researcher's own experiences in the synthesis of the report and encourages a more subjective experience in which the researcher does not separate themselves from the data but uses their viewpoints to further shape the gathered information (Medelyan, 2019). Hermeneutic coding also does not rely on a strict analytical technique, but rather allows for both the researcher and the studied phenomenon to shape the interpretation of the gathered data (Bynum and Varpio, 2018).

This method was used to analyze the collected interview data to understand the similarities and differences across respondents' biomimetic design processes. With respect to using hermeneutic coding as a data synthesis method, Thiselton (2009) asserted that two main realizations can be made to support the use of this method and its importance in analyzing respondent data. First, researchers have learned through this process to analyze and interpret the data to which they minimize the effects of their own self-interests and inherent biases. Secondly, researchers can become more empathetic to different viewpoints and ideas they were not previously familiar with when analyzing these data (Thiselton, 2009). Hermeneutic coding is also a dependable and consistent means of data analysis and organization. As stated by Higgs (2005) and Patterson (2002) stated, hermeneutic coding can contribute to the credibility and trustworthiness of the research methods used, in that the process of hermeneutic coding can further delineate and outline the information for the reader in a clear and concise manner.

Data Collection and Analysis

Data Collection

Before beginning the interview process, the researcher obtained approval from the University of Colorado Boulder's Institutional Review Board (IRB Protocol Number 19-0569) to conduct interviews with human subjects (see Appendix C). The researcher established a list of interview questions to guide the interview process and to ensure adequate data collection across interviews. Interview participants were chosen based on a set of criteria, including their level of expertise in both the field of architecture and biomimicry. All architects are well-known and prominent practitioners selected through a series of internet searches. The selected participants were then contacted through email to establish interview dates. Consent forms were sent to each participant and were signed by both the researcher and the interviewee. Interviews took place over one hour either face-to-face or via telephone or video conference conversations. The interviewer also employed the aforementioned snowball sampling technique, in which each interviewee was asked to identify additional respondents who are experts in the research area.

Participants were asked a series of 15 open-ended questions, both to allow the interviewee to structure the conversation and to encourage the participants to speak broadly about their thoughts and experiences (see Appendix A). All interviews took place over a three-month period between December 2019 and February 2020. All interviews were audiotaped, notes were taken throughout the interview process, and consent was obtained by the researcher from the interviewee to audio record. The interviews were then transcribed verbatim, with audio recordings used to authenticate research findings. In adherence to the guidelines set by the University of Colorado Boulder's Institutional Review Board, all transcriptions were secured on a password-protected computer and all physical notes were kept in a locked cabinet to which only the research had access. The researcher assigned all interview respondents a unique identification code to protect their identity and to ensure that any statements used in this research could not be connected to either them or their organization. Data collected from interviews with design professionals were then analyzed through a process of hermeneutic coding.

Data Analysis

As discussed above, all interview data were analyzed using a hermeneutic coding process that identified relevant themes, concerns, and topics. Hermeneutic coding is the art of understanding such as that it is an interpretive act of integrating words, signs, and events into a meaningful whole (Zimmermann, 2015). Each interview transcript was reviewed multiple times to allow relevant themes to emerge across the interviews, including common principles, viewpoints, and vernacular. After all relevant themes were discerned, the researcher presented these themes by presenting statements taken from the interviews in distinct sections. These themes are discussed in the following sections.

Results

Based on the data collected from interviews with design professionals and the analysis of this data through the process of hermeneutic coding, a set of results were compiled in the form of five main themes: the biomimetic design process, systems thinking, resources, opportunities and existing gaps, and constraints. When appropriate, these themes have also been organized into subthemes.

Theme 1: Biomimetic Design Process

One of the most important findings that emerged from the data pertained to the biomimetic design process adopted and implemented by various biomimetic design professionals. Participants discussed their own or their firm's biomimetic design process, how they employed this process in their work, and where they felt biomimicry fit into the traditional architectural design process. Of the eight architects interviewed, six provided significant information on their design process as it pertains to biomimicry.

> (D1): With formal design, we start with a concept, then go to schematic design, and design development and then to construction drawings and then contract administration. We typically end it there, but some clients are realizing, and now with building modeling systems and different rating programs like LEED[1], you need to monitor ongoing compartments, so that's ongoing maintenance. [This is] critical because whenever you are creating something or remodeling something, that's one thing, but that lives on in the people using it. So, you need to know that it's about the long-term. If you look at architecture construction, traditionally it is linear,

1 "LEED (Leadership in Energy and Environmental Design)," https://www.usgbc.org/leed

but by bringing in this ongoing monitor, maintenance, and feedback, it's circular.

That's our basic design process. If we do that ongoing maintenance, it feeds back and takes this linear process a little bit more back to design develop and sometimes it might even go as far back as schematic design, when you need to revisit and adjust and then you're starting the process over again.

How that relates to the biomimicry process is that the methodology is broken down from scoping, figuring out function. What is it you're achieving? Discovering? Modeling? That moves into the prototype of your design, coming up with something and then that moves into your feedback. How is it working? Maybe it didn't work right and that immediately takes you right back to scoping, so it's always a circular process.

