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Biomimicry and Innovation in Sustainable Design: Understanding its Innovation Supporting Characteristics Compared to Ecodesign

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Résumé

Depuis la dernière décennie, le biomimétisme est une discipline en plein essor dans le monde du design durable. De plus en plus, cette stratégie prend place dans plusieurs facettes du design, que ce soit dans le design industriel, dans l'architecture ou encore dans le design urbain. Le livre de Janine Benyus intitulé *Biomimétisme: Quand la Nature Inspire des Innovations Durables* (1997) est largement reconnu comme étant le catalyseur de la stratégie et comme l'indique le titre du livre, le biomimétisme est très souvent associé à l'innovation.

Le but principal de cette recherche est de mieux comprendre le lien entre le biomimétisme et l'innovation. Cette recherche sur le biomimétisme comprend un objectif mineur et deux objectifs majeurs. Le premier objectif cherche à comprendre le véritable lien entre le biomimétisme et l'écodesign. Le second objectif vise non seulement à valider la théorie selon laquelle le biomimétisme est une stratégie menant à des solutions de design innovantes, mais également à établir quels types d'innovations ont été générés par cette stratégie. Finalement, le troisième objectif est d'identifier les aspects du biomimétisme qui mènent à des solutions de design innovantes. Pour accomplir ces objectifs, cette recherche utilisera une approche qualitative supportée par des études de cas et une revue de littérature.

Afin de contextualiser les deux derniers objectifs, cette étude établit que le biomimétisme et l'écodesign sont des stratégies complémentaires plutôt qu'en compétition. Les conclusions de cette recherche démontrent que la théorie proposant que le biomimétisme soit une stratégie d'innovation est valide et que la discipline est surtout apte à générer l'innovation radicale. Finalement, la recherche indique que l'analogie de distance et la transdisciplinarité sont les deux aspects du biomimétisme aidant à produire des solutions de design innovantes.

Le biomimétisme est mieux connu dans le contexte du design durable et cette recherche permet de mieux comprendre le biomimétisme dans le contexte de l'innovation. Considérant que le biomimétisme est une discipline qui suscite beaucoup d'intérêt des milieux académiques et privés, cette recherche participe à l'expansion de la connaissance sur le sujet et propose de nouvelles pistes de recherche sur le biomimétisme et l'innovation.

Mots-clés: Analogie, biomimétisme, bioinspiration, design, design durable, écodesign, innovation, transdisciplinarité

Abstract

Biomimicry is a growing design discipline that has gained much recognition throughout the last decade in sustainable design. The bioinspired design approach is finding its way across design disciplines from product design to architecture and urban design. The book, *Biomimicry: Innovation Inspired by Nature*, by Janine Benyus is credited to launch the design movement and as indicated in the title, biomimicry is often presented as a strategy for design innovation.

The goal of this thesis is to gain a better understanding of biomimicry in the context of innovation. This study has two principal objectives and a minor objective. The first objective aims at understanding the correlation between biomimicry and ecodesign. The second objective is to validate the notion that biomimicry is a strategy supporting design innovation by establishing what kinds of innovation has been spawned by this approach. And finally the third objective is to identify the aspects of biomimicry that lead to innovative design solutions. To fulfill these objectives, this research will employ a qualitative approach and supported literature review and case studies.

To contextualize the last two objectives, the study clarifies that the qualitative approach of biomimicry and the quantitative approach of ecodesign are actually complimentary and thus together form a more comprehensive approach to sustainable design. The findings of this study also validate that biomimicry supports innovation, specifically radical innovation. To finalize, the study demonstrates that the two aspects of biomimicry responsible for innovation are the use of distant analogy and transdisciplinarity.

Biomimicry is typically observed in the context of sustainability and this thesis aims to observe and understand biomimicry in the context of innovation. Given the growing interest in biomimicry by academia and the private sector, this research also will propose new paths of research in biomimicry and innovation and thus hopefully provoke new insights on the subject.

Keywords: Analogy, biomimicry, bioinspiration, design, ecodesign, innovation, sustainable design, transdisciplinarity

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List of Acronyms and Abbreviations

BaDT	Biologist at the Design table
BDP	Biomimicry Design Process
BHA	Bionic Handling Assistant
BID	Biologically Inspired Design
CDC	Center for Disease Control
CDP	Conventional Design Process
CFP	Columbia Forest Products
CEO	Chief Executive Officer
CMO	Chief Marketing Officer
CTO	Chief Technology Officer
EDA	Ecological Design Association
EPD	Environmental Product Declaration
EPS	Extracellular Polymeric Substance
FBEI	Fermanian Business & Economic Institute
HAI	Hospital Acquired Infections
HVAC	Heating, Ventilation and Air Conditioning
IARC	International Agency for Research on Cancer
ISO	International Organization for Standardization
LCA	Life-Cycle Assessment
LCD	Life Cycle Design
L-DOPA	L-3,4-dihydroxyphenylalanine
MAP	Marine Adhesive Protein
MIT	Massachusetts Institute of Technology
R&D	Research and Development
SETAC	Society of Environmental Toxicology and Chemistry
STEM	Science, Technology, Engineering and Mathematics
STEAM	Science, Technology, Engineering, Arts and Mathematics
TAC	Toxic Air Contaminant
UF	Urea Formaldehyde

UNEP	United Nations Environment Programme
VOC	Volatile Organic Compound
WWF	World Wide Fund for Nature

Je dédie ce mémoire à tous les designers, scientifiques et artistes dédiés à créer un avenir durable.

I dedicate this thesis to all the designers, scientists, and artists who are actively redesigning the future sustainably.

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I want to particularly thank my research director M. Sylvain Plouffe for accepting to be my research director, for his patience, guidance and conversation, especially all the off subject discussions we had on our meetings. They were greatly appreciated. I'd also like to thank Isabel Prochner, Dann Godin and Andréanne Milette for the comradery through this academic journey, the discussions and advice. They often really helped putting things in perspective, especially when I changed directions on my research subject. I'd like to also thank the teachers and staff of the Université de Montréal, precisely Mr. Pierre DeConinck for convincing me to enter the program when I came to him inquiring about it, Mme Simone Zriel for her generosity and patience and Mme Mirlande Félix for the conversations and encouragement.

Last but most importantly, I'd like to thank my parents, family and close friends for their support.

Merci à tous.

“I would feel more optimistic about a bright future for man if he spent less time proving that he can outwit Nature and more time tasting her sweetness and respecting her seniority.”

-E.B. White

“Those who are inspired by a model other than nature, a mistress above all masters, are laboring in vain.”

-Leonardo Da Vinci

Introduction

'Human subtlety will never devise an invention more beautiful, more simple or more direct than does Nature, because in her inventions, nothing is lacking and nothing is superfluous."

-Leonardo Da Vinci/ artist, engineer & inventor

René Descartes represented a mindset responsible for the conceptual separation of mind and body, humanity and nature, and subject and object. A mindset based on binary thinking (Nicolescu, 2012), on the concept of dualism, of mutually exclusive categories: the basis for a reductionistic science of objectivism (Wahl, 2006). This reductionist mindset has been perpetuated well into the industrial revolution/modern era and has led to further perceive nature as a commodity, as an inventory, as a resource only to be exploited, thus leading modern society to destroy more of nature than the preceding history of mankind. Over the generations, people have moved away from the countryside to migrate into the city which further strengthened the culture and mindset of separateness and disconnect from the natural world. The industrial revolution has provided modern society with undeniable advancement and has greatly expanded the possibilities for the material development of humankind and continues to do so today, but at a severe price. It has resulted in environmental degradation, the deterioration of the environment through the depletion of resources, the destruction of ecosystems, life supporting systems and the extinction of wildlife (Hawken, Lovins, & Lovins, 1999, p.2). Consequently, human industry functions through a system of production that attempts to work by its own laws which disregards those of the natural world, disconnected from the laws which have permitted the natural world to sustain life for 3.8 billion years.

As Albert Einstein's dictum so cleverly says "Problems cannot be solved with the same mindset that created them". A new industrial revolution is now making its way with a strong focus on sustainable design strategies, a new way to close the gap between our technology and nature by encouraging a rethinking of industry which would create a kind of symbiosis between the technosphere and biosphere. It not only represents a new paradigm in how to design the built environment but also one where previously disconnected disciplines are now overlapping, converging and looking into the natural world for answers to reverse the unintended consequences of the previous paradigm. The pressing need for resource efficiency is creating new opportunities for practioners across various disciplines such as chemistry, physics, engineering, biology, architecture and industrial design (Hawken et al., 1999). There is an approach which has gained much recognition and momentum in the field of sustainable design: Biomimicry.

Biomimicry is a new approach where designers, engineers and architects are guided by trained biologists to take inspiration and emulate nature to solve human problems by examining its models, systems, and processes. It emphasizes sustainability as an objective by redesigning industrial systems on biological lines, enabling the constant reuse of materials in continuous closed loop cycles. "Doing it nature's way has the potential to change the way we grow food, make materials, harness energy, heal ourselves, store information, and conduct business" (Benyus, 1997, p.2). The emulation of life's strategies and processes is a survival strategy for the human race, a path towards a sustainable future. The paramount approach to create an industrial system which works in symbiosis with the natural world is to create a system that works according to the rules of the natural world, to search for solutions in the 3.8 billion years of R&D life has tried and tested. This approach signals an intention to shift from a mindset of control and manipulation of nature to one of participation with nature. This means that through biomimicry, designers move from a detached, reductionist perspective of being apart from nature to a holistic, participatory perspective of learning from nature.

Biomimicry has gained much notoriety and experienced significant growth in the recent years. It is gaining importance as a wide-spread movement in design for environmentally conscious, sustainable development that often results in innovation. As Rebecca Bagley (2014), a Forbes contributor insisted, "…the discipline is no longer just an academic exercise". It has become an innovation tool that allows companies to develop a new class of products and services. Benyus and its advocates present biomimicry as an approach to generate innovation, claiming that this approach creates innovative sustainable design solutions. Through biomimicry, designers, engineers, and scientists are learning to study the complex structures found in nature to create greener and more efficient products and processes for our homes and lives (Paul, 2010).

Environmentally friendly design is not a new subject so why is biomimicry becoming such a focus for sustainable design solutions as compared to ecodesign? Using biomimicry as a design approach has not only lead to innovative design solutions but also to unexpected results, end results that could seem to counter conventional thinking. To the likes of Dana Baumeister, Paul Hawken, Melissa Sterry and countless other advocates, biomimicry has become synonymous with innovation. Benyus herself stated in an interview on Greenbiz.com "We often come in not even through the sustainability office, but through the innovation office…" (Clancy, 2014). Which leads us to the purpose of this study:

The main subject this research aims to investigate is what makes biomimicry a tool for innovation in sustainable design. The question we aim to answer is: *what supports biomimicry as a strategy of design innovation and what aspect(s) of biomimicry lead(s) to produce more innovative sustainable design solutions as compared to ecodesign?* To answer this question, this research will investigate 1) the relationship between ecodesign and biomimicry, 2) on the types of innovations that have been generated by this approach and validate biomimicry as a strategy of design innovation, and 3) the characteristics of this approach that have led to such results.

This research will take a qualitative approach to answer the question cited above.

Chapter one will look at the context of this research in matters of innovation in design, nature inspired design and biomimicry. Chapter two will deal with the methodology used to conduct this research. Chapter three will compare ecodesign and biomimicry in regards to their philosophy, objectives and the people involved in their respective processes and establish the accurate relationship between the two approaches. Chapter four will be an overview of the most prominent cases used in this study. Chapter five will determine what kind of innovations were produced by using biomimicry. Chapter six will investigate on the aspects identified as the innovation generating elements operating "behind the curtains" in the biomimicry process. And finally, chapter seven will answer the research question and provide general observations.

1 Chapter One_The Context of Biomimicry and Innovation

"The mimesis of other life-forms and the behaviours of those forms, both floral and faunal, has played an integral role in human development- socially, culturally and technologically."

-Melissa Sterry/ design scientist & futurist

1.1 Sustainability is Design's Wicked Problem

Popularized by design theorist Horst Rittel and Prof. Richard Buchanan, a wicked problem is a form of social or cultural problem that is difficult to solve because of incomplete, contradictory, and changing requirements. Design problems are wicked problems in that they have no single correct solution, only good solutions or bad solutions (Buchanan as cited by Colby, 2011).

1.1.1 Ill Conceived Industrial System and Environmental Degradation

The first industrial revolution has provided modern society with undeniable advancement and greatly expanded the possibilities for the material development of humankind but at what expense? The gains in science and technique (hygiene, sanitary, etc.) have allowed, at least in the western world, for an increase in population due in part to a decrease in infant mortality rate and an increase in life expectancy (Bellemare, 2011). The shadow side of the gains made in quality of life through this advancement is that it presently is the cause of countless underlying issues, which ironically, are greatly undermining these very gains.

Hawken, Lovins et al. (1999) state in their book *Natural Capitalism: Creating the Next industrial Revolution* "…since the mid-eighteenth century more of nature has been destroyed than in all prior history. While industrial systems have reached pinnacles of success, able to muster and accumulate human-made capital on vast levels, natural capital[1], on which civilization depends to create economic prosperity, is deteriorating worldwide at an unprecedented rate". As the industrial revolution progressed, humans have adhered to a culture, economic system and industrial infrastructure which has been progressively disconnected from the natural world. It is part of an economic system which has consistently regarded the natural world as an infinite resource only to be exploited. Consequently, human industry functions by means of a system of production (goods, materials, and energy) that attempts to work by its own laws which disregards those of the natural world. It is powered by brutish and artificial sources of energy that are environmentally depleting (McDonough & Braungart, 2002, p.17), hence putting natural ecosystems under tremendous stress and causing severe damages and decline: a single product can create many different kinds of environmental damage. Environmental impacts are typically grouped into three general groups: ecological damage, human health damage and resource depletion (White, St. Pierre, & Belletire, 2013). Climate change, ecotoxicity, depletion of topsoil and fresh water are among the leading environmental impacts of this system.

For instance, according to the World Wide Fund for Nature's (WWF) Living Planet Report of 2013, the numbers showing human impact on the biosphere are rather stark. In regards to environmental damage and resource depletion, carbon dioxide (CO_2) emissions have gone from 14.9 gigatonnes (Gt) in 1970, to 35.6Gt in 2012 and expected to reach 80Gt by 2050. The estimated forest loss in Brazil and Indonesia from 1990 to 2010 was 58.2m ha and 26m ha and resulted in 25.8Gt and 13.1Gt of greenhouse gas emitted respectively. As of 2003, 27% of the world's coral reefs were lost and at this current rate, it is estimated that by 2033 60% will be lost. The Yangtze River dolphin population went from 6,000 in 1950 to 400 in 1980 and as of 2006 has been declared functionally extinct. As of 2013, nesting marine turtles have declined by 90%, in some areas as a result fisheries bycatch. The stress is such that while one Earth could meet our demands for natural resources in 1970, it would require 1.5 Earths in 2013 and 3 Earths in 2050 to meet these demands

[1] Natural capital includes all the familiar resources used by humankind: water, minerals, oil, trees, fish, soil, air etc. But it also encompasses living systems, which include grasslands, savannas, wetlands, estuaries, oceans, coral reefs, riparian corridors, tundras, and rainforests (Hawken et al., 1999, p.2).

(WWF, 2013). These increases on the Earth's resources coincide with an exponential increase in population and accordingly an increase in demand for food and water.

Ultimately the environmental problems which have been generated since the Industrial Revolution is a design problem: it is a failure of design. Notwithstanding that technically, the industrial revolution was not designed: it took shape as gradually as industrialists, engineers, and designers tried to solve problems and take immediate advantage of what they considered to be opportunities in an unprecedented period of massive change (McDonough & Braungart, 2002, p.18). Although the consequences of the industrial system were not designed nor planned, as McDonough iterates "it is ultimately our de facto plan. It may not have been the plan to cause the collapse of ecosystems, environmental degradation, the depletion of resources, and a rise in chronic illnesses but it is inadvertently the result of such a system."

We are however in the early stages of paradigm shift, we have an opportunity to design the next industrial revolution. It is a shift where business leaders, designers, engineers and scientists are beginning to understand the pressing need to redesign industry on biological lines and therefore mitigate the technosphere's impact on the biosphere.

1.1.2 Design and the Environment

"...you have to design with positive principles and positive goals. Modern industrial culture doesn't seem to have principles, except something like: "If brute force isn't working, you are not using enough of it." While its goals are unclear, its de facto goal appears to be to create ecological and human tragedy…" -William McDonough

Alastair Fuad-Luke (2006) suggests in this following text that even in its early beginnings, many people like the members of the British Arts and Crafts movement, recognized the potential damage this emerging system of production could cause, that what we consider as the ecological design movement had its beginnings as early as the mid-nineteenth century.

"*What we now consider as the concept of ecologically sustainable development and design was the norm for many cultures before the industrial revolution. Goods such as furniture and utility items tended to be made locally by craftsmen such as blacksmiths, wheelwrights and woodland workers, from readily available local resources. The* *founders of the British Arts and Crafts movement (1850-1914) were quick to note the environmental degradation associated with the new industries of the times. Their concerns about the poor quality of many mass-manufactured goods and the associated environmental damage prompted them to examine new methods combining inherently lower impact with increased production. For various social and technical reasons, only a small section of society reaped the benefits of the Arts and Crafts movement but the seeds were sown for development of early modernist movements in Europe".*

The problem is that in that era, the subjugation of nature was synonymous with progress. Nature was seen as a boundless and infinite entity to be controlled and impervious to how we interacted with it: our actions were of no consequence to it. It would take more evident and tangible consequences for an ecological design movement to begin to take hold.

Since Rachel Carson's pivotal book Silent Spring[2] in 1962, many have gone on not only to denounce the devastating effects of our systems of production, manufacturing and the disposal of the products we consume but also to devise new ways of manufacturing, producing and building our built environment in ways that will have a lesser effect of degradation on our natural environment; from reducing our consumption of natural resources to the disposal of those products at the end of their useful life. It was however designer Victor Papanek who was the first to recognize and criticize the immense role and responsibility of designers in unsustainable design practices in his 1971 book *Design for the Real World: Human Ecology and Social Change*. Papanek was unabashed about his criticism of the design community's lack of social responsibility and selling out to commercial interest (Fuad-Luke, 2006, p.11). While Carson and Papanek were obvious champions of the ecological design movement, another event, specifically an artifact, is largely overlooked. It is one that helped better put in perspective not only our place in the universe, but to understand that the planet that sustains us, that sustains life is not as limitless as we imagined but rather very finite and that it is inherently in our benefit to begin to participate in preserving it rather than

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[2] Silent Spring, written by Rachel Carson in 1962, is generally viewed as the preeminent work which propelled not only ecological consciousness but accordingly the ecological design movement.

damaging it. That artifact is the Earth Rise photography taken in the Apollo 8 space mission in 1968 (figure 1).

Figure 1. Earth Rise photo taken during the Apollo 8 mission. Retrieved from nasa.gov

In the mid-1980s begins the first consideration of the technical aspects associated with the practice of a design action towards lowering the environmental impact of products (Guidice, La Rosa, & Risitano, 2006), green design emerged as a significant new factor in product and graphic design. Though it is, by no means, fully developed and accepted, and only just recently implemented in design education, there is a broad consensus that environmental issues can no longer be ignored by designers and critics (Madge, 1997). In the early 1990s, these first experiences were followed by a phase of greater understanding of new needs to safeguard resources, which consolidated in a wide diffusion of new ideas and experiences developed with the clear objective of integrating environmental demands in traditional design procedures (Guidice et al., 2006).

In a 1997 Design Issues article, *Ecological Design: A New Critique*, Pauline Madge points to three movements of ecologically responsible design, each representing the evolution of the approach: green design, ecodesign and sustainable design. The transition or evolution from "green" to "eco-" to "sustainable" in the design field represents a steady broadening of scope in theory and practice, and to a certain extent, an increasingly critical perspective on ecology and design (Madge, 1997).

Green design was prevalent in the 1980s, the term was borrowed referencing the politics of the time. There was a growing concern to assure that green design wasn't anti-business, which for many was signaling that green design was beginning to reinforce the very behavior which contributed to environmental issues: consumerism. The movement was very critical of the culture of consumption but some elements of the movement was, for lack of a better word, encouraging it, as long as the products were green. This dichotomy created a deep division within the movement between those who advocated a radical rejection of the status quo, a critique of the paradigm of modern industrial society (dark green), and those supporting the idea of modifying existing institutions and practices (light green) (Madge, 1997). Madge explains that shades of green were used in reference to the degrees of ideology: the darker the shade, the more radical the ideology. Light green and dark green were referred to as "ecocentric" and "technocentric" respectively. Essentially, the former is based on bioethics, putting emphasis on low-impact technology, a concern with the environmental impact of rampant economic growth and instead focusing on morally and ecologically sound alternatives. The latter is based on the idea that environmental damages can be mitigated through science and high technology: an ideology of progress, rationality, efficiency and control (Madge, 1997).

Ecodesign has constantly borrowed ideas and terminology from ecology and environmentalism (Madge, 1997). The first use of the term "ecodesign" came about in the late 80s by the Ecological Design Association (EDA), whose journal was aptly called *Ecodesign*. The EDA defined ecodesign as "the design of materials and products, projects and systems environments communities which are friendly to living species and planetary ecology." Ecodesign is also defined as the use of ecological design principles and strategies to design our built environment and our ways of life so that they integrate benignly and seamlessly with the natural environment that includes the biosphere, which contains all the forms of life that exist on earth (Yeang, 2006). ISO/TR 14062 defined ecodesign as an activity that integrates environmental aspects into product design and development. The integrated activities led to continual improvement of the environmental performance of the product through technological innovation (ISO, 2001). That era represented an evolution, a broader understanding of how to better resolve the environmental issues related to design/industry and also to represent a departure from the consumerism-enabling approach of green design: a shift from product-centric to system-centric. Out of that movement, various forms/strategies of responsible design appeared such as design for disassembly which would ease the recuperation of a product's components for recycling (see figure 2).

Figure 2. Steelcase Think Chair. Designed for disassembly and recyclability. The chair is 99% recyclable. Retrieved from www.notcot.com

Sustainable design is a concept which was associated with the most radical theories of the 70s and resurfaced as a prominent theory in the 1990s. Sustainability is rooted in a concept of "futurity": "…meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). Wahl and Baxter (2008) define sustainability as "*the understanding that a complexity of interrelated ecological, social, cultural, economic, and psychological problems interact and converge in the current crisis of our unsustainable civilization*" (as cited in Colby

2011). In terms of human development, or sustainable development, as it is known, it is a concept that recognizes that human civilization is an integral part of the natural world and that nature must be preserved and perpetuated if the human community itself is to survive (Colby, 2011). When applied to design, this reintroduces the notions of ethical and social responsibility and the notion of meeting the needs of future generations represents one of time and timescale (Madge, 1997). The relation to products and consumption is also redefined. Products are redefined in terms of categories such as "service", "dematerialization", as well as life cycle design and longevity (Madge, 1997).

The great disconnect about this current industrial and economic system that was recognized by the Brundtland report (1987) as well Herman Daly, an American ecological economist in his book *Steady-State Economics* (1977) is the paradox of unlimited economic growth in the face of limited resources. Daly warns that the global economy is now so large that society can no longer safely pretend it operates within a limitless ecosystem (Colby, 2011) just as the early industrialists once believed. Growth means to increase in size through the addition of material while development means to bring gradually to a better state (Colby, 2011). It is absolutely impossible to have infinite growth from a system (economy/industry) which operates within a finite parent system (biosphere). This fallacious notion is still perpetuated and ingrained within our economic system and business schools.

In the book, Natural Capitalism, the authors determine four central strategies to achieve a sustainable economy and future: 1) radical resource productivity, 2) service and flow economy, 3) investing in natural capital and 4) biomimicry (Hawken et al., 1999, p.10).

1.2 A Brief History of Biologically Inspired Design

1.2.1 Nature as Model of Aesthetic and Function

Humans have long been inspired by the natural world to guide them in creating anything from art to new technologies. The desire to follow nature, to adhere to its underlying forms in the pursuit of harmony, can be traced back to antiquity, to the writings of Vitruvius, as well as Goethe's work on morphology and the Romantic notion that certain truths were observable in nature and unknowable to reason (Myers, 2012). Ancient Greeks have looked to natural organisms as offering perfect models of that harmonious balance and proportion between the parts of a design which is synonymous with the classical ideal of beauty (Steadman, 2008). For instance, in ancient Greek architecture, the Ionic and Corinthian columns were inspired by the forms of a ram's horns and leaves respectively. The spiral shape or vortex was of tremendous significance to the Greek due to its ubiquitous occurrence in horns, shells, and flowers. This phenomenon was also of great interest to early mathematicians such as Euclid due to its ubiquity in nature and relationship to the ideal of beauty; also known as the Golden Ratio or the Divine Proportion.

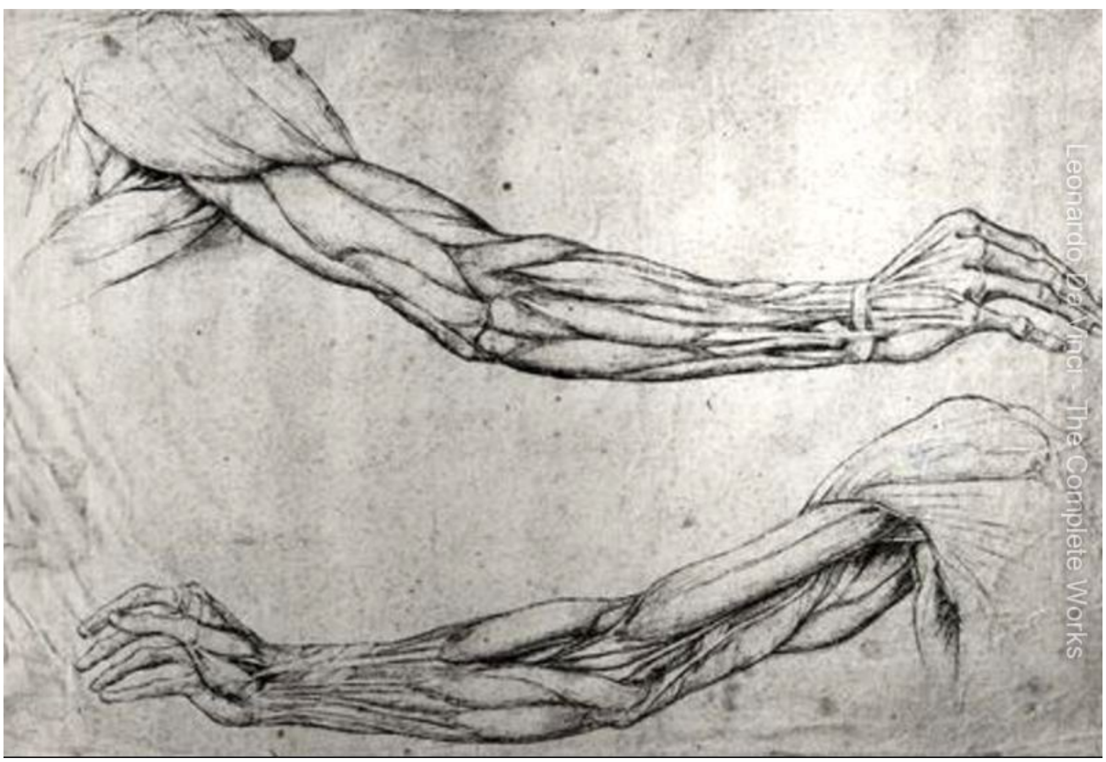

Figure 3. Leonardo Da Vinci arm musculature study. Retrieved from www.leonardoda-vinci.org

It is very well documented that great designers and inventors have observed the structures and mechanisms found in nature to help them inform their designs and inventions. Da Vinci was profoundly intrigued by the natural world and left an extensive amount of painstaking drawings examining the functioning of muscles, the structures of skeletons, the disposition and functions of organs (figure 3). Da Vinci was also fascinated by the phenomenon of flight, producing many studies of the flight of birds, including his Codex on flight, as well as several flying machines, including a light hand glider and a machine resembling of a helicopter. Subsequently, during the era of pursuing human flight, pioneers such as Clement Ader, Otto Lilienthal, Octave Chanute and most notably the Wright Brothers thoroughly observed the flight of birds and the anatomy of bird wings to understand flight which evidently led to the first human flight (figures 4 & 5). They acutely observed and noticed how birds soared into the wind and that the air flowing over the curved surface of their wings created lift and that they could turn and maneuver by changing the shape of their wings. Through these observations, the Orville and Wilbur Wright believed they could use this technique to obtain roll control by warping, or changing the shape of a portion of the wing (Bellis, N/D).

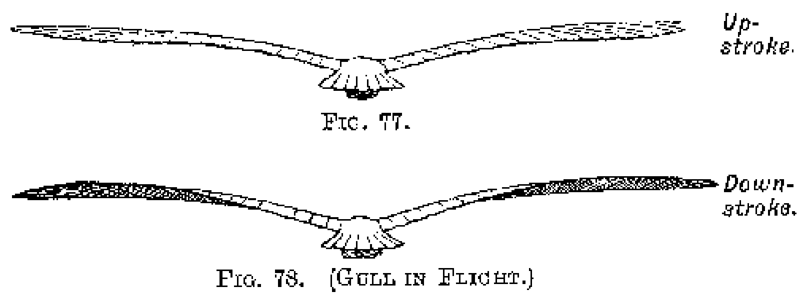

Figure 4. Otto Lilienthal study of Gull in flight. Retrieved from www.lilienthal-museum.de

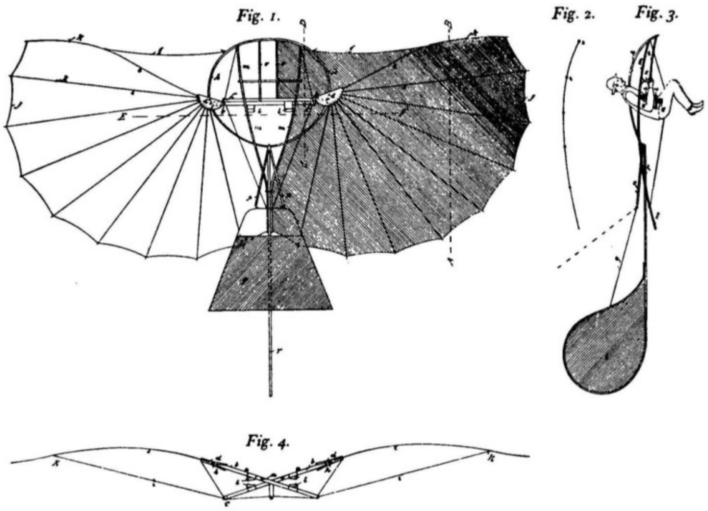

Figure 5. Otto Lilienthal standard glider drawing. Retrieved from www.wright-brothers.org

Interest in nature as a model or tool for design remained a consistent, if minor, current in architecture of the late 20th century. This was particularly so in the works of figures such as Rennie Mackintosh, Frank Lloyd Wright, Alvar Aalto, Mies van der Rohe, for their focus on integration of indoor and outdoor spaces, use of natural forms, natural materials, expression of structure, and consideration of architecture as a component of a larger whole, at least its immediate built surrounding (Myers, 2012). The contemporary Spanish architect Santiago Calatrava has been especially notable in his observation of natural forms in plants, birds, skeletons and the human body. He has spectacularly integrated these observations not only in form but in function and motion as well thus creating dynamic architectural structures which have challenged architectural convention. One such example is the bird wing inspired structure of the Milwaukee Art Museum in Milwaukee, Wisconsin (figure 6).

Figure 6. Winged Structure of the Milwaukee Art Museum by Santiago Calatrava. Retrieved from www.calatrava.com

Despite the fact that nature was always considered as a model to inform aesthetic and functional expression in the arts, architecture and engineering, humans' relationship of awe towards nature eventually over time turned to one of hubris towards nature. Especially since the beginning of the Industrial Revolution, humans' notion of control of nature, of separateness from nature, and nature as an apparently infinite resource to be consumed, became an ever present and problematic mindset. While the mindset of prediction and control has been the prevailing *modus operandi* of the industrial age which has led to countless environmental problems, a new way of thinking is currently emerging: one where nature is informing design, architecture, urban planning and green chemistry.

1.3 Biomimicry

1.3.1 Nature as Model, Mentor and Measure of Design Solutions

There's a growing understanding that the natural world not only provides natural resources but it can also be a great wealth of resources for design solutions. New advances in science and technology are making headlines such as biodesign, synthetic biology, biomaterials, and programmable matter to name a few, and are looking into the life sciences for answers towards new sustainable innovations. Business is now consulting the principles, processes and systems in the science of biology, marine biology, entomology, and ornithology for example in order to replicate natural methods of production and engineering to manufacture chemicals, materials, and composites.

"*A new industrial revolution is now making its way with a strong focus on sustainable design strategies, a new way to close the gap between our technology and nature by encouraging industry to reinvent itself on biological lines. Growing competitive pressures to save resources are opening up exciting frontiers for chemists, physicists, process engineers, biologists, architects and industrial designers. More and more, thinkers are looking into the natural world for answers to reverse the previous paradigm in how to design the built environment. Some of the most exciting developments have resulted from emulating nature's life-temperature, low-pressure, solar-powered assembly techniques, whose products rival anything human made*" (Hawken et al., 1999, p.15). Those developments are emerging from a new discipline called Biomimicry.

Biomimicry is a term coined by natural sciences writer, innovation consultant, and author, Janine Benyus in 1990**.** The word comes from the Greek *bios*, meaning life, and *mimesis,* meaning to imitate. Benyus is quoted as saying "*biomimicry is learning to live gracefully on this planet by consciously emulating life's genius. It is an emerging discipline that seeks sustainable solutions by emulating nature's designs and processes*." She has also described it as being the observation of the "technology of biology".

A formal definition of biomimicry is "an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies. The goal is to create products, processes, and policies -new ways of living- that are well-adapted to life on earth over the long haul" (Institute, 2011a). It can be further defined as the application of functional, organizational and chemical phenomena from organisms in manufactured products. It is learning from and then emulating natural forms, processes, and ecosystems to create sustainable designs. The science and art of emulating nature's best biological ideas to solve human problems.

