Biomimicry in Iceland: Present Status and Future Significance

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Magister Scientiarum degree in Environment and Natural Resources

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Abstract

The word biomimicry is derived from *bios* = life and *mimesis* = imitation. Biomimicry is a relative new field that studies nature´s designs and mimics them to create sustainable approaches for technical designs and innovation. The founder of biomimicry, the American biologist Janine Benyus, emphasis that answers to many of the environmental challenges we are facing today have already been provided by sustainable solutions that living organisms have developed for over 3.8 billion years. This thesis introduces the principles of biomimicry and its relation to other green and bio-inspired disciplines, followed by analyses of the status of biomimicry in Iceland. Interviews with twenty-two players of Icelandic academia and businesses revealed that the idea behind biomimicry is largely unknown in Iceland and biomimetic examples are relatively rare, but all interviewees agreed on the potential of biomimicry. Ten examples of conceivable biomimicry applications were analyzed in some detail and judged according to biomimicry requirements. The thesis discusses further the current position of biomimicry in Iceland and its future prospects in relation to the outcome of the interviews and the upcoming trends on both sides of the Atlantic Ocean.

Útdráttur

Lífhermun er tiltölulega nýtt hugtak sem byggir á því að tæknihönnun og nýsköpun noti umhverfisvænar aðferðir sem lífverur hafa þróað með sér frá því að líf kviknaði á jörðinni fyrir 3.8 milljörðum ára. Bandaríski líffræðingurinn Janine Benyus skilgreinir meginmarkið lífhermunar þannig að við eigum að tileinka okkur þau margvíslegu form og ferli sem gera lífverum kleift að takast á við síbreytilegar aðstæður. Þannig verði til áhugaverðar, hagnýtar og sjálfbærar lausnir á þeim umhverfisvanda sem mætir okkur í dag. Ritgerð þessi kynnir meginreglur lífhermunar og útskýrir tengsl hennar við aðrar umhverfisvænar stefnur. Viðtöl við tuttugu og tvo íslenska fræðimenn og þátttakendur í fyrirtækjarekstri leiddi í ljós að bakgrunnur lífhermunar er að mestu óþekktur hér á landi og dæmi um lífhermun eru tiltölulega sjaldgæf. Hins vegar voru allir viðmælendur jákvæðir á framtíðarmöguleika lífhermunar fyrir íslenskt atvinnulíf. Í ritgerðinni eru tíu verkefni greind út frá meginreglum lífhermunar. Núverandi staða lífhermunar á Íslandi og framtíðarhorfur hennar eru skoðuð í tengslum við niðurstöður viðtala og í samanburði við þróun á sviði lífhermunar beggja vegna Atlantshafsins.

Preface

I must admit, I too had not heard of biomimicry until about a year before I started to work on this thesis. Still, when looking back, I have been involved in several projects that were inspired by biological processes and biological forms. As a molecular biologist, I spent many years working on drug targeting, aiming at delivering medicine only to diseased cells in the body and thereby preventing side effects in healthy cells. All based on the ability of certain biological molecules to enter animal- and human cells. It is a perfect example of biomimicry and we, who were involved in the project, were always translating our biological observations into something we thought could be useful for medical applications. But when working in such a specific environment, you sometimes loose sight of the bigger picture. It is the view of the broader perspective that I have really enjoyed during the Environment and Natural Resources program.

Personally, working on this thesis, I have really got to admire the vision and determination of Janine Benyus, the founder of biomimicry, who has developed a strong organization around something she is very passionate about. This thesis is the first systemic analysis of biomimicry in Iceland. It probably only scratches the surface of the topic, but I do hope that it will introduce the subject to more people in Iceland and aid in stimulating innovative nature based designs, making use of 3.8 billion years of research and development processes, called evolution.

Table of Contents

List of Figures

List of Tables

Acknowledgements

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1 Introduction

Potential solutions for many of the environmental problems caused by modern human societies can be found in nature. Over 3.8 billion years, or since the first bacteria came about on Earth, organisms and ecological systems have provided answers to various challenges they need to encounter. Studying these bio-systems and understanding how biodegradation and recycling of nutrients take place; how energy consumption is effectively dealt with by various organisms; and how animal and plants have developed diverse forms and surfaces for specific applications, does not only make people appreciate the beauty of these systems, but can also offer powerful tools for sustainable approaches towards long-term prosperity.

A group of scientists, engineers and designers are rapidly embracing the concept of taking nature as an inspiration for their work. A new discipline, biomimicry, describes this field of looking at nature as a *model, mentor and measure* in order to study nature´s best designs and then imitate them to solve human problems. Biomimicry is an innovation, looking to nature as teacher. The methodology of biomimicry comprehends three levels of increasing complexity. Firstly, to mimic the natural forms, materials and structures; secondly to mimic natural processes; and thirdly to mimic ecosystems.

The aim of this thesis is to gain a better understanding of the current status of biomimicry in Iceland and its future perspective. To do so, interviews with active player in academia and businesses in Iceland were carried out. The starting point of the research was that even though the term biomimicry is relatively young and perhaps rather unknown in Iceland, it may seem plausible that academic, industrial, and designing activities are performed in Iceland, which share the ground principles of biomimicry. Ecological buildings are being designed, projects of clean energy utilization are ongoing, and scientific- and industrial clusters formed in order to create interdisciplinary scientific research and efficient industrial processes.

The thesis begins by explaining the principles of biomimicry and showing its relation to other green- and bio-inspired concepts. A brief historical background of biomimicry is given and a list of famous and interesting examples of biomimicry presented. The link of biomimicry to, respectively, biological conservation, biotechnology, and businesses is defined. Next, the methodological approach, comprising of literature research and semi-structured one-to-one interviews with representatives of academia and industry, is explained. The results section begins with a comparison of biomimicy to other green solutions, followed by a description of the outcome of the interviews, which forms the basis for the evaluation of the present status and future prospects of biomimicry in Iceland. From the interviews and literature research, 10 examples of potential biomimicry projects in Iceland emerged, which were examined in relation with the principles of biomimicry. The discussion section interprets the main results of the thesis and summarizes the status and prospects of biomimicry in Iceland, based on the outcome of the interviews and upcoming trends in Europe and USA. The thesis ends by a short concluding remark.

1.1 Research questions

The aim of the thesis is to analyze the context of biomimicry for Icelandic society. The utility of biomimicry for environmental sound performances of economic activities in Iceland is studied based on international references and Icelandic reality.

The objective is to provide answers to the following research questions:

1. What is the current importance *i.e.* the present status of biomimicry for/in Icelandic academia, engineering, design, and business?
2. How can biomimicry benefit the Icelandic society in the future?

2 The scope of biomimicry and related concepts

2.1 What is biomimicry?

The word biomimicry is derived from the Greek *bios* = life and *mimesis* = imitation. Biomimicry is both an old and a new concept, which aims at creating innovative methods for sustainable and nature-based solutions to environmental problems. The concept stimulates interconnections between education and knowledge of nature with technical improvements and modern design developments.

Nature has always been a great inspiration for entrepreneurs and scientists. However, it was not until the end of the twentieth century that biomimicry became an official discipline. The fundamental principles of biomimicry are best put forward in the book: "*Biomimicry: Innovation Inspired by Nature*" by Janine Benyus (1997). The book describes the three pillars of biomimicry. First, biomimicry is a new science that studies nature´s models and how to apply them as an inspiration for designs and processing to solve human problems. Second, biomimicry uses ecological standards developed during the 3.8 billion years that life has existed on the planet to demonstrate what works, what is appropriate, and what lasts. Third, biomimicry is a new way of viewing and valuing nature not based on what we can extract from nature, but what we can learn from it. The relationship between nature and culture acknowledges how humanity depends on healthy ecosystems and biosphere. It encourages designers to move away from the perspective of culture as detached from nature to a participatory view of culture as a component of nature (Wahl, 2006).

The vision of Janine Benyus is to put biologists at the design table together with designers and engineers to teach them about well-adapted designs of living organisms. In biomimetic design it is not the form that matters, it is the function. When designing a curvy building it is because of what that natural shape can do, not about how it looks.

In 1998, Benyus and Dayna Baumeister co-founded Biomimicry Guild, a bio-innovation consultancy bureau and in 2006 they started the Biomimicry Institute, a not-for-profit organization. In 2011 the Guild and Institute were merged into a single identity, Biomimicry 3.8 (http://biomimicry.net; youtube.com/user/Biomimicry38). The mission of Biomimicry 3.8 Institute is "*to naturalize biomimicry in the culture by promoting the transfer of ideas, designs, and strategies from biology to sustainable human design*." (http://biomimicry-static). The organization provides consultancy of nature's sustainable designs to over 250 clients, including Boeing, Nike, General Electric, Herman Miller, Interface, and Proctor & Gamble and trains and certifies biomimicry professionals and specialists. Biomimicry 3.8 is also the home of AskNature.org, a public interactive database on biological literature organized by design and function (www.asknature.org). Benyus has received numerous awards for her work, the most recent ones the 2012 National Design Mind Award from Smithsonian's Cooper-Hewitt, National Design Museum and the 2013 Gothenburg Award for Sustainable Development (www.heinzawards.net).

2.2 Why biomimicry now?

The founders of biomimicry emphasize the urgency of exploring biomimicry today. The increase in human population, intensified agriculture, and growing urbanization cause enormous ecological pressure through pollution, physical alteration of habitats, and overharvesting, which have resulted in extensive demand for resources and worldwide waste problems. At the same time, terrestrial and marine biodiversity is diminishing, largely because of human actions. The rate of species extinction is greater than at any time in the past million years (Primack, 2010, p. 133). It is clear that the "2010 biodiversity target" of the United Nations Millennium Development Goals has not been sufficient to address the pressures on biodiversity. In spite of some local successes, the global diversity of genes, species and ecosystems continues to decline with no significant recent reductions in rate (Butchart et al., 2010). The underlying drivers of biodiversity loss have not been reduced and the integration of biodiversity issues into broader policies, strategies, programs, and actions has been insufficient (www.cbd.int, 2010).

> "*Just as we are beginning to recognize all there is to learn from the natural world, our models are starting to blink out. ... That makes biomimicry more than just a new way of viewing and valuing nature. It's also a race to the rescue*" (Conversation with Janine, taken from http://biomimicry.net).

In the broadest sense, biomimicry concerns itself with the complex processes behind the development of biodiversity losses and is a way to influence people´s attitude towards sustainability. Biomimicry has the potential to contribute to changing the customs of growing food, making materials, harnessing energy, healing, storing information, and conducting business.

2.3 Historical Background

Although biomimicry is a new term, it is not a new practice. Listening to and learning from nature is intertwined with the ancient cultures. African tribes, Native Americans, Australian Aborigines, Inuit people in the Arctic and Yupik people of the Siberian Tundra have all adapted to extreme conditions by learning from the animal behavior and by observing the land and environment for their benefits. The intimate relationship to the land and ecosystems forms a foundation on which traditional ecological knowledge is built. As a matter of survival for the communities this knowledge of nature passes down the generations.

Interaction between humans and nature also plays a significant role in all main world religions. Buddhism and Hinduism express nature as the source of life. According to Buddha, humans are part of nature and therefore would be destroyed if they change or destroy nature. In the Islamic religion, nature and planet Earth belong to God and humans are tasked with their maintenance, while in the Christian-Jewish religion, humans are the master of nature and responsible for its fate (Yachkaschi & Yachkaschi, 2012).

Due to these various cultural and religious roots, bio-inspired design has a rich heritage. The models Leonardo da Vinci (1452 – 1519) created of flying machines and artificial wings based on his analysis of birds can be considered as one of the first known examples of such a bio-inspired design (Ball, 2001). There are also several examples of bio-inspired buildings. Joseph Paxton, a gardener and an architect, is said to have paid tribute to the ribbed stem of a giant lily leaf to provide the support needed for his Crystal Palace building, which housed the Great Exhibition of 1851 (Attenborough, 1995, p. 295). Another examples are the elegant curves of the Eiffel tower that are inspired by bone structure to supports its immense weight (Ball, 2001) and the tree-like columns, spiral forming stairways, and honeycomb windows of the Sagrada Familia that reflect Gaudi´s vision to honor nature (Park, 2005). The architect Michael Pawlyn prefers not to call these examples biomimicry, but biomorphism. In his opinion, the characteristic of biomorphism is to use nature as a source for unconventional forms and for symbolic association. Its lack of functional relevance separates biomorphism from biomimicry" (Pawlyn, 2011, p. 2). With this in mind, the most famous early example of a biomimetic solution, which focuses on the function and not merely on the form, is probably the 1941 invention of the Velcro brand fasteners by the Swiss engineer George de Mestral. He became inspired by the way burrs stuck to his dog´s hair and subsequently discovered under his microscope the miniature hooks on the end of the burr´s spines that enabled the burr to stick strongly to clothing, hair or animal fur. From that, he designed the famous two-part system of Velcro with the scratchy side acting like burrs and the soft side like fur (Steffen, 2006).

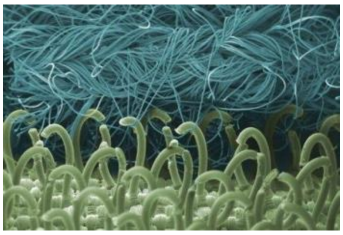

Figure 2.1. Velcro inspiration. Photo was found at http://landarchs.com.

The twentieth century is probably the most innovative century of human history. The period between 1900 and 2000 gave birth to an overwhelming number of scientific and technological inventions and new design that undeniably improved the living standard of people in modern societies. However, simultaneously, the hidden connections linking human activities to ecosystems and the biosphere gradually faded away until they became largely ignored. This, on the other hand, then led to responses against the technocratic approaches and unsustainable management of environmental issues.

Already in the 1930s the self-taught designer and architect Richard Buckminster Fuller proposed that nature´s teaching offered the perfect tool for green design (Steffen, 2006). In the 1940s the author and ecologist Aldo Leopold put forward an environmental ethic preferring a tight relationship between humans and nature in *A Sand County Almanac* (1949) and *Silent Spring* by the biologist Rachel Carson is a typical example of the emerging realization of the extent of environmental threats the world was facing in the early sixties of the twentieth century (Carson, 1962). Carson painted out a landscape in which no bird sang and pointed out how human-made pesticides, particularly DTT, were detrimental to the natural world. Following these and other publications, the idea was emerging among several groups of people that the western human societies were behaving like what ecologists refer to as Type I species, *i.e.* opportunistic pioneers rapidly taking over an area after a disturbance, using more resources than they return without investing in the long-term health of the ecosystem. As Herman Daly pointed out, today humans are a large population in a limited world (Daly, 2003). Following that line of thoughts, humans need to move their strategy away from the pioneering behavior and to start acting more like a mature forest; where few material resources come in, and no waste goes out. A forest economy thrive by deep roots, symbiotic relationships, mutualism, cooperation, and tight feedback loops because there is nowhere else to go and the species need to make the most of the limited pool of resources.