If you look, you can get on the Biomimicry Institute[2] website and you can see the basic process. They're spirals and you can finish in different places from where you start. It's a circular process and that's just how life works, I can't even say nature works that late. It's life.

(D2): [Our firm] comes in during conceptual design and schematic design and helps architecture firms implement biological solutions because they probably don't have a background in biomimicry or the natural sciences. We are also working on biomimetic product design in the built environment; that way, we have products that are doing biomimicry, and we are trying to make them commercially available.

We are also working on … a web-based application that translates the language of biology into the language of design, so that any firm all over the world can license the software and get all these biomimetic principles from it. [Another] part is really about education, because even though biomimicry was coined in 1997, it's still a relatively new field, and a lot of people get confused with what is biomimicry versus bio-morphism, versus bio-assisted, versus bio-utilized, and biophilia.

[This] dovetails very nicely into the traditional architectural process, in that there are four major categories for biomimicry—scoping, discovering, creating, and evaluating—and those four phases can also be found in architecture. The only difference is that during the discovering phase, you reframe the question so that instead of being what you want your design to be, you ask what you want your design to do. And by doing that, you can then discover natural models that solve that function. Biomimicry also

2 "Biomimicry Institute," 2006, https://biomimicry.org
3 "Life's Principles," 2016, https://asknature.org/resource/lifes-principles/

has a set of guidelines called Life's Principles[3] [Biomimicry Institute]. There are 26 again guidelines, [but they] are not black & white rules, because not every organism follows them, but 99.9% do, and those are the already distilled kind of principles that nature already uses. Ultimately, you don't necessarily have to do the biological research if you're incorporating Life's Principles.

(D3): I try to figure out ways that designers can tap into biomimicry without having to learn two years' worth of information because it's not an easy thing to do. I work a lot with Life's Principles [Biomimicry Institute]….They apply really well for visual communication, but they also serve as good design principles no matter which discipline you are in.

(D5): We work along different steps, or rather, principles. We use primarily five of those. First, we look to understand the emergent trajectory of the land we are working with. If a project is based in a forest in India, for example, what does the land want to do? What is its current trajectory? If we keep letting it be that way, what are the ecosystem services that we will get and how will we work with them if we build on 50% [of the land]? What would that look like if we built on 25%?

Second, we find ecological assets that can be used and replicated. [This involves] understanding the ecosystem services that the land already provides and can range from pollination to water regulation and water management strategies.

Third, we [research] local organisms to reframe our challenges to understand how these organisms have adapted to existing conditions and how this could help us solve our challenges. Here we use both biology to design and design to biology, so being inspired and also asking certain questions and then finding inspiration.

Fourth, we create design fiction scenarios for strategic foresight—fictional scenarios using inspiration, while not necessarily limiting ourselves to the practical applicable aspects but going forward and understanding these fictional scenarios where you can work. Maybe some of them can be realized at 90% and maybe some of them at 10%, but then we can understand the technological material handicaps.

Fifth, we integrate technologies that are inspired by nature. This means using existing technologies across the globe and finding synergies and symbioses within those that we can use within our processes.

(D7): We look at buildings on a unique building-by-building basis and ask how each building performs in its time and place. I think the future is going to be to look at how buildings perform in an interconnected basis; the process of biomimicry has a lot of feedback in the large systems of the building.

(D8): The most specific example is a project we're working on here locally, where we are employing ecological performance standards. Essentially, what we do to apply biomimicry to our work, is to have a client that's receptive to thinking differently. We have to identify those key clients that we think would benefit from this approach and that are receptive to us incorporating the methodology into the work we're doing within the fee structure.

For our own methodology, we do a boots-on-the-ground assessment of ecological performance on an adjacent intact system. We do ecosystem assessments of both services and functions on the sites themselves, and what emerges is a delta in performance. So, you get a differential between how the subject site is performing ecologically and how that intact system is performing and it's the delta that becomes a benchmark, a measurement, that we then task our design team with emulating….Specific elements such as clean water and air and sequestering carbon become functions that we want to solve for and what we want to take on as part of being regenerative and performing ecologically.

We need the expertise of engineers to calculate and measure, so it's important that they understand what it is we're chasing and then it becomes part of the vocabulary and the underlying sort of benchmarking of the kind of solution space that we work through the normal design process. There are a lot of layers to it.

Ultimately, it's really about checking in and consistently looping back. It's very iterative. It's very back and forth and there are aspects of the benchmarking that you set out that fall away.

We measure to what extent the built environment space or solution that we've actually constructed is contributing to that [ecological performance], or what is it that is inherent in the operating conditions of that place that may be different or could change.

Biomimicry is really emulating all of the attributes in the landscape that are actually performing those functions. So, we're really trying to understand what those attributes are. How can we emulate all the different characteristics in the landscape that actually contribute to specific functions? We're making it up as we go in terms of the methodology. We are very much trying to work within the normalized process that we see for the practice of architecture and the practice of design in the built environment.