Biomimicry is an emerging discipline where designers, engineers and architects are guided by trained biologists to take inspiration and emulate nature to solve human problems by examining its models, systems, processes, elements and emphasizes sustainability as an objective. Hawken et al. (1999) assert this discipline is quickly becoming the corner stone of sustainable design by looking into remaking the way we produce by following nature’s examples, redesigning industrial systems on biological lines that change the nature of industrial processes and materials, enabling the constant reuse of materials in continuous closed loop cycles and often the elimination of toxicity.

Biologically inspired design is gaining importance as a wide-spread movement in design for environmentally conscious sustainable development that often results in innovation (Benyus, 1997). We now have the investigative tools of measurement and imaging (down to nano level and below) to be able to study how nature has evolved solutions to the problems it faces. Insights into these mechanisms can inspire and inform human engineering. Research across traditional academic subject boundaries is rapidly increasing and is leading to innovative approaches to a whole host of design problems in areas as diverse as architecture and signal processing (Allen, 2010), material science and swarm technology. Designers, architects and engineers are apprenticing themselves to nature to learn the benign chemistry of its processes and so to eventually in the future replicate the intricate materials such as spider silk and abalone shells, or studying a leaf to invent a better solar cell.

Figure 7. Scanning electron micrograph of silk producing spider spinnerets and spider silk. Retrieved from abovetopsecret.com

Spiders make silk that is five (5) times stronger than steel, strong as Kevlar but much tougher, and more flexible than nylon from digested crickets and flies, without needing boiling sulfuric acid and high-temperature extruders (see figure 7). The abalone generates an inner shell twice as tough as our best ceramics, and diatoms make glass, both processes employing seawater with no furnaces. Trees turn sunlight, water, and air into cellulose, a sugar stiffer and stronger than nylon, and bind it into wood, a natural composite with a higher bending strength and stiffness than concrete or steel (Hawken et al., 1999, p.15). "Doing it nature's way" has the potential to change the way we grow food, make materials, harness energy, heal ourselves, store information, and conduct business (Benyus, 1997, p.2). The conscious emulation of life's genius is a survival strategy for the human race, a path to a sustainable future (Benyus, 2008).

Biomimicry is a tool for innovation which can be applied to all design fields, from industrial design to engineering; from architecture to urban design thus making biomimicry universally applicable. In recent years, it has even been applied in economics. The complex process of applying biomimicry requires highly specialized knowledge about biology (White et al., 2013), therefore, at the design level, a biomimicry project can involve industrial designers, architects, and engineers but unlike conventional design projects, most importantly, it requires the presence of a biologist or a

Biologist at the Design Table (BaDT). BaDTs are trained to effectively communicate and translate the language of biology to that of the design disciplines and vice versa. It may also demand that designers either invest considerable time studying biotic processes, work with biologists, or both (White et al., 2013).

1.3.2 Biomimicry 3.8

Biomimicry 3.8 is the leading biomimicry organization founded by Dana Baumeister and Janine Benyus. Biomimicry 3.8 (formerly the Biomimicry Group, Biomimicry Institute and Biomimicry Guild) helps innovators learn from and emulate natural models through workshops, research reports, biological consulting, and field excursions. Biomimicry 3.8 works on developing a design process to enable designers, architects and engineers to use biomimicry as a tool, as a supplement to traditional design methods. They have created various programs to train professionals of all walks interested in learning from this new approach in order to help them resolve their design problems. Companies such has Nike, Interface FLOR, HOK Architects have sought after their services.

The success of biomimicry hinges on educating, promoting, and nurturing a community of biomimics who will amplify this strategy from schools to businesses. Working as a social enterprise, Biomimicry 3.8 runs a workshop bureau, a speaker's bureau, a consulting bureau, and a training and certification program called Professional Pathways.

The Biomimicry Guild, LLC is a for-profit consulting arm of Biomimicry 3.8. The BaDT helps design teams consult nature, helping create eco-friendly solutions and companies. They provide biomimicry counsel to diverse economic sectors such as city planning, architecture, commercial interiors, wastewater treatment, healthcare, transportation, apparel, food, and consumer products. The Biomimicry Institute, the non-profit arm, trains the next generation of biomimics, starting with K-12 curricula and informal education ranging from films to zoo programs. At the university level, they have a growing list of faculty fellows integrating biomimicry tools and concepts into their courses, biomimetic design studios, as well as affiliate schools working towards offering biomimicry degrees to design, architecture, biology, engineering, and business students. They are also committed to educating the next generation of biologists to sit at the design table, filling a demand that is growing by leaps and bounds (Biomimicry_3.8, 2012). In 2008 the Biomimicry Institute launched AskNature, a free, online database of over 1, 800 of natural phenomena and design solutions. It is unique in organizing nature's strategies by biological function thus providing references to help biomimics solve their design challenges (Institute, 2011a).

1.3.3 Clarifying the Difference between Bionics and Biomimicry

Since the rise in popularity of ecologically responsible design, recently much emphasis has been put on biologically inspired design as a way to inform our design practice towards sustainable innovations. A certain confusion has been building up about these philosophies and approaches. The confusion has much to do with the names, terminologies and inherent differences between the various types of biologically inspired design out there: bionics, biomimetics, and biomimicry are amongst the most mentioned approaches. They are often presented as being different but this perceived difference is far from obvious since often times, these terms are used interchangeably as a result of their obvious similarity in inspiration source. This section aims to clear the confusion between these terms which are too frequently used in a substitutable manner by most.

1) Bionics

Table 1. Principles of Bionic Design by Werner Nachtigall (Wahl, 2006)

PRINCIPLES OF BIONIC DESIGN
1. Integrated instead of additive construction *2. Optimisation of the whole, rather than maximization of individual elements* *3. Multi-functionality instead of mono-functionality* *4. Fine-tuning adapted to particular environments* *5. Energy saving instead of energy squandering* *6. Direct and indirect use of solar energy* *7. Temporal limitation instead of unnecessary durability* *8. Total recycling instead of waste accumulation* *9. Networks instead of linearity* *10. Development through the process of trial and error*

The Merriam-Webster dictionary gives this definition of Bionics:

bi·on·ics, Pronunciation:\bī-ä-niks\; Function: noun plural but singular or plural in construction; Date: 1960; Definition *: a science concerned with the application of data about the functioning of biological systems to the solution of engineering problems*.

Bionics first appeared in the lexicon in parallel with the emergence of ecological design (Wahl, 2006), the term *Bionics* was first coined by US Air force medical doctor Jack E. Steele, in 1960 at a meeting at Wright-Patterson Air Force Base in Dayton, OH (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006). The term possibly originating from the Greek *bion*, meaning "unit of life" and the suffix *–ic*, meaning "having the form of" or "in the manner of". He defined it as "*the science of systems which have some functions copied from nature, or which represents characteristics of natural systems or their analogues*" (Vincent et al., 2006). The definition of the word then took on a different connotation when Martin Caidin referenced Steele's work in the novel cyborg which was later translated in the famed television series *The Six Million Dollar Man* and the *Bionic Woman*. The main protagonists were humans given superhuman powers by electromechanical prosthetic eye, arms and legs.

Most people associate the word with the combination of electronics and organic parts. In medicine, bionic means the replacement or enhancement of organs or other body parts by mechanical versions. Bionic implants differ from ordinary prostheses by mimicking the original function very closely, or even surpassing it. The field of bionics is currently gaining in scope and popularity. The best known examples of bionics is the cochlear implant; a surgically implanted device that provides a sense of sound to a person who is profoundly deaf or severely hard of hearing.

2) Biological Design

Table 2. Precepts of Biological Design by John Todd & Nancy Jack Todd (Wahl, 2006)

PRECEPTS OF BIOLOGICAL DESIGN
1. *The living world is a matrix for all design*
2. *Design should follow, not oppose the laws of life*
3. *Biological equity must determine design*
4. *Design must reflect bioregionality*
5. *Projects should be based on renewable energy sources*
6. *Design should be sustainable through the integration of living systems*
7. *Design should be co-evolutionary with the natural world*
8. *Building and design should help heal the planet*
9. *Design should follow a sacred ecology*
10. *Everyone is a designer*

"Let us consider what Bionics has come to mean operationally and what it or some word like it (I prefer Biomimetics) ought to mean in order to make good use of the technical skills of scientists specializing or rather, I should say, despecializing into this area of research. Presumably our common interest is in examining biological phenomenology in the hope of gaining insight and inspiration for developing physical or composite bio-physical systems in the image of life" (Harkness, 2001).

This quote by Jon Harkness then leads us to the term *Biomimetics*. The term Biomimetics coined by biophysicist and polymath Otto H. Schmitt in 1969, represents the studies and imitation of nature's methods, mechanisms, and processes (Bar-Cohen, 2006). The term is described to originate from the Greek *bios*, meaning "life", and the suffix *–mimesis*, meaning "to imitate". The Online Etymology dictionary defines the suffix -mimetic as "having an aptitude for mimicry", mimicry being a word originally used in the 1630s from the Greek word *mimetikos*, meaning "imitative".

The first researchers to offer a list of principles for ecologically or biologically informed design were John Todd and his wife Nancy Jack-Todd. During the 1970s, research at the New Alchemy Institute began to explore how ecology, biology, and bio-cybernetic systems approach, could inform more sustainable solutions to meeting fundamental needs. Table 2 demonstrates their proposed nine (9) precepts which later became ten (10) with another point to stress the centrality of design as an expression of intentionality in all human interactions (Wahl, 2006), in other words, we have a responsibility in the consequences of all our designs/actions.

The biological design precepts list (table 2) clearly reflects the holistic and participatory worldview that informs integrated sustainable design (Wahl, 2006). The Todd/Jack-Todd biological design precepts is the first such list of biologically inspired design which makes a clear emphasis on not only learning about nature but also learning from nature, where the biological world is considered not just for how nature can inform our designs but also how will our design impact the natural world. This is the first manifestation of an approach called *salutogenesis* or salutogenic design, "health promoting" design. Making the case that true biologically inspired design needs to be both holistic and salutogenic.

3) Biomimicry

Table 3. The Biomimicry Approach by Janine Benyus & Dana Baumeister (Biomimicry 3.8, 2012)

THE BIOMIMICRY APPROACH
*1. **NATURE AS MODEL.** Biomimicry is a new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems.* *2. **NATURE AS MEASURE.** Biomimicry uses an ecological standard to judge the "rightness" of our innovations. After 3.8 billion years of evolution, nature has learned: What works. What is appropriate. What lasts.* *3. **NATURE AS MENTOR**. Biomimicry is a new way of viewing and valuing nature. It introduces an era based not on what we can extract from the natural world, but on what we can learn from it*

In 1997, Janine Benyus wrote the seminal book titled *Biomimicry; Innovation Inspired by Nature*. Conversely, the term is described as having the same origin as Schmitt's term. The philosophy behind the biomimicry approach is that looking into biology and natural systems for design inspiration can help solve human design problems and that by emulating nature's forms, processes, ecosystems and green chemistry we can learn to design and develop better materials, products, buildings, and cities that will seamlessly integrate with the natural environment. The belief is that by making our built environment the way nature has done for billions of years, we then can create a built environment that is in symbiosis with the natural environment and therefore reduce our negative impact on the environment. The basic belief with the biomimicry approach is to transform the principles of nature into successful design strategies.

4) Their Fundamental Differences

As mentioned earlier, all the terms originating from the biologically inspired design movement have all come to be used interchangeably, people made no real distinction between the origins of the terms, the philosophy, and objectives of each approach. Since the proponents of these movements were all referencing biology as their source of inspiration, apparently most didn't give much importance about aleatorically calling bionics-biomimicry, or biomimetics-bionics and so forth. While the differences are not very obvious on the surface, with some deeper understanding of these approaches, the fundamental differences, the objectives of bionics and biomimicry become rather clear. One approach prescribes to a model or mindset of control and prediction while the other to a model of participation and ecological literacy (Wahl, 2006).

For the approach coined bionics, Wahl makes the argument that although its proponents were acknowledging the importance of consulting nature to inform their designs, they unfortunately were still participants in the model of prediction and control of nature. This model has been present since pre-Industrial Revolution. Comparable to the Victorian view of nature was, it was one which believed nature was to be controlled by humans, similarly to a reductionistic, Cartesian view of separation: humanity vs. nature. Bionics recognized the superiority of nature's capabilities and technology compared to human capabilities, and adapting many of its features and characteristics can significantly improve our technology (Bar-Cohen, 2005). Bionics takes a systems approach to the realization and duplication of functions found in biological systems (Wahl, 2006) and many well-known bionics innovations have been created through such conceptions such as echolocation, sonar, aero- and fluid-dynamics to name a few. Unfortunately, the limitations of bionics was its focus being exclusively on technological innovation, to the point that it almost actively tried to discourage ecological concerns and the issue of sustainability (Wahl, 2006). Harkness' earlier reference makes no mention of sustainability but rather solely focuses on biological inspiration to design systems in the image of life. Wahl asserts that "*without acknowledging the complex context of* *sustainability and ecological and social interactions, bionics, planning, design, engineering, and resource management, all run the risk of staying trapped in a prediction and control mindset*." This is principally where the difference between bionics and biomimicry is situated.

"The avant-garde sciences, represented by quantum physics, cognitive biology and consciousness studies, chaos theory, ecosystem science, human ecology, and the theory of complex dynamic systems, are no longer dictated to the archaic paradigm of prediction and control of nature" (Wahl, 2006). Eco-literacy is "a detailed understanding of nature as complex, interacting, creative process in which humans participate. It emphasizes that humanity is an integral participant in natural processes, which are fundamentally unpredictable and uncontrollable" (Wahl, 2006). The chaos theory has effectively proven that this idea of controlling and predicting nature is a fallacy. The root cause of the unsustainability of modern civilization lies in the dualistic separation of nature and culture. Daniel Wahl says it is in nature that all people and all species unite into a community of life. Yet modern culture is commonly conceived of as **apart from** nature, rather than **a part of** nature (Wahl, 2006). A design movement which bases its principles and guidelines on eco-literacy is one which can effectively change this paradigm.

When we take a closer look into the three (3) principles of biomimicry, the only true similarity between biomimicry and bionics is in the first principle-**Nature as model**. The second principle- **Nature as measure**- clearly indicates design should use an ecological standard to judge the rightness of its innovations, meaning a design (product, building, etc.) should be sustainable, it should use nature as a way to measure how well it interacts or affects the natural world throughout its life, a point that isn't clearly made in bionics. The third principle- **Nature as mentor**- indicates how biomimicry takes from the mindset of participation and eco-literacy described by Daniel Wahl. Benyus and Baumeister often reiterate that biomimicry introduces an era based not on what we can extract from the natural world, but on what we can learn from it. To regard nature as a mentor presents a paradigm shift from one of control to one of participation.

To summarize it all, at the present moment it appears that the main difference between the two approaches is about which design paradigm they to belong to in regards to their relationship to the natural world. Bionics belongs to the old paradigm of control, prediction and manipulation while biomimicry belongs to the new paradigm of holistic design, participation and eco-literacy. On the surface however, the differences between the two approaches are rather fuzzy and unclear, which is the primary explanation why the terms have for so long been used interchangeably. In his paper, *Bionics vs Biomimicry: from control of nature to sustainable participation* (2006), Wahl concludes "It is of limited uses to draw a sharp line between the approaches of bionics and biomimicry, based on the relative importance these approaches give to achieving greater sustainability…both fields, if they are indeed distinct, can contribute greatly to more sustainable solutions".

1.3.4 The Future of Biomimicry

The strategy of emulating nature's blueprints is experiencing yearly growth due in part to our search for more sustainable methods of agriculture, manufacturing, chemistry, energy generation, healthcare and business. Also contributing are the amazing lab techniques and imaging technologies that allow us to better characterize how nature's materials, processes, and ecosystems work down to the nano level and which will make our ability to emulate life's strategies more possible. As the approach gains recognition, new interdisciplinary centers are forming, including the Wyss Institute for Biologically Inspired Engineering at Harvard, the Biodesign Institute at Arizona State University, the Center for Biologically Inspired Design at Georgia Tech, the Center for Biologically Inspired Materials & Materials Systems at Duke University, and the Swedish Center for Biomimetic Fiber Engineering, which is comprised of collaborative groups from the Royal Institute of technology, Umea Plant Science Center, and the R&D company Inventia. Further signs of the maturing discipline are an increasing number of annual conferences, such as the Biomimicry Education Summit, technical books, and journals such as Bioinspiration & Biomimetics, Journal of Bionic Engineering, and Journal of Biomimetics, Biomaterials, and Tissue Engineering.

As sustainable design is increasingly becoming necessary, biomimicry is constantly gaining ground in the area of sustainable development and design. This is also an indication that biomimicry is not just being explored in academia and laboratories but is increasingly being explored by research and development laboratories and by industries.

According to a study by Richard Bonser (2006), the number of global patents containing the term "biomimetic" or "bioinspired" in their title increased by a factor of 93 from 1985 to 2005, compared to a factor of 2.7 increase for non-biomimetic patents. To measure and track this new field, the Fermanian Business and Economic Institute (FBEI) developed the Da Vinci Index, which seeks to measure biomimicry activity by monitoring academia and the real world in a yearly report. To track and measure such activity, the data is drawn from the number of scholarly articles, number of patents, number of grants and dollar value of grants. The year 2000 was used as a baseline with an index score of 100. The Da Vinci Index in the year 2010 yielded 713. This suggested a seven-fold rise in biomimicry in just ten years (Mariano, 2011).

The FBEI states that bioinspired technology has the potential to transform large slices of the economy, penetrating many industries, particularly those in manufacturing. Agriculture, mining, construction, waste management, and information technology could also see sizeable impacts. The greatest inroads now appear to be occurring in chemistry, materials science, and engineering. At this rate, globally, by 2030 bioinspiration could generate $1.6 trillion of total output or GDP (Fermanian Business & Economic Institute, 2013).

1.4 What is Innovation in the Context of Design?

1.4.1 Defining Innovation

Main entry: in-no-va-tion, function: noun

a) the introduction of something new
b) a new idea, method or device

The word innovation derives from the Latin word *innovatus*, which is the noun form of *innovare* "to renew or change", stemming from *in*-"into" + *novus*- "new". There is little consensus about how to exactly define innovation. There is a range of definitions, books, works, publications, and journal articles on the subject. Each has their own twist or focus and it represents the variety of approaches that scholars in different disciplines, such as Clayton Christensen, and Henry Chesbrough, have followed to make sense of what innovation is.

An innovation can be defined as creativity with a purpose; that is a creative idea in which one sees value in and then immediately begins to put that idea into action. It is the result of the process involved in taking an inventor's creation to the market. If an invention improves a product, process or service for the broader public, it then becomes an innovation. The word innovation then refers to any new change that inherently improves, creates better products, processes, services or technologies. Businesses rely upon innovation not only to remain competitive with the competition, but to exceed its own and its competition and by doing so the business preserves a competitive advantage (n/a, 2006).

The words "invention" and "innovation" are often mistakenly used interchangeably, there is however a significant difference between the two words and although connected, they are not the same. *Invention* is a new technology, in the form of new products or techniques, which are very interdependent. The term mainly describes the idea and first development of a new process or product, therefore invention is discovering or creating things that have never been discovered or created before. *Innovation,* on the other hand, is the discovery of new ways of creating value, it is an extension of an invention, meaning extending the invention to further development and utilization as a product or process. Innovations will only be successful if they provide the public (the market) with a certain service which the public could not use before, if they improve an existing service and/or if they lead to lower cost (Horbach, 2005). Innovation differs from invention by the fact that innovation refers to the use of a new idea or method, whereas invention refers more directly to the creation of the idea or method itself. If the invention improves some product, process or service for the public, then that invention transforms into an innovation. Innovation may involve invention, and it often does, but innovation is the process by which inventions get commercialized. In other words, an invention is useful only to the inventor unless it is offered to the public, however niche that public may be. While not all innovations are inventions, all inventions are innovative, accordingly not everyone can be an inventor but everyone can be innovative (Khan & Al-Ansari, n.d.). In the book *Innovation: Désordre Progrès*, Pierre Tabatoni (2005), elaborates that "the processes of innovation are dynamic (non-linear, "vision" uncertainty, risk, mobilization, rhythm), paradoxal by the contradictions and non-coherence of goals, means, interests, positions they engender and must solve. They are at the same time process of creativity, and hence originality, contestation, legitimation and engagement in a new society" (p.10).

It should be noted that innovation is not simply the application of technological inventions; it can also express a new idea, a new concept, a novel approach to organization which allows offering new products and services, it is not limited to technical ideas. Pierre Tabatoni (2005) states that it is the implementation of creativity in all elements of the economic process. That it can consist of organization and structures, sales, finance, human resources, R&D, procurement, logistic, public relations, relations to public authority, relations to suppliers, internalization, but also models of management, information and communication. Therefore innovation may be referring to:

- *institutional innovation*, which concerns legislative or regulatory framework
- *organizational innovation*, which concerns new organization modes for activities
- *cultural innovation*, which is relative to mentalities, attitudes, norms concerning the actions of a collective.

1.4.2 Different Spectrums of Innovation

The literature on innovation further recognizes that there are differences in the nature of an innovation implemented. To improve their efficiency or effectiveness, companies may attempt to innovate either their process, products, services or all three (Orlikowski, 1991).

This study focuses on biomimicry through the lens of innovation in design and will investigate biomimicry through two spectrums of innovation: technology and the market. The technology spectrum involves incremental and radical innovations while the market spectrum involves sustaining and disruptive innovations. For reasons which will be clarified further in this paper however, the principal focus of this study is the technology spectrum, but considering the importance of disruptive innovation, a minor emphasis will be put onto the market spectrum.

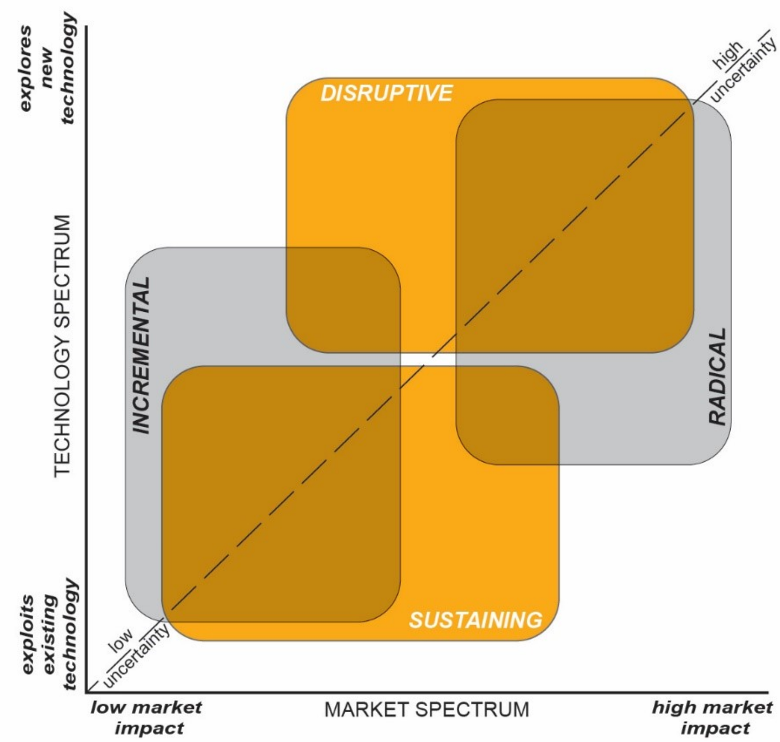

Figure 8. Technology and Market Spectrum Model. ©Yves A. Michel 2014

1.4.2.1 The Technology Spectrum

Incremental innovation implies a linear, cumulative change in a process or product, representing "minor improvements or simple adjustments in current technology" (Dewar and Dutton, 1986). It can be defined as improvements within a given frame of solutions, i.e., "doing better what we already do" (Norman & Verganti, 2012). Incremental innovation does not create new markets or value networks but rather only evolves existing ones with better value, allowing the firms within to compete against each other's incremental improvements. Incremental innovations may be discontinuous (revolutionary) or continuous (evolutionary). An evolutionary innovation is an innovation that improves an existing market in ways that customers are expecting while a revolutionary innovation is an innovation that is unexpected, but nonetheless does not affect existing markets (Norman & Verganti, 2012).

A successful organization is a creative organization because creativity is the single most important contribution employees can contribute for its success. In a successful organization, innovation is of benefit only if it creates value. Innovation is incremental and on-going, rather than a process characterized by a succession of "boom and bust" events. A sustainable innovative organization must be fluid and "organic", almost biological in nature to foster the constant creativity vital for the success of a modern organization (Khan & Al-Ansari, n.d.).

An example of incremental innovation is the next generation iPhone. The first generation of iPhone was a radical (and disruptive) innovation since it completely transformed the smart phone industry. However, subsequent generations of the iPhone (2, 3G, 4, 4S, 5 and 6) all represent incremental innovations. Apple remained a leader in smart phone sales after the disruption of 2007 by providing improved, faster, thinner versions of the iPhone. Practically all Apple's direct competitors (such as Samsung and HTC), and all current smartphones now take cues from the original iPhone. The competition is about who has the best specs; that is, who can generate and maintain incremental innovation (Tarvainen, 2011).

Radical innovation implies a non-linear, paradigmatic changes, representing significant departures from existing practice or knowledge (Dewar and Dutton, 1986). It can be defined as a change of frame , i.e. "doing what we did not do before" (Norman & Verganti, 2012). Radical innovation almost always seems to mean an order of magnitude improvement in performance or a significant shift from existing performance or solving complex problem that existing products don't solve. This means more sophisticated technology, based on pushing the boundaries of knowledge (Krishnan, 2012) and on different sets of engineering or scientific principles (Eybpoosh & Fidan, n.d.). In a Design Issues article, Donald Norman and Roberto Verganti (2012) further explain that the fundamental difference between incremental and radical innovation[3] is whether or not the

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[3] The main difference between the two is whether the innovation is perceived as a continuous modification of previously accepted practices or whether it is new, unique, and discontinuous. Incremental product innovation refers to the small changes in a product that help to improve its performance, lower its costs, and enhance its desirability, or simply result in a new model release. Though

innovation brings about a change in paradigm or best practices. The modifications through incremental innovation are rather similar to updates or evolutionary, allowing the innovation to improve with each subsequent iterations and usually resulting in lower cost. Whereas radical innovation represents a break in tradition, in best practices. It is discontinuous and by nature presents more opportunities to bring about unforeseen innovations. Radical innovation is revolutionary, it is what most organizations desire, however it is at the same time the most difficult to consistently produce and usually radical innovations are rarely readily accepted. Most radical concepts or designs must become incremental innovations in order to succeed on the market (Norman & Verganti, 2012).

Table 4. The Dimensions of Incremental vs Radical Innovation

Incremental Innovations (Evolutionary)	**Radical Innovations** (Revolutionary)
-Exploits existing technology	*-Explores new technology*
-Low uncertainty	*-High uncertainty*
-Focuses on cost or feature improvements in existing products or services, processes, marketing or business model	*-Focuses on processes, products or services with unprecedented features*
Improves competitiveness within current markets or industries	*-Creates a dramatic change that transforms existing markets or industries, or creates new ones*

One can say that a radical invention is something novel, that it has distinctive features missing in previously observed inventions (Dahlin & Behrens, 2005). Jeff Stibel[4] further elaborates that radical innovation is most prized by organizations because its non-linear characteristics shows more potential for major technological advances (Jeff Stibel cited by Ohr, 2012). Essentially, in

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not as exciting it is nonetheless important. Radical innovation is what everyone wants given its significant potential to differentiate, but successful radical innovation is surprisingly rare and most attempts at it fail. They take considerable time to become accepted, and seldom live to their potential when they are first introduced. Incremental innovations meanwhile, are necessary to transform the radical idea into a form that is acceptable to the consumers who follow the early adopters.

[4] While both types of innovation play a vital role in the developmental ecosystem of technology, industry and business, it is the non-linear or revolutionary innovations that make the most significant advances. These are the ones that make the real difference. The really huge achievements in technology and the world at large are the result of visionary activists who imagine and then build something none of us had previously thought possible. (…) Reasonable people can debate whether a particular innovation belongs in the first category or the second. What is not debatable is that while both play a role in the ecology of innovation, it is the truly revolutionary innovations that make all subsequent incremental improvements possible.

much of the literature, a radical innovation implies a break or shift with the past through design approach and/or technology. The bottom line is both forms of innovations are necessary. Radical innovation brings new domains and new paradigms, and it creates a potential for major changes. Incremental innovation is how the value of that potential is captured. Without radical innovation, incremental innovation reaches a limit. Without incremental innovation, the potential enabled by radical change is not captured (Dahlin & Behrens, 2005).

Here, Dahlin and Behrens (2005) present three criteria for radicalness. The first two criteria define radicalness, the third one success. The criteria also suggest three time periods: past, present and future.

- Criterion 1: The invention must be novel: it needs to be dissimilar from prior inventions.
- Criterion 2: The invention must be unique: It needs to be dissimilar from current inventions.
- Criterion 3: The invention must be adopted: It needs to influence the content of future inventions.

1.4.2.2 The Market Spectrum

Disruptive innovation is often mistaken as being a synonym of radical innovation but there is a noteworthy difference between the two terms. The term was coined by Harvard Business School professor Clayton Christensen in a 1995 article titled *Disruptive Technologies: Catching the Wave*. A disruptive innovation involves a new product, process or service that enters at the bottom of the market, with relatively insignificant impact and with time and improvement, eventually goes on to disrupt an existing market, displace and replace the market leaders, hence, rendering the current technology obsolete. The term is used in business and technology literature to describe innovations that improve a product or service in ways that the market does not expect, typically first by designing for a different set of consumers in the new market and later by lowering prices in the existing market. Two (2) characteristics of a disruptive innovation are a) it initially provides inferior performance (as measured by the prevailing industry) to existing products available and b) it is adopted by a market that is currently underserved or not served at all, in other words serves a market that did not exist before (Krishnan, 2012).

Dragos Pirvu (2012) describes a notable and classic example[5] of disruptive innovation in the case of Kodak, the leader in film photography, being completely displaced in the market by digital photography. Ironically, Kodak was the first to develop digital photography but not wanting to compete with their profitable film market share, Kodak chose not to further develop the very technology that would eventually cause its demise. This phenomenon is what Clayton Christensen calls in his influential 1997 book, *The Innovator's Dilemma,* "the saga of good companies hitting hard times", which is the dilemma industry leaders face when getting blindsided by a disruptive technology as a result of capitalizing solely on their current lucrative technology and ignoring emerging markets.

As Christensen explains, it is important to understand that a disruptive innovation is not a breakthrough innovation, such as one that makes a good product much better. A disruptive innovation specifically transforms a product that was historically expensive and complicated into a much more affordable and accessible product to the general population and thus creating a new market. Not to confuse with a disruptive technology; which is a wild and unexpected technological breakthrough that requires corporations to radically rethink their very existence. At first they seem of insignificant relevance, often overlooked or perceived as useless by the very company or firm that created it but its value is eventually recognized by an outside firm or company and then manages to completely overturn existing products and markets.

That said, while Christensen's leading market theory is comprised of disruptive and sustaining innovation, Christensen's theory may be missing an important point which could explain the iPhone in terms of disruption (Gans, 2012). Gans explains that academics like Rebecca Henderson and

[5] The replacement of film photography with digital cameras and images is an example of disruptive innovation. Kodak, the past leader in the photography industry, was slow to recognize that digital technology would eventually displace film and has since struggled to survive to a point where the former photography giant had to file for bankruptcy in January of 2012. Interestingly, Kodak had pioneered the digital camera sometime in the 70s, being aware that such a device represents the future. The company was right, but it failed to release a commercial digital camera in the following years and its competitors took action. Kodak did not want to jeopardize its lucrative print sales business so it opted to delay the release of a digital camera (Pirvu, 2012)

Kim Clark support the theory that a technology can also have success on the market through the creation of a new market by making an existing product better through a better "architecture", which explains the disruptive nature of the iPhone. The technology used by Apple was not out of reach for incumbents such as RIM, Samsung and HTC. While incumbents favored the keyboard and stylus approach, Apple simply sought the opportunity to take overlooked approach of the touchscreen which provided a larger screen, desktop like web pages and a new intuitive interface (Gans, 2015). This explains how Apple remains the leader in smartphone sales despite their product being relatively expensive. Apple disrupted the market through a better and innovative product architecture, not through a better and cheaper smartphone.

The categories of radical and incremental are intended as ends of a continuum representing the level of new knowledge embedded in an innovation, and not as exclusive categories and the middle values of this continuum are difficult to interpret as stated by Dewar and Dutton in their 1986 paper (Orlikowski, 1991). While incremental and radical innovation represent a technological dimension, sustaining and disruptive innovation represent a market dimension. As stated before, there is much (for lack of a better term) confusion about defining innovation, and even more so about the difference between radical and disruptive innovation. According to the literature, the difference is situated in whether an innovation represents a paradigm shift in matters of technology or the market. Radical innovations represent a paradigm shift in technology while disruptive innovations represent a paradigm shift in the market as well: all disruptive innovations can at times be radical but not all radical innovations can be disruptive.

The second category of innovation in the market spectrum is called **sustaining innovation**. It is analogical to the principles of incremental innovation but in the context of the market. There is a third category of innovation which was very recently recognized by Dr. Christensen which is called **efficiency innovation**. Christensen defines it has "an innovation which makes existing products more proficiently. This type of innovation economizes on capital and labour, to free up both capital and jobs"(Hurst, 2013). This is not necessarily a strategy used by the companies featured in the case study. It is more often used by large, established companies focused on exploitation rather than exploration and for this reason, efficiency innovation will not be part of this study.

These criteria will be referenced in this paper to identify which types of innovations have been generated through biomimicry. It is important to specify that while both spectrums will be examined in this research, the emphasis will be put however on innovation in the technology spectrum because 1) the subject of innovation in biomimicry mostly often pertains to technology, 2) investigating biomimicry in the market would require access to more quantitative information, and 3) biomimicry and innovation in the market could be an entire research on its own. Therefore innovation in the market spectrum, although it has some importance, it will be treated as a minor context.

2 Chapter Two_ Research and Methodology

"I look for what needs to be done. After all, that's how the universe designs itself."

-Buckminster Fuller/ designer & futurist

2.1 The Research Problem

There has been an increasing awareness in recent years for the need to change the current design paradigm in terms of sustainability. Many designers, engineers, scientists and scholars hold the belief that biomimicry is a design approach that will better inform us on how to make our built environment, how to make materials, how to design efficiently and sustainably due to the design solutions which can be found in nature and also due to the often unexpected results this approach has brought forth.