In 1969 the marine biologists John Todd, William McLarney and the writer and editor Nancy Jack Todd founded the New Alchemy Institute in response to what they felt was a technologically addicted society. Their aim was to apply nature's design lessons to the creation of more sustainable human infrastructures, products, and processes (Wahl, 2006). In that same year, the Pennsylvanian professor and landscape architect Ian McHarg promoted new integration of human and natural environments in his book *Design with Nature* (McHarg, 1969). The writings of McHarg and earlier work of Buckminster Fuller, who famously designed the geodesic domes (Baldwin, 1996), have had a major influence on a large group of architects and landscape architects ever since.

In the 1960´s and 70´s the development of ecological design for sustainable solutions to fundamental human needs was strongly driven by pioneers in North America. However, concerns about protecting the environment were felt in other countries as well and in 1972 the UN Convention in Stockholm created fundamental principles for preserving and improving human environment, aiming at international consensus and cooperation between nations (www.un-documents.net, 1972). In 1987 the famous definition of sustainable development: "*Development that meets the need of the present without compromising the ability of future generations to meet their own need*," was put forward in a report by a commission headed by Gro Harlem Brundtland (Our Common Future, 1987). The Brundtland report defines the environment in where we live and the development, *i.e*. everything we do to improve our lot, inseparable. Further emphasis on the relationship between human development and environmental protection was the core issue of the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro 1992 and the World Summit on Sustainable Development (WSSD) in Johannesburg 2002 with the recent follow-up in Rio de Janeiro 2012 (Rio 20+, United Nations Conference on Sustainable Development).

It is in light of all this development that the biologist Janine Benyus published her book about biomimicry in 1997. However, it is clear that the fundaments for the philosophy of biomimicry originate more from the grass root movements of the 60´s and 70´s, less from international treaties and declarations.

2.4 Other green and bio-inspired solutions

Many movements for green solutions have emerged parallel to biomimicry. These include ecological engineering and ecological design, green chemistry and green engineering, and the concept of cradle to cradle. These schools of thoughts have in common with biomimicry the wish to converge technology with life, utilize natural processes, prevent depletion of natural resources, and contribute to environmental solutions. They are not merely about restricting consumption and adopt a hands-off approach to nature as earlier biocentric environmentalists had demanded, instead, they all aim to integrate socioeconomic processes with ecological processes and move alongside the principles of sustainable development (Mathews, 2011). On the other hand, movements like bionics have focused on bio-inspired solutions, with less emphasis on sustainability. Here below, a short description of these movements is given.

2.4.1 Ecological engineering and ecological design

Ecological engineering has been defined as the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both (Mitsch & Jørgensen, 2003). One of the core principles of ecological engineering is to recognize that humanity is inseparable from and dependent on natural systems.

The term ecological engineering was used in 1957 by Howard Odum to describe conscious use of ecosystem self design (Odum & Odum, 2003). Restoration of the landscape goes back to Aldo Leopold in the 1940s. Ecological engineering and ecological design further roots in the work of pioneers like Jack Todd and his coworkers in the 1960s (Todd et al., 2003). Ecological engineering takes advantage of the ecosystems as natural resources, combining outputs from the economy to generate value. Ecological engineering embraces the view that a growing human population and -consumption have already disturbed global ecosystems (Bergen et al., 2001). The goals of ecological engineering include the restoration of these ecosystems. However, environmental problems cannot be solved through solely technological means (Odum & Odum, 2003). Ecological engineering should result in the development of sustainable ecosystems with both human and ecological values (Mitsch, 2012) and the wisdom of ecosystems must be applied to redesign human support technologies (Todd et al., 2003).

The main idea of ecological engineering and ecological design has been to establish a new engineering discipline with ecological science as its basis. The discipline is based on (1) the self-designing capacity of ecosystems; (2) systematic testing of ecological theories; (3) system approaches, which includes to think of the ecosystem as a whole, instead of linear relationship between cause and effects; (4) conservation of non-renewable energy sources; and (5) biological conservation, primarily build on increased recognition of ecosystem values, both economic and intrinsic values (Mitsch, 2012; Mitsch & Jørgensen, 2003).

In the past couple of decennia there has been a rapidly increasing development in the principles and practices of ecological engineering. The international journal *Ecological Engineering* has been published since 1992 and has been important platform for studies in the field (Barot et al., 2012). This journal is meant to serve as a bridge between ecologists and engineers and to attract those that are involved in designing, monitoring, or constructing ecosystems. By 1993 the International Ecological Engineering Society (IEES) was formed. In 2004 two ecological engineering textbooks were published (Kangas, 2004; Mitsch & Jørgensen, 2004) and soon after ecological engineering programs started to develop in several universities in the USA. As today, academic programs in ecological engineering are provided worldwide and ecological design has become an important discipline within (landscape) architecture and planning. The number of private firms specializing in sustainable restoration and rehabilitation of land, rivers, lakes, forest, grasslands, and wetlands is growing. However, the integration of ecology and engineering is not always a symbiotic process and the present limitations still concern the lack of acceptance of this field by tradition-bound disciplines of engineering (Mitsch, 2012).

From the literature it seems that the movement of ecological engineering has reached to a crossroad. The initial enthusiasm of independent thinkers has now to evolve into a collective movement with clearly defined goals and practical solutions. In a recent editorial Clive Jones pointed out several ethical, relational and intellectual challenges that the broad concept of ecological engineering is facing (Jones, 2012). Jones discusses the ethical position of ecological engineering in the center between the anthropocentric and ecocentric extremes, making it open to various interpretations of different stakeholders. He stresses that clear articulation of ethics is needed to prevent confusion and non-acceptance. Ecological engineering must take position towards difficult questions on social issues such as population growth, economic growth and poverty. Within the relational challenge Jones accentuates the significance of bringing together practitioners, policy makers and scientists from many fields, such as ecological, chemical, engineering, social and economical sciences. Otherwise, he points out, ecological engineering will lack the necessary support from both the academic and the economic world. Interaction is also necessary with other green initiatives aiming at sustainability. In the words of Jones: "*We need to reconfigure the connections between science, technology and practice; not just boost information flow*" (Jones, 2012, p. 81).

2.4.2 Green chemistry and green engineering

Green chemistry has been defined as the design of safer chemical products and processes that reduce or eliminate the use and generation of hazardous substances (Anastas & Kirchhoff, 2002), while green engineering is more broadly defined as a discipline on how to achieve sustainability through science and technology (Anastas & Zimmerman, 2003). There is a strong connection between green chemistry and green engineering, as the prior can be seen as an integral part of the latter (Kirchhoff, 2003). Both green chemistry and green engineering provide a framework of 12 principles (Table 2.1) for the design of new materials, products, processes, and systems (Anastas & Warner, 1998; Anastas & Zimmerman, 2003). These frameworks aim to consider environmental, economic, and social aspects. The best approach for maximizing efficiency, minimizing waste and increasing profitability is to combine green chemistry and green engineering at the earliest design stages.

Around 1980, the worldwide chemical industry was faced with a poor environmental reputation. Huge chemical disasters, such as the 1978 Love Canal incident in Niagara Falls, New York and the enormous gas leak in Bhopal, India in 1984 played a huge role in this (Sanderson, 2011). The discovery of buried toxic waste in the Love Cannel incident forced the abandonment of an entire neighborhood (Fletcher, 2002). At a Union Carbide pesticide plant in Bhopal thousands of people died within days and hundreds of thousands were injured by a toxic gas leak. Many of those affected by the gas leak live with chronic illnesses (Sharma, 2002). These and other accidents resulted in more stringent environmental regulations that needed to be met by the chemical industry. Hence companies started to move towards "green chemistry", a term introduced in 1991 by Paul Anastas. The movement of green chemistry is about redesigning chemical processes from the beginning, making them safer, cleaner and more energy-efficient (Sanderson, 2011).

Green chemistry has been applied both in the chemical and the pharmaceutical industry. A green route has been developed for the synthesis of the important industrial solvent ethyl acetate from alcohol, omitting acetic acid (Garcia-Serna et al., 2007). The ibuprofen production is an example within the pharmaceutical industry. A green synthesis method that uses only three steps, instead of six in the traditional process, and lessens greatly the need for disposal and mediation of waste products was put into practice in 1992 (Cann & Connelly, 2000). Typically, it is the pharmaceutical sector that has welcomed green chemistry with most interest, perhaps because there is plenty of room to increase efficiency — and cut costs. Pharmaceutical plants create on average 25 to 100 kilograms of waste per kilogram of product (Sanderson, 2011).

In the USA the industrial-wide move towards greener chemistry has led to a significant reduction in the output of hazardous waste, from 278 million tons in 1991 to 35 million tons in 2009 (Sanderson, 2011). However, some observers claim that the process of green chemistry is still too slow. It focuses too much only on incremental improvements in existing processes and suffers from a trade-off among benefits, feasibility and costs. Possibly, the greatest barrier to a broader adoption of green chemistry is that chemists do not get acquainted to engineering, product design, or life-cycle analysis during their training period. The same observers state that the real 'green revolution', in the form of processes redesigned

Table 2.1. The 12 principles of Green Chemistry and Green Engineering (Garcia-Serna et al., 2007).

Principles	Green Chemistry	Green Engineering
1	Better to prevent waste than to treat or clean up waste after it has been created.	Designers need to strive to ensure that all material and energy inputs and outputs are as inherently nonhazardous as possible.
2	Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.	It is better to prevent waste than to treat or clean up waste after it is formed.
3	Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment	Separation and purification operations should be designed to minimize energy consumption and materials use.
4	Chemical products should be designed to effect their desired function while minimizing their toxicity.	Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.
5	The use of solvents, separation agents, etc. should be made unnecessary wherever possible and innocuous when used.	Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.
6	Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.	Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.
7	A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.	Targeted durability, not immortality, should be a design goal.
8	Unnecessary derivatization (use of blocking groups, protection/deprotection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.	Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.
9	Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.	Material diversity in multicomponent products should be minimized to promote disassembly and value retention.
10	Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment	Design of products, processes, and systems must include integration and inter-connectivity with available energy and materials flows.
11	Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.	Products, processes, and systems should be designed for performance in a commercial "afterlife".
12	Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.	Material and energy inputs should be renewable rather than depleting

from scratch and plants rebuilt from the ground up, has only just begun (Sanderson, 2011).

García-Sterna et al. (2007) classified the 12 principles of green engineering (Table 2.1) into six main areas, *i.e*. design (principle 1), prevention (principle 2), energy use (principles 3, 4 and 10), production system (principles 5 and 8), raw materials (principles 6, 9 and 12), and product use (principles 7 and 11). The importance of the width of the applicability of these principles is stressed by Anastas & Zimmerman (2003). Whether it is the molecular architecture of chemical compounds, product architecture for an automobile or urban architecture to build a city—the same green engineering principles can by applied. The principles should not been seen as a list of goals but as a set of methodologies that need to be integrated to realize genuine sustainability of a particular design. In comparison to the Cradle to Cradle system, discussed next, which concentrates on *what* one should do to reach sustainable design, the 12 principle of green engineering tells one *how* to perform. The practical approach of green engineering builds on technical excellence and systems thinking in which the engineers need to contextually understand when to balance one principle, or a collection of principle with another (McDonough et al., 2003).

2.4.3 Cradle to cradle

The concept of Cradle to Cradle (C2C) was presented by the German chemist Michael Braungart and the American architect William McDonough in their book *Cradle to Cradle, Remaking the Way We Make Things* (Braungart & McDonough, 2002). The term refers to the life cycle of a product, which should not end at the grave, but should circle back to a cradle of a new product life cycle. The authors started a C2C certification program in 2005 through their company McDonough Braungart Design Chemistry (www.mbdc.com). The three precepts of C2C are:

1. Waste equals food
2. Use current solar income
3. Respect and celebrate biodiversity

Products and processes must be designed from the very beginning, based on the understanding that waste does not exist, similar to the natural output of one organism that is used as a valuable input for other organism. Solar energy and passive solar processes, should be accumulated into C2C systems. Example is to letting daylight penetrate into indoor space. Similarly, wind power and other renewable energy sources should be captured. Natural systems thrive on diversity, each of which has developed a unique response to its surroundings. The diversity provides many models for humans to imitate. Optimal C2C design solutions draw information from and fit within local natural system and furthermore express an understanding of ecological relationships (McDonough et al., 2003).

Reducing, reusing, and recycling are not sufficient according to the C2C philosophy, as reducing the amount of dangerous toxins does not necessarily prevent toxic effects to be present. Similarly, reusing wastes can mean that waste is only transferred to another place, sometimes even to countries with weaker infrastructures and less stringent environmental policies. Composting can present problems if the materials are not specifically designed to ultimately become safe food for nature. The problem about most recycling, Braungart and McDonough say, is that it is actually down-cycling the product, resulting in a weaker and less useful products. The focus of C2C is rather to design output to nourish and support biological systems, while also satisfying the wants of consumers. The key to C2C design philosophy is the elimination of waste, or conversion of waste into resource (Mathews, 2011). In the second chapter of their book, the founders of C2C describe *Why being "less bad" is not good enough* (Braungart & McDonough, 2002). Here they question the term "efficiency," which does not have independent value. Instead, efficiency depends on the value of the system of which it belongs to. Efficiency may make destruction even more harmful. A world dominated by efficiency serves only narrow and practical purposes, while excluding beauty, creativity, fantasy, enjoyment, and inspiration. It is a world without delight, it is not much fun.