Theme 2: Systems Thinking

The second key finding involves system thinking, or how a system's parts interrelate to one another and how they work overtime in the context of larger systems. The participants identified what they determined to be a successful biomimetic design and the principles that accompany a successful biomimetic design. Out of the eight architects interviewed, four discussed that systems thinking or relating to and connecting with the surrounding landscape as a component of successful biomimetic design.

> (D1): [We work to understand] the connection to the structures, the open space or the street around it [the project] and what is happening there? Now, you've created a different kind of ecosystem within another larger ecosystem and then you also have to consider not just the physical aspects, but the social and cultural aspects. How does [the project] affect the behavior of people, both inside programmatically, and outside in the greater neighborhood?
>
> It's about understanding and realizing how everything is connected. [We consider] systems thinking, system space so that we understand how everything is connected. So, if you're looking at a product or material that is used in the built environment, you need to look at where it came from, and where and how it was sourced. How did it impact the health of organisms, including humans, when it was being manufactured? How does it impact living?
>
> (D4): The process is really more systemic, meaning looking not at the problem directly and in isolation, but how it relates to its context and how it relates to the context of the whole. In my design [projects], this is the first thing I look at. The second is at the building's environmental context.
>
> (D7): It is evident to me in designing that being conscious of a site, being conscious of views, wind, sunlight and the link between a building and the land is a part of what allows for successful biomimetic design implementation.
>
> (D8): We need to ask what the most immediate things are that we need to be doing and what things we need to be doing in service to a larger paradigm shift in how we conceive of or execute our built environment. We have to stop thinking, "if I only had a blank site," "if I only had the perfect

client," and "if I only had endless money" then I could design the right solutions. This doesn't exist. We're left to work with disturbed landscapes, and as designers, we manage this on a site-by-site or context-by-context basis.

We have got to stop scraping [sites] clean and starting over. We need to look at what's there [on a site], which includes all the senseless things that humans have done because nature's already at work. If we look at our built environment the same way and stop saying, "I have to pull all that up and then do differently." It's about what we can do with that [the site] as a starting point.

There isn't this kind of neutrality of what a human environment is. It's about how we evolve these environments so they're far more attuned to ecology and the ecological performance of specific places. We're going to see more site-specific solutions by recognizing all of the characteristics of what landscapes are doing and evolve them too.

Theme 3: Resources

In the third major finding, the participants identified the resources they use to find information on biomimicry and principles of biomimicry that could then be applied to architecture. Designers were also able to discuss what key resources they use to inform their biomimetic design process. Within this category, the researcher identified two sub-categories: internet/electronic resources and non-internet resources.

Internet/electronic resources

(D1): There are several resources I use, and Genius of Place[3]… reports are great to use. Ask Nature[4] is also a great website that I use to inform my biomimetic design process.

(D2): I use the website AskNature.org. This resource is amazing because it is organized by function and gives you a range of [information about] organisms. But then you need to take the next step to translate this information. I also use resources like the Encyclopedia of Life[5] [EO Wilson], which to catalogs eight million organisms. There's lots of resources out there, including different science publications, magazine articles, and research journals.

3 Gretchen Hooker, "Genius of Place," April 12, 2017, https://asknature.org/collections/genius-of-place/)
4 "AskNature," 2006, https://asknature.org
5 "Encyclopedia of Life," 2008, https://eol.org
6 "Google Scholar," 2004, https://scholar.google.com

(D3): I often work with Life's Principles [Biomimicry Institute] in my work in biomimicry.

(D5): AskNature.com is a very comprehensive database and an ever-growing one, which is really great to [review] now and again in our design work.

(D6): My main resource is Google Scholar[6] [Google] when looking for information on biomimicry.

(D8): Some of the resources we use are the Biomimicry Lens[7] and Life's Principles in particular, although they are pretty limited and may only have one or two examples. Those resources parallel well with the principles that are in the language of designing buildings in the Living Building Challenge[8] [International Living Future Institute]. The Living Future Institute[9] [International Living Future Institute] is a great resource because you get access to projects that are active around the world, so you can see and probably parse out people that are working toward biomimetic approaches.

Non-internet sources

(D1): I'm continually building my library of different books to learn more because my biggest learning curve is biology. I also like to get a really good template that I can adapt to all kinds of different situations, such as a questionnaire for asking people questions, to build my resources of what [examples of] natural genius are around here that I can draw upon. The other thing I do with my associate base is to find local naturalists, biologists—different people who have expertise. And my backyard, just going outside, is really great.

(D2): With biomimicry, you can get inspiration anywhere. You can get inspired walking—you know, going for a hike here in [US state]—or in front of your computer or watching documentaries.

(D4): I always try to source scientific papers or to talk with scientists. For example, I begin my research looking at animals, and I always start with their scientific names… and that brings me to descriptions that are less [well-known].

7 "Biomimicry DesignLens," 2015, https://biomimicry.net/the-buzz/resources/biomimicry-designlens/
8 "Living Building Challenge," 2009, https://living-future.org/lbc/
9 "International Living Future Institute," 2009, https://living-future.org

> (D5): We work with ‘champion’ organisms [species that are particularly adept at surviving in a given habitat] where necessary, so it really depends on the project and what kind of design challenge we are working with. For example, we look at ‘champion’ organisms that show aspects of cooling or heating, and we also look at larger ecosystem principles or biological principles of patterns that exist.
>
> We often contact other industry professionals. We also access to case studies. The Biomimicry Institute is put forward as a kind of the leader—and yes, it is—but there are others working in this space.