As Rebecca Bagley stated, in her article *Biomimicry: How Can Nature Streamline Your Business For Innovation*, biomimicry is transforming the way we design, produce, transport and distribute goods and services; as more and more companies are approaching Mother Nature for innovative ideas to help solve complex human problems (Bagley, 2014) and that the natural world is a largely untapped resource for innovative design solutions. Tom Tyrell, founder and CEO of Great Lakes Biomimicry says this field is just emerging and it is estimated by the FBEI that by 2025, biomimicry will account for 1.6 million U.S. jobs and represent $1 trillion of global GDP (Bagley, 2014).

Given the factor that biomimicry is most often presented as a strategy for design innovation by its advocates as well as by outside observers, and considering the amount of capital invested by the private sector, governments and academia to develop and promote innovation through biomimicry; what variables explain this association of biomimicry to innovation?

2.1.1 Primary Research Question

This research aims to investigate and explore what makes biomimicry a tool for innovation in sustainable design. The research question is:

What supports biomimicry as a strategy of design innovation and what aspect(s) of biomimicry lead(s) to produce innovative sustainable design solutions as compared to ecodesign?

2.1.2 Research Objectives

There are three objectives to this research.

1) The first objective will be to investigate what is the difference between biomimicry compared to ecodesign and establish the true relationship between the two approaches. This objective aims to put the following two objectives into context.

2) The second objective is to gain a better view of the innovations produced in biomimicry. This research investigates through available literature and case studies a number of documented biomimicry projects to understand what types of innovations have been produced by the approach.

3) The third objective is to identify and describe which is (are) the aspect(s) that enables biomimicry to produce innovative design solutions.

This research should not only provide a larger understanding of biomimicry and innovation but also generate questions which could lead to further research in the future.

2.2 The Methodology

On the surface it is understood that biomimicry is a novel approach by the simple fact that it references nature for design ideas, but what is it that operates "behind the curtains" of biomimicry that has lead this approach to gain such attention? Biomimicry is generally viewed through the scope of sustainability or innovation; these two aspects are intrinsic to biomimicry and not necessarily exclusive. Many companies approach biomimicry not primarily as a strategy for sustainability but rather as one of innovation which frequently results in sustainable solutions. This solidifies the intrinsic link between the two contexts. Therefore, biomimicry can be observed in one of two ways: 1) within the context of sustainability or 2) within the context of innovation.

This study principally aims to get a deeper understanding of the biomimicry approach through the lens of innovation.

2.2.1 A Qualitative Approach

To guide this study, the qualitative approach is most appropriate. John Creswell (2007) describes qualitative research[6] as a method to understand a phenomenon where certain aspects of the research subject may be unknown or not quite understood. Qualitative research is used when the researcher needs to test a theory or assumptions about a phenomenon. In this case, the study aims to reveal and understand the variables involved in the context of innovation produced through biomimicry. Qualitative research through the examination of various forms of data such as interviews, documents, and scholarly articles allow the researcher to expose recurring patterns which then enable the researcher to gain a deeper understanding of the phenomenon and the variables at play within the said phenomenon.

2.2.2 A Case Study Research Supported by Literature Review

As Creswell explained, qualitative research is both inductive and deductive. To gather information inductively, this study will use particular examples of biomimicry (cases) to search for patterns, categories and themes to lead to a general conclusion about the research subject. Accordingly, the research will use deductive reasoning to reach a conclusion from that information. Thus, the case study method best allows for such a study.

The case study is a research strategy which focuses on understanding the dynamics present within single settings. This research approach is especially appropriate in new topic areas (Eisenhardt, 1989) as is the case with biomimicry being a fairly new field of design. Case study research involves the study of an issue explored through one or more cases within a bounded system

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[6] "Qualitative research begins with assumptions and the use of interpretive/theoretical frameworks that inform the study of research problems addressing the meaning individuals or groups ascribe to a social or human problem. To study this problem, qualitative researchers use an emerging qualitative approach to inquiry, the collection of data in a natural setting sensitive to the people and places under study, and data analysis that is both inductive and deductive and establishes patterns or themes." Furthermore, Creswell explains that "qualitative researchers typically gather multiple forms of data, such as interviews, observations, and documents, rather than rely on a single data source. Then they review all of the data and make sense of it, organizing it into categories or themes that cut across all of the data sources…qualitative research today involves closer attention to the interpretive nature of inquiry and situating the study within the political, social, and cultural context of the researchers..." (Creswell, 2007)

(Creswell, 2007). Thus, this study will specifically be using what Robert Stake calls a *multiple case study* or *collective case study*. Stake asserts that this approach is appropriate because "... a number of cases maybe studied jointly in order to investigate a phenomenon, population, or general condition" (Stake, 2005). Therefore, studying multiple cases of biomimicry will allow to gain a general understanding and establish patterns inherent to biomimicry in the context of innovation. To gather information on design innovation and biomimicry, this study will comprehensively rely on information in the literature in the form of documents, books, case studies, scholarly articles, reports, as well as the researcher's experience with the subject to a lesser extent.

2.2.3 Analysis

First Objective: *to investigate on what is the difference between the biomimicry approach compared to the ecodesign approach and establish the true relationship between the two approaches.*

The first objective aims to contextualize the next two objectives. To investigate on the relationship between the two approaches, a comparative study was conducted by identifying the characteristics of the approaches objectives and processes. A qualitative interpretation of the findings were then used to present a view of the actual relationship between the two approaches.

Second Objective: *to gain a better view of the innovations produced in biomimicry. The research investigates through case studies and available literature a number of documented biomimicry projects to understand what types of innovations have been produced by the approach.*

The second objective aims to specify what types of innovation have been produced by the biomimicry approach. To realize this objective, information available in the literature (in the forms of case studies, articles, interviews, and reports) on fifteen (15) biomimicry cases has been gathered. Three "qualification grids" were then created to gauge whether a case qualified as incremental, radical or disruptive innovations. To investigate this, the criteria or characteristics found in the literature for each type of innovation were used. For incremental and radical innovation, the paper makes use of the most recurring criteria in various innovation sources (see table 4), and for disruptive innovation it makes use of the criteria defined by Prof. Clayton Christensen. These criteria were organized in the vertical axis of the grid and the cases organized in horizontal axis of the grid. Based on the available information it can specified whether or not a case met a criterion. This process then provides two sets of results: The number of criteria met by a case and the number of cases which have met a specific criterion. In section 3.1.2.1, the cases have largely shown to qualify as radical innovations. To verify this result, another grid was used by referencing the criteria for radical innovation by Dahlin and Behrens (2005). The results were qualitatively interpreted to assess the types of innovations the biomimicry approach produced.

Third Objective: *to identify and describe which is (are) the aspect(s) that enables biomimicry to produce innovative design solutions.*

To fulfill this objective, two aspects of biomimicry have stood out as the principal engines of innovation in the process: analogical reasoning and transdisciplinarity. A literature review was conducted and the information gathered was used to describe how these two aspects of biomimicry support innovation.

2.2.4 Research Disclaimer

Biomimicry is a new discipline or phenomenon and therefore it is a fairly new subject of research. Poupart *et al.* state that when studying a new research subject, in qualitative research it is necessary to have a good framework, to expect the research to have an iterative and retroactive aspect to it (Bellemare, 2011). This was the case in regards to chapter five where it was found necessary to add elements to this chapter which were not originally part of the planned methodology in order to provide a valid conclusion to this chapter.

2.2.5 Research Limitations

There will be certain factors which will put on limitations on this research.

1) Design is a broad term which can relate to products, architecture and urban planning. This research will solely focus on biomimicry in product design for the reasons that a) the number of projects to observe would be too large and b) the design process in these aforementioned fields are not similar. The process to design a building is not the same as the process to design footwear, therefore it is better to investigate design projects from a

singular field which would most likely use a similar design process. It would be too large a task to investigate all product design biomimicry projects; therefore we will focus on a limited number of projects to make this investigation.

2) The available information on various biomimicry projects is not uniform, meaning that the amount of information on length of the project, people and disciplines involved, details of the design process, market impact and acceptance for example varies. In some cases, the information is simply unavailable.

3) To be able to fully investigate disruptive and sustaining innovation warrants more information to get more in-depth/conclusive answers. The results gathered paint a general view of the types of innovations generated in the 15 biomimicry cases studied, but there are many variables that need further investigating. Disruptive innovation deals with innovation in the market spectrum hence more detailed and quantitative information would be needed such as a company's market share, annual sales, competitor's annual sales, etc.

4) The goal of this study is to portray a general understanding of biomimicry in relation to innovation. To classify the cases as incremental, radical or disruptive innovations, the paper determines whether or not a case meets a criteria based on the information available, hence the results may sometimes be subjective.

3 Chapter Three_ Understanding the Relationship between Ecodesign and Biomimicry

"No matter what product you are designing, nature is always the best database. There is more in the world to be discovered than there is to be invented."

-Franco Lodato/ designer

3.1 Philosophy and Objectives

Throughout the years, there have been various theories and practices on what is the best approach to environmentally conscious design. These approaches vary mainly in their philosophy, on where the focus needs to be in order to reduce environmental impact (materials, consumption, recycling, re-use, reduce, etc.) but their end goal remains largely the same. As new knowledge is acquired, new strategies emerge due to a broader understanding of the issue at hand. This section aims to understand the fundamental differences between ecodesign and biomimicry: the former being the established approach to ecological design and the latter being the emerging approach.

3.1.1 Philosophy and Objectives of Ecodesign

The fundamental objective of ecodesign is to develop an environmentally sustainable product, and this objective must be clear to and accepted by all members of the design team (Guidice et al., 2006). The adoption of a systems approach rather than a product approach is largely where ecodesign differentiated itself from its predecessor (green design). As European countries were the most progressive on the issue, Pauline Madge adds that "much of the research in the UK and elsewhere focused on the minutiae of ecodesign practice, adopting a systems approach either to the individual product or product system, or to industry as a whole…this was related to the new interdisciplinary subject of industrial ecology which was closely modeled on ecological systems" (Madge, 1997). Life Cycle Design (LCD) is a similar application of the lifecycle concept to the design phase of the product development process, indicates a design approach akin to natural systems, meaning that all the phases of a product's life cycle (development, production, distribution, use, maintenance, disposal, and recovery) remain in a closed loop cycle (Guidice et al., 2006).

The Society of Environmental Toxicology and Chemistry (SETAC) had for objective to develop and promote tools to evaluate the environmental impacts of a technique or activity. Since the 80s, raw materials, energy, solid wastes, water pollution and air pollution have been integrated in environmental impact analysis to gain a better and more complete vision of the impacts generated by products or systems (Plouffe, 2010). Life-Cycle Assessment (LCA) is one of the main tools of ecodesign which differentiates it from green design and which to this day has made ecodesign a successful approach to environmentally conscious design. LCA evaluates impacts on the environment from various activities associated to a product, a service or a system; from extraction of raw materials to waste disposal. It allows identifying where a product's environmental performance can be improved (Plouffe, 2010). The main parts of LCA as defined by SETAC are: life-cycle inventory, life-cycle impact analysis, and life-cycle improvement analysis. Based on that methodology, SETAC conducted many case studies which allowed them to establish a data base and fine tune its method. Today, there are more than fifty computer programs to calculate LCAs. It has become the most prominent tool in regards to product analysis from an environmental standpoint.

As ecodesign progressed, various new design approaches to reduce environmental impacts were created. Depending on the targeted goals of an organization or company, a design team may decide upon a combination of these design approaches to meet their objectives. These design approaches are instrumental to generate design options that can be checked against the feasibility and potential benefits for customers, the organization and stakeholders (ISO, 2001). Systemic design, technology for sustainability, service design, improvement of materials efficiency, design for reuse, and recovery and recycling to name a few are some of these top ecodesign strategies.

3.1.2 Philosophy and Objectives of Biomimicry

Biomimicry is not the first form of bioinspired design, many other forms have preceded it thus it is quite important to understand the philosophy and aspects of biomimicry which differentiates it from its predecessors. Biomimicry 3.8 promotes three (3) critical elements which essentially represent the foundation of the biomimicry philosophy: ***emulate***, ***(re)connect*** and ***ethos***. By combining these essential elements, bioinspired design becomes biomimicry.

> ***Ethos***- forms the essence of the biomimicry philosophy and ethics. It represents an ethic for a practice rooted in respect and responsibility to all life forms. Holding this element should lead towards solutions that are conducive to life (Biomimicry 3.8, 2012).
>
> ***(Re) connect***- is about regaining an understanding that people and nature are deeply intertwined. It is a practice and mindset that explores the relationship between humans and nature. To quiet human cleverness means to take a step back and pay close attention into life's solutions, patterns and deep principles which have evolved over 3.8 billion years of R&D (Biomimicry 3.8, 2012).
>
> ***Emulate***- to conduct design as nature would by referencing nature as model, measure and mentor. Biomimicry is emulation, it is to solve problems through bioinspiration as a means to reduce human impact on the planet's life support system (Biomimicry 3.8, 2012).

3.1.2.1 Three Forms of Inspiration

Biomimicry is emulation. However, it is not simply to imitate as imitation is rather superficial but emulating is replicating through a fundamental understanding of the how and the why of nature. There are three (3) fundamental levels of biomimicry as each form represent a certain degree of complexity and scale: ***inspiration by forms*** (morphology), ***inspiration by process*** (chemistry), and ***inspiration by systems*** (strategy).

Inspiration by Natural Form: Considered the first level of biomimicry. It consists of looking at the shapes that various organisms have developed to adapt to their environment. Shapes that enable them to gather water, save energy, protection from parasites, color through structure and how nature builds with minimal materials among many examples.

Inspiration by Process: Considered the second level of biomimicry, also called deeper biomimicry. It consists of looking at the processes and techniques that various organisms have used to make materials and substances. Nature makes materials at low temperatures, using only few polymers and minimal energy use. The growing new field of green chemistry is attempting to replicate these non-toxic formulas.

Inspiration by Systems: Considered the third level of biomimicry. It means looking at how organisms and ecosystems function to be as effective as possible. What are nature's strategies to build using minimal materials, how to use minimal energy, how nature creates diversity and benefits from that diversity and for all material to remain within close loop cycles.

3.1.2.2 Nature as Model, Mentor and Measure

In order to consciously emulate the natural world, nature must be looked at differently, it requires a shift in our relationship towards the natural world. Biomimicry entails learning *from* nature which inherently means that nature must be looked at differently than when one attempts to learn *about* nature. Although, the more one learns about nature enables one to learn more from nature. To learn about nature means observing the behavior of the various organisms of the natural world, however to learn from nature means to observe the how and why of the various organisms and species in the natural world. Baumeister and Benyus further describes this biomimicry principle by explaining that nature must be looked at as a model, measure, and mentor (see table 3).

To further enable designers to create designs that are following nature's laws, Biomimicry 3.8 created the Life's Principles wheel (see figure 9) based on the recognition that life on earth is interconnected and interdependent, and subject to the same set of operating conditions which evolved a set of strategies that have sustained life over 3.8 billion years (Biomimicry_3.8, 2012). Each principles can be used early in a project in order to provide a project with a certain framework. There are six (6) Life's Principles: 1) Evolve to Survive, 2) Adapt to Changing Conditions, 3) Be Locally Attuned and Responsive, 4) Use Life-Friendly Chemistry, 5) Be Resource Efficient (Material and Energy), and 6) Integrate Development with Growth.

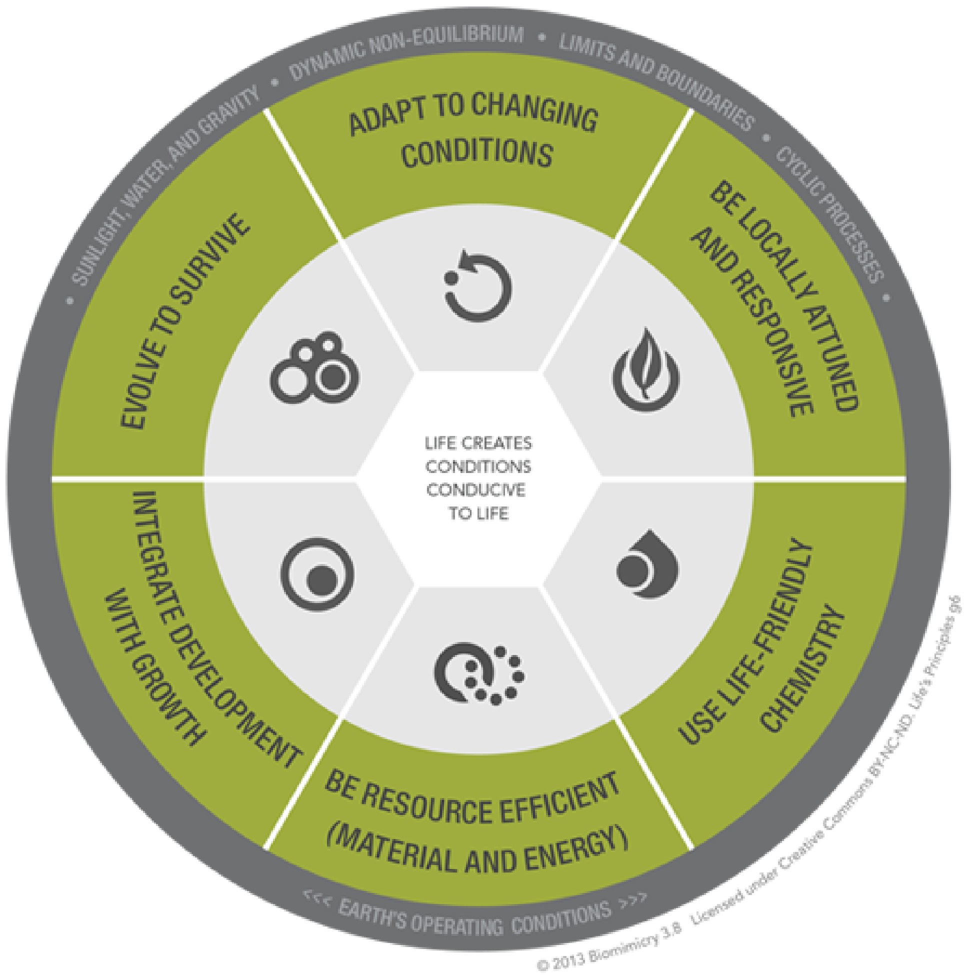

Figure 9. Biomimicry 3.8's Life's Principles. (Biomimicry_3.8, N.D.-b)

To emulate nature's designs, we must "quiet human cleverness", meaning that we must take a step back and stop relying so much on the thought process which has created much of the progress humans have come to enjoy but which is also responsible for much of the ills and devastation we are now facing as a species. It calls for the need to look into nature's design principles; to its 3.8 billion years of R&D to appropriately inform our design practices. The need to shift the focus from learning *about* nature to that of learning *from* nature as a way to better inform our design decisions (Biomimicry_3.8, 2012). It's the understanding that looking into biology and natural systems for design inspiration can help solve human design problems and that by emulating nature's forms, processes, ecosystems and green chemistry we can learn to design and develop better materials, products, buildings and cities that will seamlessly integrate with the natural environment and thereby mitigate our negative impact on the environment. Therefore the core objective of biomimicry is the design and creation of products, buildings, and cities that are well adapted to life by transforming the principles of nature into successful design strategies: to create a symbiosis between the technosphere and the biosphere.

3.2 Differences in Their Process

As previously stated, all iterations of environmental design approaches vary in their philosophy and objectives toward a common goal of reducing environmental impacts. The difference between ecodesign and biomimicry resides mostly in their process. To properly compare the design process of ecodesign to that of biomimicry, it is necessary to also analyze the traditional design process.

3.2.1 Traditional Design Process

To get a design from a concept to a product, designers must adhere to a set of activities called the design process. The procedure of product design is common in most design firms and corporate design offices. In the literature, the product development process has been described in detail by many researchers and they all describe a few main steps that must be carried out during the design process (Aguas, N/D). In general, most descriptions may vary between five (5) to eight (8) steps. By observing various models of the product design process, the variations in number of steps usually stem from the integration of two or more steps of the process into a single one. The design process or design thinking process is best thought of as a system of overlapping spaces rather than a sequence of orderly steps (Brown, 2014), real-life design is executed in an iterative fashion, and the real creative mental process is still unknown despite almost all models of the product development process appear in linear, sequential flowchart form (Aguas, N/D). According to Tim brown, president and CEO of IDEO, there are commonly three phases to the design process: inspiration, ideation and implementation (Brown, 2014). Phase I consists of problem definition, research, strategy, and inspiration. Phase II is where the designers explore possible options through brainstorming, ideation, sketching and testing ideas. Finally phase III is about execution and consists of detailed design development, communication and creating deliverables.

The model below (figure 10) shows the design process according to Pahl and Beitz (1997). Figure 11 and table 5 show the product design process according to Ulrich and Eppinger (2004). As mentioned above, various models of the process have been generated over the past years, each representing the process as understood or envisioned by the authors. However, the Ulrich and Eppinger model seems the most accurate (based on the author's experience).

The design process is a unique creative problem solving process, very different from the scientific method, it is commonly used to solve wicked problems have no single solution (Buchanan cited by Colby, 2011).

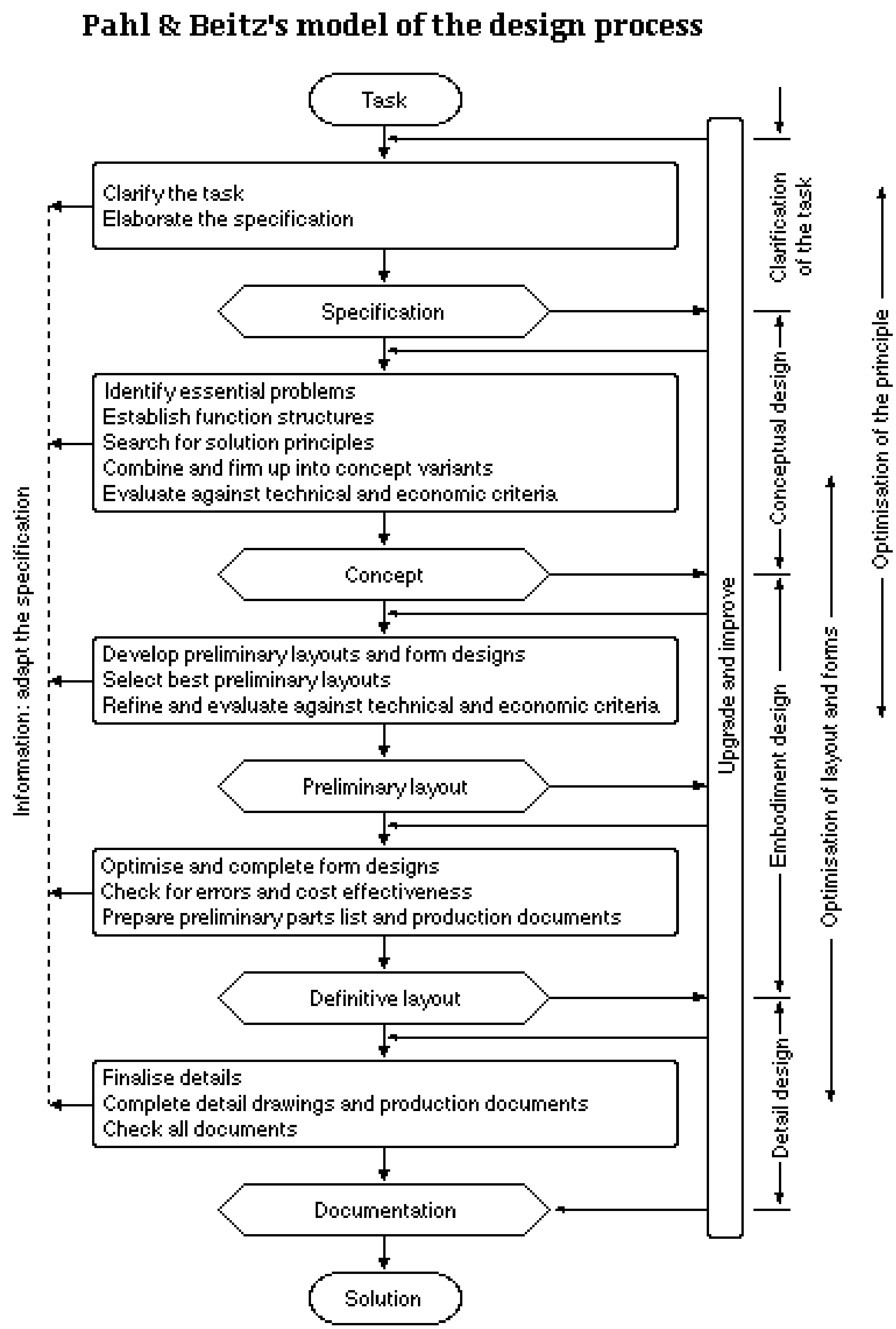

Figure 10. Model of the Design Process by Pahl & Beitz (1997). Retrieved from www-mdp.eng.cam.ac.uk

Table 5. Product Design Process. (Ulrich & Eppinger, 2004)

PRODUCT DESIGN PROCESS (ULRICH AND EPPINGER, 2004)	
Planning Phase	• Generate mission statement (target market, business goals, key assumptions and constraints)
Concept Development	• Identify needs of target market; Select several product concepts for further development and testing
System-Level Design	• Define product architecture • Decompose product into subsystems and components • Define final assembly scheme
Detail design	• Complete specification of geometry, materials and tolerances of all parts • List of standard parts to be purchased • Detailed drawings • Process plans for fabrication and assembly
Testing and Refinement	• Building of alpha- and beta- prototypes • Alpha: same material and geometry does it work? Does it satisfy customer needs? • Beta: parts supplied by production process • Tested internally and by customers. Tested for performance and reliability
Production Ramp-Up	• Small volume production to train workforce and work out any remaining problems

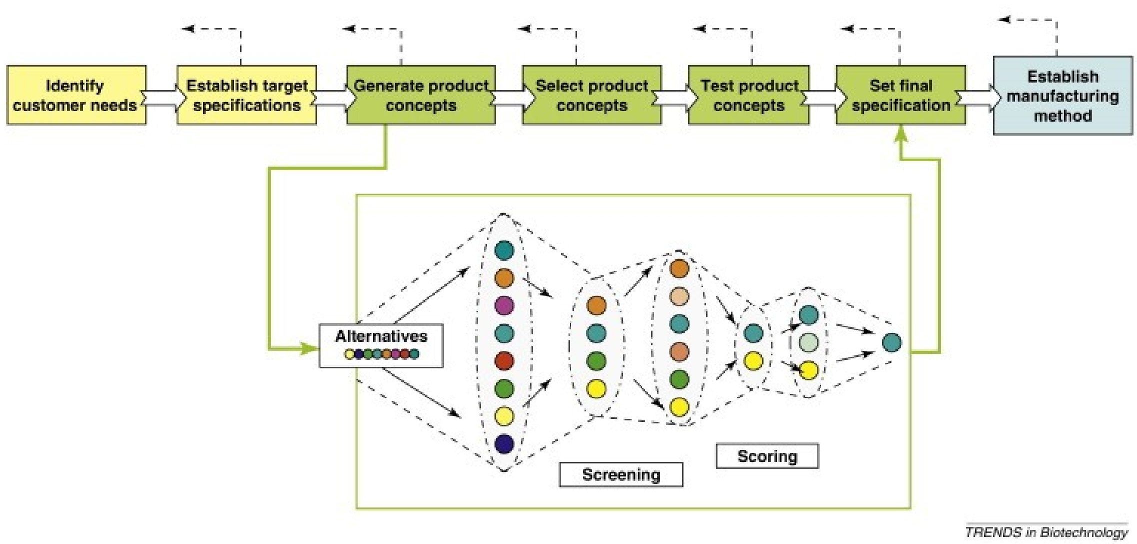

Figure 11. Product Development Process by Ulrich & Eppinger (2004). Retrieved from www.cell.com

3.2.2 Ecodesign Process

The objective of ecodesign is to reduce the impact of the built environment on the natural environment, therefore the manner the first observers of ecodesign saw fit to resolve the problem has been to establish a set of added strategies within the design process. To establish guidelines which will reduce the negative impact of a product or service before the design process even begins. To design environment-friendly products, new constraints have to be taken in consideration such as material use optimization, clean manufacturing, efficient distribution, clean use/operation and end of life optimization. The environmental guidelines the design team desires to implement have to be integrated with all the other requirements and constraints of the traditional design process (Aguas, N/D). The Eco-Design Manual from Brezet *et al.* (1996), suggests seven steps to the design process of ecologically responsible products as it is shown in table 6.

The ecodesign process is not unlike that of the traditional process. In Brezet et al.'s 1996 model for example, we can see that the process is essentially the same as in the traditional model. In that model, the difference resides in steps 1 (Organization of an Ecodesign Project) and step 3 (Establish Ecodesign Strategies). In these steps, the design team will establish ecological guidelines, strategies and requirements to ensure the design of an environment friendly product.

Table 6. Ecodesign Process Model by Brezet et al. (1996)

ECODESIGN PROCESS (BREZET *et al.* , 1996)	
Product Planning	• Step 1_Organization of an Ecodesign Project • Step 2_Product Selection
Product Specification	• Step 3 _Establish Ecodesign Strategies
Conceptual Design	• Step 4_Generation of Ideas
Detail design	• Step 5_Detailing the Design Concept
Testing and Refinement	• Step 6_Communication and product Launch • Step 7_Organization of Follow-Up Activities

3.2.3 Biomimicry Thinking

Many early biomimicry projects have been created without a clear method specific to biomimicry because it is a fairly new approach and many happened by accident or after gaining a certain insight and recognizing the potential of a natural feature. Hence, there aren't many methodologies that have been developed to help designers use this approach. The Biomimicry Institute (Biomimicry 3.8) so far has been the only organization to have established a clear and concise methodology for designers to use this approach called Biomimicry Thinking.

The design strategy of biomimicry or Biomimicry Thinking falls in two (2) categories:

1) **Challenge to Biology**- To define a design problem or human need and to consult the ways that various faunal, floral, bacterial organisms or ecosystems solve this issue.

2) **Biology to Design**- To identify a particular characteristic, behavior or function in various faunal, floral, bacterial organisms or ecosystem and to translate it into human designs.

Of the three elements of biomimicry thinking (ethos, (re)connect, emulate), the most common element to most people is **emulate**. Emulation is fundamental to biomimicry and provides an understanding of how it fits into the process of any design discipline. Unlike the other essential elements, emulate most clearly needs a disciplined practice of integrating biomimicry thinking. Over the years, Biomimicry 3.8 has created and tested different versions of what was formerly called a biomimicry methodology and as a result of time and experience, they have come to the understanding that there isn't just a single methodology, from start to finish, which applies to all design disciplines and all applications (Biomimicry_3.8, N/D) and they have found that specific terminology used in methodology meant entirely different things to different disciplines. Biomimicry thinking is therefore a framework or a set of parameters on how to best apply biomimicry into any design project rather than a methodology and thereby facilitating introducing it into any design discipline.

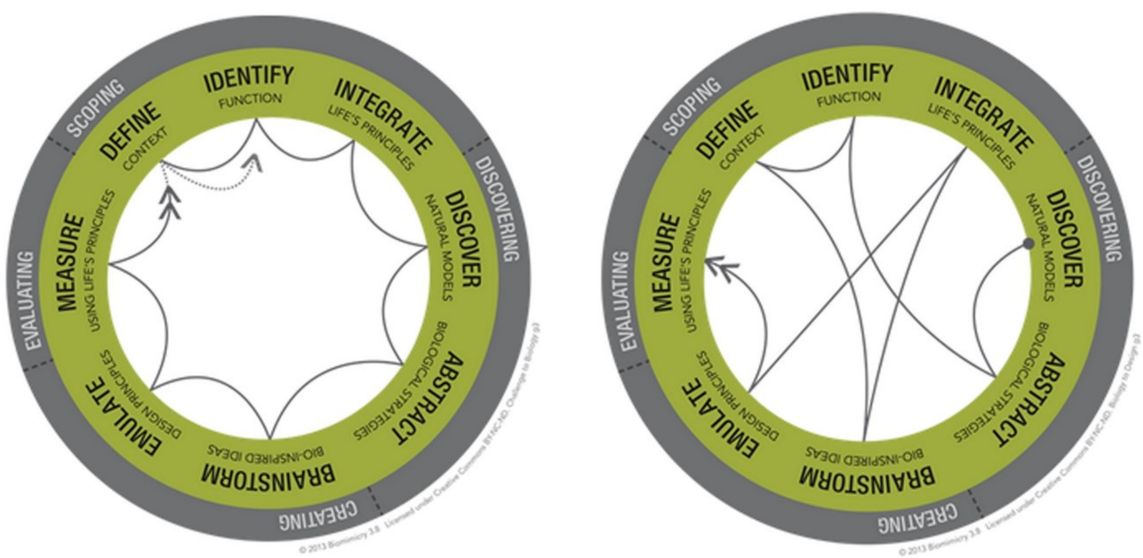

Figure 12. Challenge to Biology Process & the Biology to Design Process. (Biomimicry_3.8, N.D.-a)

For Biomimicry 3.8, emulation means bringing the principles, patterns, strategies, and functions found in nature to inform design (Biomimicry_3.8, N/D). The biomimicry process is composed of four (4) realms or phases to guide the design process: **scoping, discovering, creating, and evaluating**. Following is Biomimicry 3.8's description of the four realms.

> **Scoping**- the purpose of the scoping phase is to identify the problem to be solved together with its context, criteria, and constraints. Scoping occurs prior to actual design and includes preparatory work determining the project's challenges, collecting and analyzing the facts, setting goals, and harmonizing the project team (Biomimicry 3.8, 2012).
>
> **Discovering**- usually occurs after the team has a sense of the challenge and/or opportunity for design and seeks inspiration and ideas. This phase includes research, which often includes fieldwork, and exploration into tangential yet related designs that might provide fodder for the creating phase, especially brainstorming (Biomimicry 3.8, 2012).
>
> **Creating**- the high profile piece of designing. To create something new, putting things together in a new way, making and inventing. The ideation phase of creating traditionally involves a combination of exploring how others have solved for that opportunity or challenge and brainstorm new solutions. This phase includes concepts sketches, prototype modeling, and material sample comparison for example. In the end, it results in a new human product or design (Biomimicry 3.8, 2012).