The C2C strategy has been integrated into several designs. Already in 1993, the Swiss firm Rohner and the US-based company DesignTex developed a textile that could be assimilated with natural systems without any toxicological concerns (Kaelin, 2001). All chemicals containing any form of mutagen, carcinogen, heavy metal, endocrine disrupter, or bioaccumulative substance were eliminated from consideration, identifying 38 suitable chemicals for a material designed to be a biological nutrient and capable of producing textile with all necessary quality standards. In 1999, Shaw Industries presented a fully recyclable PVC-free carpet with a revolutionary new backing material called EcoWorx, (Segars et al., 2003). The design of this award winning product represents life cycle considerations of a C2C product strategy that puts technical nutrient recovered materials into repeated use (McDonough et al., 2003). Yet another C2C project is the restoration of the Ford Motor Company's historic manufacturing complex in Michigan (Litt, 2004), representing a 4,000 hectares assembly plant with a vegetation-covered roof that filters storm water run-off for $35 million less than the typical storm water management systems would do (McDonough et al., 2003). Furthermore, Ford presented in 2003 the concept car Model U, introducing the use of C2C materials as well as other material with low environmental impact (www.mbdc.com).

2.4.4 Bionics

The American engineer Jack E. Steele is commonly referred to as "the father of bionics". In his original definition, bionics means the use of biological prototypes for the design of man-made synthetic systems (Papanek, 1971, p. 188). However, many explain the term bionics as a portmanteau from *bio*logy and electro*nics*. Sometimes bionics is also called biomimetics and occasionally is used as a synonym for biomimicry (Vincent et al., 2006). Both bionics and biomimicry draw inspiration and innovation from nature. However, to discriminate bionics from biomimicry, it is fair to say that Benuys´ biomimicry method integrates sustainable design solutions, while the former term does not.

Applications of bionics are mainly in the automation technology and health care and represent for instance building robots and prosthetics. An example is the company Festo (www.festo.com) that in cooperation with various universities and institutes provides advanced technology and industrial applications based on principles from nature such as the ExoHand. It is an assistance system for industrial production, based on human hand movements (FestoHC, on YouTube). Another project by Festo is SmartBird, where engineers and scientists take inspiration from herring gull to decipher bird flight (Fischer, 2011).

2.4.5 Bioutilization and biophilia

There are two more terms that have association to biomimicry. Bioutilization refers to the direct use of nature for beneficial purposes. An example is to incorporate planting in and around building to produce evaporate cooling, as can be used for instance in ecological building systems (Pawlyn, 2011). According to Pawlyn, this approach does play an important role in biomimetic systems thinking (Pawlyn, Ch 3). However, Janine Benyus emphasizes the difference between bioutilization and biomimicry. According to her, the former entails harvesting a product or producer, such as cutting wood for floors or wildcrafting medicinal plants, while biomimicry is based not on what we can extract from organisms and their ecosystems, but on what we can learn from them. Benyus also points out the difference between biomimicry and bio-assisted technologies, which engage domesticating an organism to accomplish a function, *e.g.*, bacterial purification of water or cows bred to produce milk.

> *"Instead of harvesting or domesticating, biomimics consult organisms; they are inspired by an idea, be it a physical blueprint, a process step in a chemical reaction, or an ecosystem principle such as nutrient cycling. Borrowing an idea is like copying a picture - the original image can remain to inspire others."* (www.biomimicryinstitute.org).

Another interesting term is biophilia, which was proposed by the biologist E. O. Wilson in 1984 and refers to a hypothesis that there is an instinctive bond between human beings and other living organisms (Wilson, 1984). Biophilia has become an important concept in landscape architecture, aiming at providing nature in cities and preserve wilderness for public use (Ulrich, 1993, p. 81). The difference between biophilia and biomimicry is in the words of Benyus that although biophilic design recognizes that reminders of nature contribute to our well being, enhancing both productivity and creativity:

> *"[A] picture of spiral grain painted on a building column that reminds you of a tree trunk is biophilic design. But if you actually twist the column's material like a tree trunk to make it lighter but just as strong, that's biomimicry."* (Malone, 2011)

2.5 Biomimicry - principles and practice

2.5.1 Life´s principles

One of the many definitions of biomimicry is that it imitates natural forms, processes, and ecosystems to create more sustainable designs. The core idea is that solutions of many of the problems we are facing in the field of energy, food production, climate control, chemistry, and transportation have already been solved by nature. Schematically, biomimicry can be depicted as a circle with interactions between biology, technology, design, nature, innovation, and life (Fig. 2.2).

The principles underlying biomimicry have recently been re-defined by Benyus and coworkers (http://biomimicry.net). These are divided into "Deep-principles" and "Life´s principles". The deep principles are patterns that are shared by several organisms and emerge when scientifically studying how nature works. An illustration are the mechanism that are used by several plants and animals to control the movement of a liquid capillary action on the surface and are based on the physical property of surface tension. The typical example of this is the high water repellence exhibited by the leaves of the lotus flower.

Life´s principles are even more common across species and are found uniformly across almost all organisms. These principles are used to drive and evaluate sustainability and appropriateness of biomimicry designs. They are categorized into six groups and each group into three to four principles as shown in Fig. 2.3.

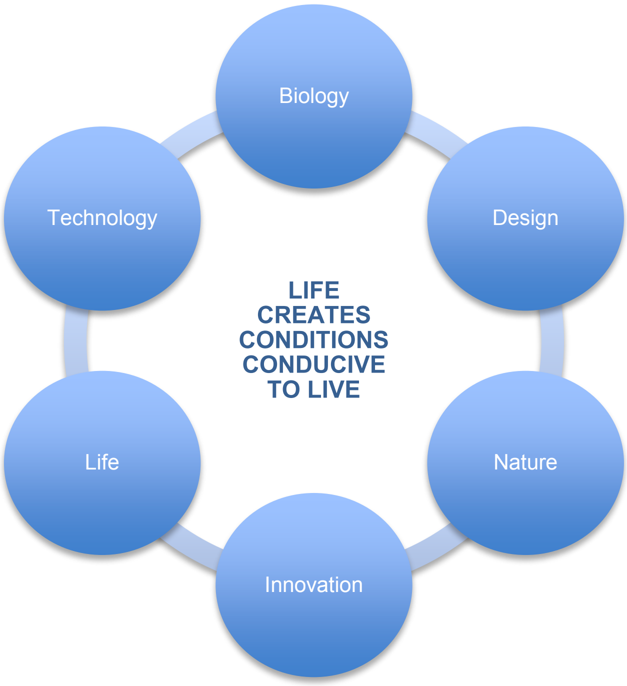

Figure 2.2. Schematic representation of biomimicry. Modified from Biomimicry DesignLens, retrieved from www.biomimicry.net.

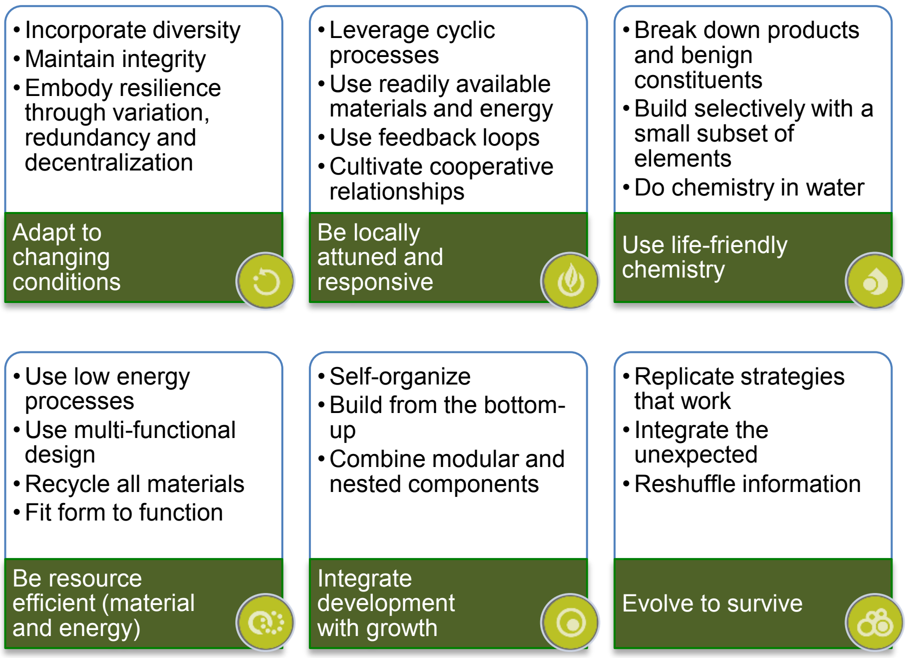

Figure 2.3. Life´s Principles. Appropriateness and sustainability of biomimicry designs are driven and evaluated according to these principles. Modified from Biomimicry DesignLens, retrieved from www.biomimicry.net.

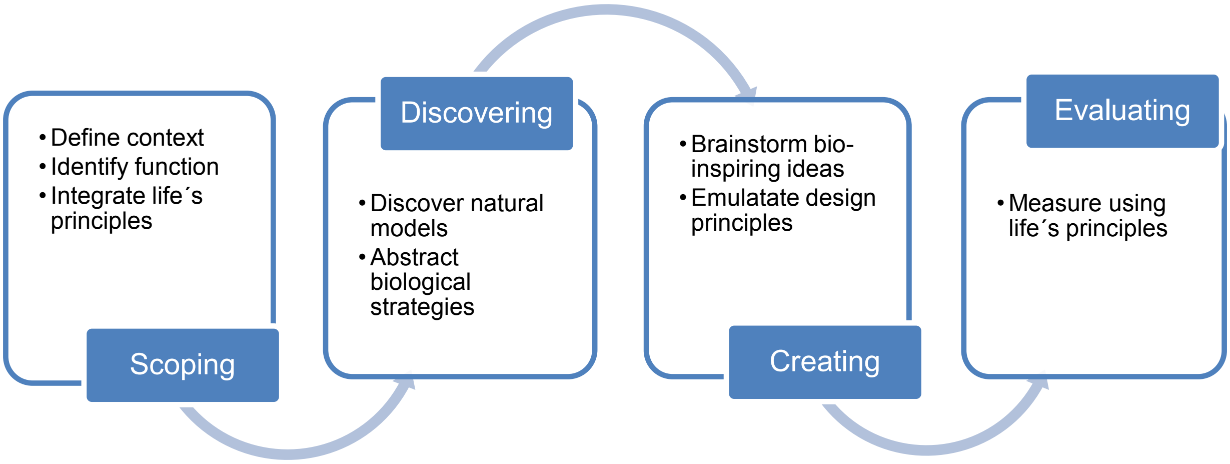

Figure 2.4. Biomimicry Thinking. The steps within the areas Scoping – Discovering – Creating – Evaluating can ben repeated as long as necessary to create biomimetic design. Modified from Biomimicry DesignLens, retrieved from www.biomimicry.net.

Further, to provide a context to where, how, what, and why biomimicry fits into the process of designing, Benyus and her partners have published the "Biomimicry Thinking" (http://biomimicry.net). This framework is intended to aid people to practice biomimicry. It includes four important areas the design process must cover, independent of the discipline in which it is integrated: Scoping, discovering, creating, and evaluating (Fig. 2.4). Each area contains specific steps to follow, which should lead to effective integration of life´s strategies into human design. The guidance reflects new discoveries in science and applications and continues to evolve, according to the webpage http://biomimicry.net.

2.5.2 Direct & indirect biomimicry - Shallow & deep biomimicry

Some scholars prefer to talk about biomimicry in the terms of direct and indirect biomimicry (Faludi, 2005). The direct biomimicry method is when one observes how a particular organism or natural process deals with a particular problem and translates that into a manufactured solution; the designer or engineer can point to an organism or process and say "it´s like that". On the other hand, when applying indirect biomimicry one has to extract general principles when designing. These principles can include:

- Nature makes gradual transitions in structures rather than sharp corners.
- Nature makes things out of few components that vary internally. Instead, we make things out of many homogeneous components
- Nature designs for strength and toughness, while we design for stiffness.
- Nature often uses diffusion, surface tension, and laminar flow, whereas we often use gravity, thermal conductivity, and turbulence.

Another manner to explain biomimicry is to discriminate between shallow and deeper biomimicry. Benyus describes three levels of biomimicry (Conversation with Janine, taken from http://biomimicry.net) The first level is the mimicking of natural form. This is just the beginning of true biomimicry and the design does not per definition give a sustainable output. An example is to mimic the frayed edges of owl´s feathers that are responsible for the silent flight of the owl. Deeper biomimicry adds a second layer, which is the mimicking of the natural process, *i.e*. how the product is made. This for instance excludes the use of high-pressure or toxic chemicals, and touches upon the principles of green chemistry. To go back to the example of the owl feather, its natural chemistry involves self-assembly at body temperature in the absence of toxins and high pressures; copying the feather also requires mimicking this natural process. The third level concerns mimicking of natural ecosystems. In here, the bio-inspired product must be fabricated as a part of sustainable surrounding, like the owl feather that in the words of Benyus is "*part of an owl, that is part of a forest that is part of a biome that is part of a sustaining biosphere*" (Conversation with Janine, taken from http://biomimicry.net). Similarly, the bio-inspired product, created according to deep biomimicry, must be a part of a larger economy aiming at restoring rather than depleting the earth. The final product should be designed, transported, sold, and reabsorbed so it cherishes a "forest-like" economy intending at creating life-contributing conditions. According to Benyus, with deep biomimicry we are mimicking what all well-adapted organisms have learned to do.

2.5.3 Examples of biomimicry

Examples of biomimetic applications are growing rapidly. Applications vary greatly, from the scale of nanotechnology and biomedical research to everyday practices and landscape architecture. Currently, the extended database of AskNature.org contains more than 2100 nature-inspired technological innovations and ideas and different lists of favorite bio-inspired innovations can be found in the literature and on the Internet. An illustration is the annual Top 10 list of biomimetic inventions, published on www.greenbiz.com by Tom McKeag since 2010 (McKeag, 2010, 2011, 2012, 2013b). Here below several, but by no means a comprehensive list of biomimetic applications are given, categorized into 12 groups. Many of these examples are presented on the homepage of Biomimicry 3.8 (http://biomimicry.net):

1. **Energy: Learning from humpback whales how to create efficient wind power.**
   The flippers of the humpback whale (*Megaptera novaeangliae*) have large, irregular looking bumps called tubercules across their leading edges, allowing these big animals to swim in tight circles to produce nets of bubbles only 1.5 meters across, which enclose their prey (Fig. 2.5). Inspired by the flippers of humpback whales, turbine blades with bumps have been shown in wind tunnel test to have 32% less drag and an 8% increased lift in their movement through air and water, as well as providing 20% increase in efficiency compared to smooth surface fins (www.whalepower.com).

Figure 2.5. Biomimicry example: Energy. Photos were found at http://bimimicry.net.