Theme 4: Opportunities and Existing Gaps

For the fourth finding, architects identified opportunities with respect to the future of biomimetic design and improvements that could be made to encourage a broader use of biomimicry in the architectural community. The respondents also discussed existing gaps in biomimetic design processes that tend to hinder biomimetic design implementation. This category has been subdivided into four subcategories: education, biologist at the table, a common language among professionals, and encouraging designers to become engaged.

Education

> (D1): I think a big shift needs to happen professionally in the field, but also education-wise. And [this is] not just in design education programs, but in K-through-12 education. When we design anything, we need to think about function, and that's what we apply to any project that we work on: what is the is function?
>
> (D2): I hope that [biomimicry] is taught at most architectural schools as a class or a studio, just to get people aware of it, and then I hope this education is broadened in terms of architectural students needing to take introductory biology courses.
>
> Education a really big component of teaching biomimicry and exploring all the awesome organisms that are out there, because if you don't have a science background, you're not going to come in contact with this kind of information.

(D3): I think we need more education at the moment. I teach in a biomimicry master's program, and my students have to go out and create their own positions, because [biomimicry] is not mainstream yet in that companies search for [this training]. Right now, there are trailblazers trying to create those positions.

(D6): It's important to bring biomimicry into the education system. It would be really nice already [to start] from elementary school and gradually increase the depth of understanding, and then, [we can consider] possible applications at the university level.

(D7): I think professors and universities are interested in including [biomimicry] in their curriculum. They are interested in knowing a little more about it and in introducing concepts of biomimicry to their students. They are also interested in tackling overwhelming design challenges with a biomimetic approach and adding this to criteria for assignments.

(D8): We need to [teach] design from day one. Kids should be fluent in design [principles], and this is something we should nurture. [Design] should be a required course, like math. It's a way of thinking and a way of being in the world in that everything is a design problem.

Biologist at the table

(D1): What I love about the green building industry and the USGBC[10] is its integrated teams. These teams include engineers, architects, and owners—[this involves] getting more people to the table. You also need primary subcontractors, the plumbing lead, the mechanical system lead—not just the engineer, but the people who are working in the field, because they bring a different level [of expertise]. And then, if we want to fit in better, then we need biologists and foresters there—those people need to be at the table too.

(D2): It's important to bring biologists to the design table, because having a background in architecture, I definitely understand that process… but I don't have a background in biology.

(D4): I'm always trying to either source scientific papers or to talk with scientists. When I hit a wall and I don't understand what I'm reading, I [call on] my colleagues and friends who are scientists. I think this is very critical and important because I don't believe in biomimetic design without [having a] biologist at the table.

10 "U.S. Green Building Council," 1993, https://www.usgbc.org

(D6): As long as [a biomimetic design process involves] just an architect with an education in architecture without addressing any of the biomimetic issues, then I think it will be a struggle to really adopt these approaches quickly without [having] experience in biology or trying it out before.

(D7): One of the key members of the design team in my firm is [always] a naturalist or a biologist.

(D8); What's desperately needed are phenomenal resources from the scientific community. We are in desperate need of scientists to distill [information] and think in terms of how their research would be applied to inform someone who is actually designing. There is a need for more collaboration; it's essential for scientists to be at the table. We have to gain literacy in the natural world and literacy in the scientific world so that we can communicate at that level and there is not a divide between us and them.

Common language among professions

(D1): It amazes me that the more different fields I become emerged in, I realize that [biomimicry involves] the same process…. Different industries and disciplines have different languages, but it's the same process at the end of the day. I think it's important, for the [architectural] field as it grows and for people's comprehension, to keep to one definition of biomimicry.

(D2): Biomimicry is all about the translation from the language of biology to the language of design. The main gap is to [encourage] different disciplines to begin talking with each other because right now everyone [i.e. many professions] operate independently from each other.

(D8): It's about adding another section to the primary piece of research—translation. What does this [i.e. design conclusions] actually mean? What were my findings? What was the actual mechanism or the process or the system, in really kind of accessible language, that allows people like myself to take [information] and translate it into the solution space in design?

We're busy drawing from [natural systems], and our tools are not equipped to do that. It would be amazing to have a library of mechanisms that [could] translate between scientists and the design community so that we can take parametric models and bring them into our design space and inspire solutions.

Encouraging designers to become engaged

> (D1): Finding tools and processes for people to use—such as checklists or rating systems—is important. We're very competitive in the field of architecture and it is [important to] find those things that will engage people.
>
> (D2): For example, the Leadership in Energy and Environmental Design program, [LEED], has gained traction because the government compelled public projects to have LEED ratings. I believe this will help propel that [biomimicry] metric. So, sadly, we might need to be forced in order to make biomimicry happen.
>
> (D8): The bottom line is that we need more case studies and a vehicle for disseminating those studies. It's not an approach in which you tell all the shiny happy stories. It's about successes, and most importantly failures, and the processes of biomimetic design that got you there—what worked and what didn't work. Part of systemic change involves deriving the humility that allows us to see beyond ourselves and immediate gratification and to see the rewards associated with achieving something. [This involves] seeing ourselves in a larger context, rather than making decisions based on an election cycle or a funding cycle. It's thinking multiple generations ahead and accumulating knowledge and expertise across time.