Evaluating- generally occurs once a specific product, process, solution, or opportunity is identified. It is used to assess the appropriateness and viability over the long-term and across a specific context. It is the opportunity to look for missed limits and boundaries, to reflect on original intentions and goals, and to ensure (at a minimum) that baseline quality and safety standards are addressed. It is sometimes unfortunately left to the very end and only given a token effort, with the exception of perhaps the financial analysis (Biomimicry 3.8, 2012).

Like all the traditional design processes, biomimicry thinking is iterative, non-linear and fluid, thus to present the process in a linear progression would not be an accurate portrayal of the actual process. Even within the same design field, no two projects follow the exact same progression.

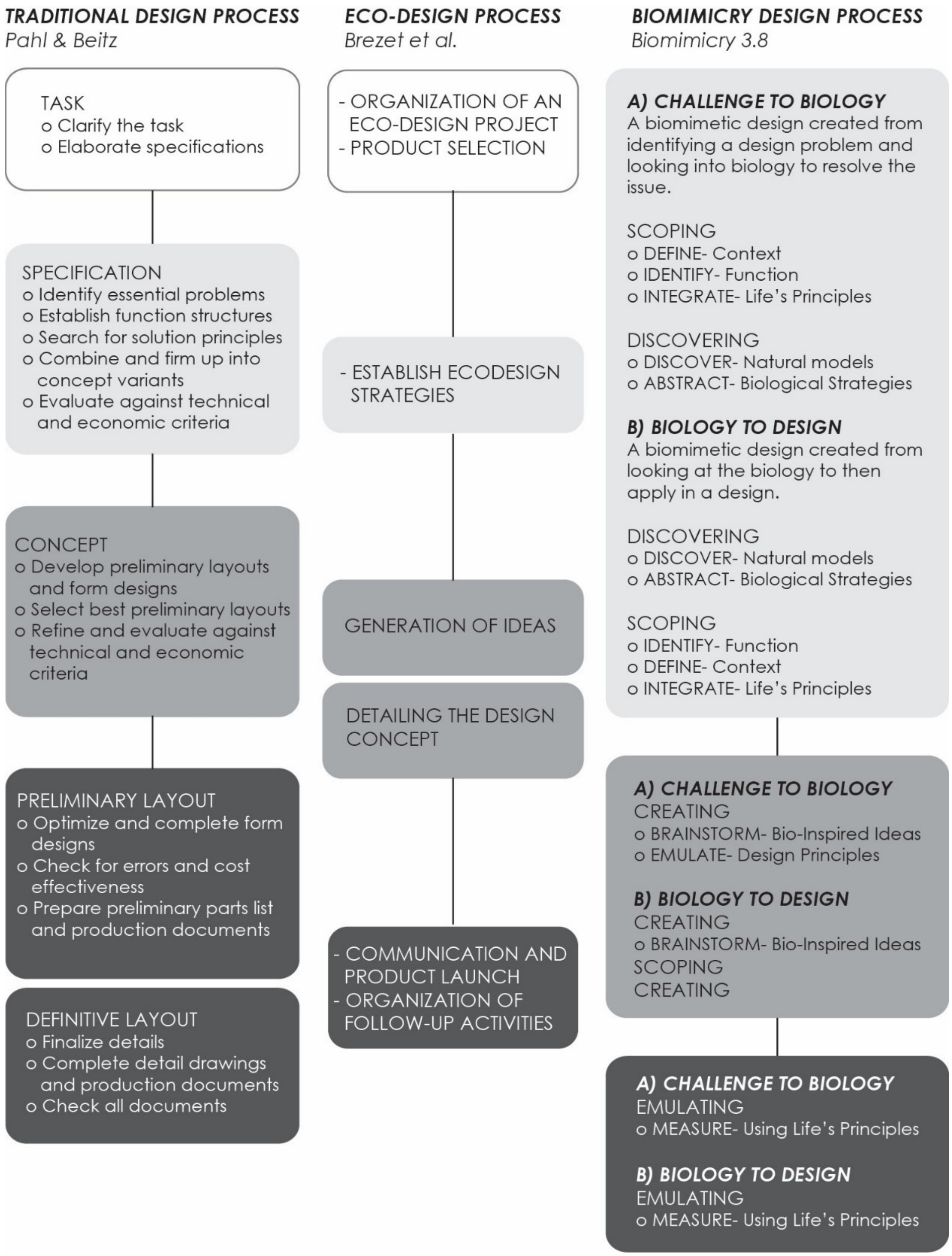

Figure 13. A Comparison of the Traditional, Ecodesign and Biomimicry Thinking Processes.

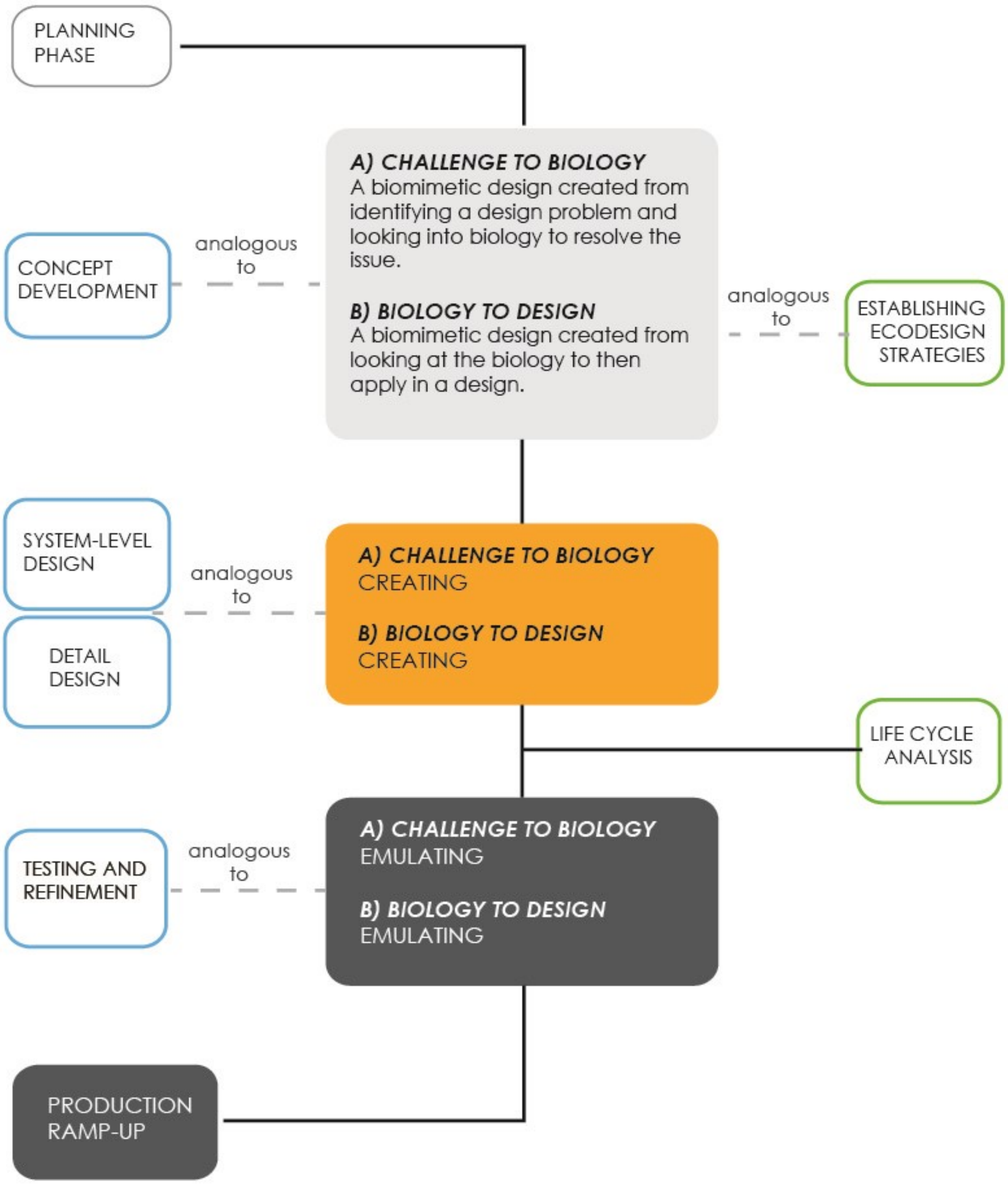

Figure 14. Biomimicry Thinking in Relation to Ecodesign and the Traditional Design Process.

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3.3 Interpretation and Conclusion

In comparison to the traditional design process, the ecodesign process is inherently a modified version of the traditional process as it shares all of the primary steps of the traditional process. The difference is situated in the steps that were added in order to insure that from the beginning of the project and throughout, the necessary steps were taken to reduce the impact of design on the environment (as shown in table 6).

The biomimicry design process is not necessarily a stand-alone process as Biomimicry 3.8's model doesn't show certain steps like the planning phase and production ramp-up (the very beginning and very end of the design process). While biomimicry thinking shows obvious differences when compared to the traditional and ecodesign processes, these differences are essentially a difference in method in the brainstorm phase (*Scoping*), the idea generation phase (*Creating*) and refinement phase (*Emulating*) (see figure 13). The model in figure 14 illustrates the biomimicry process in relation to elements of the traditional design and ecodesign process.

Ecodesign not only shares similar steps to traditional design but the procedure remains essentially the same. The brainstorm phase and the idea generation phase for example, are conducted in the same manner in both approaches. As aforementioned, the difference resides in the steps added to the process of traditional design, so in comparison to ecodesign, biomimicry thinking shares similar steps as well. If we look at Brezet *et al.*'s brainstorm phase, *Establish Eco-Design Strategies*, it is fundamentally a similar phase as the *Scoping* phase of biomimicry thinking. It is in that phase that the design team will establish guidelines as to how the biomimetic design will meet the criteria of *Life's Principles,* in other words, how the design will meet requirements to produce environmentally friendly designs. Conversely, biomimicry thinking is an entirely different approach from ecodesign, the brainstorm and idea generation phase of biomimicry thinking, *scoping*, is an entirely different procedure by its method, references, and people involved in the process.

Essentially, despite these differences, ecodesign and biomimicry aim for the same goal and considering the similarities between the traditional and ecodesign process, the latter can just as well be integrated to biomimicry thinking as shown in figure 14. Both approaches have their specific tools/methods to ensure that a design is environmentally friendly: biomimicry uses its Life's

Principles whereas ecodesign uses Life Cycle Assessment. The tools of ecodesign (LCA) could seamlessly be used in conjunction to biomimicry and in this manner, better gauge the "rightness" of a biomimetic design to ensure a solution that is conducive to life.

To reiterate, biomimicry's Life's Principles represent the overarching patterns found amongst the species surviving and thriving on Earth. Case studies of bioinspiration result from the inclusion of biological insights and strategies into design and characterize the vast bulk of examples of biomimetic technologies (Biomimicry_3.8, N/D). Nature integrates and optimizes these strategies to create conditions contributing to life and by emulating from these natural principles as design benchmarks, we can model innovative design strategies, measure our designs against these sustainable benchmarks, and allow our design endeavours to be informed by nature's Life's Principles (Biomimicry_3.8, 2012) which are essentially a life-conducive R&D databank. Ecodesign's Life Cycle Assessment (or Life Cycle Analysis) is a tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle, from its conception, production, use, and to its disposal. LCA provides an adequate instrument for environmental decision support. Reliable LCA performance is crucial to achieve a life-cycle economy. The International Organization for Standardization (ISO), a world-wide federation of national standards bodies, has standardized this framework within the series ISO 14040 on LCA (UNEP, N/D).

Therefore, after observing biomimicry and ecodesign through their process, this research reaches the conclusion that the two are not mutually exclusive and that the two approaches are actually rather complimentary by the very fact that one approach is ***qualitative*** while the other is ***quantitative***. Biomimicry's Life's Principles references nature not only as inspiration but also as measure in order to qualitatively create designs that are environmentally benign, whereas ecodesign's LCA is a tool to quantitatively measure, from the conception stages of product or service and throughout its life-cycle, the environmental impact it will generate. It is specifically that distinction that makes both approaches compatible, hence making ecodesign, through its tool LCA, complimentary to biomimicry. Biomimicry and ecodesign, despite being two different approaches, are not competing approaches as they are often portrayed or understood but if the two are combined, it turns them into a more comprehensive approach to sustainable design.

4 Chapter Four_ The Biomimicry Cases

"You could look at nature as being like a catalog of products, and all of those have benefited from a 3.8 billion year research and development period. And given that level of investment, it makes sense to use it."

-Michael Pawlin/ architect

To guide this study, a total of fifteen (15) cases were chosen in order to understand the link between biomimicry and innovation. As explained in the research limitations section of the previous chapter, the cases were chosen primarily on the basis that they had to be product related. In the next chapter, these fifteen cases were examined to help determine whether they met the various requirements for an innovation to be considered incremental, radical, or disruptive.

The following seven (7) cases stood out in further explaining the various criteria involved in innovation.

4.1 PureBond Technology by Columbia Forest Products

PureBond Technology is a urea formaldehyde-free wood glue created by Dr. Kaichang Li for Columbia Forest Products (CFP) and inspired by the blue mussel. Dr. Li, a Ph. D. in wood chemistry and a professor in the Department of Wood Science & Engineering at Oregon State University, took interest in a fascinating phenomenon in the blue mussel (Institute, 2011a).

Figure 15. Blue mussels (*Mytilus Edulis*) and PureBond Technology. Images retrieved from asknature.org and prweb.com

The Columbia Forest Products company was searching for a non-toxic, sustainable and environmentally friendly solution to the use of conventional wood glues. Conventional wood glues are made of urea formaldehyde, a known carcinogenic substance due to their off-gassing of volatile organic compounds (VOCs). VOCs are recognized by the World Health Organization (WHO)(Watson, N/D) and the International Agency for Research on Cancer (IARC)(Li, 2005) as directly responsible for adverse health effects such as eye, nose and throat irritation to liver, kidney and nervous system damage (Watson, N/D).

Blue mussels *(Mytilus edulis)*, are a bivalved shell native to the Pacific Ocean (Institute, 2011a). Dr. Li noticed the ability of the shells to adhere to rocks, other shells and slippery, uneven surfaces underwater despite the strength of the waves (Watson, N/D). After months of research, Li discovered that the mussels produce filaments called byssal threads which secrete a unique amino acid called 3,4-dihydroxyphenilalanine (DOPA or L-DOPA)(Institute, 2011a) which allowed them to achieve this impressive feat.

In collaboration with CFP, Dr. Li went on to further his research on how to replicate and produce the blue mussels' marine adhesive proteins (MAPs) and found that by manipulating the composition of soy protein he was able to produce a glue very similar in performance to MAPs resulting in PureBond Technology (Watson, N/D). Compared to conventional glues, PureBond is cost competitive and outperforms in strength and water resistance. As of 2007, CFP entirely incorporated PureBond Technology in their wood products becoming the first wood company to offer such a product across their lines. The sustainability and health benefits of the product not only added to their marketability but allowed the company to weather the 2008 economic recession as well as gaining market shares in the industry while other companies weren't so fortunate.

4.2 GreenShield Fabric Finish by BigSky Technologies

GreenShield Fabric Finish is a nano-particle fabric water/oil repellant and stain resistant finish developed by Big Sky Technologies. The technology is inspired by the hydrophobic surfaces of the Lotus leaf and the Morpho butterfly's wings.

Figure 16. Electron micrograph of leaf nanostructure/GreenShield Fabric technology. Images retrieved from asknature.org and biomimicry.net

The key ingredient in products like stain resistant fabrics and non-stick cookware are chemicals called fluorochemicals; most specifically perfluorooctanoic acid (PFOA). PFOA is a known carcinogen as well as a bioaccumulative substance, meaning it is a toxic substance absorbed by organism either directly from exposure to a contaminated medium or food containing the substance or chemical (EPA, 2010) at a rate that exceeds the organism's ability to discharge the substance from its system (EPA, 1993).

The surface of the lotus leaf or the wing of the Morpho butterfly are self-cleaning surfaces due to their microscopic roughness which prevents water to adhere to its surface, also known as a hydrophobic structures. The interaction between the properties of the water molecule and the nano-topography of the surface prevents water to adhere (Institute, 2011a). As the water beads and rolls on the surface, it picks up dirt and rolls off the surface effectively cleaning the surface.

Dr. Joseph Bringley, the Chief Technology Officer at G3i explains that in the early stages of the design process, GreenShield Fabrics was designed to be as green as possible by using a 100% yield water-based process (no waste), using less chemistry and thus reducing the amount of VOCs in the product and waste produced. Compared to other stain resistant finishes, by using green nanotechnology principles, the process is conducted at room temperature which also makes the process energy efficient (Rodie, 2008). This innovative process makes GreenShield Fabrics the first textile finish to be certified by the Scientific Certification System (SCS) as their process as significantly reduced adverse human health and environmental effects by reducing PFOA by 8-10 times all the while maximizing product performance (GreenShield, N/D). Since 2009, BigSky technologies' GreenShield Fabrics increased their sales by 50% (Tarquino, 2011).

4.3 **Aquaporin Inside** by Aquaporin

Aquaporin Inside is a biomimetic filtering membrane inspired by the process employed by organs to move water molecules through membranes while keeping out impurities.

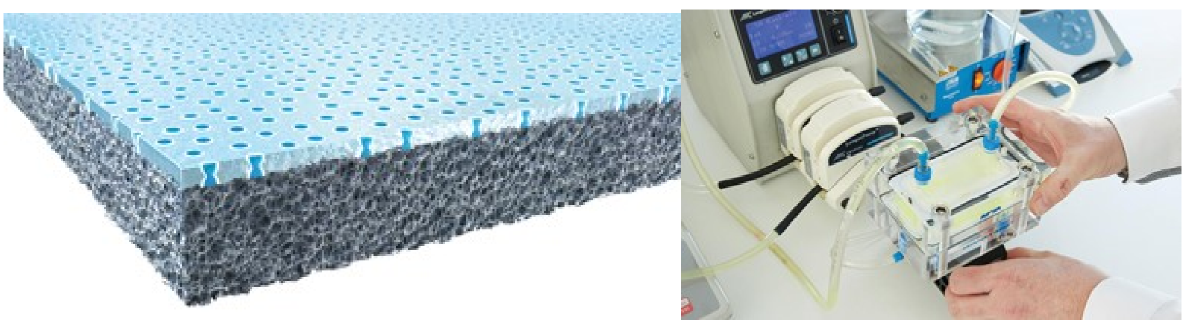


Figure 17. Aquaporin Inside technology. Images retrieved from waterworld.com

As we are facing various environmental issues, one of the most pressing issues is water conservation and the pollution of freshwater by industrial activities. Typically the two most common methods used to treat water (water purification and desalination) are reverse osmosis and evaporation (GermiNature, 2014). The problem with filtration membranes is that they are made of dense polymeric sheets consisting of micron- to nanometer sized holes (depending on the application it is used for) which requires intensive energy use to push the water through at high pressures (Institute, 2011a).

The water filtering process in pores or organs like the kidneys, is performed by the lipid bilayer of cells which are made of selective membrane channel proteins called aquaporins. The aquaporin protein solely allow the water molecule to pass through the membrane while rejecting any other unwanted particles or polar molecules (Aquaporin, N/D).

Replicating this model is the ideal strategy to filter water through a much less energy intensive technique. The Aquaporin Company is aiming to create a new water filtration technology based on the process of the selective aquaporin protein. The Danish company is replicating this natural strategy by creating artificial membranes imbued with aquaporin proteins for various water filtering devices; first to be applied and tested in labs and next to be scaled for household and industrial water filtration devices (Institute, 2011a). Aquaporins are ubiquitous and can easily be produced using bacterial or algae (GermiNature, 2014).

4.4 Sharklet AF by Sharklet Technologies

Sharklet Technology produce various surfaces mimicking the architecture and ultimately topology of shark skin to deter biofouling without the use of toxic chemicals.

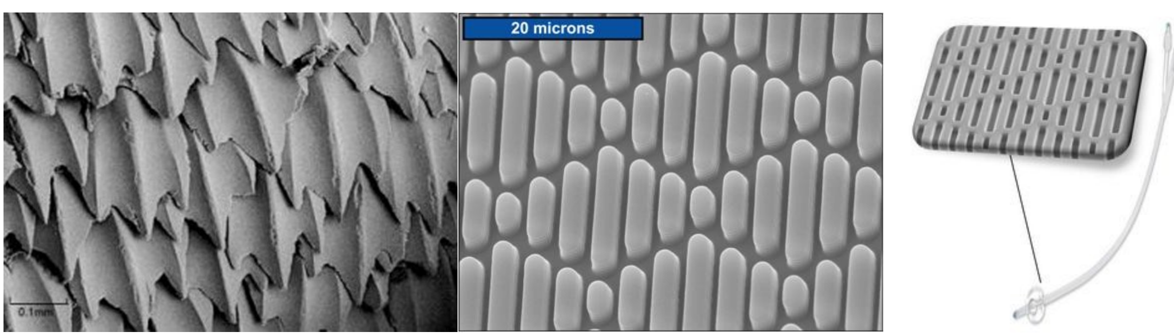


Figure 18. Shark skin nanostructure, Sharklet AF nanostructure, Sharklet cateter. Images retrieved from asknature.org, biomimicryla.org and pinterest.com

Biofouling is a process of accumulation or colonization where organisms like bacteria or barnacles adhere to a surface to access food sources. In the case of bacteria, this process allows them to multiply at a rapid rate and to protect themselves with a biofilm also called extracellular polymeric substance (EPS) which provides them protection and stability in order to keep on colonizing. In order to combat biofouling on high touch surfaces, toxic chemical are traditionally sprayed on the surfaces to kill the bacteria (Terrapin-Bright-Green, N/D). This practice in hospital settings has led to new strains of chemical resistant bacteria called "superbugs" which are responsible for the increasing number of hospital acquired infections (HAI). Each year, in American hospitals, 5 to 10 percent of hospitalized patients are affected by the phenomenon resulting in 99,000 deaths and an estimated $20 billion in healthcare costs (CDC, N/D).

The skin of sharks is made of unique enamel covered scales called dermal denticles. Dermal denticles have microscopic ridges and are arranged in a distinct diamond shaped pattern which creates a micro-topography that prevents bacteria to adhere to its surface hence effectively preventing more than 85% of bacteria from adhering to its skin. The microscopic ridges create gaps, an uneven surface which places great amounts of stress on the bacteria's cells. This requires the bacteria to spend more energy to comfortably colonize on the surface thus greatly reducing the bacteria's ability to survive (Terrapin-Bright-Green, N/D).

Dr. Anthony Brennan, founder of Sharklet Technologies, was searching for anti-fouling solutions in nature in order to counter the toxic methods traditionally used to remove the build-up of algae and barnacles on boat hulls. As he realized that large, basking sharks had little to no biofouls on their skin, he began to further research the architecture of shark skin. Through years of testing, they understood that the architecture was also very effective on preventing bacteria to colonize. Sharklet went on to test various micro-patterns and establish which was best suited for preventing various species of bacteria to communicate, multiply and form biofilms. Their unique shark skin inspired topography boasts a pattern with microscopic ridges of 3μm by 2μm (Terrapin-Bright-Green, N/D) making the ridges 1/10th of human hair, therefore the texture is invisible to the eye and non-detectable to the touch (Alsever, 2013). Depending on the species, Sharklet's micro-pattern cut bacteria by 90 to 99% (Alsever, 2013). Sharklet is taking two approaches to dispense their technology: the formation of licensing model where companies pay to use Sharklet's technology and their own medical product line. This bio-inspired technology introduces a truly innovative and environmentally responsible approach to reduce risk of transmission of human pathogens in healthcare settings, schools, and offices (Chung, Reddy, Houck, Brennan, & Rand, N.D.).

4.5 **Bionic Handling Assistant** by Festo

Festo's Bionic Handling Assistant (BHA) is biomechatronic robotic arm inspired by the elephant's trunk.

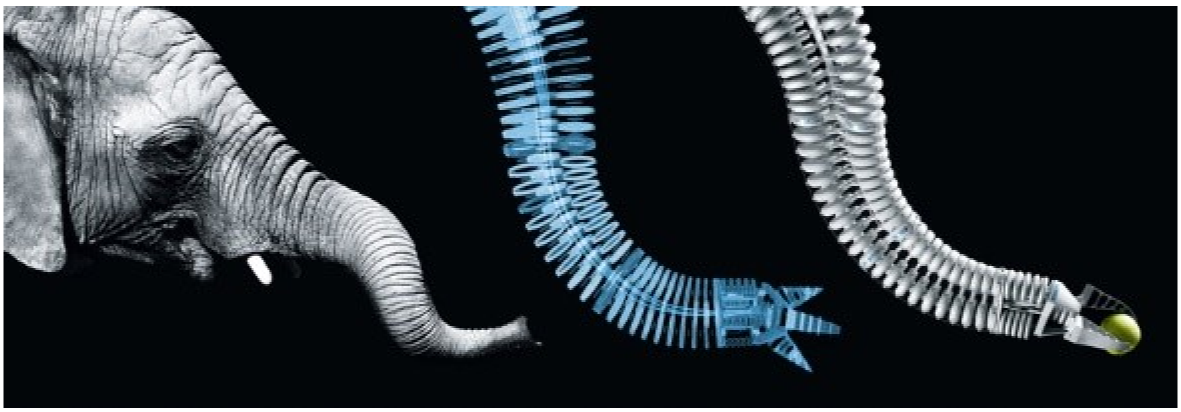


Figure 19. Elephant trunk and Festo Bionic Handling Assistant. Images retrieved from .asknature.org

There is a looming danger of injury in labs when working in close quarters with robotic assistants as compliance is not feature of these machines which is the reason why lab workers are often separated by a physical barrier to prevent injuries (Institute, 2011a).

The elephant trunk is a marvel of nature for its ability to perform fluid, subtle, complex three-dimensional, antagonistic movements, meaning that while one muscle group contracts an opposite elongates, which creates bending. This complexity allows the elephant to do so with tremendous strength and precision. The trunk is made of about 40,000 muscle bundles arranged in three (3) patterns called muscular hydrostats, structures composed of incompressible "fluid" or tightly packed muscle fibers to maintain the same volume through a variety of complex movements (Institute, 2011a).

Based on this natural principle, Festo developed the BHA which comprises three (3) basic elements for spatial movement with eleven degrees of freedom, a hand axis and a gripper (Festo, 2012). The technology is innovative for its use of bioinspiration, new manufacturing technologies such as additive manufacturing and new materials. The use of polyamide makes the structure of the BHA very flexible and compliant, stiffened by pneumatics to allow for the various motions. A combination of the use of polyamide, which renders the structure "softer" compared to traditional robots and a high degree of motion control significantly reduces the risks of injuries in direct human-machine contact (Festo, 2012). Developed by Festo through an association of interdisciplinary teams formed by universities, institutes and development companies, they rely on bioinspiration to foster technological and industrial innovations (Festo, 2012). Festo has since applied the technology in a series production, the Robotino XT learning system.

4.6 OptiStruct by Altair

OptiStruct is an engineering optimization software inspired by the process by which bone structures are optimized by their response to external stimuli.

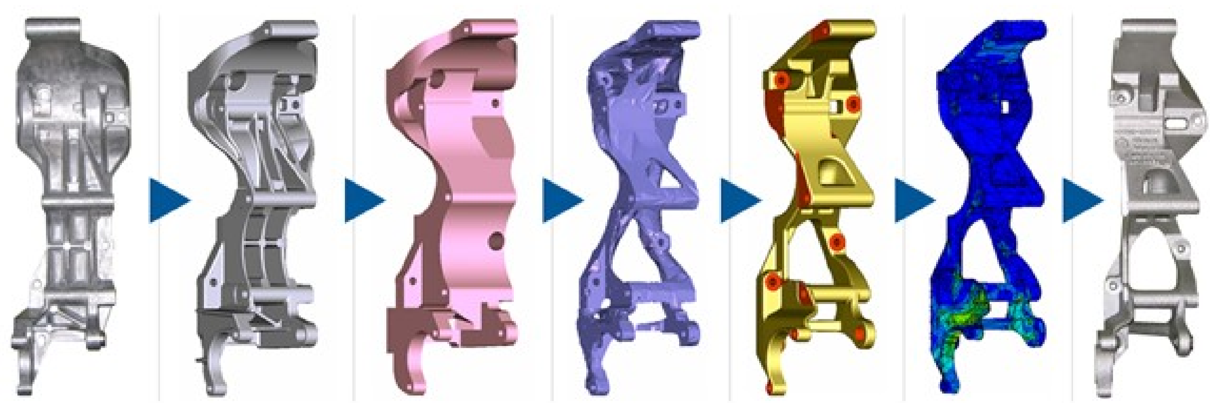


Figure 20. Drive train part transformed by OptiStruct program. Images retrieved from insider.altairhyperworks.com

CAD and structural analysis programs are based on conventional engineering principles and often result in parts that are structurally inefficient and heavier as they contain more material than necessary. Heavier components in transportation designs are directly related to greater energy demand and consumption.

Wolff's law is the theory that bones in healthy humans and animals can adapt and are responsive to the loads under which they are placed. The bone will remodel itself over time and allocate material in the appropriate places to render the bone stronger and better adapted to the loading (O' Connor 2010) while removing material where deemed unnecessary to make it lighter. This activity is performed by cells called osteoblasts which are responsible for the formation of new bones and while cells called osteoclasts are responsible for the resorption of bone. Bone remodelling is thus a temporally and spatially regulated process that results in the formation and resorption of bone tissue (Institute, 2011a).

OptiStruct is a topology optimization program modeled after the principle of bone modelling. It is a CAD modelling and analytics program based on an algorithm mimicking how bones respond to external stimuli in order to add material in response to its environment (Orf, 2013) and simulating bone growth for structural analysis and optimization for linear and non-linear structural problems under static and dynamic loadings (Bonino, 2014). This biomimetic process enables for the design of optimized parts and structures and to rapidly develop innovative, lightweight, more durable and structurally efficient designs (Bonino, 2014). Due to the strange looking, counter-intuitive designs created by the program, OptiStruct experienced much resistance by engineers as the results challenged engineering convention as well as manufacturing processes. Over time, with changes such as manufacturing constraint algorithms, the technology's strange, biomorphic designs came to eventually be widely accepted and labeled as "bionic" and elegant (Bonino, 2014). Altair's OptiStruct is now used by more than 3,000 clients in various industries such as BMW, Honda, Boeing, Lockheed Martin, NASA and notoriously now gaining traction in the architecture industry (Konrad, 2013).

4.7 Kalundborg Eco-Industrial Park

Kalundborg eco-industrial park is an example of industrial symbiosis based on the closed loop principle of ecosystems or the continuous repurposing of materials and nutrients by various organisms.


Figure 21. Forest ecosystem/ Kalundborg Eco-Industrial park. Images retrieved from .asknature.org

Most industries are often in industrial parks where their facilities will manufacture any given products. In order for any company to generate products, there needs to be an inflow of materials or raw materials that will be processed, transformed and shaped into products specific to a given company. On the other side of that process, besides the products, by-product or waste is generated which is of little to no value to the company. This unwanted by-product has to be safely disposed of and the company is solely responsible for the management and safe disposal of these residuals which demands time, energy and money to collect, organize, and dispose of their waste.

Symbiosis is defined as the co-existence between diverse organisms in which each may benefit from the other. Various organisms of a given area will usually form a community or eco-system where an organism may benefit from the waste generated by another: waste is a resource. As there is no waste in nature, essentially every resource or material at some point that is considered waste for one organism will serve as a valuable resource for another.

Industrial symbiosis is part of a new field called industrial ecology which is concerned with the flow of materials and energy through systems at different scales, from products to factories and up to national and global levels as a means to achieve sustainable industrial development (Chertow, 2008). As Kalundborg became a major industrial center, there was a conscious effort to minimize the use of limited ground water. An oil refinery suggested it uses surface water from a nearby lake and the city offered to build the pipeline for the refinery marking this as the first collaboration between the city and an industry in Kalundborg industrial park as a means to reduce costs and finding value in waste products generated within the park. It became understood that using the waste/ by-products of another company not only reduced cost associated with waste management but also reduced cost of acquiring virgin materials which also reduced environmental impact (Suarez, 2012). Over time, the environmental benefits of such partnerships became increasingly evident to industrial partners and city residents as well. By the 1980s, the partnerships were organically self-organizing into what is now the most recognized example of industrial symbiosis. The primary partners in Kalundborg Eco-Industrial Park are: an oil refinery, a power station, a gypsum board facility, and a pharmaceutical company. The partnership involves the sharing of ground water, wastewater, steam, fuel and a variety of by-products that become feedstocks in other processes (Chertow, 2008), excess heat for fish farming, heating of nearby homes, and greenhouse agriculture while other unusable by-products by the park's partners like sulfur, fly ash, and sludge are sold to companies in the vicinity (Institute, 2011a). Many new industrial symbiosis programs are being set up in China and India.

5 Chapter Five_ Understanding Biomimicry and Innovation

"Design, if it is to be ecologically responsible and socially responsive, must be evolutionary and radical."

-Victor Papanek/ designer & educator

The association of biomimicry and innovation traces back to its very beginnings in the title of the book which is credited to launch the biomimicry movement: *Biomimicry: Innovation Inspired by Nature* by Janine Benyus.

Since the advent of this seminal book, this new field has shown significant growth in activity and interest in the form of patents, research grants, and scholarly articles. According to the FBEI, the growth and interest in biomimicry is expected to transform large slices of the economy and could account for $425 billion of US gross domestic product (GDP) and another $65 billion could be attributed to the savings biomimicry could offer in terms of reduced resource depletion and pollution. We have not yet reached a tipping point where investors fully recognize and embrace bioinspiration due to lack of awareness and tangible evidence of its success, but as indicated by the trends and aforementioned numbers, we are in an era marking a paradigm shift. This shift persists not simply because biomimicry is "green", but rather because nature is becoming recognized as a "treasure trove" of innovation (Fermanian Business & Economic Institute, 2013).

Which leads to ask what supports biomimicry as a strategy of innovation? What types of innovation has been produced through biomimicry? How strong the evidence is that biomimicry leads to innovative design solutions?

As explained in the first chapter (section 1.4.2.), the literature focuses on three types of innovation: incremental vs radical innovation (technology spectrum) and disruptive innovation (market spectrum). The following sections aim to gain a general understanding of the types of innovations generated by biomimicry.