2. **Tidal power system: learning from highly efficient propulsion of thunniform swimming species such as tuna, shark, and mackerel**.
   Tunas, like sharks and mackerels, are extremely designed for aquatic locomotion in terms of their specialized anatomy and physiology. The Australian firm Biopower mimicked the shape and motion of these species to develop the so-called bioSTREAM system to extract renewable energy from moving water (www.biopowersystems.com). The bioSTREAMsystem is a fixed device in a moving stream. An onboard computer

continually adjusts the angle of the hydrofoil (fin) relative to the oncoming flow. This allows for a combination of high conversion efficiency and ability to continuously align with the current direction (Fig. 2.6).

Figure 2.6. Biomimicry example: Tidal power system. Left hand photo was found at http://article.wn.com , right hand photo at www.nextnature.net.

3. **Human Safety: Learning from dolphins how to warn people about tsunamis.**
   Dolphins have developed remarkable acoustic production and reception systems by producing both narrowband whistles and broadband echolocation pulses that they use to investigate the environment and to communicate (Harley, 2008). EvoLogics has developed technology (Fig. 2.7) that mimics the dolphin sound pattern and that is able to warn people long before tsunami waves reach land (www.evologics.de). This technology is currently employed in the tsunami early warning system throughout the Indian Ocean as well as in autonomous research and measurement submarines and oceanographic measurement stations (Bullinger, 2009, p. 183).

Figure 2.7. Biomimcry example: Human safety. Left hand photo was found at http://ignite.me, right hand photo at http://subseaworldnews.com.

4. **Industrial Design: Learning from trees and bones how to optimize strength and materials.**
   Trees build firm material only where needed. In other words, trees add wood only to the points of their structure that obtain the greatest mechanical load. The German physicist Claus Mattheck has created a design-software, called Soft Kill Option (SKO), which reflects these efficient ways to distribute strength and loads (Baumgartner et al., 1991; Mattheck, 1998). In animals the efficiency of this process is even greater. Obviously, it becomes enormously advantageous to reduce the amount of material used because many animals need to move quickly around. In human bones for instance, specialized cells have the function to remove unnecessary material. This results in a porous light-weighted bone structure (Fig. 2.8). Based on SKO, the car companies DaimlerChrysler and Opel have designed light and stable engine mount and car bodies that are as crash safe as conventional cars, yet up to 30% lighter (www.asknature.org). The DaimlerChrysler car was furthermore based on the streamlined shape of the tropical boxfish (*Ostracion*

cubicus). This resulted in a superb aerodynamic, 20% lower fuel consumption and up to 80% lower nitrogen oxide emissions, compared with similar series-production cars. The SKO principle has also been applied in the so-called “Bone furniture line” by the Dutch artist Joris Laarman (www.dexigner.com; www.jorislaarman.com) (Fig. 2.8).

Figure 2.8. Biomimicry example: Industrial design. Upper left hand photo was found at www.angeloaktree.org, photos of auto skeleton and bone furniture line were found at http://ungroundedarchitecture.blogspot.com, and photos of tropical boxfish and DaimlerChrysler concept car were found at www.asknature.org.

5. **Strength: Learning from spider silk and mussel´s glue.**
   Spiders have the ability to manufacture silk; a material that is strong, fine, and tough. Weight-for-weight, silk is stronger than steel, finer than human hair, more resilient than any synthetic fiber, and completely biodegradable. Theoretically, spider silk is a perfect model polymer for high performance biomimetic fibers. The only problem is that people have not managed to produce silk as effectively as the spider does. Recently, Ingi Agnarsson and his coworkers of the Puerto Rico University discovered a spider that constructs a giant orb web (Fig. 2.9) with anchor threads as long as 25 meters (Kuntner & Agnarsson, 2010). This silk the toughest silk in ever described silk and over 10 times better than Kevlar®, the toughest synthetic material available (Agnarsson et al., 2010).

   Blue mussels attach themselves tightly to rocks in the turbulent intertidal zone with a fibrous appendage called the byssus. Remarkably, the mussel is able to produce this strong adhesive underwater, at ambient temperatures, and with no toxic byproducts (Fig. 2.9). Researchers have developed non-toxic, formaldehyde-free wood glue that is now used in hardwood, plywood, and particleboard projects by mimicking how blue mussels attach firmly under the water using flexible, thread-like tentacles (Vierra, 2011). This was not done by using the marine adhesive protein itself, because it is difficult and costly to produce, but by adding the chemical groups responsible for the adhesive properties to a more abundant and cheaper soy beans protein (Liu, 2005).

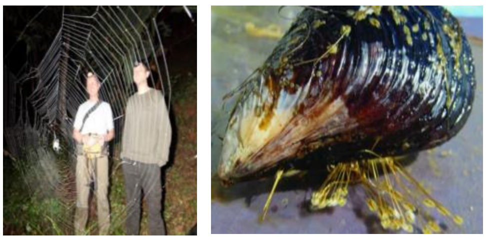

Figure 2.9. Biomimicry example: Strength. Photo of the largest spider in the world was found at http://factspy.net and photo of the mussel with fibrous appendage (byssus) was found at www.robaid.com.

6. **Protection: Learning from woodpecker and sea snail.**
   A woodpecker is known to drum the hard woody surface of a tree at drumming rates of 18 to 22 times per second with a deceleration of 1200 g, yet with no sign of blackout or brain damage. Still, the drumming sessions may be repeated 500-600 times per day (Yoon & Park, 2011). The woodpecker´s ability to withstand the repeated heavy impact, thanks to the unique corrugated cartilage structure that separates the bird´s beak from skull, was an inspiration for a bicycle helmet, called Kranium that was constructed from cardboard (Fig. 2.10). The Kranium helmet contains honeycomb cells in its structure that trap air and act as a compression membrane, similar to the cartilage structure. It is 15% lighter than standard helmets, while absorbing 3 times more energy during collision.

   Another animal that is a focus for biomimicry investigation is the scaly-foot snail (*Crysomallon squamiferum*) because of its extremely strong iron-plated shell (Yao et al., 2010). The snail lives in a relatively harsh environment on the floor of the Indian Ocean, near hydrothermal vents that emit hot water, exposed to fluctuations in temperature as well as high acidity, and facing attack from predators such as crabs and other snail species (Waren et al., 2003). The strong three-layered shell allows the snail to defend itself. Scientist at the MIT in Boston aim to mimic the snail´s unique stability and penetration resistance for improved biologically inspired structural materials, for example soldier and military vehicle armor applications (Trafton, 2010) (Fig. 2.10).

Figure 2.10. Biomimicry example: Protection. Photos of the spider and helmets were found at www.inhabitat.com(a), photo of the snail at www.asknature.org and photo of soldier armor www.thenakedscientists.com.

7. **Robots that stick, run and jump: Learning from insects.**
   There are many examples that the supreme ability of insects to traverse miscellaneous terrain and climb vertical surfaces has inspired the imagination of robot developers (Fig. 2.11). Geckos climb rapidly up smooth walls and walk on ceilings. They do so by dry adhesive mechanisms (Autumn et al., 2000). Inspired by the gecko, scientists at Stanford University have designed Stickybot, a robot useful for inspection, surveillance, and disaster relief applications (Kim et al., 2008; Quick, 2010). At least two robots, DynoClimber that scuttles up walls, and VelociRoACH that scrambles across varying terrain and over obstacles at high speed, are inspired by the cockroach (Haldane & Fearing, 2013; Lynch et al., 2012). The jumping mechanism of the grasshopper represent a model for Jollbot, a jumping robot with potential of exploring rough terrain (Seaman, 2009).

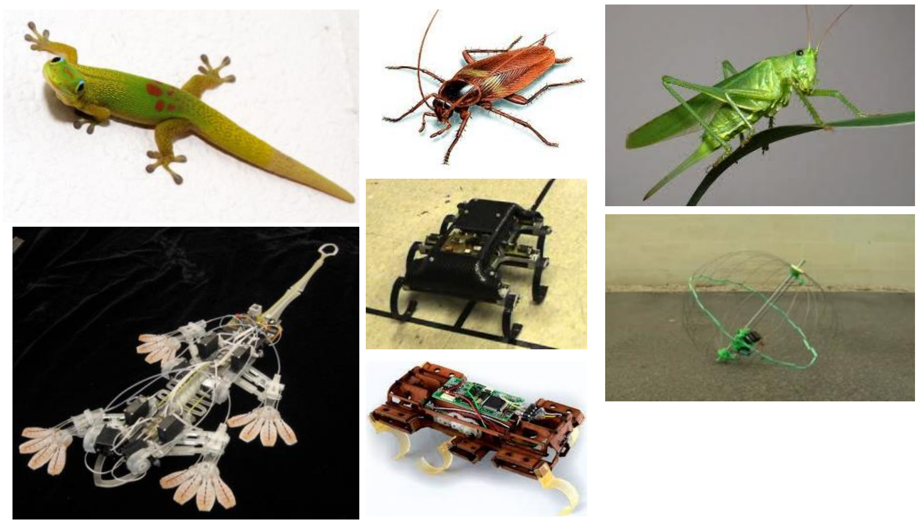

Figure 2.11. Biomimicry example: Robots. Photos of Gecko was found at http://eartheasy.com, photo of Stickybot at www.designboom.com, photo of cockroach at http://www.orkin.com, photo of DynoClimber at www.youtube.com, photo of VelociRoACH at http://inhabitat.com(b), photo of grasshopper at www.seamstressfortheband.org, and photo of Jollbot at http://technabob.com.

8. Natural Cleansing: Learning from lotus plants how to clean without cleaners.
Lotus plants (*Nelumbo nucifera*) live in typically muddy aqueous habitats, yet stay dirt-free without using detergents. This is accomplished through the micro-topography of their leaf surfaces, making the plant extremely water repellent (super-hydrophobic). Dirt particles on the leaf's surface stick to water droplets on the leaf and when the water droplets roll off the attached dirt particles are removed with them, cleaning the leaf without using detergent (Fig. 2.12). Surface finishes inspired by the self-cleaning mechanism of lotus plants and other organisms, including many large-winged insects, have been applied in *i.e.* self-coating paint (Lotusan®) (www.stocorp.com) and clay-roof (Erlus Lotus® clay roof) (www.erlus.com), reducing the need for chemical detergents and costly labor.

Figure 2.12 Biomimicry example: Natural cleansing. Photo of a lotus leave with water droplets was found at www.sto.be, photo of a surface coated with Lotusan, offering a water- and dirt repellent microstructures similar to a lotus leaf was found at http://transmaterial.net.

9. Structures to prevent adhesion of micoorganisms: learning from sharkskin.
Sharkskins contain denticles that are arranged in a distinct diamond pattern with tiny riblets (Fig. 2.13). This roughened nano-texture reduces the available surface area for marine organisms to adhere ("foul"). Applications that mimic these structures are found in the healthcare sector, including medical devices and surface coverings that prevent growth of human pathogens (www.sharklet.com). Interestingly, it is structure, not chemistry that repels the pathogens.

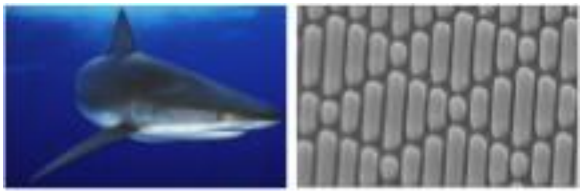

Figure 2.13. Biomimicry example: Structures that prevent adhesion. Mimimicking the microbe-resistant properties of a sharkskin results in a medical device with surface comprised of millions of tine diamonds arranged in a distinct pattern that inhibit bacterial contamination. Photos were found at http://science.howstuffworks.com.

10. Transportation. Learning efficiency from kingfishers.

The kingfishers are known for their spectacular diving skills. They barely make a splash as they plunge into water to catch small fish (Fig. 2.14). The reason for this is the ideal aerodynamic shape of their beak allowing the bird to cut through sudden pressure changes. Similar pressure changes take place when high-speed trains enter a tunnel. The result is load thunderclaps of noise as the train goes through the tunnel. One of the fastest train in the word is the Japanese Shinkansen Bullet Train. This train is equipped with approximately 15 m long kingfisher-shaped nose. Thereby the train is not only quieter, but also lowers its energy use by 15 percent, while traveling 10 percent faster (Bagley, 2009; www.asknature.org).

Figure 2.14. Biomimicry example: Transport. Photo of kingfisher was found at http://carolinabirds.org and photo of Shinkansen Bullet Train at www.gojapango.com.

11. Sustainable carpet: Learning from how nature makes floor.

The carpet company Interface has worked together with the Biomimicry Institute to manufacture sustainable closed-loop products, based on the “organized chaos” of nature, where no two units are the same shape, size, or color, yet together they form a cohesive pattern (Fig. 2.15). Interface designed totally random tiles, each slightly different in pattern and color (www.interfaceglobal.com). This increases the flexibility, makes installation faster, repair easier, and reduces waste. Further, Interface designed a carpet tile installation system that uses small adhesive squares to connect carpet. By this the company omitted the need for glue and made the installation process easier and faster, resulting in 90% lower environmental footprint.

Figure 2.15. Biomimicry example: Sustainable carpet. Photo was found at http://blog.interface.com

12. **Building nanostructures from bottom up. Learning genetic control from biological systems.**
Genetically controlled self-assembly is the structural basis of proteins and many other biological molecules. Furthermore, organic molecules can in principle control the assembly of inorganic nanostructures (Seeman & Belcher, 2002). An example is the abalone shell (Fig. 2.16). The sea snail produces negatively charged proteins that are able to pull calcium out of the environment and structure strong calcium carbonate tiles in stacks like bricks. Inspired by the abalone shell, Angela Belcher and coworkers at MIT have used M13 bacteriephage display to select peptide sequences that bind to various metal particles and thereby produce biomolecular interactions with various elements of the periodic table. By this they are able to use natural strategy to create interactions that normally do not occur in nature (Mao et al., 2004). This relatively easy genetic system allows for fast screenings of promising peptides out of billion candidates. Potential applications are manifold: assembly of nanowires for high power lithium battery electrodes made at room temperature (K. T. Nam et al., 2006); enhanced solar cell efficiency with virus-carbon nanotubes complexes; and clean hydrogen fuels with sustained light-driven water oxidation (Y. S. Nam et al., 2010).