Theme 5: Constraints

For this final key finding, participants discussed the constraints of using biomimicry in architectural design. From the eight designers interviewed, six were able to offer key insights into the constraints in using biomimetic design. This category has been subdivided into two subcategories: time/budget, and cultural/social factors.

Time/budget

> (D1): I think we are all learning the constraints and learning takes time, and how I'm paid is for my time, and there's a budget. Sometimes, what happens is I know what the budget is and what we're allowed to spend on something. So that limits the amount of time that we can [use for] research….
>
> (D2): In the architecture field we need to do a lot more. We have a lot more responsibility. It's not necessarily just designing buildings and coming up with details. If you look at drawing construction document sets

from 50 years ago, they are around 10 pages. But now, [drawing sets] are hundreds of pages, so we have to do so much more. But clients don't want to pay as much and want [projects] faster. Architects lack time and funds.

We just did a market validation survey. We asked a bunch of designers why they consider their firms to be innovative and if they would be interested in using biomimicry. [Also, we asked] if they can define what biomimicry is and what stops them from doing innovative sustainable things. Over 90% of firms said cost.

[Biomimicry] is just not accepted yet, because we're still in this old paradigm of only looking at design in terms of profit and needing to do certain things. But, at the end of the day, all that really matters is the economics of it. That's really how we've been operating as a species for a while. But we need to start looking at the triple bottom line, which is people, profits, and the planet.

(D4): Like any research and development [process], [biomimicry] takes time. So, with research, it comes very early in the curve of innovation and then takes a lot to commercialize something. I started studying sustainable design over 20 years ago, and today we are just starting to say that climate change is happening.

You also have a budget; you have all the traditional elements that you really cannot substitute with bio-inspired [thinking]. So, bio-inspired [thinking] involves intrinsically including but not eliminating [these factors].

(D5): For a traditional architecture firm, [biomimicry] might seem like an increased investment, knowing that they will need to spend more money on the number of hours people spend on the research. And you come across dead ends quite a lot because not enough biological research is available. So that is definitely one kind of constraint.

[Design for] larger scales can be hard because that means a lot more money invested on [the client's] part. That's exactly when budget constraints come in. But for smaller [projects], which are either already in the concept stage or proof of concept stage, it is easier, because then you can convince [clients] that this is doable.

(D6): [Biomimetic processes are] more about skill, culture and how we were educated. I think over the years this could change, but it cannot change quickly.

(D7): [Biomimicry] takes a fair amount of funding. I think the affordability issue is huge and is a property owner's focus.

(D8): We are very much trying to work within the normalized process that we see for the practice of architecture and the practice of design, and that is driven by two things. One is the fee structures that we operate under and the kind of timeframes and expectations that clients have. Very few people are looking to innovate—these are unusual clients. We do have some, but it's an unusual client that will pay for that kind of additional approach. The second is the insurance industry, and the reason for this is the liability. That's a reality—we have to have errors and omissions insurance. We also don't always have time to draw on nature's wisdom, and we do not have the tools to allow for that, but we need access. We need to be able to move forward quickly to translate that into ideation for the built environment.

Cultural/social factors

(D1): The majority of those projects are client driven. That means you have a client who knows about [biomimicry] and is willing to do a project. Pretty much everything else—which would be the other 90%—is if you, as a biomimicry professional, can be clever enough to find ways to integrate it.

When I got my certification in biomimicry—and this happens to a lot of my colleagues—we're so ingrained in it. We go out and we think it is great… but how do you engage people? How do you bring this language into what you're doing? And we all try to do it in much the same way…. And the reality is that it doesn't work that way.

Even if you bring it up [to clients] in different ways and try to explain it, people glaze over and they just don't get it. You can tell them stories and give them examples, but very few people will really resonate with it in a way that they see how it could be applied to whatever it is you're doing.

So, I think I can say the majority of us, like 60-70 percent at least, have really struggled to find the right way [to support biomimicry]. Our training [in biomimicry] addresses this a lot, but it isn't until you go back and focus on what you're doing that you can really integrate it into your work.

I think it [concerns] a lack of knowledge, education, understanding, and perception. We, especially here in America—and I'm stereotyping—we think we're separate from nature. It's us and then there's nature—that's the biggest problem. We don't even realize that our individual body is an entire ecosystem. we don't know that we have face mites that are critical to our immune system, that we are covered with living things. Inside us are these complete systems that are living…. We don't get it, and so I think that's our biggest challenge. I think that's the biggest thing we need to do—to get people on board with the understanding that we're not separate from nature. We are nature and everything we're doing impacts the air, the water, and comes back to us. We're seeing that now with plastics and the pollution in the oceans, and we are nature. That's the biggest gap.