5.1 Biomimicry and Innovation in the Technology Spectrum

Concerning incremental and radical innovation, five (5) criteria or dimensions have been identified in order to classify a technology as incremental or radical: 1) technology, 2) innovation target/ strategic focus, 3) strategic goals, 4) culture, and 5) risk profile (Mattes & Ohr, 2013).

Technology: deals with the type of technology used in an innovation.

Innovation target/ strategic focus: deals with the strategy used to bring the innovation to market.

Strategic goal: deals with the market share the innovation needs to target.

Culture: deals with the company culture to foster innovation.

Risk profile: deals with the level of uncertainty involved in taking an innovation to market. Uncertainty can be classified into eight categories: technological, market, regulatory, social and political, acceptance and legitimacy, managerial, timing, and consequence uncertainty (Jalonen & Lehtonen, 2011). Technological and market uncertainty have the most established status. According to Harris & Woolley (2009), technological uncertainty involves product specification and production processes. The former involves an innovation's technical feasibility, usefulness, functionality or quality which is dependent on the newness of the technology. The latter involves the processes, techniques and knowledge used to produce products and services. New technologies cause uncertainty because they require not only new technical skills but also new business models in which those technical capabilities become valuable (Valikangas & Gibbert, 2005 as cited by Jalonen and Lehtonen).

The following table shows the difference between incremental and radical innovation in respect to the five dimensions mentioned above.

Table 7. The Dimensions of Incremental vs Radical Innovation. (Mattes & Ohr, 2013)

	Incremental Innovation	***Radical Innovation***
Technology	*-Exploits an existing technology*	*-Explores a new technology*
Innovation Target/ Strategic Focus	*-Focuses on cost or feature improvements in existing products in existing products, processes or services* *-Optimization of existing business models*	*-Focuses on products, processes or services with unprecedented performance features* *-New business models*
Strategic Goals	*-Improves competitiveness within current markets or industries*	*-Create a dramatic change that transforms existing markets/ industries or creates new ones*
Culture	*-Determined by existing procedures and organizational set-up (Stick to the rules)* *-Controllability as key determinant*	*-Open, externally oriented* *-Risk taking* *-Agility, speed, flexibility, experimentation* *-Intensive collaboration and teamwork*
Risk Profile	*-Low to medium uncertainty*	*-High uncertainty*

5.1.1 Incremental Innovation

Incremental innovation is the most predictable and most accessible form of innovation because it involves less risk, less unknown or uncertainties and mostly relies on improving a previous technology. In general, a product, process or service will be considered as an incremental innovation if it meets most of the five following criteria: 1) exploits an existing technology, 2) focuses on cost or feature improvements in existing products, process, or service, 3) improves competitiveness within current markets or industries, 4) determined by existing procedures and organizational set-up, sticking to the rules, 5) low to medium uncertainty.

Exploits an existing technology: The product, process or service's main feature uses a technology readily available in a previous version. The technology is not new to the market.

Focuses on cost or feature improvements in existing products, processes or services. Optimization of existing business models: The goal is to improve on the previous market introduced version of a product, process or service. It can be improved by adding new features or simply making the technology faster for example. It relies on improving and building upon an existing business model.

Improves competitiveness within current markets or industries: The goal is to make a product, process or service more competitive than the previous version and the competition through the use of added features and improvements the previous version did not possess.

Determined by existing procedures and organizational set-up (Stick to the rules). Controllability as key determinant: By relying on an existing technology and business model, the guidelines involved in taking a successful technology to market do not need to be reinvented but rather followed according to the same rules or guidelines that have allowed for the success of the existing technology.

Involves low to medium levels of uncertainty: All unknowns and uncertainties involved in taking a new technology to the market (i.e. conception, prototyping, manufacturing/production, and market acceptance) have mostly been dealt with in the previous version of a product, process or service.

5.1.1.1 Case Study Analysis

The following table lists the criteria of incremental innovation and illustrates how the 15 biomimicry cases in this study fare in meeting each criterion. The results in table 8 will help to establish whether or not the cases qualify as incremental innovations.

Table 8. Incremental Innovation in Biomimicry

Criteria of Incremental Innovation	PureBond	GreenShield	Ornilux	Aquaporins	WhalePower	InterfaceFLOR	Sharklet	Pax Water	Novomer	REGEN	Festo	Biolytix	OptiStruct	LAZER	Kalundborg	
Exploits existing technology	N	N	N	N	N	N	N	Y	N	Y	N	N	Y	N	Y	***4***
Focuses on cost or features improvements in existing products, process or services	N	N	N	N	N	N	N	Y	N	Y	N	N	Y	N	Y	***4***
Improves competitiveness within current markets or industries	Y	Y	---	---	N	Y	N	Y	---	Y	N	N	Y	N	---	***6***
Determined by existing procedures and organizational set-up (Stick to the rules). Controllability as key determinant	N	N	N	N	N	N	N	Y	N	Y	N	N	Y	N	Y	***4***
Involves low to medium levels of uncertainty	N	N	N	N	N	N	N	Y	N	Y	N	N	Y	N	Y	***4***
	1	***1***	***0***	***0***	***0***	***1***	***0***	***5***	***0***	***5***	***0***	***0***	***5***	***0***	***4***	

- Exploits an existing technology: **4/15**
- Focuses on cost or feature improvements in existing products, process, or service: **4/15**
- Improves competitiveness within current markets or industries: **6/15**
- Determined by existing procedures and organizational set-up, sticking to the rules: **4/15**
- Low to medium uncertainty: **4/15**

1) **Exploits an existing technology:** *The product, process or service's main feature uses a technology readily available in a previous version. The technology is not new to the market.*

Only 4 out of the 15 cases use an existing technology as the main feature: Pax Water, REGEN, Optistruct and Kalundborg.

For instance, Altair's OptiStruct is a CAD and engineering program based on the way bones optimize their structure in response to stress/external stimuli, that bones adapt to the loads under which it is placed, also known as Wolff's law (O'Connor 2010). In transportation design and engineering, CAD and structural analysis programs are used to design parts and components. Conventional CAD and structural analysis programs are based on conventional engineering principles. The resulting designs can often use more material than necessary which can be highly inefficient in terms of material economy and energy use: heavier parts means greater energy demand/fuel consumption. A modeling program that mimics bone topology can allow to rapidly develop innovative, lightweight and structurally efficient designs (Altair, 2014) and structures that are optimized for weight and strength, more durable and lighter-resulting in vehicles getting better fuel economy (Orf, 2013).

It is very important to clarify however, that the technology used by Altair's OptiStruct is novel by the fact that it was unlike anything in the market but can be considered as an existing technology because it has been in the works since the early 1990s. The technology challenged convention and was met with much resistance from engineers. The technology but most importantly, the designs created by through the technology were radical and therefore it took time for it to progressively be accepted by engineers. OptiStruct is now an industry leader some 20yrs later. Therefore, the technology is an existing technology in the sense that it has been around for some years and was subject to incremental improvements. Altair has been tweaking and perfecting it while it was not necessarily competitive on the market.

2) **Focuses on cost or feature improvements in existing products, processes or services. Optimization of existing business models:** *The goal is to improve on the previous market introduced version of a product, process or service. It can be improved by adding new features or*

simply making the technology faster for example. It relies on improving and building upon an existing business model.

4 out of the 15 cases did not fulfill that criteria. Pax Water, Regen, OptiStruct and Kalundborg were the exception in this category because the technology has been established for a considerable amount of time compared to the other 11 which have either entered the market for a few years or very recently entered the market. In the past two decades, they have been able to tune-in and improve their technology to make it more efficient.

3) **Improves competitiveness within current markets or industries:** *The goal is to make a product, process or service more competitive than the previous version and the competition through the use of added features and improvements the previous version did not possess.*

Kalundborg does not qualify for the reason that it is not product or service offered on the market but rather a system, therefore it does not compete with other business models of industrial symbiosis. Altair for example has improved its product through successive versions over time to become more competitive. Part of making their product more competitive was also to educate the market about the benefits and advantages of OptiStruct in order for the market to overcome its resistance to the counter-intuitive aspects of the program.

There was much resistance to the program in its beginnings due to the counter-intuitive aesthetics of the program's designs. The designs were challenging engineering convention as well as manufacturing processes. However, after adding manufacturing constraint algorithms, such as casting and stamping, 20 years later OptiStruct became an industry leader. Altair has since taken its technology from the car industry to the aerospace industry. The technology may create strange looking shapes that can be unsettling or perceived as wrong but overtime the designs produced by Optistruct are now being labeled as "bionic" and "elegant"(Bonino, 2014). Optistruct was used by the company Airbus to lighten and remove about 1100 lbs from the A380's rib-wing package, a weight reduction of nearly 40%.

OptiStruct's list of clients is now more than 3,000 including transportation companies like BMW, Honda, Opel, GM, Boeing, Lockheed Martin, NASA and the Department of Defense in aerospace. The company is equally gaining notoriety in commercial products and architecture. Half of Altair's estimated 2012 revenue of $240 million (up 13% from 2011) came from the auto industry and the company is growing 30% year after year in aerospace and electronics, three times the growth of its steady auto business (Konrad, 2013; Orf, 2013).

4) **Determined by existing procedures and organizational set-up (Stick to the rules). Controllability as key determinant:** *By relying on an existing technology and business model, the guidelines involved in taking a successful technology to market do not need to be reinvented but rather followed according to the same rules or guidelines that have allowed for the success of the existing technology.*

Pax Water, Regen, OptiStruct, and Kalundborg were again the only cases to meet this criterion since, as previously explained in the above criteria, they needed an already existing technology in order to fulfill this condition. OptiStruct has been perfecting their topology optimization program since the early 1990s struggling to get analytical engineers to accept OptiStruct software's "counter-intuitive" visual results. OptiStruct later became part of Altair's bigger HyperWorks software suite and no longer needed individual salesmen. For years the competition couldn't see why they did it, saying there was no market: now the competition is trying to catch up (Konrad, 2013). In the case of Kalundborg Eco-Industrial Park, the city has been established as an industrial center since its inception and an example of industrial symbiosis since the mid-1980s. As they've become a model of industrial symbiosis and as they recognized the cost advantages and environmental benefits of such a system, they have since built on and improved their systems, as well as attracted and added new industrial partners.

5) **Involves low to medium levels of uncertainty:** *All unknowns and uncertainties involved in taking a new technology to the market (i.e. conception, prototyping, manufacturing/production, and market acceptance) have mostly been dealt with in the previous version of a product, process or service.*

4 out of the 15 cases met this criterion. There's a plethora of issues, unknowns and problems associated with a new technology which requires much tending to; these issues represent a high level of uncertainty. Once a company understands how to navigate through its technological and operating challenges, to understand cause-and-effect in its system, it will shift into incremental innovation to enhance the said technology (Hurst, 2013) and thus reducing the amount of

uncertainties associated to a given technology. The technical issues associated with a new technology in matters of production and market acceptance for example have been worked over successive generations, which is what then becomes what is known as best practices. These issues are generally handled in criteria 2, 3 and 4.

5.1.2 Radical Innovation

According to Garcia and Calantone (2002), radical innovation implies a discontinuity with the past. It is what most organizations strive for and it is the center of attention of design studies. It is taught in design schools, and advocated by people discussing innovation and "design thinking". Successful radical innovation happens infrequently within any particular area and most radical innovations take considerable time to become accepted (Norman & Verganti, 2012). In general, a product, process or service will be considered as an radical innovation if it meets most of the five following criteria: 1) explores a new technology, 2) focuses on products, processes, and services with unprecedented performance feature, new business model, 3) creates a dramatic change that transforms existing markets or industries, 4) open, externally oriented, risk taking, agility, speed, flexibility, experimentation. Intensive collaboration and teamwork, and 5) involves high levels of uncertainty.

Explores a new technology: The product, process or service's main feature uses a new technology. A technology that is new and unprecedented to the market.

Focuses on products, processes, and services w/ unprecedented performance feature. New business model: The intent is to create a product, process, or service with unprecedented performance. It outperforms and is dissimilar to the previous versions. Requires a new business model.

Creates a dramatic change that transforms existing markets or industries: Creates a new market, one of a kind product. The innovation marks a paradigm shift.

Open, externally oriented. Risk taking. Agility, speed, flexibility, experimentation. Intensive collaboration and teamwork: The process of building value from a new technology is open to discovery. A new business model must be developed and the rules and guidelines to reach market success are to be determined.

Involves high levels of uncertainty: All uncertainties involved in taking a new technology to the market (i.e. technological uncertainty, market uncertainty, acceptance and legitimacy uncertainty, timing uncertainty) are new and/or unknown. All are unknowns that can potentially signify success or failure of the new technology.

5.1.2.1 Case Study Analysis

The following table lists the criteria of radical innovation and illustrates how the 15 biomimicry cases in this study fare in meeting each criterion. The results in table 9 will help to establish whether or not the cases qualify as radical innovations.

Table 9. Radical Innovation in Biomimicry

Criteria of Radical Innovation	PureBond	GreenShield	Ornilux	Aquaporins	WhalePower	InterfaceFLOR	Sharklet	Pax Water	Novomer	REGEN	Festo	Biolytix	OptiStruct	LAZER	Kalundborg	
Explores a new technology	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y	N	Y	N	***11***
Focuses on products, processes, and services w/ unprecedented performance feature. New business model	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	***15***
Creates a dramatic change that transforms existing markets or industries	Y	N	N	N	N	Y	Y	N	N	Y	N	N	Y	N	--	***5***
Open, externally oriented. Risk taking. Agility, speed, flexibility, experimentation. Intensive collaboration and teamwork	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	***15***
Involves high levels of uncertainty	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y	N	Y	N	***11***
	5	***4***	***4***	***4***	***4***	***5***	***5***	***2***	***4***	***3***	***4***	***4***	***3***	***4***	***1***	

- Explores a new technology: **11/15**
- Focuses on products, processes, and services w/ unprecedented performance feature. New business model: **15/15**
- Creates a dramatic change that transforms existing markets or industries: **5/15**
- Open, externally oriented. Risk taking. Agility, speed, flexibility, experimentation. Intensive collaboration and teamwork: **15/15**
- Involves high levels of uncertainty: **11/15**

1) **Explores a new technology:** *The product, process or service's main feature uses a new technology. A technology that is new and unprecedented to the market.*

11 out of the 15 cases met this criterion. These cases all use a technology that is unprecedented largely due to the fact that these technologies are inspired by the forms, processes or systems found in nature rather than referencing the competition on the market and human designs (this will be explained in further details in the next chapter).

GreenShield Fabrics by BigSky Technologies is an example of such technology. Many textiles that have stain resistant properties achieve this through the use of fluorochemicals. The problematic aspect of these fluorochemicals is that they are toxic and have been found to be bioaccumulative in living organisms (Institute, 2011a) and can have serious health effects like the possible carcinogenic perfluorooctanoic acid (PFOA) (Rodie, 2008).

GreenShield Fabrics is a new technology based on the hydrophobic, self-cleaning surfaces of Morpho butterfly wings and Lotus leaves. These surfaces use microscopic roughness to provide water repellency. GreenShield Fabric uses green chemistry/nanotechnology to make hydrophobic nano-structures. Through the use of nano-particles on the surface of a fabric, which is unnoticeable to the touch, GreenShield creates a pocket of air allowing water and oil droplets to roll carrying dirt and stains off the fabric for a self-cleaning effect. GreenShield is a multi-functional technology providing water and oil repellency and stain resistance in a single finish with greater efficiency than each function delivered separately. As indicated by Dr. Joseph F. Bringley, Chief Technology Officer at G3i, the product is designed to be as green as possible, using less chemistry and producing less harmful waste by using a water-based process that produces an essentially 100% yield and significantly reduces the use of volatile organic compounds (VOCs) and PFOA by 8-10 times (GreenShield, N/D). Another environmental benefit of this green chemistry, akin to its natural counterpart is that it uses a proprietary energy-saving, waste-saving technology by being conducted at room temperature (Rodie, 2008) and is permanent with excellent wash-durability (GreenShield, N/D). GreenShield Fabric is the first textile finish to be certified by the Scientific Certification System (SCS).

2) **Focuses on products, processes, and services w/ unprecedented performance feature. New business model:** *The intent is to create a product, process, or service with unprecedented performance. It outperforms and is dissimilar to the previous versions. Requires a new business model.*

15 out of the 15 cases met this criterion. According to the information available in various case studies, reports, and articles, these cases outperformed their traditional counterparts in matters of performance, energy efficiency, and reduction of VOCs off gassing for example. Some not only outperformed the market standard but also presented new features which were very counter-intuitive.

Sharklet technologies is a good representation of this criteria. Sharklet AF technology is inspired by shark skin. The skin's architecture is composed of millions of microscopic ridged diamond-shaped structures called denticles which inhibits fouls and bacteria from properly adhering to the surface, form biofilms and reproduce. Sharklet's unique technology replicates this strategy with a tiny diamond-shaped pattern with ridges of 3µm in length and 2µm wide (Terrapin-Bright-Green, N/D), making the ridges 1/10th of human hair (Alsever, 2013). This texture is invisible to the eye and non-detectable to the touch. The bioinspired surface reduced bacterial growth by 90 to 99% depending on the species (Alsever, 2013). This technology represents a new way of preventing biofouling through physical means rather than traditional chemical means which is largely responsible for "superbugs"[7] in hospital settings. Sharklet Technologies developed an adhesive backed film which can be applied onto surfaces and developed a new process enabling them to make tools to mold the texture onto various products.

Their original target was to introduce an environmentally-friendly way to reduce biofouling on boats. While researching and testing shark skin in the lab, by accident a researcher attempted to grow bacteria in a dish which happened to be lined by a shark skin molded surface. As the researcher realized the "error" they also came to realization that shark skin not only prevented biofouls to attach but also prevented bacteria to adhere and grow. The research led them to use the technology to reduce instances of HAI/ transmission of human pathogens in the healthcare industry (Chung

[7] The Merriam-Webster dictionary defines superbugs as "a pathogenic microorganism and especially a bacterium that has developed resistance to the medications normally used against it".

et al., N.D.). Sharklet's business model is now taking two approaches to their technology: the licensing model where companies paid to use Sharklet's technology (i.e. Tactivex) and their own medical product line. As Sharklet teaches the market about their technology, other companies are catching on Sharklet's product and creating new partnerships. Sharklet is currently venturing in cell phone covers, countertops and forming partnerships with other medical companies like Cook Medical in the healthcare industry. In 2014, Sharklet plans to venture outside the medical business and work with Steelcase and design Sharklet-patterned desks and other furniture for college classrooms and shared offices (Alsever, 2013). These partnerships and ventures have the potential to help scale manufacturing, reduce cost and create new markets.

3) **Creates a dramatic change that transforms existing markets or industries:** *Creates a new market, one of a kind product. The innovation marks a paradigm shift.*

In this category, only 5 of the 15 cases met this criterion. These five (5) cases use a new technology which outperforms the existing technology. The technology is beginning to make a significant impact on the market although not quite yet a disruptive impact.

This criteria is best exemplified by PureBond Technology developed by Dr. Kaichang Li. Composite wood products are made with conventional wood glue containing urea formaldehyde (UF). UF is labeled as a carcinogen by the World Health Organization due to their off-gassing of volatile organic compounds (VOC) and is also designated as a toxic air contaminant (TAC) in California with no safe level of exposure. VOCs and TACs have direct health effects, including eye, nose, and throat irritation as well as headaches with extensive exposure (Watson, N/D).

PureBond Technology was developed by Dr. Kaichang Li, a professor at Oregon State University's College of Forestry, and inspired by the byssal threads of the Blue Mussel, a colonial species that clings to rocks and each other using strong adhesive extensions called byssal threads. Ground breaking research led to the discovery that the adhesive pads of byssal threads contain at least half a dozen different proteins, also called marine adhesive proteins (MAP). These MAPs are made of a protein containing a rare amino acid called L-DOPA which allows them to adhere to nearly any substrate. The attachment is versatile and tough, despite continual exposure to salt water and shearing forces, mussels are able to hold on tightly using an underwater "glue" (Institute, 2011).

Dr. Li discovered that soy proteins can be modified to perform similarly to the MAPs of byssal threads. The modified proteins not only delivered phenomenal adhesion, they also offered exceptional water resistance. This breakthrough led to PureBond, proving that enhanced environmental quality and increased product performance can go hand in hand (Institute, 2011).

PureBond is sustainable, formaldehyde free, comparable in strength to formaldehyde-based adhesives and outperforms UF based glues in water resistance. Other alternative wood adhesives incorporating soy are available, but only PureBond is cost competitive to formaldehyde based resins. Adhesives that use soy protein require less time and less energy to cure before use, and are safer and easier to handle which is preferable for the health of the workers in the factory. PureBond's adhesive also creates lighter glue lines that are thus aesthetically preferable (Columbia, 2006)(Institute, 2011). CFP converted all eight (8) of its plywood plants to the PureBond manufacturing process, distinguishing it as the first company in the wood products industry to switch to a completely formaldehyde-free, soy based resin. In doing so, it replaced the use of an estimated 47 million pounds of conventional UF and PF resins and reduced emissions of hazardous air pollutants at each of its plants by 50-90% (Institute, 2011).

4) **Open, externally oriented. Risk taking. Agility, speed, flexibility, experimentation. Intensive collaboration and teamwork:** *The process of building value from a new technology is open to discovery. A new business model must be developed and the rules and guidelines to reach market success are to be determined.*

15 of the 15 cases met this criterion. This criteria is best embodied by FESTO and its Bionic Handling Assistant. FESTO's BHA is one many biomimetic robots designed by emulating the movements, displacement and motion of various animals, i.e. jellyfish, kangaroos, and penguins. There is always a danger of injury and/or performance error when working in close quarters with robots. For this reason, conventional robots and human workers are typically kept separated by physical barriers. FESTO's BHA is inspired by the elephant's trunk. The trunk of an elephant is dynamic, remarkably complex network of 40,000 muscle bundles that can perform complex, precise, strong yet delicate three dimensional motions (Institute, 2011) and antagonistic movements,

meaning that while a muscle group contracts an opposing muscle group elongates which allows for its characteristic bending motions (Festo, 2012).

The BHA was designed to be operated independently or in direct cooperation with humans. Dynamic, fluid movement facilitates human-technology cooperation in diverse settings. The equipment doesn't require extremely advanced components; it consists of elements with wide usage in other applications (Institute, 2011). Besides the BHA's performance, another innovative aspect is FESTO's use of 3D laser sintering, a type of additive manufacturing, to produce the robotic assistant. The structure is made of a compliant, yet strong material called polyamide. Polyamide has the capacity to perform heavy lifting as well as delicate procedures. Festo states that the key to such smooth motion is a hydrostatic compartmentalized structure that is flexible, with pneumatic stiffening. In total, this affords for 11 degrees of freedom for movement which allows the BHA to move freely in all directions. The gripping portion of the arm has adaptive fingers that conform to handle variable cargos, from eggs and bandages to wrenches and wires. A robotic controller unit directs patterned motion or responsive action (Institute, 2011). FESTO claims that before now, no other system this flexible has permitted such precise position calculation, a feat enabled by a newly developed control algorithms (Festo, 2012).

Much of FESTO's projects and development is open and outsourced. Their biomimetic projects are led by interdisciplinary teams: a collaboration between FESTO, universities, institutes and development companies (Institute, 2011). This aspect possibly contributes to making it one of the most innovative and experimental companies in matters of biomimetic applications in robotic science.

5) **Involves high levels of uncertainty:** *All uncertainties involved in taking a new technology to the market (i.e. technological uncertainty, market uncertainty, acceptance and legitimacy uncertainty, timing uncertainty) are new and/or unknown. All are unknowns that can potentially signify success or failure of the new technology.*

11 out of the 15 cases met this criterion. These technologies have not yet made a significant impact on the market since most of them are either in late development, new to the market or have been introduced to the market but have yet to educate the market about the advantages of their

technology. Those still in development have been showing promising results and performance but certain issues such as production or market acceptance/ resistance have yet to be overcome.

Aquaporins Inside by Aquaporin is an example that meets this criteria. Filtration of water relies on two strategies to purify and desalinate water: evaporation and reverse osmosis. Both strategies are highly energy intensive (GermiNature, 2014). Filtration is energy intensive because it relies on using intense pressure to force the water through dense polymeric separation membranes. The water is pushed through micron to nanometer sized holes in polymeric films/synthetic membranes with surface properties controlled by advanced chemical engineering (Institute, 2011).

The Aquaporin membrane technology is based on the aquaporins channel protein found in the fatty membranes of cells that allow the transfer of water through the cell pores. The aquaporin only allows for water molecules to pass through the protein and this way channel filtering out any unwanted ions or other polar molecules (Aquaporin, N/D) which makes it the perfect model for low-energy water filtration devices for industrial and household (Institute, 2011). Aquaporin is embedding aquaporins into artificial membranes to simulate the natural behavior of biological membranes. Since aquaporins are ubiquitous amongst all living organisms they can easily be produced using bacteria or algae for instance (GermiNature, 2014).

For the past 10 years, Aquaporin faced a great challenge in bringing about their technology for the reason that the concept, the process and production are all unprecedented. Aquaporins has successfully incorporated aquaporins to a biomimetic membrane, however making their aquaporins incorporated biomimetic membrane as robust, stable, scalable and cost-effective as their polymeric counterparts remains challenging (Tang, Zhao, Wang, Helix-Nielsen, & Fane, 2012) and overcome concerns about long-term robustness of the proteins (Acqueau, 2014) which are all elements of technological uncertainty and market uncertainty. Out of two production methods, Aquaporin was able to develop membranes using aquaporins stabilized in vesicular structures as structural and functional elements (Tang et al., 2012). These membranes can be established on an industrial scale which has enabled Aquaporin to begin pilot production and take their biomimetic aquaporins membranes out of the lab and out to the market in 2014. Although the company is showing promising results and already winning awards for their technology, the Aquaporin Inside's performance on the market will be another hurdle to overcome (market uncertainty).

Based on table 9, most of the cases fell under the category of radical innovation. To further verify this, the next section will use the criteria to measure radicalness by Dahlin and Behrens listed in their 2005 Research Policy paper *When is An Invention Really Radical*.

Table 10. Radical Innovation in Biomimicry based on Dahlin & Behrens' Criteria for Radicalness

Dahlin/Behrens' Criteria of Radical Innovation	*PureBond*	*GreenShield*	*Ornilux*	*Aquaporins*	*WhalePower*	*InterfaceFLOR*	*Sharklet*	*Pax Water*	*Novomer*	*REGEN*	*Festo*	*Biolytix*	*OptiStruct*	*LAZER*	*Kalundborg*	
Criterion 1: *The invention must be novel: it needs to be dissimilar from prior inventions.*	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	***15***
Criterion 2: *The invention must be unique: It needs to be dissimilar from current inventions.*	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	***15***
Criterion 3: *The invention must be adopted: It needs to influence the content of future inventions.*	Y	-	-	-	Y	Y	Y	Y	-	-	-	-	Y	-	Y	***7***
	3	***2***	***2***	***2***	***3***	***3***	***3***	***3***	***2***	***2***	***2***	***2***	***3***	***2***	***3***	

- Criterion 1- It needs to be dissimilar from prior inventions: **15/15**
- Criterion 2- It needs to be dissimilar from current inventions:: **15/15**
- Criterion 3- It needs to influence the content of future inventions: **7/15**

a. It needs to be dissimilar from prior inventions.

To meet that condition, the technology needs to be novel meaning it needs to have characteristics or features specific to it, not existent or previously seen in prior inventions (Dahlin

& Behrens, 2005). 15 out of the 15 cases met this criteria. The bioinspiration approach to these technologies can explain this result because it is an approach to problem solving which has not been used in the previous technologies, and that approach can lead to counter-intuitive solutions which were not possible to imagine in conventional problem solving methods. Cases like Ornilux, WhalePower, Pax Water, Lazer and Sharklet show obvious features not seen in previous technologies.

b. It needs to be dissimilar from current inventions.

To meet that condition, the technology needs to initiate a new technological trajectory and either start a chain of incremental improvements or represent a new technological paradigm hence making it unique (Dahlin & Behrens, 2005). All of the 15 cases met this criteria. This also relates to the previous section in regards to bioinspiration and innovation. This approach may generate design solutions which are not present in past and current technologies and thus create a new technological paradigm. 13 of the 15 cases feature a technology which is not only dissimilar to current ones but in regards to sustainable innovation feature a significant improvement in performance, reduction in energy use, etc. In this criteria, cases like Aquaporin, PureBond, Pax Water, GreenShield, Novomer, REGEN, Biolytix and, OptiStruct feature technologies that represent a significant break from the current convention.

c. It needs to influence the content of future inventions.

To meet that condition, the technology needs to influence future inventions, it should have a transformative impact on future technology, regardless of whether or not the early version succeeded on the market. That technology has the potential to be a change agent in that industry (Dahlin & Behrens, 2005). Fewer cases met this criteria, only 7 out of the 15 cases. Those who fulfilled this category are the cases that have either:

i. made a significant impact in their industry (PureBond)

ii. feature a technology which over time and incremental changes has managed to become an industry leader (OptiStruct)

iii. feature a technology which is spawning new products with the same feature (WhalePower, Interface FLOR, Pax Water, Kalundborg) or

iv. venture in different economic sectors unrelated to the original targeted economic sector (Sharklet).

5.1.2.2 Interpretation of Results

In the incremental innovation criteria study, 4 out of the 15 cases (26%) exploit an existing technology, 4 out of the 15 cases (26%) focus on cost or feature improvements in existing products, process, or service, 6 out of the 15 cases (40%) improve competitiveness within current markets or industries, 4 out of the 15 cases (26%) are determined by existing procedures and organizational set-up and 4 out of the 15 cases (26%) had low to medium uncertainty. In regards to radical innovation, 11 out of the 15 cases (73%) explore a new technology, all of the 15 cases (100%) focus on products, processes, and services with unprecedented performance feature and new business model, 5 out of the 15 cases (33%) create a dramatic change that transforms existing markets or industries, all of the 15 cases (100%) are open, externally oriented, and risk taking, agility, speed, flexibility, experimentation, and intensive collaboration and teamwork, and 11 out of the 15 cases (73%) involve high levels of uncertainty.

According to the results, out of the 15 cases studied in this paper, 11 cases would qualify as radical innovations (73%) while the remaining four (4) would qualify as incremental innovations (26%). Pax Water and Kalundborg are the only two cases to not meet at least three out of five criteria in order to qualify as radical innovations.

There is an important caveat to clarify however: REGEN and OptiStruct qualified as both incremental and radical innovations. The meaning is these two technologies started out as radical innovations to overtime become incremental. As stated by Verganti and Norman (2012), "incremental innovation is necessary to transform the radical idea into a form that is acceptable to those beyond early adopters". In the case of OptiStruct, the topology optimization program has been in the works since 1992 and as indicated by numerous scholars in the field of innovation, radical innovations takes time to be accepted in the market (Norman & Verganti, 2012). The designs generated by the program were very counter-intuitive, visually and structurally, and for most engineers it challenged engineering convention. In the span of two decades, with improvements, algorithm refinement, adapting the program to specific types of manufacturing, and education about the benefits and advantages of the program (in terms of cost and material savings/lightweighting), Altair's OptiStruct went from experiencing resistance by engineers (systemic resistance[8]) to slowly gaining notoriety amongst major car manufacturers and becoming a leader in the transportation industry, aerospace industry and now breaking into architecture. It started as a radical innovation to overtime become incremental. Now that said, as incremental innovations, these technologies are revolutionary innovations, as they are innovation that are unexpected. They do not create new markets but nevertheless they are increasingly leading an existing market.

In the technological spectrum, as stated by Norman and Verganti (2012) "radical innovation is what most organizations want, it is the focus of scholarly research and design schools" and according to these results biomimicry can help designers produce radical design solutions.

5.2 Biomimicry and Innovation in the Market Spectrum

Innovation is also observed through a market spectrum, meaning how a technology affects the market and whether or not it manages to displace an existing technology. The main objective of this section was to understand biomimicry from the technology spectrum but considering the high level of interest in disruptive innovation it appears relevant, as a minor emphasis, to investigate where the biomimicry cases faired in that spectrum.

In the market spectrum, according to Harvard School of Business professor Clayton Christensen, there are two types of innovation: sustaining innovation vs disruptive innovation. Disruptive innovation gains the most attention from scholars and is the most sought after by business organizations. In the book *The Innovator's Solution* (2013), Christensen offers a description

[8] Systemic resistance refers to the safeguarding of value systems, of traditions, of beliefs as well as positions based on political, labor union and religious affiliation. It can consist more or less of positions of collective conservatism based on certain belief systems and thus creating resistance. (Tabatoni, 2005, p.34)

of both innovations. For an innovation to be disruptive, it 1) doesn't attempt to bring better products to established customers in existing markets, 2) disrupts and redefines the trajectory by introducing products and services that are not as good as currently available, and 3) is typically simpler, more convenient, less expensive and appeals to new or less expensive customers (C. M. Christensen & Raynor, 2003). Furthermore, it transforms complicated and costly products available to a few into simpler, cheaper products accessible to many (Hurst, 2013). Finally, a disruptive technology often time will be inferior in quality and performance to the market leading technology and will only become better than the leading technology over time and with improvements (C. Christensen, 2010) and then relentlessly move up market, eventually displacing established competitors (Hurst, 2013).

On the other hand, for an innovation to be sustaining, it needs to: 1) target demanding, high-end customers; 2) offer high-end customers a product with better performance than previously available; 3) improve incrementally year by year, and; 4) possess breakthrough technology and leapfrogs beyond the competition (C. M. Christensen & Raynor, 2003). Saliently, he further adds in a 2013 interview, "sustaining innovation replaces old models with new products that often incorporate new technology and novel design features. But the new products are often substitutes for other similar items" (Hurst, 2013).

It is significant to understand that what differentiates sustaining from disruptive is not whether the innovation is incremental or radical; as a matter of fact either can become disruptive.

Case Study Analysis

The following tables illustrate how the 15 biomimicry cases in this study fare in meeting the criteria for disruptive innovation and sustaining innovation. The results in table 11 and 12 will help to establish whether or not the cases qualify as disruptive or sustaining innovations.