Figure 2.16. Biomimicry example: Building nanostructure from bottom up. Photo of abalone shell were found at www.mineralminers.com, photo representing a virus solar panel was found at http://inhabitat.com(c)

2.5.4 Biotechnology and biomimicry

The rapid development in biotechnology has revolutionized the prospects of biological and medicinal research in the past decennia. How to perform whole genome sequences of organisms and determine the molecular structure of proteins and DNA is now a common knowledge. This great ability, together with improvements in nanotechnology, is the fundament for many of the high-tech biomimetic solutions that are evolving. Biomimetic approaches have for instance contributed significantly to biomedical research, including stem cell differentiation, tissue engineering, and regenerative medicine (Zhang, 2012). However, a debate about some practices of biotechnology, in particular genetic engineering, is ongoing. Scientific uncertainties of the short- and long-term effects of introducing foreign DNA into a host genome has given rise to concerns within the public discussion with regard to biodiversity and human health; a view that is not by any means embraced by all scientists.

The biomimicry school of Benyus seems to take the side of those pointing to a precautionary approach regarding genetic engineering. On the biomimicry.3.8 webpage two issues are addressed concerning genetic engineering. Firstly, it states that genetic engineering domesticate the producer, while biomimicry imitates the producer. Secondly, it says that there is still a lot to learn about unintended consequences of genetic engineering and therefore “we should be careful with how we use it" (http://biomimicry.net). Benyus has expressed an even more outspoken dislike of genetic engineering, apparently based on ethical consideration:

> *"If we use what nature has done as a filter, we stop ourselves from, for instance, transferring genes from one class of organism to another. We wouldn't put flounder genes into a strawberry plant, for instance. Biomimicry says: if it can't be found in nature, there is probably a good reason for its absence. It may have been tried, and long ago edited out of the population. Natural selection is wisdom in action."* (www.biomimicryinstitute.org)

However, it may be that such a black and white judgment will not withstand the test of time. Genetic engineering is a relatively new technique but is rapidly advancing. Including emerging knowledge about its applicable possibilities and by taking necessary safety management into account, biotechnology can possibly complement biomimicry in obtaining sustainable solutions.

2.5.5 Biological conservation and biomimicry

Biodiversity provides vital functions to the living planet. Humans essentially depend on its goods and services, which is a strong argument for landscape- and wildlife conservation. Nature-inspired innovations are benefited by biodiversity and it is evident that the success of biomimicry is best guaranteed by a great diversity of different life forms. Hence, the viewpoint of biomimicry of the importance of creating sustainable solutions is very much intertwined with biodiversity conservation. Tropical rainforests and coral reefs are the hot spot of biodiversity but the knowledge of the number of species on Earth is far from comprehensive. Presumably, many of the yet to be discovered species are located in the vast and largely unknown oceans, which stresses the importance of marine protection. In the deep ocean organisms live under extreme conditions and their adaptions through evolution may have created interesting solutions for technological challenges. Ironically, humans may cause extinction of species that they are unaware of. As ecosystems are destroyed and species richness reduces, so may the solutions for repairing the damage shrink.

In a modern world where more than half of the population lives in cities (www.who.int), the City Zoo can have an important function in promoting biodiversity and species preservation by raising awareness by people about the manifold organisms and biological processes. The Freiburg University Botanic Garden and San Diego Zoo participate independently in a network for biomimicry and biodiversity research with the accessible reservoirs of flora and fauna operating as biological models and screenings for potential relevant biomimicry functions. The approach taken in Freiburg is to carry out basic biological research in biomechanics and functional morphology; to prepare new insights for technology for further processing; and to search for possible biological model solutions for specific technical problems (www.botanischer-garten.uni-freiburg.de). The San Diego Zoo organizes a biomimicry program with annual conferences, monthly seminars, and workshops with companies such as Qualcomm, Nike, and P&G (www.sandiegozoo.org). The vision of the San Diego Zoo is to connect people to wildlife and conservation and to collaborate on solutions to some of the conservation challenges present today. The idea is that zoo staff will research their subjects and suggest possible bio-inspired capabilities, and that companies will collaborate with them to design actual products. In this context biomimicry is seen as the business link to biodiversity that offers economically viable solutions, which result in savings in money, energy, and materials, as well as benefit conservation efforts.

2.5.6 Bringing bio-inspired innovation to the market

If biomimicry is the business link to biodiversity, how to measure its economic effects? An attempt to do so has been done by designing the so-called Da Vinci Index (www.pointloma.edu). The main purpose of the index is to monitor in numbers how the awareness on biomimicry increases and also to spread this information to investors, companies, policy makers, and universities (Palen, 2011). It is an interesting way to measure how the significance in biomimicry has increased over the years. The index focuses on biomimicry-related scholarly articles, patents, grants, and the dollar value of those grants. Much work in biomimicry has roots in academia, which justifies monitoring the publications in various scientific journals. Similarly, patents are often one of the first steps in the commercialization of bio-inspired concepts. The number of national grants (in the US) is incorporated to capture the extent of government support, and the index looks further at the dollar value of the grants awarded. The index, using the year 2000 as a baseline, indicates more than a tenfold expansion in biomimicry activities in a period of 12 years (www.pointloma.edu). The number of peer-reviewed articles on the subject has doubled in size every two to three years to about 3,000 papers and the number of biomimetic patent applications has also grown by about 100 additional entries each year (McKeag, 2013a).

It can indeed be argued that this increase in biomimicry activities is related to economic importance, as research, grants, and patents are all prerequisite to innovation and progress that translate into economic values. However, it must be considered that these numbers are all relative and a connection to other fields; research, economic growth, or otherwise, is lacking. The most conceivable conclusion of the Da Vinci Index is that it is a helpful tool for those that promote the practice of biomimicry, and that it suggests that bio-inspired projects are getting more attention.

The link between biomimicry and businesses is evident. Since 1998 the Biomimicry Institute has consulted small and large companies about bringing biomimicry to business, and is working with people and organizations to transform business models towards a design of sustainable products and bio-inspired processes (http://biomimicry.net). On the other hand, many bio-inspired projects are located within universities and laboratories. It can be difficult to predict which of those activities will become incorporated into new products. The two most famous bio-inspired products, Velcro and Lotusan paint, took many years in development before entering the market. Studies on the Gecko tape have been ongoing for several years but reliable product has not yet been presented. Likewise, no marketable product based on spider silk has emerged, although the research has clearly unraveled impressive properties of silk. At the same time, it is fair to say that the awakening in bio-inspired research goes parallel with tremendous expansion in computational power and information network. Technical improvements help to create novel opportunities to solve complex problems and share knowledge between scientists. This greatly improves investigative techniques and manufacturing technology, and for instance nanotechnology and 3-D printing contribute to the idea that many more marketable solutions are on their way. It is interesting to note that much biomimetic research lies in the areas of robotics and material science with anticipated potential business benefit in the hundreds of millions of dollars (McKeag, 2013a).

Recently, several groups in the United States have developed models to adapt bio-inspired innovations to the market (McKeag, 2013a). The San Diego Zoo aids bio-inspired technology transfer for private clients (www.sandiegozoo.org). The Zoo provides both informal education to paying customers and generates and develops in-house ideas for possible market exploitation that will be further commercialized by the client. The Wyss Institute at Harvard

University is a high profile research institute centered entirely on bio-inspiration, representing a novel model for innovation, collaboration, and technology translation (http://wyss.harvard.edu). The unique situation is that the Wyss institute was originally conceived as interdisciplinary and nature-based, rather than having grown *ad hoc* into this field, and furthermore, a substantial $125 million endowment in 2009 allows the institute to host high-risk research. The institute supports the translation of basic research innovations to the business world by partnering with private companies in testing and application development. Finally, in the energy sector, The Joint Center for Artificial Photosynthesis (JCAP) is established by the U.S. Department of Energy to develop clean energy solutions (solarfuelshub.org). The overall purpose of the program is to reduce the US dependence on oil and enhance energy security, a goal involving huge economic interests. JCAP aims to find a sustainable and cost-effective method to produce fuels using only sunlight, water, and carbon dioxide as inputs, basically mimicking plant photosynthesis.

Also in Europe, a start has been made to support and accelerate the translation from bio-inspired innovation into market-oriented solutions. In Switzerland, a focus group, called Biomimicry.CH was initiated in 2012 by the non-profit Foundation For Global Sustainability (FFGS) in cooperation with Swisscleantech, Zurich Zoo, and several institutes from the United States, namely San Diego Zoo, Biomimicry 3.8, Wyss Institute Harvard and Ethical Markets (www.biomimicry.ch). This cooperation has so far resulted in the Biomimicry Europe Innovation and Finance Summit in Zurich as a partner event to the Biomimicry Conference at the San Diego Zoo in California.

3 Methods

3.1 Literature research

A literature research focused on the definition and background of biomimicry and other green and bio-inspired solutions. The research included by preference analysis of books and per-reviewed papers. Additionally, information was obtained from relevant blogs, webpages, and (digital) newspaper articles.

3.2 Qualitative research

3.2.1 Methodology

A qualitative research method was used when performing interviews with people in different areas of research and businesses in Iceland. Qualitative research focuses on the view and experiences of interviewees and subsequently, the results are systematically collected and interpreted by the researcher. Qualitative research can be divided into five traditions of inquire: 1. Biographical, 2. Phenomenological, 3. Ethnographical, 4. Grounded theory, and 5. Case study (Creswell, 2013). The current study was performed according to the tradition of grounded theory. This discipline aims at developing a theory grounded in data obtained during the study. The researcher typically conducts as many interviews necessary to collect sufficient data to saturate the categories. The participants interviewed are theoretically chosen (theoretical sampling) in order to aid the researcher to form a theory about the research issue. In the current study the research aims at forming a theory on the status and prospects of biomimicry in Iceland.

The qualitative research was carried out with semi-structured interviews. This type of interviews is conducted according to a pre-developed interview guide, focusing on a certain themes and may include suggested questions (Kvale, 1996). It is neither an open conversation nor a highly structured questionnaire. The conversation comes close to everyday conversation but the researcher focuses on keeping the discussion within the themes in order to answer the research questions. However, the researcher asks open questions allowing the interviewees to express their opinions about these themes. Collection of data follows a "zigzag" process: out to the field to gather information, *i.e*. conduct an interview, analyze the data, back to the field to gather more information, analyze the data etc. (Creswell, 2013, p. 88). Despite the evolving, inductive nature of the approach, the process of data analysis is systematic and follows a standard format. Strauss and Corbin (1990) described a three steps method for data analysis in a grounded theory tradition. Firstly, *open coding*, where the researcher examines the text for striking categories of information. With constant comparative approach the researcher attempts to saturate the categories *i.e*. continue interviewing until new information does not further provide insight into the category. Secondly, *axial coding* interconnects the categories and makes new categories emerge. As the process moves along, axial coding becomes increasingly predominant. Elaboration on the properties of a category takes place and interactions and strategies are tested to increase the relationship between different categories. Thirdly, *selective coding* identifies a single category as the central phenomenon of interest and explores the interrelationship of categories (Creswell, 2013, pp. 195-196). The whole process of coding leads to reducing the database to a small set of themes or categories characteristic of what should be explored (Figure 3.1).

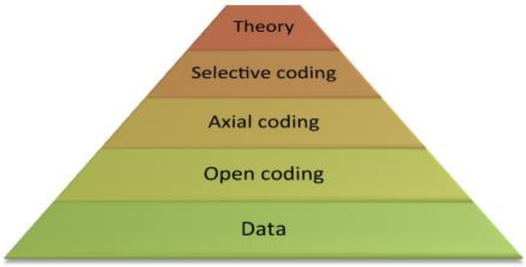

Figure 3.1. Systematic coding results in structuring and reducing the initial amount of data, aiming at constructing a grounded theory.

3.2.2 Study set-up

Electronic mail invitations were sent to potential interviewees. The e-mails introduced the study and included an attachment with a short definition of biomimicry (Appendix I). The only exception was the designer of the Airlocker, who was contacted by telephone and did not obtain the biomimicry definition. The interviews took place from February to June 2013 and their average length was 42±13 minutes (mean ± standard deviation). The interviews were carried out in a one-to-one setting at the interviewees' work place and were conducted in Icelandic. There were three exceptions to the one-to-one situation. One was at Efla, where Reynir Sævarsson and Sigurður Thorlacius were interviewed together because they work on the same project. The other two exceptions were at the Innovation Center Iceland. During an interview with the head of the institute, he phoned a scientist working there to explain his project, and following an interview with the project manager of the Light trawl project, she called four of her colleagues together to brainstorm about biomimicry. All interviews were sound recorded with the consent of the interviewees. In total 16 one-to-one interviews, 1 interview with 2 co-workers, and one brainstorm meeting were conducted. The researcher performed transcription of all interviews and text analysis.

Potential interviewees were chosen in order to solve the research questions and divided into three groups as follows (in parenthesis the number of people in each group):

1. People with overview on research, design and/or businesses in Iceland (6).
2. People that are or have been involved in project(s) with link to biomimicry (15).
3. People with theoretical knowledge on biomimicry, without necessarily being involved in biomimetic projects (1).

The initial list of people was based on literature research and discussion between the researcher and her supervisors. At the end of each interview the interviewee was asked whether she or he was aware of more people that could be interesting to talk to about the research issue. Quite commonly, new names of potential interviewees came up in this way and were included into the research (snowball sampling) in order to cover the subject more thoroughly. In total 22 persons from 10 different institutes, universities, organizations, and companies were interviewed (Table 3.1).

Table 3.1. Names, initials and institutes/companies of people interviewed

Innovation Center Iceland:	The University of Iceland:
Þorsteinn Ingi Sigfússon (ÞIS)	Hilmar Bragi Janusson (HBJ) (previously at Össur)
Halla Jónsdóttir (HJ)	Rúnar Unnþórsson (RU)
Gissur Örlygsson (GÖ)	Björn Marteinsson (BM) (holds also a part time function at Innovation Center Iceland)
Torfi Þórhallsson (TÞ)	**The Federation of Icelandic Industries:**
Geir Guðmundsson (GG)	Bryndís Skúladóttir (BS)
Guðbjörg Hrönn Óskarsdóttir (GHÓ)	**Efla, engineer consultancy**
Össur	Helga Jóna Bjarnadóttir (HJB)
Freygarður Þorsteinsson (FÞ)	Reynir Sævarsson (RS)
Magnús Oddsson (MO)	Sigurður Thorlacius (ST)
Reykjavik University:	**Icelandic Research Fund (Rannís)**
Kristinn Rúnar Þórisson (KRÞ)	Sigurður Björnsson (SB)
Hjalti Harðarson (HH)	**Krumma & BIOM (Boston)**
Ólafur Andri Ragnarsson (ÓAR)	Jenny Hrafnsdóttir (JH)
The Agricultural University of Iceland:	**Loftlás**
Áslaug Helgadóttir (ÁH)	Einar Ólafur Steinsson (EÓS)

The interviews were conducted around 6 pre-developed themes (Figure 3.2) with the aim to answer the two research questions stated in Section 1.1. The first 5 themes are related to first research question (the present status of biomimicry in Iceland), the last one to the second research question (future importance of biomimicry in Iceland). The structure of the interviews aimed at obtaining information on whether the interviewees were familiar with the concept of biomimicry; to learn about practical examples of biomimicry; to analyze the current and potential importance of biomimicry in Iceland; its possible economic and other types of advantages; and the attitude of the interviewees towards biomimicry. To do so, relevant questions from a list of 11 pre-designed questions (Appendix II) were asked during each interview and where appropriate, more detailed questions about individual projects were asked as well.