(D2): Nature likes to solve problems on a nanoscopic level. So, a lot of it is material-based biomimicry that can be applied to systems thinking [processes] which is something that we can incorporate. Then, it's still biomimicry, but it's using the infrastructure of a fossil-fuel economy. So, you know, it's a very deep rabbit hole of thinking that, yes, I've made a biomimetic product, but the old machinery that made it uses fossil fuels, and all the employees who work in factories drive cars to get there. So, we're not there yet.

In terms of getting clients to say yes, come into my firm and consult—they have to take a leap of faith because it's not like this technology has been proven and there are binders of technical data that say if you do x y and z, you'll save 10%.

(D3): I see the pressures that we have these days and the desire to be more sustainable. I see more investment into [sustainability], and once we get past some of the economic challenges, I think people will see the benefit of biomimicry. And if they invest in [biomimicry], then we have more power and stamina to take it through to the market, because there's always all these hurdles to get something to the market.

(D4): There are many gaps [to implementing biomimicry], and mostly it is societal. People or individuals. They love to drive their Tesla, but then they like to go home to their brick house with traditional furniture and there is a coziness there. So, there are a lot of gaps that we need to fill.

Biomimicry is also used a little bit as a buzzword. So, people very often still do the same old stuff but call it something new.

(D8): I think there needs to be systemic change, and by that, I mean that our industry [architecture] is very broken because it hasn't evolved to really address the significant challenges that need to be addressed in the built environment. So, for the simple things, such as the elimination of greenhouse gas emissions in our built environment, our industry is not skilled in those areas, yet that is a fundamental skill set that is desperately needed. From a systems point of view, [this concerns] how we are taught and trained and how we engage in the design process to deal with the massive regulatory changes that are afoot as well as climate change mitigation. That's a fundamental change in methodology because if you keep using the same methods you are not going to get new solutions.

The whole development industry is broken on many levels, and the regulatory environment that we have to feed into is very broken. There's the intent behind regulations which is often not understood and, in many cases, not relevant anymore. So, we are having to come up with design solutions that are consistently undermined, such as creating healthy environments. If our materials are required to be fire retardant, they're full of chemicals, which undermines our very well-being. This keeps us safe, but it is going to kill us. What are we solving for really undermines that kind of open creativity.

One of the plagues of our industry is the sensitive proprietary [nature] of our intellectual property. It's very American. We have to share our case studies and our stories, and we have to create an open network of ideas.

Discussion

This study investigated how designers employ principles of biomimicry and the challenges they face in implementing those principles in the biomimetic design processes. The study results identified relationships between various designers' use of biomimetic principles in their design processes, the challenges they faced in doing so, and the opportunities they identified for the future of biomimetic design in architecture. These findings were grouped into five main categories: the biomimetic design process, systems thinking, resources, opportunities and existing gaps, and constraints.

Many key insights emerged from the interview data analysis. First, the data show that nearly all interviewees deemed the biomimetic design process to be iterative and one that requires ongoing maintenance, even after construction completion. This corresponds with the biomimetic design process envisioned by the Biomimicry Institute, which stipulates that this process as being more iterative than that of the traditional architectural design process (Biomimicry DesignLens, 2015). The participants also identified looking to biological systems and principles for solutions, particularly in the beginning phases of the biomimetic design process. Several designers would go on to further state that the question of design must be redefined from "what do we want our buildings to be?” to “what do we want our buildings to do?” Further, architects identified the need to envision future architectural designs in the context of the built environment, rather than in isolation. This notion is supported by Mazzoleni (2013) in which she argues that biomimicry is an opportunity to view architecture as a part of the broader ecosystem, rather than an isolated instance in the built environment (Mazzoleni, 2013).

Several respondents were able to identify the resources they or their organization relies on to implement biomimetic design principles. Most designers identified the Biomimicry Institute’s Life’s Principles (2013) to be one of, if not the most, well-used resources for biomimetic design. Here, an unexpected finding was that almost all designers identified Janine Benyus and her work in the field of biomimicry to be catalysts for their careers in biomimicry, but when it came to identifying their resources, almost none of the designers identified the Biomimicry Institute as a main resource. Instead, most designers felt that it provided great examples of biological processes but failed to translate those processes into something that could be implemented in design. This result is particularly interesting, as Benyus and the Biomimicry Institute are considered to be the leaders in the field of biomimicry.

The third key set of insights involved existing gaps in employing biomimetic design approaches and opportunities to further the field. Almost all designers identified increased education in biomimetic principles, from k-12 all the way to the university level, as a major component for the future of widespread biomimetic design implementation. Most designers also felt that some form of biomimicry should be taught at the university level, whether it was an introductory course in biology or a studio with a focus on biomimicry. This would allow for biomimetic knowledge to grow from the university to the professional level as designers enter the architecture field and are able to implement their knowledge of biomimicry to make systemic changes.

Fourth, the respondents identified the need for a connection between the various professions, especially with those in the scientific community, and discussed the need for this knowledge to be accessible to designers who wish to employ biomimetic approaches. This finding corroborates those in the literature, as Bay (2010) and Zari (2015) discussed the need for collaboration amongst a range of professionals to ensure that biomimetic design goals can be successfully implemented.