Table 11. Disruptive Innovation in Biomimicry

Criteria of Disruptive Innovation	PureBond	GreenShield	Ornilux	Aquaporin	WhalePower	InterfaceFLOR	Sharklet	Pax Water	Novomer	REGEN	Festo	Biolytix	OptiStruct	Lazer Helmets	Kalundborg	
Doesn't attempt to bring better products to established customers in existing markets	N	N	N	N	N	N	Y	N	N	N	N	N	N	N	--	***1***
Disrupts and redefines the trajectory by introducing products and services that are not as good as currently available	N	N	N	N	N	N	N	N	N	N	N	N	N	N	--	***0***
Typically simpler, more convenient, less expensive that appeal to new or less expensive customers	N	N	N	N	N	N	N	N	N	N	N	N	N	N	--	***0***
Inferior in quality and performance to the market leading technology and will only become better than the leading technology over time and with improvements	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	--	***1***
	0	***0***	***0***	***0***	***0***	***0***	***1***	***0***	***0***	***1***	***0***	***0***	***1***	***0***	***0***	

- Creates new markets or significantly alters the definition of the traditional market: **1/15**
- Disrupt and redefine the trajectory by introducing products and services that are not as good as currently available: **0/15**
- Typically simpler, more convenient, less expensive that appeal to new or less expensive customers: **0/15**
- Inferior in quality and performance to the market leading technology and will only become better than the leading technology over time and with improvements: **1/15**

Table 12. Sustaining Innovation in Biomimicry

Criteria of Sustaining Innovation	PureBond	GreenShield	Ornilux	Aquaporin	WhalePower	InterfaceFLOR	Sharklet	Pax Water	Novomer	REGEN	Festo	Biolytix	OptiStruct	Lazer Helmets	Kalundborg	
Features are added and functionality is increased	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	--	***13***
Targets high end customers with better performance than previously available	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	--	***14***
Breakthrough, leapfrog beyond the competition	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	--	***14***
Replaces old models with new products that often incorporate new technology and novel design features. New products are often substitutes for other similar items	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	--	***13***
	4	***4***	***4***	***4***	***4***	***4***	***2***	***4***	***4***	***4***	***4***	***4***	***4***	***4***	***0***	

- Features are added and functionality is increased: **13/15**
- Targets high end customers with better performance than previously available: **14/15**
- Breakthrough, leapfrog beyond the competition: **14/15**
- Replaces old models with new products that often incorporate new technology and novel design features. New products are often substitutes for other similar items: **13/15**

5.2.1.1 Interpretation of Results

Based on these findings, this research deduces that the majority of the cases in this study are sustaining innovations; 14 out of the 15 cases met the criteria of sustaining innovations.

In regards to the disruptive innovations study, 1/15 (7%) create new markets or significantly alter the definition of the traditional market, 0/15 (0%) disrupt and redefine the trajectory by introducing products and services that are not as good as currently available, 0/15 (0%) are simpler, more convenient, less expensive that appeal to new or less expensive customers, and 1/15 (7%) are inferior in quality and performance to the market leading technology and will only become better than the leading technology over time and with improvements. Comparatively in the sustaining innovations study, 13/15 (87%) have added features and increased functionality, 14/15 (93%) target high end customers with better performance than previously available, 14/15 (93%) have breakthrough technology and leapfrog beyond the competition, and 13/15 (87%) replace old models with new products that often incorporate new technology and novel design features, the new products are often substitutes for other similar items.

The last criteria "**replaces old models with new products that often incorporate new technology and novel design features. New products are often substitutes for other similar items**" in conjunction to Christensen's quote "**sustaining innovation replaces old models with new products that often incorporate new technology and novel design features. But the new products are often substitutes for other similar items**" stand out as the main reason as to why these cases fall into sustaining innovations. These cases are in many ways similar to their traditional counterparts, they are for the large part environmentally friendly versions or substitutes of the latter. Hence they did not create new markets but rather compete on the same turf as their traditional counterparts. However, Sharklet, and in some aspects Interface FLOR's TacTiles, seem to be the exception of these cases.

The technology created by Sharklet is an entirely new way of fighting bacteria and biofouling. The technology has nothing to do with the traditional strategy of dousing surfaces with chemicals to kill bacteria, rather it fights bacteria through a physical strategy preventing bacteria to adhere to surface, create biofilms and multiply. It is an entirely new approach to fighting bacteria which is now enabling Sharklet to take their technology into new markets. The technology was originally conceived to prevent biofouling on boat hulls but then as the result of a student accidentally trying and failing to grow bacteria on a sharkskin-patterned dish in the testing period, they then realized the technology actually prevented bacterial growth as well (Alsever, 2013). Now Sharklet is partnering and licensing their technology to any industry involving hospital acquired infections (HAI) and high touch surfaces, i.e. Cook Medical (medical devices and catheters) and Steelcase (school desks and office furniture). If Sharklet Technologies continues to well educate and spread the word on their technology as a way to prevent the problem of biofouling and superbugs, Sharklet's technology has the potential to eventually become disruptive.

In regards to Kalundborg Eco-industrial Park, because it is technically not on the market, and even though the profitability and advantages of this system are unquestionably quantifiable, it is not included in this section (see section 2.2.5 Research Limitations).

5.3 Conclusion

The objective of this chapter focused on the relationship between biomimicry and innovation in design, meaning that the focus is on innovation in the technology dimension. The vast majority of the projects studied in this research would qualify as radical innovations (13/15), which is the most desired type of innovation in the technology spectrum and therefore based on the study's findings, the research deduces that biomimicry indeed supports and produces innovative design solutions: radical or revolutionary design solutions. However, none quite qualified as disruptive innovation, which is the most desired type in the market spectrum (0/15).

For the results in the technological spectrum, a few points need clarification. First, two cases qualified as both incremental and radical: REGEN and OptiStruct. There's an important time and market acceptance aspect to innovation and this is demonstrated by these two technologies which have both started as radical but eventually became incremental as a result of time, improvements and market education and hence, technically, all fifteen cases are actually radical innovations. Secondly, by consulting biology for design inspiration, the design teams on these cases were able to tap into a source of inspiration not commonly referenced, to create design which did not rely on human mental powers thus creating designs with novel characteristics and innovative solutions to sustainable design (see chapter 6). Which leads to the third point, the technological advances these cases have brought forth and thereby differentiating them from their traditional competitors is what ultimately qualifies them as radical. In the cases in this study, five (5) categories of technological innovation have been identified. Some cases even used a combination of the following:

1) The design uses nanotechnology,

2) The design uses bio-hybrid systems technology (the combination of biological processes and mechanical components),

3) The design uses green chemistry,

4) The design uses swarm technology,

5) The design makes use of industrial symbiosis,

In addition, as a result of the novel features taken from biology, most designs generated by this approach mechanically and environmentally outperformed their traditional counterparts, and certain cases not only showed unexpected results and advantages but also challenged and redefined scientific and engineering convention.

As for the results in the market dimension, two points need to be made. First, a common theme in innovation in the market spectrum and the above examples is that education or teaching the market about an innovation plays a major role in the success of a radical technology, especially when the said technology challenges convention as was the case for OptiStruct. Sharklet Technologies, REGEN, Pax Water and PureBond Technologies not only have the most current potential to become disruptive, but they also exemplify the ongoing phenomenon that is the increasing rate at which industry is turning to biomimicry to resolve design problems, more specifically sustainable design problems. York & Venkatraman (2010) have stated that "*customers' changing opinions concerning environmental issues may increase uncertainty for organizations as they cannot predict how environment-friendly innovations will be rewarded by the consumers and markets*" (Jalonen & Lehtonen, 2011). CFP has capitalized on customers' growing need for products without hazardous effects on human health and has been insistent in educating the market about their formaldehyde-free products. Due to their blue mussel inspired wood glue, CFP has managed to not only be profitable during an economic downturn but also to keep all of its seven plants working while their competitors were closing plants in Canada and experiencing significant drops in production (Watson, N/D). The challenge CFP faces is the plywood coming from China which has increased from 40% to 55%. CFP continues to assertively inform the customers about the environmental and health benefits of their product and the value they gain by paying $200 more for formaldehyde-free plywood compared to plywood hailing from China. If CFP can better educate the market about their product, PureBond technologies can eventually become a disruptive innovation. Conversely, not doing so despite the advantages of a technology, prevents that technology from moving up the market and potentially disrupting it. Such is the case of Biolytix BioPod, compared to traditional septic tanks, it appears to be Biolytix's lack of educating the market which causes their product not to be despite their economic and environmental advantage.

The research advances that the results do not necessarily assert that biomimicry only generates sustaining innovations but rather that the companies in this study have generated design solutions that were more focused on improving existing technologies and through biomimicry create sustainable versions of the existing technologies and thus competing in existing markets. To this point, Sharklet and to some extent Interface FLOR are possibly the exception about biomimicry generating potential disruptive innovations because they are the most dissimilar design solutions to their traditional counterparts and by being so dissimilar they have more potential to create a new market, which in turn led to an insight or a theory.

Based on the available information, these two technologies were spawned from the *challenge to biology* strategy (according to the Biomimicry Thinking process. See section 3.2.3) compared to the others which most likely came from the *biology to design* strategy. It may be possible, that by taking the challenge to biology approach, a company may be more likely to create design solutions that are so dissimilar to existing technologies that it could have more potential to be disruptive. The speculation is that the reason for this is that by taking the biology to design approach, some element of using human mental powers already gets into the process because one makes a connection from what they see in nature with a possible product design. Meanwhile, in the challenge to biology approach, one is more likely to find a solution to a design problem in nature that is completely counter-intuitive; in other words, a greater mental leap in creativity and thus a more innovative design solution (see chapter 7.2). This will be further explained in the next chapter on analogical reasoning.

The relationship between biomimicry and innovation in the market spectrum is a research subject in itself, and although it is approached as a minor objective, the technological and market spectra are too fundamentally related to be treated separately. Thus, even as a minor objective, it still allows to understand the larger picture about innovation as a whole.

6 Chapter Six_ Understanding the Inner Workings of Biomimicry

"The ability to perceive similarities and analogies is one of the most fundamental aspects of human cognition. It is crucial for recognition, classification, and learning and it plays an important role in scientific discovery and creativity."

-StellaVosniadou/ Professor

In the previous chapters this research established what types of innovations have been generated by biomimicry. In this chapter it will investigate on the aspects or the inner workings of biomimicry which support innovative design solutions.

In observation, two aspects stand out as the innovation producing elements of biomimicry. The first element is bioinspiration, the act of looking into the forms, processes, systems, and strategies of nature to solve human design issues. The second element is the addition of a biologist to the design team, commonly called a biologist at the design table or BaDT (according to the Biomimicry 3.8 process). However, it is not solely the addition of the BaDT that is different but also the interaction amongst the design team members around the BaDT that makes this approach innovative.

Precisely, the two prominent aspects of biomimicry are: analogical reasoning and transdisciplinarity. It is thus essential to further investigate these two elements to gain a better understanding into how they support the conception of innovative design solutions.

6.1 Analogical Reasoning

6.1.1 Analogy in Design

Donald Schön, a professor at the Massachusetts Institute of Technology (MIT), pointed out decades ago how powerful the transfer of concepts from one case to the next and from one field to another can be. Of the various kinds of similarities that may be activated in a process of mapping and transfer from one situation to another they single out analogy (Goldschmidt, 2001). Analogy is the cognitive process of transferring information or meaning from analogous sources. Analogical reasoning is assumed to be a general human capacity involved in most domains, although, perhaps most notably, in creative problem-solving domains, such as science, design, and art. Gentner (1998) states that analogy involves accessing and transferring elements from familiar categories in order to use it in the construction of a novel idea (B. T. Christensen & Schunn, 2007). It is a statement about how objects, persons, or situations are similar in process or relationship to one another (Lüthje, Herstatt, & Schild, 2004). Gentner and Medina have presented rich evidence to support the claim that similarity-based reasoning is a powerful engine in the solving of many types of problems. Similarly, many design theorists and considerable research have argued for the importance of analogy, in reasoning and explanation. In design, several design tools or techniques make extensive use of analogy such as Synectics[9] and TRIZ (Ward, 1998) (B. T. Christensen & Schunn, 2007).

TRIZ[10] is an innovation strategy developed by Russian author and engineer Genrich Altschuller. Altschuller was convinced that he could decipher the creative process through a set of rigorous methods, that there was an underlying logic in the invention process and that innovation was not accidental. After studying over 2 million patents, he deduced that the manipulations required to deliver these ideal results could be summarized to forty (40) *Inventive Principles*. These principles, which are selected by means of the contradiction matrix, rely heavily on the use of analogy (Domb, N/D); on the basis that any branch of technology could provide a solution to a specific problem, regardless whether that branch shares any relation to the problem or potential solution. He concluded that by defining an innovation in terms of the function it is desired to deliver, and express it in simple and relatively abstract terms the barriers most people erect between

[9] Synectics: A problem-solving technique that seeks to promote creative thinking, typically among small groups of people of diverse experience and expertise. (Oxforddictionaries.com 2014)

[10] TRIZ, the acronym of *Teorija Reshenija Izobretatel'skih Zadach* (loosely Theory of Inventive Problem Solving). An engineering system of tools and techniques developed by Russian engineer Genrich Altschuller and his colleagues.

the various areas of knowledge can be removed. Thus one can reinforce creativity and technology transfer by assessing ideas outside of one's self-defined area of competence (Allen, 2010).

The foremost aspect that differentiates biomimicry from conventional design is manifestly bioinspiration or biologically inspired design (BID). Conventional design most often relies on the mental powers of the designer and reference to human-engineered examples, while BID relies on analogy: distant analogy to be precise. There are numerous accounts of inventors making breakthrough inventions and discoveries by using distant analogical transfer such as the Wright brothers and flight, or George deMestral and the invention of Velcro. What makes analogical thinking such a powerful tool is that all methods of innovation are person-centric, meaning they rely entirely on mental powers to generate new ideas whether they are tactical or strategic in nature and provide no extra help in converging on the solution needed for business or technical breakthroughs (Slocum, 2006). According to the theory of bounded rationality, the search field of a designer (the same as any individual) is constrained. When developing solutions, the designer is only able to notice a limited section of the environment, because of his/her limited cognitive abilities (Lüthje et al., 2004) as designers frequently base their designs on ideas they have seen before (Linsey, Laux, Clauss, Wood, & Markham, 2007). In traditional product design for example, in the brainstorm/idea generation phase of a project, it is common practice for designers to conduct the brainstorm session and concept generation session around an inspiration board. That inspiration board will usually be a collection of images found in magazines or the internet of competing products and current design trends. From these examples, the design team will generate new ideas to improve on the competition and what is currently on the market. This approach exemplifies what Michael Slocum made reference to in regards to designers relying on their mental powers and their direct environment for inspiration. Most people search for solutions in the nearer context of the problem as they are led by already fixed thinking structures (Lüthje et al., 2004) and functional fixedness based on experiences of past projects can block the way to innovative solutions (Birch and Rabinowitz, 1951 as cited on Lüthje et al.). Employing exemplars or fixating on elements in either memory or the environment may constrain performance or creativity. To provide or to retrieve existing examples may inhibit the generative creative processes and may lead to a higher proportion of property transfers from the examples into the subject's own work (B. T.

Christensen & Schunn, 2007). This phenomenon is known as functional fixedness (Maier, 1931). This epitomizes the use of local analogy which will be further explained in the next section.

Analogical thinking provides that extra help by enabling to make associations to problem solving outside one's direct frame of reference, outside the limitations of memory retrieval, of a person's accessible stored information. There is no dispute that analogies are the way of innovation (Slocum, 2006). Many strategists believe in the power of analogical thinking to generate innovative ideas. Analogies can trigger breakthrough ideas in new product development and numerous examples demonstrate that substantial innovations often result from transferring problem solutions from one industry or domain to another. For instance, the designers of a novel generation of Nike running shoe, "Nike Shox", use the same suspension concept as the technologies applied for Formula One racing cars or the biological Lotus-effect led to the development of various self-cleaning surfaces (Lüthje et al., 2004). Biomimics rely on the transfer of natural form, process and system to human industry, thereby in biomimicry one can expressively rely on analogy to resolve design problems; specifically distant analogy.

6.1.2 Local vs. Distant Analogy

There are two types of analogies used in design: local and distant. Analogies rely on two elements or domains; a source domain and a target domain. The source domain (base analogue) is where a particular characteristic will be isolated to then be transferred onto another element, the target domain (target problem) . Analogy is the retrieval and the mapping of knowledge from the source domain into the target domain; the source domain contains the solution to resolve the target domain. Local analogies involve greater superficial similarity between the source and the target, as compared with the lesser amounts of superficial similarity involved in distant analogies. Accordingly, since distant analogies involve two vastly different bodies of knowledge, it may be more difficult to ensure successful transfer of solution elements in design problem solving from the source to the target because the domains may differ in multiple subtle ways (B. T. Christensen & Schunn, 2007) such as the use of a biological source to resolve a human design/engineering problem.

Local analogies are analogies where the source domain is similar to that of the target, where surface level attributes and relations between these attributes can be easily mapped (Ward, 1998). Surface level attributes are easily retrievable aspects of representation, such as color and shape (Dahl & Moreau, 2002). In local analogies, the source and target domains share many surface-level attributes hence the result from taking such an approach will often be less original since it represents such a small mental leap. Since objects from similar domains share more superficial similarity than do objects from dissimilar domains and superficial similarity is one of the key driving forces of analogical access, we would expect that the presence or availability of within-domain exemplars would increase the likelihood of within-domain analogizing (Ward, 1998). Ward states that the default approach in tasks involving the imagination (like the idea generation phase of a design project) especially when few constraints must be satisfied, is to access a specific known reference or domain and then to pattern the new entity after: resulting in less original outcomes than people who used other strategies. A study on fixation by Jansen and Smith, as cited by Christensen and Schunn, (2007), had a group of mechanical engineering students and design professionals work on a number of simple design problems with (fixation group) or without (non-fixation group) a specific example being provided by the researcher and found that the fixation group transferred much of the properties from the examples on their design. The study finding showed that most often than not, having or making examples available will bias people's creations toward features in those examples (B. T. Christensen & Schunn, 2007).

Distant analogies on the other hand, are analogies where the source domain and target domain are very different and are surface dissimilar. In this case, few surface-level attributes can be mapped and structural similarity must be relied upon (Dahl & Moreau, 2002). Distant analogies require the identification of similarities in the relational structure rather than the surface structure (Dahl & Moreau, 2002) of the source and the target domain. This specification makes the connection between the similarities the domains may share more difficult to recognize. However, when the right connection is made between the two distant domains, the result will be far more creative since it represents a greater mental leap than would have been possible with two local domains. The creativity potential of an analogy depends on the dissimilitude of the knowledge bases between which the analogy is retrieved (Lüthje et al., 2004): greater distance signifies greater creativity opportunities. Distant domains are reported to serve the purpose of envisioning, designing, and producing novel inventions (Ward, 1998) and may be positively related to originality in design. Darren Dahl and Page Moreau (2002) found that the greater percentage of analogical distance used during design, the more significantly positive the effect on the estimated originality of the design of the resulting product (B. T. Christensen & Schunn, 2007).

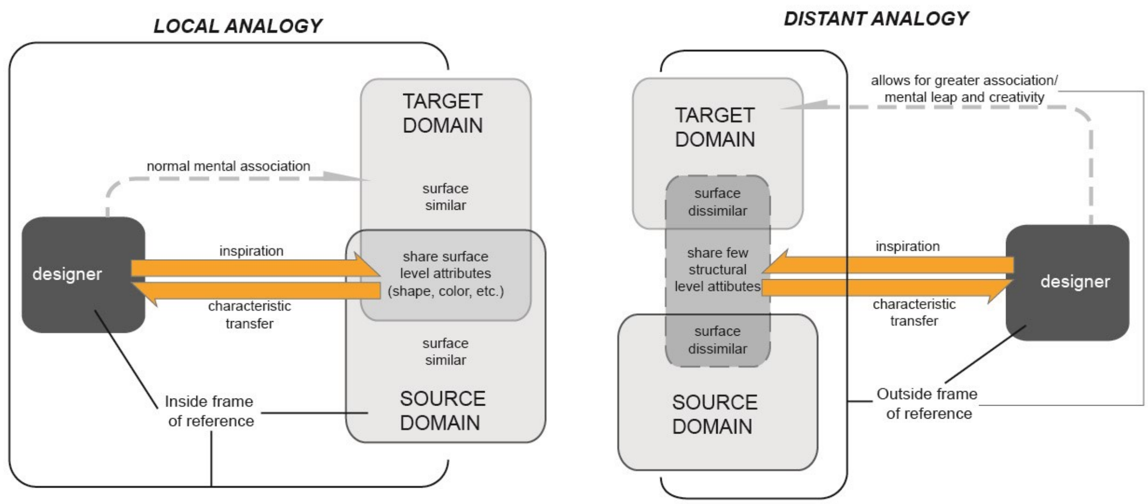


Figure 22. Illustrating Local vs Distant Analogy ©Yves A. Michel 2014

The nature and organization of biology and engineering are very different: organisms develop through a process of evolution and natural selection; biology is largely descriptive and creates classifications, whereas engineering is a result of decision-making; it is prescriptive and generates rules and regularities (Vincent et al., 2006). Thus, to transfer biological properties onto human design/engineering problems can only result in the use of distant analogy.

JR West's Shinkansen 500 Series Bullet Train is a well-recognized biomimicry project that can be used as an example to appreciate the virtues of analogical distance. The problem the designers and engineers had to wrestle with in this case was the issue of a pressure wave the train would create when entering a tunnel. The shape of the train compressed the air around it that then resulted in a shock wave or sonic boom it would create when exiting the tunnel, which in turn, could be heard a quarter of a mile away. This constituted a problem for Shinkansen for Japan has a law requiring that trains do not produce more than 70 decibels of sound while traveling through populated areas (Ingalls, 2011). When redesigning the train to address certain issues, traditionally the designers/engineers could have referenced other/ competing trains like the European *Train à Grande Vitesse*, better known as TGV as a source domain. The source and target domains share similar surface-level attributes; both are high speed trains, therefore they have comparable size, overall shape, weight, function, etc.

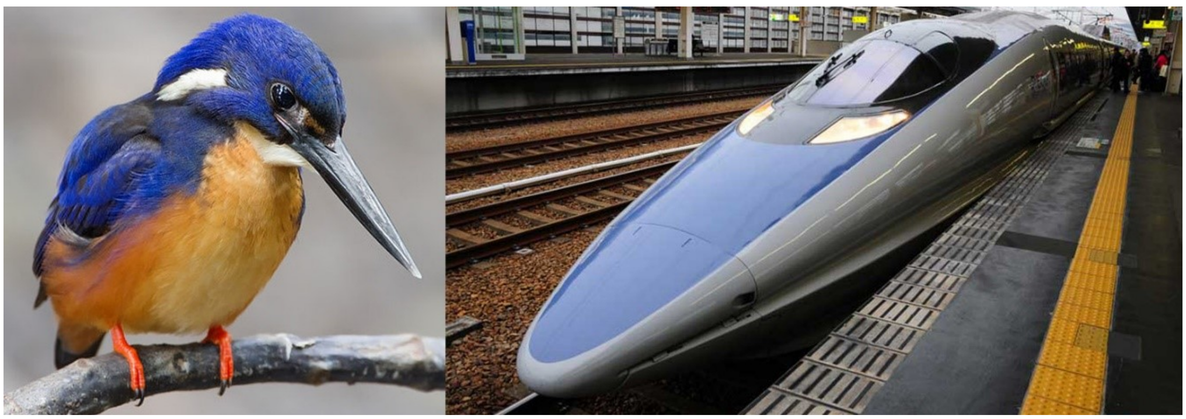


Figure 23. Kingfisher bird (source domain) and Shinkansen "bullet train" (target domain). Retrieved from blog.drwile.com and biomimicry.org

Conversely, an example of distant analogy is the Kingfisher bird. Evidently the source and target domains share no surface-level attributes; the former is a train, a machine capable of transporting approximately 1300 persons and the latter is a bird, a biological entity. The relational structure in this case resides in the function of the Kingfisher's beak. The beak has evolved with a function, it has evolved to allow the Kingfisher to dive without making a splash so the bird can see the fish as it enters the water. The relational structure is the Kingfisher's ability to go from one medium density (air) into another medium density (water) without a splash. An engineer at Shinkansen took notice to this phenomenon. He proceeded to have a team of engineers conduct various tests like shooting different bullet shapes into a pipe and found that bullets shaped like the birds' beak parted the air instead of compressing it. Further testing was then conducted in computer models (Ingalls, 2011). The transfer of that shape and that specific function from the Kingfisher's beak to the train's nose indeed resulted in eradicating the pressure wave build-up/sonic boom issue hence quieting the train. Moreover, as an unintended result the train became 10% faster using 15% less energy (Janine Benyus as cited in 2009 TED talk) (see figure 23).

From this example one can see the result enabled by using a distant analogy and the innovative solution generated by this approach. It is a counter-intuitive idea to make reference to a small bird in order to resolve the design/engineering issues of a high speed train. However, with appropriate knowledge of the target problem the engineer (who happened to be an avid birdwatcher) was able to make the proper connection to an unrelated source domain surface-level wise but appropriate relational wise.

6.2 Crossing Boundaries

6.2.1 A Resurgence of Disciplines Overlap

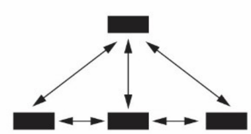
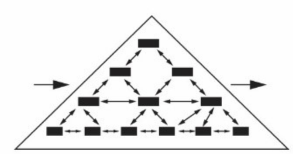
As stated in this study's introduction about the Cartesian mindset, Shrivastava and Ivanaj (2012) explain that modern society and the scientific community has relied on a particular *modus cognoscendi* in order to understand reality and the nature-human balance. They state that much of our understanding is scientific, discipline-based and highly compartmentalized. To a large degree, governments and the private sector are informed and exceedingly rely on this type of knowledge which is rational, cognitive, and scientific while consequently ignoring the emotional, embodied and intuitive forms of knowing (Shrivastava & Ivanaj, 2012).

Knowledge is often held within defined communities or organizations, with their own language and ways of working. However, there has been a growing recognition that in order to leap and advance scientifically, specialization and keeping knowledge in silos can only lead us so far. This recognition is evidenced by the growing trend in multidisciplinary and interdisciplinary collaborations in academia (Madni, 2007). Educational reform and scientific advancement over the last 60 years have precipitated a great deal of crossing of disciplinary boundaries, recognizing that the segmentation of disciplines and its limitations has led to various means of resolution (Korecki, 2008). Innovations require the right structures and attitudes to allow intellectual interests to develop across disciplines (Blackwell et al., 2010).

There has never been a clear consensus onto how to best define the crossing of boundaries and so the definition for pluridisciplinary, multidisciplinary, crossdisciplinary, interdisciplinary, and transdisciplinary has continued to evolve in recent years as researchers and scholars focus on how to best define these phenomena (see table 13).

A very salient point to be made is that the intent of this section is not to delve in a philosophical debate about crossing disciplines. It is rather an attempt to illustrate and focus on how the interaction and sharing of information differs between the different members of the design team in the ecodesign approach as compared to the biomimicry approach. For this reason, the study solely focuses on multidisciplinarity and transdisciplinarity.

Table 13. Steps for Increasing Cooperation and Coordination between Disciplines (Jantsch, 1972)

	General Concept	*System Configuration*
Multidisciplinarity	A variety of disciplines are offered simultaneously, but without making explicit possible relationships between them.	
Pluridisciplinarity	Various disciplines are juxtaposed, usually at the same hierarchical level, in such a way as to enhance the relationships between them. Cooperation but no coordination	
Cross-disciplinarity	The axiomatics of one discipilne is imposed upon other disciplines at the same hierarchical level. Rigid control from one disciplinary goal.	
Interdisciplinarity	A common axiomatics for a group of related disciplines is defined at the next higher hierarchical level or sub-level. Coordination from a higher level.	
Transdisciplinarity	All disciplines and interdisciplines in the education/ innovation system are coordinated on the basis of a generalized axiomatics. Coordination toward a common system purpose.	

Multidisciplinary: An approach which focuses on collaboration amongst individuals from multiple disciplines.

Interdisciplinary: An approach which focuses on collaboration amongst individuals from various disciplines leading to the enrichment of one or more contributing disciplines.

Transdisciplinary: An approach which focuses on unifying knowledge across disciplines by finding new connections outside of disciplinary limitations.

This study argues that transdisciplinarity is essentially the second aspect of biomimicry which differentiates it from traditional and ecodesign.

6.2.2 Ecodesign and Multidisciplinarity

Multidisciplinarity is defined as the juxtaposition of disciplines in an additive rather than integrative and interactive fashion, producing an encyclopedic alignment of multiple perspectives" (see table 13). According to Michael Seipel, a professor at Truman State University, "multidisciplinary activity draws on the knowledge of several disciplines, each of which provides a different perspective on a problem or issue" (Seipel, 2004), it is a project oriented endeavour. The implication of these descriptions is that a multidisciplinary activity is performed by members of distinct disciplines without any attempt to integrate or assimilate the knowledge or activity from each one (Korecki, 2008).

An example of a multidisciplinary enterprise in which multiple disciplines interact in defined roles according to a defined hierarchy (Blackwell et al., 2009) is traditional design. The various actors have a common project as an end goal but collaborate within their defined task and discipline to achieve that goal and as stated before, ecodesign has the same process as traditional design. The difference lies in the addition of environmental guidelines in the project and an LCA specialist to the team; hence one can then deduce that ecodesign is a multidisciplinary discipline as well. Conventionally, working on a project will be designers, engineers, developers, LCA specialists, project managers and marketers; each has a defined role in the creation of the project. After creating an initial design, the designer's creation maybe influenced by the engineer's input in regards to function or by the developer in regards to material choice. The LCA specialist may request for the developer to reconsider a material choice to meet environmental guidelines established early in the project. Similarly, the size of the designed product may be affected by the input of the marketer due to his/her concern about in-store shelf space.

In the end, no discipline is essentially influenced by the other disciplines in such a way that it will cause one to approach his/her discipline from a different perspective. However, one's discipline or knowledge will have an influence on the other's task which is necessary for the team to meet their common goal. All disciplines work together towards the conception of a product but while they may share information throughout a project, the probability of influencing the other in a fashion leading to radically novel ideas are lesser. There is an exchange of information and knowledge throughout the project without the intention of integrating another's discipline within its own. Thereby, the key word which differentiates multidisciplinary from transdisciplinary is *integration*.

6.2.3 Biomimicry and Transdisciplinarity

Knowledge is developed within communities or organizations that are restricted in some way, commonly referred to as silos. Interdisciplinarity and transdisciplinarity overflow these disciplinary boundaries and through this process, disciplines are transformed in such a way that new theories, knowledge and methods are created (Blackwell et al., 2009). The former deals with the transfer of methods from one discipline to another and this distinction leads to much confusion about their inherent differences if not properly understood. This often causes the two approaches to be used interchangeably by some (Shrivastava & Ivanaj, 2012, p.123). Biomimicry is often characterized in the literature as interdisciplinary, however this study suggests otherwise.

Seipel (2004) describes interdisciplinarity as "drawing on the specialized knowledge, concepts, or tools of academic disciplines and integrating these pieces to create new knowledge or deeper understanding". The new knowledge may be claimed by none, one, both (disciplines) or an emerging new academic discipline or profession (Madni, 2007) (Seipel, 2004). Tangentially, Erich Jantsch defines interdisciplinarity as "a whole, structurally made up of two levels with the involved disciplines serving as the parts of a whole and a common axiomatic at the next higher level serving to coordinate the involved disciplines" (as cited by Shin, 1986).

In this case, the common axiomatic, the specialized knowledge serves to coordinate the involved disciplines. Interdisciplinary enterprises are generally collaborative teams, directed and coordinated by a leader (Blackwell et al., 2010), therefore in the case of biomimicry, it can be understood why one would consider the BaDT as the leader as the project revolves around the BaDT's knowledge, around his/her understanding of the science of biology .) to create an organic, synergistic relationship between the said disciplines (Shin, 1986).

There is indeed a transfer of knowledge from biology to design, architecture, economics or chemistry, however according to the definitions of interdisciplinarity, the transferred knowledge would the incorporation of tools, methodological, epistemological concepts and data (De Coninck, 1996, p.5) of the life sciences onto the design disciplines. Within an interdisciplinary context, the biologist would lead a design team into understanding the methods of the biological sciences while remaining throughout a project within a perspective or worldview of biology; he/she is not required to venture outside the confines of his/her discipline. Consequently this concept does not apply to biomimicry. What is transferred is not the method or tools to acquiring an understanding of the natural world but rather to understand how the natural realm functions[11]. Thus the BaDT is a facilitator of knowledge transfer from the realm of the natural world to the creators of the built environment and to accomplish this task the biologist is required to venture outside the boundaries of biology. It is that specific distinction which makes biomimicry transdisciplinary rather than interdisciplinary.

The concept of transdisciplinarity, popularized by Jean Piaget in 1970, seeks to produce a holistic understanding and collaborative actions needed to resolve real problems. Society's problems are becoming too complex to be resolved from a single discipline (Madni, 2007). The reconciliation of the arts, sciences and practice can help overcome complex and wicked problems such as environmental, social and economic crises[12] in a "holistic, integrated, and embodied way". It can help create and design a future that is unrestricted by the shortcomings of disciplinary silos (Shrivastava & Ivanaj, 2012, p.117). It also seeks to renew the dualities of object-subject and human-nature relationship, thus moving society away from the Cartesian mindset and reconnect all forms of knowledge (De Coninck, 1996, p.7). Shrivastava and Ivanaj further state that

[11] But this difference is not situated at the level of methodological tools, but rather at the ideological level of knowledge. (De Coninck, 1996, p.6)

[12] Sustainability as described by the Brundtland Report encompasses three realms: environmental, social and economic.

transdisciplinary knowledge can help individuals, academia, governments and the private sector understand the complex challenges involved in sustainability in order to achieve it. In order to create a built environment that is equally sustainable and desirable and that recognizes our fundamental partnership with the rest of nature, we need a transdiciplinarity approach that dissolves the frontiers between the traditional disciplines (Costanza as cited by Shrivastava and Ivanaj, 2012, p.117). This way fostering the holistic mindset of participation advocated by Daniel Wahl in *Bionics vs Biomimicry: From Control of Nature to Sustainable Participation in Nature* (2006).