In order to achieve a more geological coverage of the whole country, an e-mail was sent to of all seven University of Iceland‘s Institute of Research Centers (a venue for the University‘s collaboration with local authorities, institutions, businesses and individuals in rural areas) that are currently run at different locations: Snæfellsnes, the West Fjords, North West Iceland, North East Iceland (Húsavík), South East Iceland (Hornafjörður), South Iceland, and Suðurnes. These e-mails contained the same short definition of biomimicry as mentioned above (Appendix I) and further included the following questions:

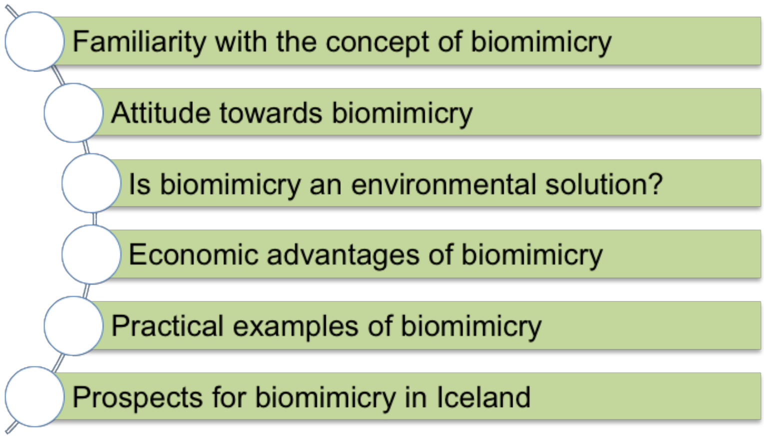

Figure 3.2. Pre-developed themes for interviews.

a. Is the University Centre that you run involved in one or more projects that are related, in one way or another, to biomimicry?
b. Are you aware of any other projects in the province or elsewhere in Iceland that are related, in one way or another, to biomimicry?
c. Can you recommend someone for additional information about possible biomimicry projects?

4 Results

4.1 Comparison of biomimicry to other green solutions

A literature research revealed that biomimicry is both a visionary and a pragmatic concept. It celebrates nature's diversity, displays alternative means to solve human problems by finding answers that are all around us, encourages human creativity, and aims at creating profitable and earth-friendly business. Janine Benyus gave the core definition of biomimicry already in 1997: Biomimicry is looking at nature as a model, mentor, and measure. Biomimicry is to study nature´s best designs and mimic them for solving human problems. Her slogan for biomimicry is *Innovation inspired by nature* (Benyus, 1997). The concept has a strong connection to sustainable development and stipulates the urge of reversing the decline in biodiversity and changing the way humans behave towards nature. In the mind of Benyus, biomimicry is a concept of learning from nature as a feasible method for sustainable design (Pulfer, 2008). However, other interpretations are known for biomimicry and depending on the author and his or her background, the focus may vary. Some stresses the technical aspect *e.g.* in the field of material science, (Miserez & Guerette, 2012) and nanotechnology (Seeman & Belcher, 2002; Tamerler & Sarikaya, 2009), while others are more prone on articulating its environmental and social facets (Mathews, 2011). Vincent and co-workers use biomimetics as a synonym with biomimicry, but also a synonym with biomimesis, bionics, biognosis, and biologically inspired design (Vincent et al., 2006, p. 471). All these variable definitions and approaches indicate that when discussing biomimicry, several different understandings of the term may be involved. This became apparent during the interviews and will be discussed below. Also, biomimicry evolves on the shoulder of several other green movements and has affinity to the social and political landscape of its times.

Figure 4.1 depicts graphically the core definition of biomimicry and its relation to other green movements, based on the literature research. Biomimicry can be defined as detecting the finest designs from nature, learning from nature what is possible and what works, and accepting nature as a teacher on rules and mechanisms. As mentioned before, it has several overlaps with other green solutions, but is motivated by (1) form and function, (2) biological process, and (3) ecosystem levels, while other green concepts are skewed towards one of the points of the triangle in Figure 4.1. Bionics, and bio-utilization concentrate on form and function while biophilia associates merely with appreciation of natural forms. The accent of green engineering and green chemistry lies on the process itself, *i.e.* how green solutions can be achieved. Cradle to cradle focuses on system levels; it deals with the lifecycle of products, aiming at making production procedure such that the waste from one system becomes the source for another production. In fact in this concept no waste is allowed, as it should circle back as a valuable input when manufacturing other products, similar to an ecosystem.

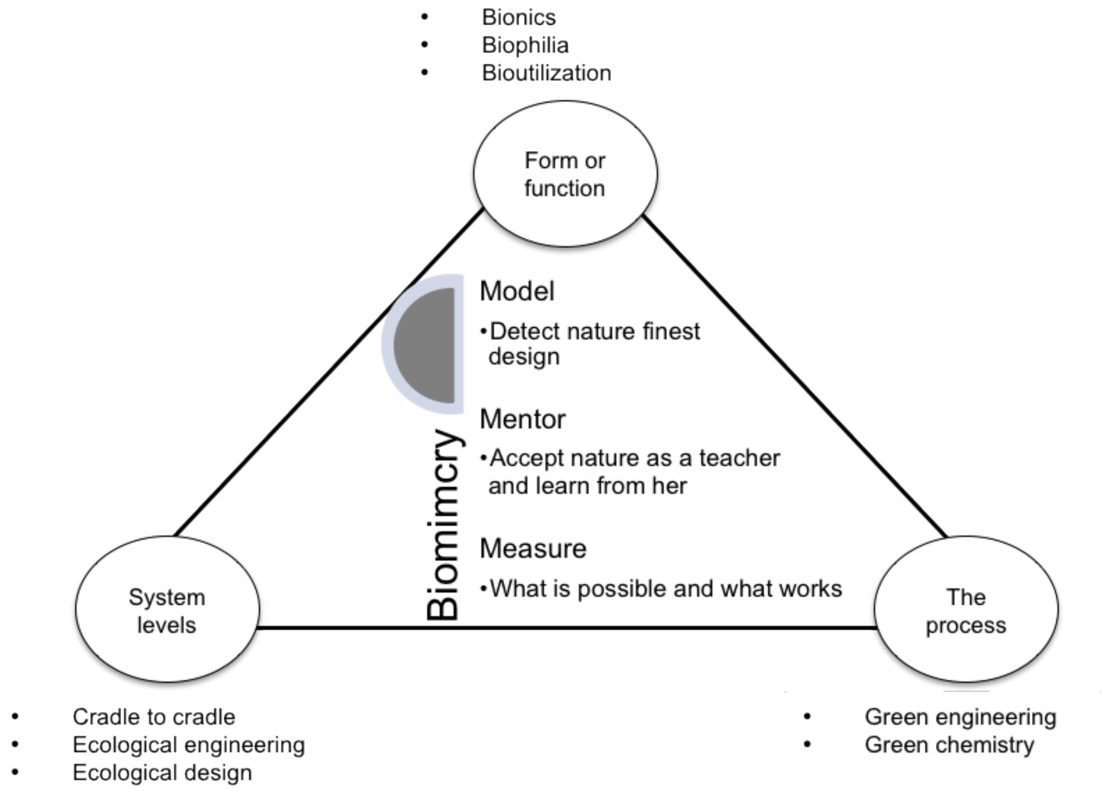

Figure 4.1. The focus of biomimicry and other green solutions. Biomimicry with nature as model, mentor and measure takes form and function, the biological process, and ecologic system level as inspirations for innovation. Bionics, biophilia and bioutilization focus on form and function, green engineering and green chemistry on the process, cradle to cradle, ecological engineering, and ecological design on the system levels.

Ecological engineering and ecological design describe a conscious use of ecosystem self-design to integrate human society with its natural environment. Both disciplines include the restoration of ecosystems and the development of new sustainable ecosystems with both human and ecological values. Therefore, ecological engineering and ecological design are located together with cradle to cradle at system levels.

Biomimicry uses bio-inspiration for innovation aiming at sustainable design; something that can be argued is not achieved fully by the other concepts discussed in this paper (Table 4.1). Probably, ecological engineering and ecological design come closest to biomimicry in using ecosystems and life processes as the mentor and measure to create sustainable design that indeed sometimes involve innovations. However, ecological engineering and ecological design are quite theoretical and in close association with the academia. The emphasis is on the interdependency of nature and man and both disciplines tend to focus on systemic ecological processes. These movements do not take individual organisms for inspiration (hence only ++ in the last column of Table 4.1), while biomimicry involves both individual organisms and ecosystems. In contrast to the biomimetic design *by* nature, where bio-inspirational examples are used with a creative twist to provide solutions for human problems, ecological design is more a design *with* nature where the aim is to reach harmony between humans and nature. Therefore, ecological engineering and -design are graded with only one + in the first column of Table 4.1.

Table 4.1. Comparison between biomimicry and other green concepts

Concept	Innovation, creative design	Sustainable design	Education from life processes
Biomimicry	+++	+++	+++
Ecological engineering & Ecological design	+	+++	++
Green engineering & Green chemistry	+++	+++	+
Cradle to Cradle	+++	+++	+/-
Bionics	+++	+/-	+++
Bioutilization	+/-	+/-	+++
Biophilia	+/-	+/-	+++

Green chemistry and design focuses on processes necessary to reduce pollution and obtain sustainable design (+++ in the middle column). These processes are not necessarily derived from nature (+ in last column) but one of its core principles is to develop new processes, leading to innovation (+++ in the first column). Similarly, cradle to cradle scores high for innovation and sustainable design but the association to nature as a mentor for the solutions is very weak (+/- in the third column). Bionics creates bio-inspired solutions (+++ in the first and third columns), while the outcome may or may not be a sustainable design (+/- in middle column). Both bioutilization and biophilia look for nature as inspiration (+++ in the last column). However, extracting nature, in the case of bioutilization, is somewhat contra dictionary to sustainable design (hence +/- in the middle column) and use of natural material does not per definition lead to innovation (+/- in the first column). Biophilia strengthens the connection between humans and nature, but biophilic design may lack the use of biological functions. Biophilic design can mimic biological form so its resemblances to nature, but does not take the design all the way to sustainable solutions or lead to true innovation (+/- in both left and middle column).

4.2 The present status of biomimicry in Iceland

One of the main aims of the thesis was to analyze the current importance of biomimicry in Iceland. Information was gained by qualitative analysis; by performing interviews with people with overview on the current research and businesses in Iceland and with those potentially involved in biomimicry projects. The interviews were subjected to a coding procedure, as explained in the Method section, aiming at reducing the database to a small set of subjects characteristic for the present status of biomimicry in Iceland. Here below, a combined result with relation to the present status of biomimicry in Iceland is given, aiming at answering the first research question. The outcome of the interviews is given along the pre-developed themes shown in Fig. 3.2. The opinion of interviewees is explored; their familiarity with and attitude to the concept biomimicry is described; and explained how the interviewees see the connection between biomimicry and environmental issues and between biomimicry and economic advantages. This is followed with an illustration of biomimicry projects detected in Iceland during this study and analysis of these projects to biomimicry criteria.

4.2.1 Familiarity with the concept of biomimicry

All interviewees agreed on that biomimicry is an unexplored and unmapped discipline in Iceland. 'This is a very wide topic that is just starting to emerge' (ÞIS).[1] 'The concept biomimicry is not the first thing that comes to ones mind when discussing technology' (ÓAR). 'Although I have been involved in environmental issues as a consultant and I am very interested in these issues I had not heard exactly this concept before, this way of thinking' (RS). With one exception, no one had previously heard of Benyus and her work concerning biomimicry. However, most interviewees could relate to the term biomimicry in one way or another. Generally, they connected biomimicry to copying natural forms; the awareness was mostly on the so-called direct biomimicry, *i.e*. observations of solutions by a particular organism or natural process and translation thereof into a manufactured solution. Quite often interviewees referred to having heard or read about the concept biomimicry and several recalled having heard about biomimicry projects taken place during their study-period abroad, sometimes more than10-20 years ago. Þorsteinn Sigfússon has written about biomimicry with relation to hydrogen production and artificial photosynthesis (Sigfússson, 2008). Bryndís Skúladóttir is a director of environmental matters at the Federation of Iceland Industries and because of her work comes in contact with various nature-inspired projects, although:

> 'I do not so much link them to biomimicry, even though such link may exist. I have heard this concept to mimic nature and use the genius of nature's design. I have not familiarized myself with this particularly, but I do hear this in relation to environmental issues' (BS).

Twelve interviewees were asked specifically to give their interpretation of biomimicry, after having read the explanation that was send to them prior to the interviews (Appendix I). All answers included that biomimicry can be explained to mimic natural forms and use them when designing technical solutions. Some answers added that biomimicry also mimics natural processes. 'Do like the nature deals with the matter' (ÞIS) and 'when you design something, you try to mimic nature or some specific properties of animals or ecosystems' (JH). Ólafur A. Ragnarsson articulated that when defining biomimicry it is also important to know exactly what we mean by the term nature:

> 'The definition of biomimicry is simple. You take ideas about shape, features and phenomena of nature and utilize them to create technology; create things we believe will be beneficial to us. But the real question is, how to define "nature". Is it only trees, animals, landscapes, and wind, or are humans a part of nature? In that case you enter medicine, artificial intelligence and all that stuff' (ÓAR).

In this context, it is worth mentioning that human physiology is indeed included as a part of nature. This becomes relevant when discussing *e.g*. prosthetic technology by Össur (see below). However, biomimicry does only incorporate living things and therefore a phenomenon like wind is beyond the concept.