The respondents also stated that there is a need for design tools and software applications that can aid in the development of biomimetic design solutions, such as drafting tools, research software, and databases that can help designers to translate principles of biology to design. This finding was unexpected, as none of the designers stated that they use existing biomimetic design processes in their work, such as Hastrich's Biomimicry Design Spiral (2014), the Biomimicry 3.8 Toolbox (2006), or BioTRIZ (2008).

Lastly, the respondents identified constraints they felt inhibited the field of biomimicry as it pertains to architecture. One of the main constraints were time and budget, as many designers stated that biomimetic design processes require a much more involved research component than traditional architecture approaches requiring additional funding and time. Other common constraints that the respondents identified to widespread biomimetic design implementation were cultural and social barriers. Many of the respondents stated that finding clients who are willing to invest the time and money that biomimetic approaches require is very rare, as clients are unaware of these methods or are unwilling to fund them. Finally, the participants identified the possibility of government regulation in the built environment to set biomimetic standards on new construction builds in order to fully implement the use of biomimetic design in regard to architectural design.

Research Limitations and Recommendations for Future Research

Limitations on this research study included constraints on time, funding, and resources. First, the researcher conducted this study over an 8-month period from August 2019 to March 2020, which limited the time that could have potentially been invested into the research process. Second, while this project was funded in part by a grant from CU's Undergraduate Research Opportunities Program (UROP) (Reference Number 4412922), limits existed to what could be spent on software and travel.

Future studies in the field of biomimicry should expand this research to include the perspective of many more designers and allied professionals in the engineering and construction fields. This research could also be built upon by studying the perspectives of other aspects of biomimetic design has such as clientele who seek to employ biomimetic design, as well as investigating government and city regulations that have allowed for or inhibited successful sustainable design initiatives in the past, such as LEED. This research could be built upon even further by providing a foundation for informing an all-encompassing biomimetic design process to which other designers can rely on, as well as build the premises for innovative biomimetic design tools to aid in widespread biomimetic design implementation for the future.

Conclusion

These results provide new insight into the process of biomimetic design from the perspective of the designer. As discussed in the literature review, to date most studies in this area have focused on precedent designs as a means to guide biomimetic processes while excluding the processes and approaches of designers themselves. As a result, this study has helped to create a clearer understanding of the perspectives and processes of biomimetic design with respect to architecture.

These results point to research and design imperatives that are crucial for the development of biomimetic design processes as they pertain to architecture. Designers identified that there is still the need for a biomimetic design process to which designers can rely on when creating their own designs. Design tools that cater to biomimetic design will be critical for the future, as well as the need for extensive collaboration between a set of diverse professions and the ability to share the array of experiences and knowledge gained by individuals in the endeavor to create biomimetic designs. The research findings suggest that broader implementation of biomimetic design at larger scales will occur through three means. First, biomimetic approaches must be implemented from a professional standpoint, i.e. from designers and firms themselves. Second, clients need to be convinced that biomimetic methods are worth the extra investment in time and budget. And third, governments and agencies should begin to mandate and codify biomimetic design regulations and standards at all levels to support the use of biomimetic approaches. By better understanding the perspective of the designer through these observations, insights, and guidelines can biomimetic design be used as a widespread solution for a greater connection between the built environment and the natural genius in which it is associated.

Key Conclusions & Implications for Architects

1. Biomimetic design is an iterative process that requires ongoing maintenance, even after construction completion.

   Implications: Architects should look to add ongoing maintenance fees for monitoring, testing, and maintenance to their contracts for biomimetic projects.

2. Biological principles and solutions are often identified in the beginning phases of the biomimetic design process.

   Implications for architects: Architects should look to add additional time and funding for research in biological principles.

3. Biomimetic design requires designers to take into account the natural context of the site, rather than envisioning it as isolated and thus removed from the environment in which it is situated.

   Implications for architects: Architects should look to implement more research and design imperatives that take into account the natural and built context into which their design proposal is taking place.

4. The Biomimicry Institute's Life's Principles (2013) is the most relied upon resource applied by designers when implementing biomimetic design principles.

   Implications for architects: Architects will need additional resources when implementing biological principles in architecture and the Biomimicry Institute's Life's Principles may serve as an introductory resource.

5. To further the field of biomimicry as it pertains to architecture, there is a need to implement educational curriculum about biological solutions at all education levels, from K-12 all the way through to university.

   Implications for architects: Architects who are looking to implement biological principles in architecture will need additional education in biology. These architects and firms will also need to look for future employees who have this education and qualification.

6. The need exists for collaboration amongst a diverse set of professions, especially that of the scientific community, as well as the need to share knowledge gained through the process of biomimetic design.

   Implications for architects: Architects will need to broaden their community of professionals to encompass many more diverse experts, especially those in the biological sciences, to ensure that biological principles can be successfully implemented in architecture.

7. The need exists to develop design tools and software applications that can aid in the development of biomimetic design solutions, such as drafting tools, research software, and databases to translate the principles of biology to design.

   Implications for architects: Architects will need to bring together their resources and expertise that can then be applied to creating new and biomimetic design tools and software databases to ensure that the principles of biology may translate to the realm of design.