According to the design process of Biomimicry 3.8, the BaDTs are biologists specifically trained to speak the language of designers, engineers, and architects in order to effectively translate nature's strategies into design solutions that effectively meet design challenges, thus helping develop products and processes which are sustainable, innovative, effective, cost-saving, and eco-friendly. While the design process revolves around the BaDT's knowledge, the biologist doesn't lead but rather adapts his/her knowledge to the language and disciplines of designer, engineers, architects, developers, business leaders and chemists.

In the Biomimicry Thinking process, the BaDT's knowledge of the natural world is integrated to the design process. The process allows the designers, engineers, and architects to view and understand their design challenge on biological lines; it allows them to properly identify the biological analogy to their design problem, in other words to make the proper connections between the source and target domains. The BaDT's role is to guide the design team and to create a bridge to biological knowledge. To support the transfer of scientific knowledge so the design team can identify the relational structure attributes between biology and the design challenge, thus the BaDT facilitates the use of analogical distance in the biomimicry design process.

To further strengthen this last point about analogical distance, Shrivastava and Ivanaj make reference to Basarab Nicolescu's *Charter of Transdiciplinarity*. The charter states "In transdisciplinarity, all disciplines are open to that which is beyond themselves, aiming for semantic and practical unification of meanings to achieve pragmatic solutions to real problems. In transdisciplinarity, openness involves acceptance of the unknown, the unexpected, the unforeseeable, even the unknowable". By seeking information in the realm of biology, design practioners inherently venture in a discipline that is outside of their field of expertise, especially when the biological analogies to their design challenges reside in the microscopic realm or in the natural processes. The knowledge gap which exists between the life sciences and the design practices or the natural and the built environments require for biomimicry practioners to have an open mind in order to fully exploit the possibilities in biology to resolve sustainable design problems.

The extent to which a project's objectives are tightly defined from the outset may affect the potential for innovation. Radical innovations tend to require freedom for the unexpected to occur (A. Blackwell et al., 2010) as the previous Bullet train example demonstrated. With specific attention and focus, collaborators from different disciplines can adopt each other's values to an extent that problems can be reformulated in radically different ways. An effective interdisciplinary innovation, designed to deliver maximum possible value, is in effect an "organized surprise" (A. Blackwell et al., 2010), that statement is equally true of transdisciplinary endeavours. It is shown that crossing disciplines or a culture of knowledge sharing inherently increases creativity and thus the potential to lead towards new knowledge and novel solutions.

The integration of biology and design, the transfer of biological science to design practices, the transfer of biological function and solutions to human design problems are all descriptive of the biomimicry enterprise, all resulting in a new holistic discipline.

6.3 Interpretation and Conclusion

Through these observations, one can deduce that ecodesign (traditional design) is conducted by multidisciplinarity teams and largely makes use of local analogy or referencing surface similar sources in the design of products. The interaction between the team members remains project oriented, as that of traditional design, even with the addition of the LCA specialist. Consequently they principally work collaboratively towards an end goal but that collaboration can be described as a parallel relationship, in other words they work in silos; no discipline is influenced by the perspective or worldview of another. Their approach to the project, to accomplishing their task remains largely unchanged based on their training and traditional experience.

Analogical reasoning and transdisciplinarity are showing to be the primary innovation producing engines of biomimicry. It's the combination of transdisciplinarity and specifically distant analogy that has led to such mental leaps. In regards to analogical reasoning in biomimicry, one can understand that biomimicry can only function through the use of analogical distance, which has been consistently referred to in the literature as a strong creative and innovative tool. The natural environment is fundamentally different than the built environment, in general they share little surface level attributes hence the ability to make connections or transfers from biology to a design problem most often leads to unexpected results. Sometimes the result can even lead us to reconsider certain scientific truths like in the case of WhalePower's Tubercle Technology Blades and hydrodynamics[13]. Furthermore, the transfer of biological properties into the design problem enables designers to solve sustainable design issues by accessing nature's own solutions to the problems designers are trying to solve, thus allowing for solutions with less negative impact on the natural environment.

Transdisciplinarity, as previously mentioned, can be described as the search for new knowledge and problem-solving by removing disciplinary barriers and involving stakeholders across the different parts of society and academia. An interesting aspect of how transdisciplinarity manifests itself in the biomimicry approach, is that all actors involved in a project will process the information disseminated by the BaDT from their respective disciplines point of view, according to their values. Thus when the team enters the *Scoping* phase (brainstorm), the combination of these different viewpoints around the BaDTs biological information should theoretically generate more

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[13] WhalePower Tubercle Technology are wind turbine blades inspired by the fins of humpback whales. Dr. F. Fish, a biomechanic, noticed a sculpture of a humpback whale with what he thought were misplaced tubercles on the whale's flipper. Having studied fluid dynamics (i.e. smooth edges are most aerodynamic) he assumed the tubercles on the leading edge were placed there by error. As he discovered the artist's rendition was correct, Dr. Fish conducted further research which indicated that at least part of the science of fluid dynamics was wrong. The tubercles on the whale's flippers and tail are a major part of the reason the great mammal is so aerodynamic or hydrodynamic. (Goodman, 2009).

novel ideas. For example, the designer may process the biological information in an entirely different way the engineer will, combining these two viewpoints may lead to a solution neither would have thought of on their own; what author Matt Ridley colloquially describes as "what happens when ideas have sex". Ridley states that the engine of human progress has been the meeting and mating of ideas to make new ideas; that what has allowed for progress is the collective brain and not the smart individual. Since ancient times, it is the exchange of ideas and goods which has fueled innovation (Ridley, N/D). One can liken this concept to the transdisciplinary approach of biomimicry.

As society becomes more diverse and as wicked problems become more complex, solutions cannot be found in the traditional thinking coming from disciplinary silos. That way of knowing has created problems it cannot solve to reprise Einstein's maxim. The complexity in the issue of sustainability requires knowledge, perspectives and actions across disciplines and across the various levels of society[14]. If current events are any indication, relying solely on disciplinary silos and the governments and the private sector operate towards solving these challenges is failing us direly (Shrivastava & Ivanaj, 2012). The solution resides across these boundaries. By reaching out and promoting biomimicry to all levels of society from primary schools to universities, from non-profit organizations to fortune 500 companies, the organization Biomimicry 3.8 recognizes that the issue of sustainability can best be resolved through transdisciplinary thinking.

In observation, it's the integration of the science of biology into the design practice coupled with the use of distant analogy to resolve design problems that are inherently the elements of biomimicry which allows designers, engineers and architects to produce innovative design solutions. That combination allows to access a virtually untapped inspiration source, a wealth of knowledge and connections that allows to generate such mental leap one couldn't possibly generate through one's own mental powers and observations.

[14] The societal challenge-oriented definition of transdiciplinarity is defined as "a new form of learning and problem-solving involving cooperation among different parts of society (including academia) to meet complex societal challenges". (Madni, 2007)

7 Chapter Seven_ General Conclusion

"I think the biggest innovations of the 21st century will be at the intersection of biology and technology. A new era is beginning."

-Steve Jobs/ entrepreneur & inventor

7.1 Research Answers and Understanding

In these times, it becomes more and more apparent how pressing is the need for a 21st century industrial revolution regarding how humans design the built environment. While the industrial revolution has brought mankind massive changes and great advancements, the repercussions of this system can no longer be ignored if we are to continue this civilization project on this planet… in a sustainable fashion. Clearly, the current modus operandi has reached its limits and it can be argued that some of the reasons of this limitation is rooted in the concept of separation from nature, of the need to tame and control nature. It is rooted in the fallacious notion of nature being an infinite resource to be consumed, transformed through brute force, temporarily use its by-products, and discard the latter by "throwing them away" as it will supposedly be absorbed by nature and disappear. The consequences of such a mindset are showing its effects not only on the health of important and sometimes fragile life support systems but also certainly on human health as well.

As the ecological design movement progressed over the past decades, various approaches and philosophies have emerged and evolved. As biology will play an undeniable role in the technology revolution of the 21st century, be it biotechnology, biohybrid systems, or synthetic biology, biomimicry is such an approach at the convergence of design, biology and technology. The decade old discipline has already begun to make its mark in allowing designers to access a virtually untapped inspiration source and thus craft novel design solutions that can redefine how mankind designs, makes materials, builds, and ultimately manifests its influence and relationship on the natural world.

The purpose of this research was to get an understanding of the relationship between biomimicry and innovation, which is perhaps in some ways less obvious than its relationship to sustainability. The goal was to get validation beyond a simple tagline that biomimicry is a strategy of design innovation and to answer the question "***What supports biomimicry as a strategy of design innovation and what aspect(s) of biomimicry lead(s) to produce innovative sustainable design solutions as compared to ecodesign?***"

To answer the research question, the study clarified the actual relationship between ecodesign and biomimicry. Then, fifteen (15) biomimicry cases were chosen and investigated in regards to the design problem aimed to be resolved, the biological inspiration referenced to resolve the said problem, and the design result/innovation brought forth by the approach. By referencing the established criteria for incremental and radical innovation, the study was able to illustrate which type of innovation was mostly generated by the bioinspired approach. To further validate the initial result, the cases were further referenced to Dahlin and Behrens' (2005) criteria for radical innovation. As a minor objective, the cases were investigated to get a more complete understanding in matters of innovation as they were referenced to Prof. Clayton Christensen's (2013) criteria for disruptive innovation. To finalize, the study explains how distant analogy and transdisciplinarity are responsible in enabling biomimicry generate novel design solutions.

The study first makes the significant point that a more comprehensive strategy to sustainable design can undoubtedly be achieved by integrating the quantitative ecodesign approach and the qualitative biomimicry approach. Technology increasingly allows science to look deeper and deeper into the forms and processes in nature thus allowing biologists to better understand natural phenomena that were previously overlooked, misunderstood, or unknown. This consequently permits designers to access inspiration sources that are largely untapped and to create solutions that will increasingly and ever so meticulously emulate natural design references. That ability coupled with quantifiable methods of evaluating the resulting designs may eventually lead to radical design innovations with little to no negative impact on the natural environment. As certain cases in the study have already shown, the radicalness of biomimicry will manifest itself not only through increased environmental performance but often through a counter-intuitive, radical yet simple and elegant aesthetic as well.

Unquestionably, the responsible variable for such mental leaps in creativity is the use of analogical distance. The greater the distance the greater the mental and creativity leap, thus the greater the radicalness in design solution and therefore the potential for a break from convention. However biomimicry is not a magic pill to marking a paradigm shift. As a result of often time unconventional designs, despite the increased performance of the biomimetic solutions, creators of biomimetic designs must understand the salient need to well educate the public but most especially the market about biomimicry in order for their innovations to truly make an impact and this way to affect change within the current paradigm. As the study demonstrates, biomimetic radicalness can be a hindrance if the market is not properly educated onto how and why the design solutions challenge traditional expectations. Therefore, for an innovation to be radical is simply not enough. To change the current modus operandi, the biomimetic innovation must be disruptive as well. Lastly, the results of the study indicate that biomimicry is a manifestation of the current and growing trend of disciplinary overlap, the growing tendency where various disciplines with no immediate and obvious relations are now combining and sharing knowledge towards creating new disciplines to further advancement and knowledge, i.e. the trending progression of STEAM[15] vs STEM[16] where biomimicry is undoubtedly a STEAM discipline.

7.2 Paths Towards Further Investigation

Biomimicry is a fairly new discipline and the research possibilities on this design approach are many. Undoubtedly, much more research will be done in the coming years on this bioinspired design discipline as it continues to gain momentum and continues to gain attention from academia and business organizations. This study has provided some insight on future research possibilities.

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[15] STEAM: Science, Technology, Engineering, Arts and Mathematics. An initiative recognizing that the innovative practices of art and design play an essential role in improving Science, Technology, Engineering, and Mathematics (STEM) education and advancing STEM research. (Congress, 2013)

[16] STEM: Science, Technology, Engineering and Mathematics

1) A limitation of this study in regards to biomimicry as a strategy of design innovation is that it observes biomimicry solely in the context of product design. It would be of great value to get an overall view of that relationship in other contexts where biomimicry is also employed, i.e. architecture, urban design, urban planning and even economy.

2) After noticing that the two cases with the most potential to become disruptive innovations were generated through the *Challenge to Biology* approach. An interesting research path would be to study whether *Challenge to Biology* or *Biology to Design* is a better approach to generate more innovation radicalness, as well as potentially more dissimilar and disruptive innovations. To study which approach capitalizes the most on the mental and creativity leap potential of distant analogical reasoning.

3) To study the influence of transdisciplinarity in the biomimetic design process, it could be valuable to conduct an in-depth study of how to best maximize on a team's various disciplines "worldview" to generate innovation. Engineers, designers, architects, developers, and marketers for example all have different training, different thought processes and most likely will each process the information they receive from the BaDT differently. Perhaps there is a way to study and cultivate this particularity as a means to capitalize on its creativity potential and generate a better design process to produce even more effective innovative design ideas.

4) To further study biomimicry in relation to innovation in the market spectrum may lead to insights onto how to better promote biomimicry and biomimetic designs/product. Innovation in the market spectrum involves a salient element of time, market education and customer behavior which means that to properly investigate on the issue requires a much larger study.

7.3 Research Limitations

It should be specified that the approach taken for this research was to investigate biomimicry through the available literature on the subject. Towards the end of the research process, it has been suspected that perhaps this research could have benefited to include interviews with the people involved in the cases and thus provide more information, and perhaps present a more accurate view of the cases in regards to the people/disciplines involved in the process. This could hence provide more information and a more accurate view in regards to the level of interdisciplinarity in each project.

7.4 Contributions

Considering the increasing interest from academia and the private sector in biomimicry, this study contributes to the understanding of biomimicry in relationship to sustainable design innovation. This study is proposing new paths of research on biomimicry and innovation and hopefully will provoke new insights on this bioinspired strategy. This research can potentially help making the case for more design professionals to adopt the bioinspired strategy not only to inform a novel approach to sustainable design but certainly to increase their potential to generate effective, efficient and innovative design solutions.

Biomimicry in the Future

This study has given a number of insight into biomimicry and its potential to better inform our design decisions. This study leads to an understanding that biomimicry is not only a manifestation of the holistic, salutogenic, and participation mindset Daniel Wahl makes reference to in *Bionics vs. biomimicry: from control of nature to sustainable participation in nature* (2006), but also that it is a substantial part of the future of sustainable design innovation. Design is increasingly turning to nature on various levels, anywhere from the design of biomaterials and products to buildings and cities. Designers, architects, engineers, scientists and artists are more than ever collaborating to resolve design problems as new disciplines are created at the intersection of art, design, technology and biology in the form of biomimicry, biodesign, synthetic biology, additive manufacturing and natural computing. Perhaps, eventually disciplines like biomimicry will continue to evolve to the point of becoming convention and that one day the built environment will truly exist in symbiosis with the natural world.

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Appendices

Appendix 1_ Case Studies

The objective of this section is to explore various biomimicry case studies and identify not only what makes the project notable, but mainly to understand whether there was advantages and benefits to taking a biomimetic approach.

1-PUREBOND TECHNOLOGIES by Columbia Forest Products

Product: PureBond formaldehyde-free hardwood plywood technology

Designed/Developed by: Dr. Kaichang Li, an associate professor in the Department of Wood Science & Engineering at Oregon State University in Corvallis, OR. Dr. Li has a college education in applied chemistry and organic synthesis, and later earned a PhD in wood chemistry.

Design Problem: After investing in ensuring that their wood was sustainably harvested, Columbia Forest Products realized that they required wood products that were toxin-free to meet market demand as well as their own sustainability commitment. Composite wood products are made with conventional wood glue containing urea formaldehyde (UF). UF is labeled as a carcinogen by the World Health Organization due to their off-gassing volatile organic compounds (VOCs) and is also designated as a toxic air contaminant (TAC) in California with no safe level of exposure. VOCs have direct health effects, including eye, nose, and throat irritation as well as headaches with extensive exposure (Watson, N/D).

Inspiring Strategy: Blue mussels

Emulating Form, Process or System: Inspiration by process

- Blue mussels, *Mytilus edulis*, are filter-feeding mollusks found in the intertidal zone of the North Atlantic coasts of North America's Pacific Northwest coast. A colonial species, they cling in large groups to rocks and each other using strong adhesive threads, called byssal threads. Despite living on wave-swept coast lines, mussels are able to hold on tightly using an underwater "glue".
- The adhesive pads of byssal threads contain at least half a dozen different proteins, also called marine adhesive proteins (MAPs). Using these adhesive compounds, mussels can adhere to nearly any substrate. The attachment is versatile and tough, despite continual exposure to salt water and shearing forces.

Design Solution: Dr. Li, a professor at Oregon State University's College of Forestry, found that mussels secrete byssal threads and pads that are made largely of collagen, which provide superior strength and extraordinary flexibility. The sticky part of the threads are made of a protein containing a rare amino acid called L-DOPA. His interest in the phenomenon led to ground breaking research

–funded by Columbia Forest Products (CFP) and others. Li discovered that soy proteins can be modified to perform similarly to byssal threads. The modified proteins not only delivered phenomenal adhesion, they also offered exceptional water resistance. This breakthrough led to PureBond, proving that enhanced environmental quality and increased product performance can go hand in hand (Institute, 2011b).

Innovation Claim: The PureBond process and the soy-based Kymene adhesive it uses are formaldehyde-free, sustainable, and comparable in strength to formaldehyde-based adhesive-based adhesive systems. The adhesive also creates lighter glue lines that are more aesthetically appealing to consumers. Other alternative wood adhesives incorporating soy are available, but only PureBond is cost competitive with formaldehyde based resins. Adhesives that use soy protein require less time and less energy to cure before use, and are safer and easier to handle. In 2006, CFP converted all seven (currently eight) of its plywood plants to the PureBond manufacturing process, distinguishing it as the first company in the wood products industry to switch to a completely formaldehyde-free, soy based resin. In doing so, it replaced the use of an estimated 47 million pounds of conventional UF and PF resins and reduced emissions of hazardous air pollutants at each of its plants by 50-90% (Institute, 2011b). Thus using products made with formaldehyde-free PureBond technology helps to reduce toxins within the indoor environment, compared to traditional hardwood plywood products.

CFP's benefits were multiple due the change in technology:

- Product differentiation was cost neutral
- Easily met California Air Resources Board CARB) Standards
- New technology gave provided a cost advantage
- Cost avoidance in capital spending on equipment to filter out emissions
- CFP now viewed as a leader and innovator not just a hardwood plywood producer

CFP implemented lean manufacturing principles in 2008 and have realized over 45 million dollars in cost savings and is continuing research on innovative adhesives. CFP's innovative stance has resulted in multiple awards such Rainforest Alliance "Sustainable Standard Setter", Home Depot Vendor of the Year, EPA's Presidential Green Chemistry Award, Architectural Record Editor's Pick and MetaFore Innovation Award to name a few (Wetherington, N/A).

Life's Principles Met: Use Life-Friendly Chemistry

2-GREENSHIELD FABRIC FINISH ***by BigSky Technologies LLC***

Product: GreenShield is a nano-particle based oil, water repellant and stain resistant finish

Designed/Developed by: n/a

Design Problem: Fluorochemicals are the key ingredients in daily products like stain-resistant pants and non-stick cookware. However, fluorochemicals have also been found to be bio-accumulative in living beings and persistent in the environment and certain versions, such as perfluorooctanoic acid (PFOA), are possible carcinogens. Old stain resistant technologies encase fabric in thick layers of polymer-based chemicals to provide protection.

Inspiring Strategy: Morpho butterfly and sacred lotus/Hydrophobic surfaces

Emulating Form, Process or System: Inspiration by form.

- In the natural world water does not wet the leaves of many plants because their leaves are rough on a small scale. The self-cleaning wing surface of the Morpho butterfly and the sacred lotus shed water and dirt due to their hydrophobic microstructure. This microscopic roughness has been used by nature to provide water repellency.

Design Solution: Microscopic roughness, hydrophobic nano-structures/surfaces is the technology behind GreenShield which leverages the enormous surface area of each nano-particle enabling the particles to efficiently deliver the appropriate chemistry to the fabric. Through the use of nano-particles on the surface of a fabric, GreenShield creates a pocket of air allowing water and oil droplets to roll carrying dirt and stains off the fabric for a self-cleaning effect. GreenShield is a multi-functional technology providing water and oil repellency and stain resistance in a single finish with greater efficiency than each function delivered separately.

The principles of green nanotechnology begin in the design stage, Dr. Joseph F. Bringley, Chief Technology Officer at G3i, says " we have designed the products up front to be as green as possible, using less chemistry and producing less waste- specifically, less harmful waste. We are using a water-based process that produces an essentially 100% yield and significantly reduces the use of volatile organic compounds" (Rodie, 2008). The process also is conducted at room temperature, using proprietary waste-eliminating, energy-saving technology that utilizes water-based solvents. Through the principle of micro-roughness, GreenShield reduces the use of fluorochemicals on fabrics. Undetectable to human touch, the microscopic surface roughness of GreenShield allows water and oil to roll off the surface of the fabric resulting in water and oil repellency and stain resistance.

Innovation Claim: It is the first textile finish to be certified by the Scientific Certification System (SCS), the processes used in manufacture of GreenShield are designed in a way that maximizes product performance while minimizing environmental, health and safety risks. The process uses benign materials such as a water based formulation, it uses energy efficiently by using a low temperature process to minimize energy requirements, and the process generates no waste. It reduces the fluorocarbons by 8-10 times, it is safe and environmentally friendly, completely water-based formulation, and is permanent with excellent wash-durability and improved hand and feel

(GreenShield, N/D). BigSky Technologies' sales have spiked since 2009, rising 50 percent, to about $225,000 (Tarquino, 2011).

Life's Principles Met: Be resource (material and energy) efficient

3-ORNILUX MIKADO ***by Arnold Glas***

Product: ORNILUX Bird Protection Glass

Designed/Developed by: Christian Irmscher/ Head of Research and Development

Design Problem: Birds are fooled by the reflection of trees and sky and cannot perceive windows as a barrier and with the popularity of expansive windows and glass walls in modern high-rise architecture, birds strikes are a major cause of avian fatalities and kill an estimated 300 million to 1 billion birds globally each year. Migratory song birds are disproportionately affected, many of which are already threatened due to hunting and shrinking habitats.

Inspiring Strategy: UV-light reflecting spider webs

Emulating Form, Process or System: Inspiration by Form and Process

- Over 3000 species of orb weaver spiders (family Araneidae), common worldwide, including the common garden spiders of North America and Europe. These spiders construct distinctive flat webs consisting of concentric circles with spokes radiating out from the center using strands of silk with remarkable mechanical properties. Some orb weavers decorate their webs with UV-reflective threads called stabilimenta. Humans cannot perceive UV light, however, birds can, thus the reflective threads prevent them from colliding with and destroying the webs (Biomimicry_3.8, 2013).
- Humans cannot perceive UV light. Ornilux Bird Protection Glass has a patterned, UV-reflective coating that mitigates large birds and wasps collisions into the webs.

Design Solution: The properties of stabilimenta used by orb weaver spiders was brought to the attention of Hans-Joachim Arnold, owner of Arnold Glas, by friend Dr. Meyerhuber. After reading an article on the subject, Meyerhuber encouraged Arnold to research how this biological phenomenon might be applied to glass to prevent birds from striking windows and killing or injuring themselves. Intrigued by the concept, Arnold managed to convince the board of directors on the innovative possibilities of this concept and began the necessary research to develop a product that would have the same UV-reflecting qualities as spider silk.

Christian Irmscher, head of Research and Development, led the technical product development of a UV-reflective glass coating that would balance visibility and invisibility: bird eyes' ability to perceive UV light (visible) combine with human eyes' inability to perceive it (invisible). The coating's process and chemistry was developed with Arnold Glas' sister company Arcon, which specializes in thin low-e and solar coatings for architectural glass, resulting in a coating patterned that is only visible to birds or other organisms that can detect UV light. During testing, they found that a patterned coating rather than a solid coating made the contrast more intense, more perceivable and although the concept was modeled after the pattern of a spider webs, the team opted for a special pattern to make the coating application process practical.

The transparent UV coating was first patented in 2001 and Arnold Glas introduced its first commercial product in 2006: the Ornilux SB1. The pattern was sometimes perceptible to the human eye but very subtle. In 2009 the second generation of the product was introduced: the Ornilux Mikado. The second generation featured an improved coating and a criss-crossed pattern, much more reminiscent of the spiders' web, and nearly invisible to the human eye (Biomimicry_3.8, 2013).

Innovation Claim: Independent pre-market testing by the Max Planck Institute for Ornithology in Germany demonstrated that Ornilux windows are highly effective at protecting against bird strikes. The glass is claimed to reduce bird collisions by 76%, which means that some birds see the spider web design coating on the glass which otherwise makes no reduction in the glass' transparency (Edwards, 2010). Out of 108 tests flights with 19 species of garden birds and wild birds, 82 of the birds flew towards the glass pane and avoided the Ornilux (Edwards, 2010). From 2003 to 2010, a total of 1384 flights were conducted in a 30ft long tunnel with two glass windowpanes situated at the far end of the tunnel. The birds tried to fly out through the "perceived" opening to then be stopped by a net to prevent them from striking the glass. Bird strikes were significantly reduced by the UV pattern. Urban planners, architects and city officials are increasingly becoming aware of the dangers the use of glass in buildings presents to birds and a growing number of cities are implementing bird safety building requirements (Biomimicry_3.8, 2013).

Life's Principles Met: Use multi-functional design; be locally attuned and responsive

4-AQUAPORIN INSIDE ***by Aquaporin***

Product: Aquaporin filtering membrane technology.

Designed by: n/a

Design Problem: Water conservation is a growing issue to due growing population and increasing pollution of fresh water by industrial activities. Evaporation and reverse osmosis are the two main strategies used to purify and desalinate water, both are highly energy intensive and thus less economical (GermiNature, 2014). Most filtration membranes in use today consist of dense polymeric films where the surface properties are controlled by advanced chemical engineering. This has resulted in a vast array of separation membranes specifically designed for certain applications. However, almost all of these synthetic membranes are made of polymer sheets consisting of micron- to nanometer sized holes and require the use of intense pressure to push water through the membranes (Institute, 2011a).

Inspiring Strategy: Pores move water through membranes: cells

Emulating Form, Process or System: Inspiration by Form

- Inspired by the process by which kidneys filter impurities and how pores move water through membranes. Aquaporins are selective membranes channel proteins found in the lipid bilayer of living cells that work to transport water across the cell membrane. Aquaporins accomplish this task while excluding any unwanted ions or other polar molecules, making them a perfect model for the formulation of low-energy water filtration systems. The result is that only water molecules and nothing else can pass though aquaporin water pores (Aquaporin, N/D).

Design Solution: The Aquaporin Company is focusing on mimicking the ability of lipid bilayers in biological cells to transport water back and forth across membranes by way of membrane channel proteins called aquaporins. Aquaporins can facilitate this transport while excluding any particles or ions that are not water. The Aquaporin company's goal is to create a new class of water filtration membranes that use aquaporins as cornerstones in water filtering devices to be employed in industrial and household water filtration and purification (Institute, 2011a). Aquaporins are embedded into artificial membranes simulating the natural behavior of biological membranes. Since aquaporins are ubiquitous among all living organisms they can easily be produced using bacteria or algae for instance (GermiNature, 2014).

Life's Principles Met: Be resource (material and energy) efficient/ Evolve to Survive

5-TUBERCLE TECHNOLOGY BLADES ***by WhalePower***

Product: A new fan and wind turbine blade designed using tubercle technology.

Designed by: Dr. Frank Fish, professor of biology

Design Problem: Current wind turbine blades require steady, high winds to generate electricity. The efficiency of electric fans depends upon how much energy they need to move air. These speeds are more prevalent under most operating conditions than high wind speeds. Stronger generators and blades can be employed at high winds but are ineffective at low wind speeds. The main approach to improving this issue is to increase the angle of attack, however, the recurring problem is that increasing the angle eventually forces the blade to stall. Stalling is determined by wind speed and direction and is difficult to predict. To counter this, manufacturers develop blades with limited operating angles to ensure that stalling is minimized which leads to inferior performance (Canter, 2008).

Inspiring Strategy: Humpback whales flippers

Emulating Form, Process or System: Inspiration by Form

- WhalePower wind turbine blades are inspired by the flippers of humpback whales, which have tubercles or bumps on the leading edges channeling flow and increasing aerodynamic efficiency.
- Dr. Frank Fish, whose field is biomechanics, came about his observations of the humpback whale serendipitously when he noticed a sculpture of a humpback whale with what he thought were misplaced tubercles on the whale's flipper. Because of his study of fluid dynamics (i.e. smooth edges are most aerodynamic) he assumed the tubercles on the leading edge were placed there by error. As he discovered the artist's rendition was correct, Fish conducted further research which indicated that at least part of the science of fluid dynamics was wrong. The tubercles on the whale's flippers and tail is a major part of the reason the great mammal is so aerodynamic (or as MIT's Technology Review called it, hydrodynamic (Goodman, 2009).

Design Solution: Previous experiments have shown, however, that the angle of attack of a humpback whale-flipper can be up to 40% steeper than that of a smooth flipper before stall occurs. A Harvard research team showed that the bumps on the humpback flipper, known as tubercles, change the distribution of pressure on the flipper so that some parts of it stall before others. Since different parts of the flipper stall at different angles of attack, abrupt stalling is easier to avoid. This effect also gives the whale more freedom to attack at higher angles and the ability to better predict its hydrodynamic limitations.

Innovation Claim: Blades designed using Tubercle Technology are more energy efficient. The company says this new blade design could increase annual electrical production for existing wind farms by 20% (Merolla, 2009). The wind turbine blades require lower wind speeds, increasing the amount of time and the number of locations where they can actively generate electricity. The 16 degree stall angle found in the first wind tunnel experiment has been enhanced to produce airfoils that don't stall until they reach an astounding 31 degrees; far above anything previously known. Unlike virtually every other airfoil which can stall violently and even damage the machines they're employed on, tubercle airfoils always stall gradually (WhalePower, 2012). Early wind tunnel tests of model flippers with tubercles by the US Naval Academy showed that wind drag was reversed by 32% and lift increased by 8%. Other studies showed similar results, thus corresponding design changes to airplane wings would seem to make sense considering these results (Goodman, 2009).

Life's Principles Met: Evolve to Survive/Be Resource efficient

6-ENTROPY & I2 MODULAR CARPETS ***by InterfaceFLOR***

Product: Line of modular carpet.

Designed/developed by: - David Oakey, head of product design

- Ray Anderson, founder

-Paul Hawken, advisor

-Janine Benyus, advisor

Design Problem: Traditional carpets are large surfaces that most often will need to be trimmed to fit the area to be covered. Traditional carpet tiles must all match exactly, and must be installed uniformly and in the same direction. However, when an area of that carpet needs to be replaced due to damage, wear and tear or spill, an area much larger than the damaged surface if not the entire carpet will need to be removed and then sent off to the landfill. In addition, traditional carpets use glues that off-gas volatile organic compounds (VOCs) and impede the recycling of carpet tiles. Conventional modular carpets are glued to floors using liquid glues that issue VOCs as they cure. VOCs can contribute to poor indoor air quality (Watson, 2008).

Inspiring Strategy: Inspired by forest floors

Emulating Form, Process or System: Inspiration by form

- Inspired by the forest floors covered by a blanket of fallen leaves to a bed of river stones, no two units are the same shape, size, or color, yet collectively they form a cohesive pattern and aesthetically seamless surfaces by exhibiting organized chaos.

Design Solution: Ray Anderson, CEO of InterfaceFLOR, launched what is now known as Mission Zero; setting a goal to make InterfaceFLOR 100% sustainable and closed loop by 2020. With the help of Biomimicry 3.8 (at the time Biomimicry Guild) the team at InterfaceFLOR realized that they had been asking the wrong questions in regards to how to eliminate glues from the installation process when the right question was how to keep a surface covered. Rather than issue glues, nature uses simpler concepts; gravity holds things in place on a surface. If each modular tile in a carpet is held together, gravity can do the work of keeping the tiles on the floor, and there should be no conventional glued carpet. The design team invented the *TacTiles*, a slim, post-it sized stamp that use a thin layer of resealable glue on one side to adhere tiles to each other, creating conglomerates of tiles that acts as a wall-to-wall carpeting. The construction of the tiles prevent them from bending at the corners, and gravity holds the carpet down, hence also eliminating the need to use each tile to the floor as well as eliminating damage to the floor.

David Oakey, head of product design/textile designer at InterfaceFLOR, points out that in nature, the beauty lies in the variations with materials such as marbles, wood, and stone. In the industrial world, variation has traditionally been seen as imperfection where using biomimicry in this process has enabled to incorporate into the industrial process our natural admiration of variation.

Innovation Claim: Entropy and i2 carpet tiles can be replaced individually and many of the components can be recycled by InterfaceFLOR resulting in significant reductions in wastes and cost. The intentional color variations eliminate common concerns over dye lots, meaning that consumers no longer need to purchase large quantities of "attic stock" in order to ensure matching replacement tiles, significantly increasing the lifecycle of the product. The non-directional, random, non-repeating pattern also results in installation savings, resulting in only 1.5% average installation waste versus 14% average for broadloom carpet, greatly improving their manufacturing efficiency. The TacTiles innovation, on the hand, resulted in an ecological footprint 90% lower than that of the original glue adhesives (Colby, 2011). All Entropy and i2 products are Environmental Product Declaration (EPD) and LCA accredited. According to Ray Anderson, Entropy became Interface's most popular product in the company's history with sales increasing steadily since their release by 3.1 million yards and by 2009 the company's accumulated avoided costs from its waste elimination activities, including the substitution of standard tiles with the i2 line equaled $433 million.

As well as being a significant transition towards zero waste in manufacturing and a major step InterfaceFLOR's sustainability goals. The total greenhouse gas emissions of the entire life of the carpet are offset through the support of projects that reduce greenhouse gas emissions approved by the Climate Neutral Network (Watson, 2008). This approach to biomimicry may be seen by some as simplistic but yet its success cannot be denied.

Life's Principles Met: Integrate Development with Growth

7-SHARKLET AF by Sharklet Technologies, LLC

Product: A synthetic surface which deters colonization of biofouling without the use biocidal toxic chemicals.

Designed by: Dr. Anthony Brennan, Chief Technology Officer/Founder

Design Problem: Biofouling occurs everywhere, it is the process by which bacteria adhere to a surface to access to food sources especially on wet or oily surfaces. This in turn enables them to multiply by creating a substance called extracellular polymeric substance (EPS) or biofilm which provides them stability and protection in order to colonize grow and colonize a surface.