[1] Quotes are translated from Icelandic and are followed by the initials found in Table 4.1. The researcher has taken the liberty to summarize what the interviewees said with the intention to represent the substance of the interviewees' words.

Hilmar B. Janusson explained that he knew and used only a restricted part of the term biomimicry, while he was aware of the fact that the term has multifarious meanings:

> ’but in my mind biomimicry is first and foremost to mimic biological forms, not biological processes in the synthesis of the product’ (HBJ).

Similarly, Kristinn R. Þórisson stated he knew biomimicry from the robot world. However, the definition by Benyus was new to him:

> ’In robotics we are not working according to how Benyus defines biomimicry. If we call what I do in the artificial intelligence field biomimicry, then probably everything in science is biomimicry, as science is about understanding the processes of life in its widest possible manner. In the field of artificial intelligence we study knowledge, which obviously is a natural phenomenon. The other angle is the engineering part *i.e.* how to use this knowledge. Therefore, one can conclude we are dealing with biomimicry, but still it is far away from the idea of Benyus, who looks at it in a very holistic manner’ (KRÞ).

A rather technical explanation of biomimicry was dominant by those mimicking the human body to make prostheses. ’Biomimcry would allow us to produce the perfect product that would completely simulate the body’ (MO). Björn Marteinsson describes biomimicry in architecture as a ’design by nature’, while Halla Jóndóttir described the term biomimicry from the viewpoint of a biologist:

> ’We use development from billions of years to shorten our path towards technical solutions. This is not necessarily the only correct solution, but obviously evolution has lead to great results through all this time’ (HJ).

It became evident that the definition of biomimicry differed between the interviewees. Several interviewees were aware of the fact that that the appearance of biomimicry can be at different levels and many were unsure about the boundaries of biomimicry and how to categorize biomimicry projects. Taken together, the common denominator in the definitions is “nature-inspired” projects. This broad definition, which can be interpreted as including also non-living natural phenomenon, is quite different to the detailed definition given by Benyus, who not only has several outspoken slogans what biomimicry is about, but also adds to the term broad goals in relation to sustainability. Noteworthy, the relation to sustainable development was lacking in the definitions given by all interviewees but one. In general, the familiarity to the background of the concept was marginal. Although some interviewees were aware of examples of biomimetic applications elsewhere, knowledge about the systemic methodology of biomimicry thinking and the paths recommended to reach biomimicry solutions was absent in all cases. Apparently, biomimicry as a concept is still at its infancy in Iceland.

4.2.2 Attitude towards biomimicry

The interviewees did generally not talk about biomimicry as something they perform consciously. Instead, they explain their experience of biomimicry as an unconscious process, not an intended design of sustainable and environmental friendly solutions based on lessons from nature:

> ’I was just at home at the kitchen table wondering what to do when the idea of this bird came along, probably because I had the experience of the unmanned submarine and know about its shortcomings’ (HH).

Obviously, a bird has the capacity both to fly and dive, which is a valuable concept behind the idea of Flapping-wing MAV (micro air vehicle), but the approach to this project was completely technical. Helga J. Bjarnadóttir explained that she is involved in several ecological design projects that are possible examples of biomimicry, although she pointed out that she never used the term biomimicry in her work. However, Halla Jónsdóttir gave a much stronger affinity to biomimicry. Her definition comes very close to how Benyus explains biomimicry:

> ’Nature has found a number of innovative ways, both in nanotechnology and other technologies during all this time, which is evident we should use. This is a toolbox we have. To me, biomimicry is just so obvious. I have always thought like this, even before I heard the word “biomimicry”. I find it so straightforward to use everything that has already been developed over a very long time. Although one can also find other desirable solutions, it is much easier to first look into the data bank of Mother Nature’ (HJ).

On the whole, the attitude towards biomimicry was positive:

> ’To look at biomimicry in an all-inclusive way, as Benyus does, is a very good idea and fits perfectly with my vision on life; not to look at nature as an enemy one needs to tame, but an environment we must adjust to’ (KRÞ).

Most interviewees were convinced that using natural solutions makes sense:

> ’Natural systems have developed for billions of year and therefore everything points to the fact they are efficient. One can therefore argue that building your method on biomimicry will be successful (FÞ).

> ’The life that has developed over the last billion years has found solutions to many problems. To apply them is just a matter of thinking outside the box’ (ST).

> ’In a larger context biomimicry allows us to discover opportunities that are not obvious. Just by observing the environment we see that nature has often found ways to solve problems. Life is based on iteration after iteration after iteration through billions of years, tailoring away the shortcomings. Therefore what is around us today is the best result given the prevailing circumstances. This is perhaps the most exciting point about biomimicry. Much development has already been done for you. It may very well happen that you get a problem-solving idea while visiting the zoo’ (MO).

And further:

> ’Nature has the tendency to find equilibrium. If you study biological processes, most likely your research will build on these principles and therefore, if you can apply them with technical processes, it is more likely you will get optimal results’ (MO).

Rúnar Unnþórsson mentioned that sometimes natural models can be very obvious and everyone can make the connection to them, while other times the solutions are not on the surface and only experts can point them out to you: ’In that case, I believe engineers will benefit much from a cooperation with biologists’ (RU).

Björn Marteinsson teaches students of engineering and architecture:

> ’I try to tell my students they should not be too narrow-minded. New movements, like biomimicry, open ups peoples mind, develop one´s ability to think differently. It is easier to tell this to the students of architecture at the Academy of Arts, they are not as technically confined as most students of engineering become almost immediately at the initial stages of their study’ (BM).

Some interviewees emphasized the relation of natural solutions and biomimicry to creativity further: ’By understanding the system makes us think outside the box and approach the problem from a different angle (FÞ).

Jenný Hrafnsdóttir commented:

> ’The benefit of creating natural organic structures is to give more freedom to ones mind. It enhances creative thinking; different to if only conventional forms surround you. Getting creative ideas is easier if I get away from conventional formal environment. I believe these things have influence on people’ (JH).

Ólafur A. Ragnarsson underlines that improved technological ability is a prerequisite when imitating nature solutions:

> ’In nature, evolution takes many generations. Often, organisms must die for better ones to emerge. Technology evolves exactly like nature, through generations. We are now living in a period that can be defined as the third industrial revolution, characterized by exponential growth of technological improvements in software- and robot technology. Of course, robots are a little bit related to biomimicry, but also 3D printers are extremely important. In the past decennia, the technique and especially software, has developed very fast allowing us for the first time to understand natural processes better, but also to create and manufacture products with natural shapes. Nature has many examples of organisms that are streamlined. To mimic this, emerging technology, like the 3D printers, will become extremely important’ (ÓAR).

Hilmar B. Janusson pointed to the robustness of biological solutions:

> ’Biological processes are much more complicated than how we tend to solve problems. Solutions by nature are very robust; we underestimate robustness. Nature has many control functions. Nature would let everyone in a car control it, something that would not even cross our mind’ (HBJ).

He also stresses the complexity of nature and the importance of understanding it in its own right:

> ’I truly believe in the concept, but because natural processes are complex, I feel biomimicry is rather undeveloped and the solutions people are presenting sometimes far-fetched. You have to obtain real knowledge about the biological principles. Only when you start to understand them properly, then you can draw important information from them. You have to stop looking at the problems from outside, from the human point of view, and to start looking at it from inside in order to obtain comprehension of the matter’ (HBJ).

Although approached and formulated differently, this emphasis on the deep involvement into nature is present in the work of the Australian philosopher Freya Mathew:

> "*Biomimicry will not furnish a key to sustainability until we act not only in imitation of nature but also from within, so to speak, the mind-set of nature, where this means allowing nature to "redesign" not only our commodities but also our own desires*." (Mathews, 2011, p. 382)

Benyus (1997, pp. 287-288) discusses the importance of immersing ourselves in the natural world as the first step to a biomimetic future, which can be seen as somewhat related to this subject.

4.2.3 Biomimicry as a solution to environmental problems?

The basic principle of biomimicry is that during its 3.8 billion years of research and development nature has evolved highly efficient systems and processes, which can produce solutions to many of the waste, resource efficiency and environmental problems that we cope with today. However, the awareness of a connection of biomimicry and environmental management varied between the interviewee´s. In most cases it was limited. Hilmar B. Janusson stated that biomimicry at Össur does not involve environmental considerations. On the other hand, Freygarður Þorsteinsson pointed out that one year ago Össur received Iso14001 certification and that the company is looking at possible environmental improvements in the production process.

> 'Although so far the steps of moving to ecological friendly procedures have been very small, the certification process has made us more aware about the whole route of manufacturing. To choose materials that are created by less polluting processes is gradually entering the design process but we still have a long way to go' (FÞ).

Apparently though, the environmental considerations did not emerge from biomimicry. When asked whether he sees a relationship between biomimicry and the environmental policy, Þorsteinsson replied:

> 'Our primary measure is to be efficient without reducing quality standards. If biomimicry fits into the process we will use it but intrinsically it is not our goal' (FÞ).

Magnús Oddson argued that mimicking the human body indirectly forces the design to cause less environmental impact.

> 'As an example, the development of a natural gait results in efficient use of both body energy and electric energy of the prosthetics, making it possible to use smaller batteries and hence reduce the disposal of heavy metals' (MO).

Kristinn R. Þórisson explained that the theory of Benyus was very much different to the everyday world he experiences:

> 'As I understand Benyus, the environmental issue is the essence of her interpretation of biomimicry. The reason is that she takes a holistic view of the term and includes the universal status of humans, in contrast to what we normally do in those isolated scientific disciplines. Biology has no obligations to consider the role of man. That is not a part of the search for knowledge within biology. The same applies to the artificial intelligence center. We are researching intelligence and thoughts, but we do

> not have those obligations. We just aim at a better understanding of the subject. That seems to be our only goal’ (KRÞ).

He also added:

> ’As a concept to prevent direct environmental impact, biomimicry is associated with hardware rather than software. There are the atoms that pollute. Biomimicry has a direct effect on the environment through biotechnology, engineering, construction, public administration and management’ (KRÞ).

The impression of Ólafur A. Ragnarsson was that biomimicry is a part of environmental awakening:

> ’There is a revival of looking for environmental healthy solutions. What is happening right now is that we can create clever things. We can design clever software. Before, everything we made was clumsy. It was not possible to construct organic shapes or at least, that was not cost-efficient. Now, people are beginning to look to nature for answers. Because of extreme population growth and increased welfare in the developing countries that expand the worldwide consumption, renewables and sustainability have become the buzzwords today’ (ÓAR).

Jenný Hrafnsdóttir had not connected biomimicry to environmental friendly thinking before the interview:

> ’I can relate to this connection from Benyus´ definition of the concept, but I´ve never put it into this perspective before. The connection becomes clearer when you start mimicking processes, instead of just natural forms. For instance, the chemical processes that are used to make our basic material are synthetic and carried out at high temperatures. Yes, I can relate to this now’ (JH).

Björn Marteinsson reflected on the lack of technical urgency for the building industry in Iceland to reduce material use:

> ’It is very clear that in the society there is a growing tendency to minimize material use, to reduce utilization of natural resources, including energy and water, and to reduce pollution. Biomimicry can add to this ongoing process. In some cases, people are definitely looking to nature for solutions, but I believe we can learn much more from nature. This is happening in the material and chemical industries, but so far there has been little technical urgency for the building industry [in Iceland] to change how buildings are made’ (BM).

Áslaug Helgadóttir pointed to the potential of biomimicry in agriculture.

> ’Loss of nutrients from agriculture is a general environmental problem. To regain nutrients via natural processes combined with technical skills is very important and I believe here we could learn from nature’ (ÁH).

At the same time she admitted that this line of thoughts is not present in agricultural research in Iceland.

Taken together, the notion that biomimicry contributes to a solution of environmental problems was not strong by most interviewees. However, in the Light trawl project environmental issues were important from the beginning:

> ’We started this project because we felt that the oil consumption of the fishing fleet was much too high. This is partly caused by the friction of trawls to the sea bottom. At its best, bottom trawls only increases oil consumption but they may also cause environmental impact by physical interactions with the sea bottom. A damage to sea bottom can be hard to prove because that is difficult to investigate, but we can always concentrate on lowering the fuel consumption. In my mind it is clear that in the case of the Light trawl, biomimicry results in environmental advantages’ (HJ).

4.2.4 Economic advantages of biomimicry in Iceland

Potential economic advantages of biomimicry were discussed during several of the interviews. Benyus explains biomimicry as a profitable and earth-friendly business, and since 1998 Biomimicry Guild (now Biomimicry 3.8) have consulted businesses, including Fortune 500 companies, entrepreneurial organization, universities, and governments to generate cost-effective and innovative products according to the philosophy of biomimicry (http://biomimicry.net). Still, economical advantage was not the prevailing idea that came to interviewees mind. In fact no one talked about that he or she saw biomimicry as an economically rewarding approach. However, Bryndís Skúladóttir explained that all the examples she mentioned during the interview were indeed production related and industrial driven, indicating their economic relevance. Also, the bases for the success of Össur, which is one of the leading companies in Iceland and a world-leader in development, manufacture, and sale of non-invasive orthopedics, is the company´s achievement in translating human physiology to artificial objects by technical innovations. Although the products of Össur may not be developed entirely according to the philosophy of Benyus (see further below), undoubtedly the production is biomimicry in the wide definition of the term. Bearing that in mind, economical benefit of biomimicry in Iceland is significant.

The Light trawl project of Halla Jónsdóttir (discussed in detail below) is still in development. Already, the project has been a success because it has increased our knowledge, but Jónsdóttir also expects that it will in the future have a positive return of investment in the form of companies´ taxes to the state etc. Other economic benefit that is aimed at by this project is to lower the considerable oil use of the fishing fleet.

Hjalti Harðarson mentioned that the Flapping-wing MAV project has received “mixed receptions” and that its economic benefit was still a question mark, but he emphasized the intellectual benefits of the project:

> ’The way we can exactly mimic the many types of the natural movements of birdwings is unique and it is this innovative character of our project that has raised interest by the Technology Development Fund (TDF)’ (HH).

Sigurður Björnsson (Head of Science and Innovation by TDF) confirmed that when funding projects, the emphasis lies on the technical developments: ’It is important to build up knowledge for the Icelandic economy and stimulate innovation; whether it includes biological processes is irrelevant’ (SB).