8. Constraints as they pertain to biomimetic principles in architecture fall into two categories; time/budget, and social barriers. Research in the beginning phases of the biomimetic design process require more time and funding than the more traditional practice of architecture, as well as there are few existing clients who are willing to invest the time and money into biomimetic design innovations.

   Implications for architects: Architects will need to account for additional funding and time when working with biological principles, as well as be able to successfully convince and attain clientele who are willing to put forth this additional funding and time.

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Appendix A: Interview Questionnaire

1. What is your background and education in design, and specifically biomimetic design?

2. What is your job title and place within your current firm or company?

3. In your own terms, how would you define 'biomimicry'?

4. Can you please tell me about your experience with biomimetic design?

    a. How did you first learn about the biomimetic design field and what got you interested in pursuing this type of design?

    b. What is your typical scale of work and what biomimetic principles do you generally incorporate in your practice/work?

5. Would you please tell me more about your/your firm's/your company's biomimetic design process and how you employ this process in your work?

    a. Please name a few projects in which you or your firm/company has employed biomimetic design processes. Do you think the use of biomimetic design in any past or recent projects was a success? Why or why not?
        i. Follow Up Question: If so, what made it successful or unsuccessful? Are there any specific examples?

    b. Typically speaking, what steps do you (or your firm/company) take to employ and deploy biomimetic design in your work?

    c. What are the constraints to using the biomimetic process in your work? (e.g. clients, budget, climate, hydrology, soils, age groups/abilities, or physical constraints)

    d. What are some of your key resources you use to inform your biomimetic design process? (i.e. social, biological and natural processes, etc.)

    e. What are some of the existing gaps in biomimetic design and gaps in biomimetic knowledge from your perspective?

    f. From your perspective, what are some of the challenges or hinderances to widespread biomimetic design implementation in architecture?

    g. To you, how might biomimicry fit into the conventional design process?
        i. Follow Up Question: Does your biomimetic design process differ from more conventional design processes? Does it remain the same?

h. What do you see as the future of biomimetic design?
    i. Follow Up Question: What do you see as the role of biomimicry in the future of design, and do you see other colleagues and professionals employing this process more in the future? Please provide specific examples.

6. Is there anything else you would like to discuss regarding your/your firm's biomimetic design process that you have not already covered?

Appendix B: Interview Participants

1. Dr. Lidia Badarnah; Architect and Researcher in Biomimetics. Senior Lecturer in Architecture at the University of the West of England, Bristol, UK.

2. Michelle Fehler; Designer and Researcher in Biomimetics. Clinical Assistant Professor in Visual Communication Design at Arizona State University, Tempe, AZ.

3. Cynthia Fishman; Practicing Architect specializing in Biomimicry. Director and Founder of the Biomimicry Design Alliance, Denver, CO.

4. Christine Lintott; Practicing Architect specializing in Biomimicry. Principal and Founder of Christine Lintott Architects Inc., Victoria, BC.

5. Colleen Mahoney; Practicing Architect specializing in Biomimicry. Principal and Founder of Mahoney Architects and Interiors, Petaluma, CA.

6. Ilaria Mazzoleni; Architect and Researcher in Biomimetics. Principal at IM Studio Milano, Los Angeles, CA.

7. Asha Singhal; Architect and Researcher in Biomimetics. Design Lead at Biomimicry Frontiers and Research Advisor of Sustainability at Biomimicry Academy, Berlin, GER.

8. Cheryl Spector; Practicing Architect specializing in Biomimicry. Biomimicry Specialist at Biomimicry Colorado and Principle at Spector and Associates, Denver, CO.

Appendix C: IRB Approval

Office of Research Integrity
UNIVERSITY OF COLORADO **BOULDER**
INSTITUTIONAL REVIEW BOARD

Institutional Review Board
563 UCB
Boulder, CO 80309
Phone: 303.735.3702
Fax: 303.735.5185
FWA: 00003492

APPROVAL

11-Nov-2019

Dear Danielle Brodrick,

On 11-Nov-2019 the IRB reviewed the following protocol:

Type of Submission:	Initial Application
Review Category:	Exempt - Category 2 -
Risk Level:	Minimal
Title:	Implementation of a Biomimetic Design Process to aid in the mitigation of Interior Air Pollution within the Built Environment
Investigator:	Brodrick, Danielle
Protocol #:	19-0569
Funding:	Non-Federal
Documents Approved:	19-0569 Protocol (11Nov19); Brodrick_Danielle_InterviewQuestions.docx; 19-0569 Conent Form (11Nov19);
Documents Reviewed:	Protocol; HRP-211: FORM - Initial Application v9;

The IRB confirmed the Exemption of this protocol on **11-Nov-2019**.

You are required to use the IRB Approved versions of study documents to conduct your research. The IRB Approved documents can be found here: Approved Documents

In conducting this protocol you must follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,
Douglas Grafel
IRB Admin Review Coordinator
Institutional Review Board

This letter has been electronically signed in accordance with all applicable regulations, and a copy is retained within the University of Colorado Boulder's IRB records.