The prevailing technique to remove biofouling, algae and barnacles from boat hulls leaches large amounts of toxins in the water creating evolutionary pressures on the microbes. The organisms who survive are the most resistant to the toxins hence making the next generations of algae and bacteria more difficult and costlier to eliminate. Nearly 70% of the world's industrial shipping and recreational boat fleet use copper-based paints as antifouling strategy. These bottom paints are designed to slowly release copper into surface waters to kill and slow the growth of micro-organism and as a result copper and other metals have compounded to often toxic levels in our oceans, lakes and waterways (Sharklet, 2010). Conversely, surfaces in hospitals are usually sprayed with anti-bacterial and cleansers to kill bacteria and microbes. The adverse effect is the creation of anti-microbial resistant strains of bacteria, hence creating a vicious circle: the bacteria are becoming harsher and more toxic both potentially impacting human health.

Biofouling has enormous health and economic impacts, primarily in the marine shipping and healthcare industries. A coating of algae and barnacles can cause a 16%-86% decrease in power efficiency, dramatically impacting energy and fuel use. The US Navy constitutes roughly 0.5% of the world's fleet and annually spends $260 million in annual cost whereas the marine shipping industry annually spends an estimated $60 billion in fighting against biofouling. Similarly, in the health care industry biofouling is an expensive problem and can additionally be lethal (Terrapin-Bright-Green, N/D). Effective antifouling strategies can save billions of dollars in hospital healthcare by reducing the amount of toxic chemicals used to eradicate biofouling which can usually spread on various surfaces. Toxic chemical use has led to a strain of chemical resistant bacteria known as "superbugs" in hospital settings which are increasing the number of hospital-acquired infections (HAI) each year. According to the Center for Disease Control (CDC), five (5) to ten (10) percent of hospitalized patients are affected by HAI each year in American hospitals, for approximately 1.7 million HAI cases resulting in 99,000 deaths and an estimated $20 billion in healthcare costs (CDC, N/D).

Inspiring Strategy: The skin of sharks prevents microbes and other organisms from attaching due to surface micro-topography. The solution to biofouling lies in preventing rather than eradicating.

Emulating Form, Process or System: Inspiration by form

- The skin of sharks prevents microbes and other organisms from attaching due to surface micro-topography. Shark scales, or dermal denticles, are structurally different than most fish scales. They are covered in enamel that is analogous to human teeth and can repel more than 85% of algae that comes in contact with the scales. The scales have a distinct topography comprised of microscopic ridges arranged in diamond patterns, sometime lacking in most other large marine animals such as whales.
- The theory is that the key to the pattern's ability to prevent bacteria to colonize and produce biofilms was that the pattern dramatically increases the energy required for bacteria to colonize a surface. The cells have to suspend over large gaps or bend to the contour of the surface placing great amounts of stress and tension on the cells forcing the bacteria to move elsewhere or die (Terrapin-Bright-Green, N/D).

Design Solution: Dr. Brennan was researching antifouling methods found in nature for US Office of Naval Research as they were trying to resolve how to reduce the buildup of algae on ship hulls that did not involve toxic paints and reduced maintenance and dry dock costs. The analogous natural reference to large boats were large slow moving large marine animals and discovered that sharks were largely free on any biofouls due to their skin architecture. Sharklet developed/design a diamond pattern mimicking the shark' skin showing tremendous potential as the company over years has tested various pattern to determine which were most effective against a wide variety bacterial species. Through years of testing, Sharklet has been able to establish which micro-pattern had the best antifouling effects, which best reduced bacteria colonies' ability to communicate, multiply and form biofilms. Their unique biologically-inspired topography boasts a pattern with ridges of 3μm in length and 2μm wide (Terrapin-Bright-Green, N/D) making the ridges 1/10th of human hair, hence the texture is invisible to the eye and non-detectable to fingers (Alsever, 2013)

Sharklet is taking two approaches to their technology: the formation of licensing model where companies paid to use Sharklet's technology and their own medical product line.

Innovation Claim: The Sharklet micro-pattern has a unique "quarantine-like" effect on micro-organisms that come in contact with the surface. The pattern is associated with a decrease in bacterial survival and is less likely to transfer bacteria to finger tips by touch. The micro-pattern surface demonstrated reduced attachment when exposed to bacteria, reduced survival time of attached bacteria, and reduced surface-to-finger transference of attached bacteria. Depending on bacteria species the bioinspired surface cut bacteria by 90% to 99% (Alsever, 2013). Sharklet surfaces introduce an environmentally friendly approach to reduce risk of transmission of human pathogens in the healthcare setting (Chung et al., N.D.). As the words spreads on Sharklet's technology, the company increases its joint agreements with other medical companies such as Cook Medical, makers of telephones, and countertops which in turn will help scale manufacturing and reduce cost. In 2014, Sharklet plans to venture outside the medical business and work with Steelcase, providing Sharklet-patterned desks and other furniture for college classrooms and shared offices (Alsever, 2013).

Life's Principles Met: Evolve to Survive

8-PAX WATER TECHNOLOGIES ***by PAX Scientific***

Product: Water propeller technology based on the centripetal spiral, a recurrent form in nature

Designed/Developed by: Jay Harman, founder

Design Problem: Rotational equipment like traditional fans and propellers consist of planar surfaces, or surfaces with simple curvature in only one axis. These geometries generate centrifugal forces which then generate turbulence that causes the gas or fluid to move or mix. Aside of incremental improvements and modifications in the past 150 years (Institute, 2011a), the design of rotational equipment hasn't changed much since their development 4,000 years ago. The designs remain largely inefficient with design faults such as drag resistance, low output, energy inefficiency, excessive noise, and component wear and tear (Terrapin-Bright-Green, n/a-b).

Inspiring Strategy: Spiral-shaped flow or centripetal spiral/Fibonacci sequence/Golden ratio

Emulating Form, Process or System: Inspiration by form

- From water flows, to kelp patterns, to shell architecture, nature recurrently uses 3-dimensional centripetal spirals oriented towards the center of curvature for liquid flows. The most efficient way to move matter and energy is not a straight line but a curve known as phi or the Fibonacci sequence.
- The pervasive logarithmic spiral pattern found throughout the natural world is an optimal flow form, allowing fluids to travel as fast as possible without transitioning from a laminar to turbulent flow (Institute, 2011a).

Design Solution: By using reverse engineering of the geometry, studying fluid flow efficiencies in natural systems such as air and ocean currents, Harman was able to observe what he called the "PAX streamlining principle"; a principle based on a scalable geometry of compound curves in multiple axes, resulting in an organic shape derived from the Fibonacci sequence.

Innovation Claim: Centrifugal pumps consume massive amounts of energy and generate cavitation (tiny bubbles) as they work, causing vibration that makes them noisy and inefficient. The nature-spiraled volute doesn't cavitate, and thus uses 20% to 40% less energy (Rockwood, 2008) and reduces noise by 75% (Institute, 2011a). The PAX Water Mixer is a submerged mechanical mixing system. No other mechanical solution had offered a compact, efficient solution to the stratification and stagnation problem. The PAX water system requires no bulky installations by focusing on continuous operation to deliver 24/7 mixing and the installation process requires no modifications and can be done in a matter of hours with or without draining the tank. The system mixes continuously to eliminate stratification, distribute disinfectants uniformly and prevent nitrification. In a matter of 2-3 weeks biofilms are killed and residual chlorine is nearly eliminated which also results rapid chemical dispersion and significant reduction in chemical use once effective circulation is established. Effective circulation of the water inhibits biofilms to from growing inside the tank and minimizes ice formation which in turn prevents damage to the tank. Furthermore, the ratio of impeller size to mixed water volume capacity is unprecedented, generating a ring-shaped vortex that efficiently moves water throughout the tank, in a form of organized turbulence which reduces friction and provides optimal mixing. In most installations, the PAX Water system provides financial payback averaging 3-5 years derived from the decreased dumping of aged water, decreased energy consumption, decreased chemical application and decreased labor costs. PAX has been able to quantitatively demonstrate the superior performance and lower energy cost of their technology. (Terrapin-Bright-Green, n/a-b).

Since the Lilly Impeller, PAX Scientific has identified various other potential applications/business opportunities hence the creation of many subsidiaries derived from the streamlining principle: PAX Water, PAX Mixer, and PAX Fan. PAX recently got funding from VC

Vinod Khosla and is bringing its ultra-efficient spiral to aerospace and medicine, heat exchange and air-conditioning, wind turbine and marine propulsion (Rockwood, 2008).

Life's Principles Met: Be Resource Efficient/ Evolve to Survive

9-NOVOMER CARBON DIOXIDE-BASED PLASTICS ***by Novomer***

Product: A propriety catalyst system that transforms waste carbon dioxide into high performance, low cost polymers for a variety of applications: carbon dioxide based plastics.

Designed/Developed by: n/a

Design Problem: Plastics are carbon-based materials composed of one or more building blocks strung together into long chains called polymers. Conventionally, the building blocks, called monomers, are formed by distilling crude oil and "cracking" its large carbon molecules into small, two-carbon molecules. These small molecules are then used to create an array of commercial plastics including polycarbonate plastics. The conventional production process is energy intensive and uses hazardous chemicals such as the suspected endocrine disrupting chemical, bisphenol-A and phosgene, infamous for its history as a chemical weapon (Institute, 2011a).

Inspiring Strategy: CO2 activation used in organic compound manufacturing. Plants use CO2 to make cellulose.

Emulating Form, Process or System: Inspiration by process

- Photosynthetic organisms have found a life-friendly route to produce a wide range of complex, polymeric compounds such as polysaccharides and proteins. Solar energy drives a cyclic system that draws carbon from atmospheric CO2. Carbon dioxide doesn't share it's carbon atom easily, so nature devised the rubisco enzyme to coax carbon dioxide into bonding with the carbon atom of an organic molecule. The key step of the Calvin Cycle produces the building block from which all other carbon-based compounds in photosynthetic organisms are produced (Institute, 2011a).

Design Solution: Novomer's plastics are made with conventional petroleum feedstocks, but they only use about half the amount that typical plastic manufacturing requires, the other half being CO2. It would seem rather counter-intuitive to use to make a solid but that approach comes from the basis that CO2 shares a common element with petroleum: carbon. That carbon can be harvested by extracting carbon molecules from CO2. Novomer has developed this process into an industrial process which allows them to extract CO2 from industrial fermentation processes where the waste gas is fairly pure, such as ammonia production or ethanol refining rather conventional petroleum sources such tar sands or deep ocean wells (Casey, 2011).

Novomer's process to make polymers by sequestering carbon by mimicking photosynthesizing organisms, such as plants and corals, marks an important shift from traditional plastic production processes. Novomer's acrylic acid, acrylate esters, butanediol and succinic anhydride can be synthesized cost competitively from bio-based feedstocks using existing technology. For example, in Brazil, the fermentation and gasification of sugarcane can be used to generate ethylene oxide and carbon monoxide. These raw materials can then be combined with Novomer's catalyst to make materials and chemicals with a negative carbon footprint. Therefore, Novomer's technology could lead to diapers, packaging and paints which sequester carbon monoxide and carbon dioxide over the product lifecycle, mitigating global warming and climate change (Novomer, 2010). Novomer industrially produces polypropylene carbonate (PPC) polyols, produced using carbon dioxide and propylene oxide, to replace conventional polyether, polyester and polycarbonate polyols. The company recently began production of CO2-based acrylic acid using CO and shale gas-based ethylene oxide (De Guzman, 2013).

Innovation Claim: In March 2013, Novomer received a $5 million grant from the US Department of Energy (DoE) as part of the Clean Energy Manufacturing Initiative (CEMI). Interest in Novomer's technology is largely due to its cost and environmental advantages. Novomer expects cost saving of 20-40%. With regards to energy consumption, Novomer's catalysts can operate at around 30-50 degree Celsius compared to conventional acrylic acid processing that operates above 250 degree Celsius and none of the catalyst used are wasted in the process. Energy productivity of their acrylic acid processing is expected to increase by 30-70%. Novomer's process is reportedly reducing its carbon footprint by 40%-110% depending on the target chemical (De Guzman, 2013).

Life's Principles Met: Be resource efficient/Be locally attuned and responsive

10-ENVIROGRID CONTROLLER ***by REGEN Energy***

Product: Wireless energy controllers

Designed/Developed by: Mark Kerbel / co-founder & EVP, computer/electrical engineer
Roman Kulyk / co-founder& CTO, mathematics/computer science

Design Problem: Different types of building equipment usually operate in isolation from each other, obeying a single thermostat or a timer that has no knowledge of what else is currently operating in the facility. Since these loads do not communicate with each other, they often operate simultaneously- unnecessarily boosting the highest demand level in a given month, and causing higher than expected bills. Other microcontrollers are more concerned with preset configurations of lighting and temperature than with cyclical demand of these devices (Institute, 2011a). Buildings are a key source of peak energy demands and account for 39% of total US energy. Air-conditioner use in homes and offices increase to a peak in afternoon periods leading the electricity grid to struggle to accommodate this high level of energy demand. To accommodate this energy demand, older "peaker plants" are turned on to supply additional energy, using lower-grade and dirtier fuels without the advanced scrubbing mechanisms that newer plants use to reduce pollution (Terrapin-Bright-Green, n/a-a).

Inspiring Strategy: Bee hives/ Swarm intelligence or swarm logic, the way bees communicate with each other using simple rules/Emergence.

Emulating Form, Process or System: Inspiration by system

- Social insects like bees and ants have been successful and are pervasive in the ecosystem because of three (3) characteristics: **flexibility** (the colony adapts to changing environments), **robustness** (even when one or more individuals fail, the group can still perform its tasks), and **self-organization** (activities are neither centrally nor locally supervised, they are bottom-up systems rather than top-down).
- This system is called swarm intelligence or emergence. The principle being simple organisms operates and performs seemingly simple tasks but collectively form a rather flexible, robust complex system capable of self-organization. Many social organisms seem to make sophisticated adjustments and decisions based on relatively simple rules. Bees operate adaptive colonial groups despite lacking top down management or "intelligence" because through self-organization, the behavior of the group emerges from the collective interactions of all the individuals. When individuals follow simple rules, the resulting group behavior can be surprisingly complex and remarkably effective (Bonabeau and Meyer, 2001 cited in AskNature).

Design Solution: Heating, Ventilation and Air Conditioning systems (HVAC), compressors, pumps and other building appliances constantly cycle on and off and the fact that they are ignorant of each other and can often turn on at the same time is at the basis of the problem resulting in high energy demands. After reading Steven Johnson's book *Emergence: The Connected Lives of Ants, Brains, Cities, and Software*, Kerbel and Kulyk came to realize that the ideal concept for their technology lied in the phenomenon of emergence which is common to hives of bees. To solve the problem of Kerbel and Kulyk developed an algorithm based on the communication between bees that allows all pieces of building equipment to simultaneously detect each other, to red flag unnecessary power consumption: the REGEN EnviroGrid Controller.

The EnviroGrid Controller connects to the control box on each piece of equipment to function as a smart power switch. Each device monitors its appliance's energy use every two minutes and broadcasts its reading to all other controllers in the system. Once all activated, they learn the power cycles of each appliance and use a networking standard called ZigBee to communally negotiate the best times to turn equipment on and off. Every node connected to the REGEN "hive" thinks for itself, before making a decision, a node considers the circumstances of other nodes in the network (Terrapin-Bright-Green, n/a-a).

Innovation Claim: Most of REGEN's clients see an overall energy demand reduction of nearly 20%. EnviroGrid Controllers establish a mesh wireless network. The devices effectively use Smart Grid technology as they communicate among themselves autonomously.

Since its start in 2005, REGEN has experienced growth measured in multiples: sales increased by a factor of 8 between 2009 and 2010. After expanding to California and other West Coast markets, the proportion of REGEN installations in the US went from 0% in 2008 to over 67% of the electricity load under REGEN systems management in 2010.

Life's Principles Met: Integrate Development with Growth/Be locally Attuned and Responsive/ Be resource Efficient

11-BIONIC HANDLING ASSISTANT ***by Festo***

Product: Biomechatronic handling assistant/Robotic assistant

Designed/Developed by: Interdisciplinary teams formed by Festo, renowned universities, institutes, and development companies.

Design Problem: Compliance is not a feature of traditional robot assistants. This present danger of injury and/or performance error. For this reason, conventional robots and human workers are typically segregated by safeguards or physical barriers. This product can operate independently or in direct cooperation with humans. Dynamic, fluid movement facilitates human-technology cooperation in diverse settings. The equipment doesn't require extremely advanced components; it consists of elements with wide usage in other applications (Institute, 2011a).

Inspiring Strategy: Elephant trunk perform complex three-dimensional motions

Emulating Form, Process or System: Inspiration by form

- An elephant's trunk is highly dynamic, able to not only move in a variety of directions but also able to do so with immense strength and precision. Despite the lack of skeletal support, the trunk is able to perform antagonistic movements, meaning that while one muscle group contracts an opposing muscle group elongates, thus providing a bending movement. The trunk is made up of structures composed of incompressible "fluid" known as muscular hydrostats that maintains its volume to remain constant through a variety of movements. These muscles are arranged in three (3) patterns and provide versatility to the movement of the trunk.

Design Solution: The arm contains no steel or iron. It is produced using 3D laser sintering, a form of additive manufacturing. The structural material, polyamide, is compliant, yet strong enough to perform manual lifting, and can also perform delicate procedures. The key to such smooth motion is a hydrostatic compartmentalized structure that is flexible, with pneumatic stiffening. In total, this affords for 11 degrees of freedom for movement. The gripping portion of the arm has adaptive fingers that conform to handle variable cargos, from eggs and bandages to wrenches and wires. A robotic controller unit directs patterned motion or responsive action (Institute, 2011a).

Innovation Claim: With eleven degrees of freedom, the Bionic Handling Assistant can be moved freely in all directions. Before now, no other system this flexible has permitted such precise position calculation. Festo used entirely new control algorithms to develop a kinematic model to calculate the exact position of the gripper. Another innovative technology in the biomechatronic arm is the use of reverse transformation to determine the position in global coordinates (Festo, 2012).

Life's Principles Met: Evolve to survive/Integrate development with growth

12-BIOLYTIX BIOPOD WATER FILTER ***by Biolytix Water***

Product: Water filtering system

Designed/Developed by: Dean Cameron

Design Problem: Septic tanks and aerated systems can be large and necessitate great amounts of land (around 26 meters^2) to be excavated to accommodate them, which can be an added burden when a saturated tank needs to be excavated to be replaced. They have anaerobic bacteria which even on a domestic level, often produce considerable greenhouse gas emissions such as methane and hydrogen sulphide. These gases are toxic and foul smelling, and in fact, methane is 21 more times damaging as a greenhouse gas than carbon dioxide. Many aerated systems use a combination of chlorine disinfection and dripline irrigation, which can result in the discharge of toxic chlorination by-products into one's garden, which can be potentially harmful environmentally (Biolytix, 2014).

Inspiring Strategy: Biolytic process/Soil ecosystem supports plant growth through interactions of millions of organisms that work together to break down chemicals and aerate the soil.

Emulating Form, Process or System: Inspiration by system

- From the tundras to the savannas, complex communities thrive in the top soil, the top five (5) to ten (10) centimeters of the soil, where much of the annual flow and exchange of carbon and nutrients takes place. Possibly the most important contributors of such ecosystems are the microflora, the bacteria and fungi that are the most abundant and metabolically versatile organisms in the soil. These organisms specialize in breaking down proteins, carbohydrates, and other complex organic molecules into simpler organic acids, to then mineralize them into inorganic forms such as nitrate which plants can use. Others process slow-rotting natural polymers such as lignin, cellulose, and pectins. Aside of bacteria and fungi, larger and more complex animals such invertebrates accelerate the rate at which speeds the process of decomposition shredding, consuming, digesting and excreting organic debris. They also graze on the present bacteria and fungi assuring the release and recycling of energy and materials tied up in the smallest life forms. The soil ecosystem is composed of three levels of fauna: microfauna (i.e. roundworms), mesofauna (i.e. mites), and macrofauna (earthworms) (Baskin, 1997 as cited in AskNature).

Design Solution: The BioPod is a single, 3000 litre compact polymer tank about ten (10) times smaller than a conventional septic tank at a size of 2.8 meters^2, making it far easier to install. The BioPod is installed, set in the ground, with only the inspection port and a small electrical control box visible. Unlike septic tanks, Biolytix BioPod uses the biolytic process: the highly efficient decomposition of waste by a complex range of soil organisms which in turn is fueled by oxygen, the more oxygen available, the quicker process takes effect (Biolytix, 2014). The system removes wastes from wastewater immediately. Then selected worms, beetles, and microscopic organisms convert the waste into structured humus, which acts as a filter to turn the waste into garden irrigation (Institute, 2011a) or as a huge lung with an estimated 450 kilometers square of the surface area per cubic meter which oxygenates and cleanses the wastewater as it trickles through (Biolytix, 2014). The system requires no chemicals like chlorine and thus produces water that is safe for the environment (Institute, 2011a).

Innovation Claim: The main innovative feature of the BioPod is that where the waste remains a problem in a septic tank, that problem becomes the solution in Biolytix's system. Mechanical wastewater system are water-based and require energy intensive aerators to pump oxygen into the wastewater (which equates to less than 5 parts oxygen per million available). Whereas the BioPod's oxygen rich humus creates the ideal environment for worms and other biolytic organisms to directly draw from the available oxygen in the air (which equates to 210,000 parts oxygen per million available) hence making the biolytic process much more efficient.

One of the main competitive advantages of the BioPod is its much reduced use of electricity. Conventional systems' aerators pump air 12-24 hours per day to provide enough oxygen for the limited range aquatic organisms to break down the waste. The BioPod works without large machinery but rather uses a tiny fish pump to keep the water that has been treated. The work is done silently by up to a million complex organisms per cubic centimeter process the waste (Biolytix, 2014).

Since entering the market, Biolytix's sales have doubled from 2011 to 2013. Biolytix is now venturing into the commercial space for schools, vineyards and camp sites which accounts for 25% of total sales.

Life's Principles Met: Be locally attuned and responsive/Be resource efficient

13-OPTISTRUCT ***by Altair Engineering***

Product: Engineering optimization software

Designed/Developed by: Jeff Brennan/CMO, biomedical & mechanical engineer

James Scapa/CEO, co-founder

Jim Brancheau/CTO, co-founder

Design Problem: CAD and structural analysis programs are based on conventional engineering principles often resulting in parts which are often structurally inefficient because they contain more material than necessary. This results is heavier parts which in transportation for example, is directly related to greater energy and fuel consumption.

Inspiring Strategy: Bone structures are optimized in response to external stimuli to find an optimal structure and microstructure in reaction to stress.

Emulating Form, Process or System: Inspired by process and form

- Wolff's law is the theory that bones in healthy human and animals can adapt to the loads under which it is placed. The bone will remodel itself over time to become stronger to resist that sort of loading (O'Connor 2010).
- Bone remodeling is the result of the coordinated activity of osteoblasts, which form new matrix, and osteoclasts, which resorb bone. Bone remodeling is a temporally and spatially regulated process that results in the coordinated resorption and formation of skeletal tissue (Institute, 2011a).

Design Solution: In the early 1990s, Jeff Brennan (currently Altair CMO) was studying topology optimization at the University of Michigan as part of his graduate work in biomedical engineering researching bone growth patterns and the theory that bones respond directly to external stimuli, also known as Wolff's law. In the spring of 1992, Brennan joined Altair as CTO Jim Brancheau and CEO James Scapa expressed interest in his research to pursue topology optimization as a commercial software. OptiStruct is a CAD modeling and analytics program based on an algorithm mimicking bone growth for structural analysis and optimization for linear and non-linear structural problems under static and dynamic loadings (Bonino, 2014). The program is based on an algorithm replicating how bones respond to external stimuli in order to put down material in response to its environment (external stimuli) or how bones optimize, adding material where needed and remove material where unnecessary. Replicating this process in a modeling program enables to design and build structures that are optimized for weight and strength, more durable and lighter-resulting in vehicles getting better fuel economy (Orf, 2013). OptiStruct helps designers and engineers analyze and optimize structures for their strength, durability and NVH characteristics (noise, vibration and harshness) and rapidly develop innovative, lightweight and structurally efficient designs (Altair, 2014).

Innovation Claim: Optistruct has developed into a disruptive technology for topology optimization of structures. There was much resistance to the program in its beginnings due to the counter-intuitive looks of the program's results, the designs were challenging engineering convention as well as manufacturing processes. However, after adding manufacturing constraint algorithms, such as casting and stamping, 20 years later OptiStruct is now an industry leader. Altair has taken its technology from the car industry to the aerospace industry. The technology may create strange looking shapes that can be unsettling or perceived as wrong but overtime the designs produced by Optistruct are now being labeled as "bionic" and "elegant"(Bonino, 2014).

Optistruct was used by the company Airbus to lighten and remove about 1100 lbs from the A380's rib-wing package, a weight reduction of nearly 40%. The technology is now also finding its way into electronics, where 1 more gram of plastic in more than 1 million devices can have a huge effect (Bonino, 2014). Its advanced optimization algorithm allows users to combine topology, topography, size and shape optimization methods to create better and more alternative design proposals leading to structurally sound and lightweight design which can potentially minimize the cost of travel as lightweight design is the easiest way to minimize fuel consumption and CO2 emissions. The program's potential will be far greater when considering emerging materials and manufacturing processes like additive manufacturing.

Altair now works with more than 3,000 clients including BMW, Honda, Opel, GM, Boeing, Lockheed Martin, NASA and the Department of Defense. The company is equally gaining notoriety in commercial products and architecture. Half of Altair's estimated 2012 revenue of $240 million (up 13% from 2011) came from the auto industry and the company is growing 30% year after year in aerospace and electronics, three times the growth of its steady auto business (Konrad, 2013; Orf, 2013).

Life's Principles Met: Evolve to Survive

14-LAZER SUPERSKIN MOTORCYCLE HELMET ***by Philips Head Protection System***

Product: Motorcycle helmet

Designed/Developed by: Dr. Ken Phillips

Design Problem: Conventional helmets including motorcycle helmets provide good protection from impact injuries via a hard shell comprised of a rigid thermoplastic or fiber plus a cushioning layer approximately 30-40mm thick. These aspects remain vital for head safety and protection against linear brain injury (Institute, 2011a). Conventional head protection systems and safety wear only protect against part of the danger from head impacts and thus only address half of the problem.

Various studies have shown that there's one potential-lethal injury that they conventional helmets don't protect against- rotational injury, also known as intracerebral shearing. When a rider's helmet hits the road, its rigid shell catches against the pavement and causes the helmet to very rapidly twist around. The rider's head twists with the helmet, but does it so quickly that the brain doesn't quite keep up, moving a few milliseconds after the skull it's contained in. The result is the shearing of nerves and blood vessels, resulting in disabilities or even death (Coxworth, 2010).

Inspiring Strategy:

Emulating Form, Process or System: Inspired by forms

- The thick bone of the skull of the skull provides much of the direct protection against a severe blow, the skin on the outside acts as a further protection whenever the head receives an impact.

Design Solution: The Phillips Head Protection System (PHPS) enhances traditional helmet design by adding a specifically designed lubricated high-tech polymer membrane over the outside of the helmet. The membrane is designed to slip in a controlled manner over the inner shell of the helmet thus preventing rotational injury. The PHPS technology is used by Lazer Helmets on their SuperSkin line. Lazer has developed an anti-rotational membrane and a lubricant that imitate the natural movement of the skin over the skull. In the case of the motorcycle helmet, at the point when a helmet hits the road and during the critical milliseconds following the impact, the PHPS membrane essentially forms an additional interface between the helmet and the tarmac. It decreases the friction of the helmet surface by moving and sliding over the hard shell. The rider's head therefore slips and slides over the road surface instead of sharply and immediately twisting around (Lazer, 2012).

Innovation Claim: No other company has ever taken this approach to motorcycle helmet design and protection. This technology significantly reduces the head trauma and the risk of traumatic brain injury. Exhaustive test performed on the first commercial implementation of the PHPS by Lazer Helmets verified that upon head impact the Lazer SuperSkin helmet reduced the risk of intracerebral shearing by 67.5% (Lazer, 2012).

Life's Principles Met: Evolve to survive

15-KALUNDBORG ECO-INDUSTRIAL PARK ***in Kalundborg, Denmark***

Product: Kalundborg industrial park

Designed/Developed by: Municipality of Kalundborg, Industrial Symbiosis Institute, DONG Energy, Gyproc, Novo Nordisk, Novozymes, Statoil, RGS 90, and Kara/Noveren

Design Problem: Companies are often located in industrial parks where their facilities will manufacture any given products. Each industries produce industrial residuals or by-products as a result of their manufacturing process and these by-products are essentially considered as waste by companies as they have no use for that by-product. In addition, they are responsible for the management and safe disposal of these residuals which requires them to spend significant time, energy, and money to collect, organize, and dispose of their waste product.

Inspiring Strategy: Symbiosis/Ecosystems manages poor soil

Emulating Form, Process or System: Inspiration by systems

- Symbiosis means co-existence between diverse organisms in which each may benefit from the other. Various organisms of a given area will usually form a community or eco-system where all benefit from the other by cycling resources within that system: fundamentally a closed loop system. As there is no waste in nature, essentially every resource, every material at some point that is considered as "waste" by one organism will serve as a resource for another.

Design Solution: Industrial symbiosis is part of a new field called industrial ecology which is concerned with the flow of materials and energy through systems at different scales, from products to factories and up to national and global levels as a means to achieve sustainable industrial development (Chertow, 2008). Not long after Kalundborg became a major industrial center, in an effort to minimize the use of the limited ground water, an oil refinery wanted to use surface water from nearby Lake Tisso. The oil refinery financed the project as the city offered to build the pipeline marking the first of many collaborations between the city and industry in the said industrial park. The key motivation behind these partnerships and exchanges was to reduce costs by finding cash-positive applications for waste products (Suarez, 2012). The industrial partners and residents of the city later came to understand the environmental benefits of these partnerships as well; by using the products of another company as a resource, not only reduced the cost of managing and disposing waste but also reduced the need for buying and using virgin resources hence less environmental impact. By the late 1980s, these partners effectively self-organized into what has become the most recognized example of industrial symbiosis. Since, the primary partners in this industrial ecosystem are an oil refinery, a power station, a gypsum board facility, and a pharmaceutical company; they share ground water, surface water, wastewater, steam, fuel and a variety of by-products that become feedstocks in other processes (Chertow, 2008). Excess heat is used for fish farming, heating of nearby homes, and greenhouse agriculture while other by-products not usable within the industrial park, such as sulfur, fly ash, and sludge are sold to companies in the vicinity (Institute, 2011a).

Innovation Claim: Globalization, miniaturization, and resource scarcity will all play roles in the future of industrial symbiosis. As important as resource conservation in western countries, it is dramatically more important in developing countries where resources are already scarce and expansion is large and rapid. Key industrial symbiosis programs have recently begun in Chinese industrial parks with the cooperation of the State Environmental Protection Administration and the National Development and Research Council. The Resource Optimization Initiative of India has found the systems approach of industrial ecology critical to understanding the potential of inter-firm and inter-farm sharing. That industrial symbiosis mitigates some global warming impacts is becoming clearer, emphasizing that cycling of water, energy and materials conserves freshwater, reduces fossil fuel consumption, and eases long distance material transport (Chertow, 2008), in other words, the outcome of such a system is reduced consumption of resources and a significant reduction in environmental strain (Institute, 2011a).

Life's Principles Met: Be resource (material and energy) efficient

Appendix 2_ Design Process of Biomimetic Cases

Design Process/ Disciplines Involved/ Inspiration	PureBond	GreenShield	Ornilux	Aquaporins	WhalePower	InterfaceFLOR	Sharklet	Pax Water	Novomer	REGEN	Festo	Biolytix	OptiStruct	LAZER Helmets	Kalundborg	
Biologist involved	--	--	--	--	--	Y	--	--	--	--	Y	--	--	--	N	***2***
Interdisciplinary team	--	--	--	--	--	Y	--	--	--	--	Y	--	--	--	Y	***3***
Design w/ Biomimicry Thinking process	--	--	--	--	--	Y	--	--	--	N	--	--	N	--	N	***1***
Insp. By form	N	Y	Y	N	Y	Y	Y	Y	N	N	Y	N	Y	Y	N	***9***
Insp. By process	N	N	N	Y	N	N	N	N	Y	N	N	Y	N	N	N	***3***
Insp. By system	N	N	N	N	N	N	N	N	N	Y	N	Y	N	N	Y	3

Appendix 3_ Technological Innovations of Biomimetic Cases

Technological Innovations	PureBond	GreenShield	Ornilux	Aquaporins	WhalePower	InterfaceFLOR	Sharklet	Pax Water	Novomer	REGEN	Festo	Biolytix	OptiStruct	LAZER Helmets	Kalundborg	
Outperforms Traditional Counterparts	**X**	**X**		**X**	**X**		**X**	**X**		**X**	**X**	**X**	**X**	**X**		***11***
Unexpected Results/ Challenged Conventions	**X**				**X**		**X**						**X**			***4***
Uses Hybrid Technology				**X**								**X**				***2***
Uses Nanotechnology		**X**		**X**												***2***
Uses Green Chemistry	**X**	**X**							**X**							***3***

Appendix 4_ Environmental Performance/Impact of Biomimetic Cases

Direct (**D**) -Product is designed for a specific environmental performance/impact

Indirect (**I**) -The environmental performance/impact is a result of the design

Environmental Performance	PureBond	GreenShield	Ornilux	Aquaporins	WhalePower	InterfaceFLOR	Sharklet	Pax Water	Novomer	REGEN	Festo	Biolytix	OptiStruct	LAZER Helmets	Kalundborg	
Manufactured at Room Temperature	**D**	**D**		**D**					**D**							
Reduced Use of Toxic Chemicals	**D**	**D**		**D**		**I**	**I**	**I**	**D**			**D**			**D**	
Reduced Energy Use				**I**	**I**			**D**	**D**	**D**		**D**			**D**	
Reduced Use of Resources/ Materials						**D**							**D**		**D**	
Reduced Waste						**D**						**D**			**D**	
Reduced Impact on Human Health	**I**	**I**				**I**	**I**	**I**				**I**			**I**	