Noteworthy, Freygarður Þorsteinsson explained the interest in biomimicry projects a bit differently when talking about international collaboration that Össur is involved in:

> 'In some of our [European] projects, it is this new approach that sells the project. Clearly, people are looking more and more to bio-inspired projects. I believe that when you can make the person reading over your project see the connection to the living world from how you explain it, that will sell the projects very well' (FÞ).

Magnús Oddsson added:

> 'To put a biomimicry-label on a project when looking for an investment partner or funding can be a good approach. Then the story behind the project is definitely more interesting to many. It becomes easier to start the project because people can place it into context with something they know' (MO).

In summary, the interviewees were reluctant to acknowledge economic benefit of biomimicry in Iceland but this may be an underestimation of the true situation. Össur is a world leading company in its field and its economic importance for Iceland is evident. Several new and established companies aim for the development of highly profitable medical devices and biological active compounds based on biomimicry (see below). Examples of industrial symbiosis are present in Iceland, which contribute to efficient utilization of resources. Some biomimicry projects that were discussed during the interviews are still in a developmental phase and hence difficult to determine their potential economic advantage. Several practical examples of biomimicry in Iceland are discussed below.

4.2.5 Practical examples

Potential biomimicry projects were discovered by searching the Internet and from newspaper articles published in the past year, while other projects emerged from the interviews. Interesting proposals that came forth during the initial interviews directed the choice of interviewees. This kind of a snowball effect method (approaching new interviewees on bases of tips from the previous interviews) was followed throughout the whole period of interviewing. Due to a lack of time it was not possible to contact all those primarily responsible for every potential biomimicry project; in those cases information about the projects was obtained from the Internet. Requests to the seven managing directors of University of Iceland's Institute of Research Centers throughout the country by e-mail, asking about potential biomimicry projects were unsuccessful. No reply were obtained from two research centers and the other five answers stated that the Research Center was not involved in any biomimicry project (answer to question a; see Method section), nor was the managing director aware of a biomimicry project in the region (answer to question b). Some recommendations were attained about people to contact about additional information (question c), but these were not pursued further.

During the interviews, potential cases of biomimicry projects in Iceland were discussed. Several representative examples were inspected in some detail in relation to the characteristics of biomimicry. These projects are presented here below (Table 4.2). By no means is this a conclusive list, but it illustrates the typical status of the biomimicry approach in Iceland.

Table 4.2. Examples of biomimicry in Iceland

1	Robotics	Flapping-wing MAV, Reykjavik University	Mimic flying movements and diving capacity of seagulls
		Automatic indoor camera, Iceland Innovation Center	Mimic eyes function and the combined effects of the eyes and vestibular organs of the inner ear
2	Prosthetics	Össur	Mimic the human musculoskeletal systems and neurotransmission
3	Urban water management	Efla, consulting engineers	Mimic circulation of ecological systems
4	Industrial symbiosis	Svartsengi power station, Blue Lagoon, Carbon Recycling International	Mimic the natural principle of ecological systems that output becomes input
		GeoChem	
		Prokatin	
		Íslensk matorka	
5	Bioactive compounds	Pensim	Mimic the ability of organisms to defend themselves
		Una Skin Care	
		Chitosan, Genís	
		Keracis	
6	Playground equipment	Krumma	Mimics natural forms and promotes imagination and creativity of children
7	Pressure retarded osmosis	Iceland Innovation Center	Mimic the flow of liquid through cell-membranes
8	Fin drive propulsion	University of Iceland	Mimic the locomotion of fishes for marine propulsion applications
9	Light trawl	Iceland Innovation Center	Mimic technique of using light for collecting fish schools
10	Airlocker	Einar Ólafur Steinsson	Mimic bubble-netting of humpback whales to fish herring and capelin

One of the difficulties of characterizing a biomimicry design is the fact that biomimicry can be defined in many ways. The widest definition is the literary translation of the word, *i.e.* imitation of life. However, it is desirable to give a more precise explanation of the term in order to categorize potential biomimicry projects. As the explanation of biomimicry given by Benyus was not familiar to most interviewees it cannot be anticipated that the Icelandic examples fulfill her definition entirely. The researcher chose to inspect the Icelandic projects with eight relevant aspects in mind that were developed during this study (Table 4.3). Primarily, it was analyzed if the project was inspired by nature and whether it mimics biological forms, processes or systems. The project should focus on biological function rather than only biological forms and on learning from nature rather than on utilizing organisms. Each project was considered on the basis of its interdisciplinary approach. Furthermore, the biomimicry design should involve some kind of a technological innovation and preferably result in energy efficient and environmental friendly solutions. All ten projects were analyzed according to each of those eight categories and were included although they did not fulfill all of them.

Table 4.3. Consideration for biomimicry examples in Iceland

1	Are the designs inspired by nature?
2	Do the designs mimic biological forms, biological processes and/or ecosystems?
3	Are the designs based on function rather than merely form?
4	Are the designs based on learning from nature rather than bio-utilization?
5	Do the designs involve interdisciplinary approach to incorporate biological knowledge and technological know-how?
6	Do the designs involve technological innovations?
7	Do the designs aim at providing energy efficient solutions?
8	Do the designs aim at providing environmental friendly solutions?

1. Robotics

Bio-inspiration has a strong position inside robotics (McKeag, 2013a). This is represented by two Icelandic projects: the Flapping-wing MAV and an Automatic indoor camera.[2]

The Flapping wing project develops an artificial bird that resembles the seagull with emphasis on imitating the bird´s wings, including joints and skeleton (www.flygildi.com). It is a very sophisticated design that is still in development. The project is headed by Hjalti Harðarson and Leifur Þór Leifsson at the Reykjavik University. The artificial bird is able to accurately cover all of the natural bird's movements, including flapping the wings through the air. It can move the wings up and down, tilt them back and forth, pull them in and spread them out. Interestingly, the artificial bird can contain an autopilot system in which it is possible to create a route description by a computer and navigate the bird to a certain point, to scan a certain area, to perform measurements, or send data. A future aim is to make the Flapping wing MAV capable of both flying and diving. Because of the lower resistance of air compared to water, a possible application of the Flapping wing MAV would be to let it fly over a large distance and dive where necessary.

A somewhat similar artificial bird, called SmartBird, has been presented by the German company Festo (Fischer, 2011; www.festo.com). However, the SmartBird is a much more simple device. It is only remotely controlled similar to toy birds that can be purchased in hobby stores, while according to Harðarson: 'The Flapping wing MAV that we are using now in our experiments can fly alone and unaided' (HH).

The Automatic indoor camera project is supervised by Torfi Þórhallsson at the Iceland Innovation Center. It develops a moving camera technology, which is able to take pictures in any lighting conditions and extract information from those images. The system uses a logarithmic response to light, similar to human retina responses, instead of linear responses normally used in cameras. The camera is combined with angular speed sensor, which measures rotation speed and direction of gravity and monitors the movement of the device when the camera has no criteria to follow, either because of homogeneous environment or

[2] As explained in Section 3.4 bio-inspired robotics are often categorized as bionics. However, a strict discrimination between bionics and biomimicry is not applied when discussing the Icelandic biomimicry projects.

high speed, which makes the pictures unfocused. Joined information from camera and angular speed sensor mimics the human balance system, which relies on a close linkage between the inner ear's vestibular organs and the eyes, the so-called vestibulo-ocular reflex, or VOR. The VOR normally generates eye movements that maintain clear vision with head movements.

> 'The movable camera uses photo sensor, similar to the eyes, to monitor the movements of a fixed number of points in the space around it and separately contains an angular speed sensor, similar to the inner ear, to monitor its own movements. Resembling the human body, the information gathered from both sensors is added together to obtain better results' (TÞ).

Both the Flapping wing MAV and the automatic indoor camera fulfill 4 of the 8 criteria (Table 4.3). The designs, mimic natural forms and processes, concentrate on function, do not include bio-utilization, and clearly include technological innovation. On the other hand, the designers were not truly inspired by nature, but approached the subject on technical premises. Only engineers were involved in the projects, although a consultation with biologists would probably benefit both these projects. No emphasis is on energy efficient or environmental friendly solutions.

Table 4.4 Inspections of biomimicry projects: Robotics

	Inspiration by nature	Mimic biological forms/ processes/ systems	Mimic function rather than merely form	Learning from nature rather than bio-utilization	Interdisciplinary approach	Technological innovation	Energy efficient solution	Environmental friendly solution
Flapping-wing MAV	-	+	+	+	-	+	-	-
Automatic Indoor Camera	-	+	+	+	-	+	-	-

2. Prosthetics

The foundation for the success of Össur can be traced back approximately 40 years to the use of a silicone socket liner (www.ossur.is). Silicone is a soft bio-inert plastic material and the silicone liner functions as the interface between the skin and the harder inner socket wall. This provides comfort for amputees while wearing their prosthesis. The socket layer mimics the elastic features of human skin. It is designed to improve blood circulation, while controlling swelling, and to protect the skin and newly formed or sensitive scar tissue by reducing pressure peaks and absorbing shear force.

> 'The effect on skin condition is one of the problems related to loosing a limb. All the weight of the body is now transferred through the skin of the amputated leg, while normally it is transferred through the skeleton and then out through the feet that have evolved to be suited to withstand the load' (MO).

Production of prosthetics is constantly under development. Currently, the accent lies on integrating the device as much as possible with the user. This requires in some cases the usage of electronics and artificial intelligence. The software aims at making the device behave in a natural manner.

> 'We foresee that the next step in our technology is to connect directly with the nervous system so that the device can respond directly to signals from the person using the device. An important nature of such control system is that it allows you to walk without having to think about every single step' (MO).

Also at BIOM in Boston, where the Icelandic engineer Jenný Hrafnsdóttir works, the effort focuses on integrating the device to human body. The development is aimed at mimicking the muscles to make a new type of prosthetic technology that enables natural and personalized movements.

> 'This system gives you back positive energy and basically simulates how much energy each individual needs based on his or her muscle strength. The prosthetic seems to be alive because it gives you energy. This is extremely important for people´s perception' (JH).

Prosthetic designs satisfy 7 out of the 8 biomimicry criteria (Table 4.5). The designs are inspired on nature, concentrate on human biology and are tailored to be energy efficient. Interdisciplinary approaches play an important role in prosthetic design and the whole process includes specialized input of scientists, neurologists, physical therapists, engineers, industrial designers, graphical designers etc. However, only preliminary stages of environmental awareness were present concerning material use and the production process.

Table 4.5 Inspections of biomimicry projects: Prosthetics

	Inspiration by nature	Mimic biological forms/ processes/ systems	Mimic function rather than merely form	Learning from nature rather than bio-utilization	Interdisciplinary approach	Technological innovation	Energy efficient solution	Environmental friendly solution
Prosthetics	+	+	+	+	+	+	+	-

3. Urban Water Management

A couple of urban water management projects to simulate natural water circulation for surface water have been accomplished or are under development at Efla consulting engineers (www.efla.is). Streets in the relatively new Urriðaholt area integrate specifically designed drainage systems to protect the ecology of the nearby lake Urriðavatn. Parking areas include permeable surfaces and water is guided to surface water channels towards ponds and swales for filtering and slowing down the water flow. From there, water sinks into the ground and slowly enters the lake (http://urridaholt.is). A similar drainage system is under development for the new Landspítali hospital, allowing the surface water to enter the Vatnsmýri and Reykjavik Pond, while the older drainage system in this neighborhood removes surface water directly away to the sea. 'The idea is to disrupt the ecologic system as little as possible, while cleaning the water at the same time' (HJB).

These examples of urban water management show a simple and environmental friendly performance (Table 4.6). Although these projects do not intrinsically include technological innovation, they provide a more straightforward solution than conventional sewage systems and offer a profitable condition for the local environmental system. However, the link to ecological engineering and ecological design is perhaps stronger than to biomimicry, based on the low impact of technological innovation and the fact that this method involves bio-utilization of soil organisms.

Table 4.6 Inspections of biomimicry projects: Urban water management

	Inspiration by nature	**Mimic biological forms/ processes/ systems**	**Mimic function rather than merely form**	**Learning from nature rather than bio-utilization**	**Interdisciplinary approach**	**Technological innovation**	**Energy efficient solution**	**Environmental friendly solution**
Urban water management	+	+	+	+/-	+	-	+	+

4. Industrial symbiosis

Industrial symbiosis aims at mimicking the natural principle of ecological systems that output becomes input, *i.e.* the byproduct of a one company becomes the raw material of another company. A beginning of industrial symbiosis is clearly visible around the Svartsengi geothermal energy power station. The Blue Lagoon uses the remaining geothermal seawater for its popular spa and health center and various cosmetic and dermatological products are made from the silica mud that precipitates when the temperature of the water drops (www.bluelagoon.com). The company Carbon Recycling International uses power generated by the Svartsengi geothermal power plant and captures CO_2 from its emission to convert it into methanol that is used as a blend fuel for automobiles (www.carbonrecycling.is).

Other projects aiming at efficient use of byproducts from geothermal power plant stations are under development. These comprise of projects to design and build a photobioreactor-based algae factory to fix CO_2 into valuable chemicals (Brynjólfsdóttir & Svavarsson, 2012; www.georg.hi.is) and to make microbial biomass that produces high quality protein-rich feed for animals and aquacultures from H_2, H_2S and CO_2 as energy sources (www.prokatin.is).

Another example of industrial symbiosis can be found at the company Íslensk matorka, which utilizes renewable energy sources for energy-intensive food production in a closed loop system and recycles waste into resources. The production process integrates poly-culture of Tilapia and Arctic charr with horticulture. This includes a technique called aquaponics; a combination of aquaculture (the ability to grow fish and aquatic organisms) and hydrophonics (growing of plant without soil). Water and nutrients from the fish species recirculate into a production system for plants that bind CO_2 and filter water for the fish. Reusing the water minimizes the water addition needed into the system and provides nutrients for vegetable production (www.matorka.is).

Industrial symbiosis ha features of cradle to cradle, but can also be considered a biomimicry solution (Table 4.7). It mimics functions, such as energy saving and waste reducing processes inspired by ecological systems. It is clearly a technological innovation with interdisciplinary approach. It is economically effective and beneficial to businesses. Still these processes include bio-utilization.

Table 4.7. Inspections of biomimicry projects: Industrial symbiosis

	Inspiration by nature	Mimic biological forms/ processes/ systems	Mimic function rather than merely form	Learning from nature rather than bio-utilization	Interdisciplinary approach	Technological innovation	Energy efficient solution	Environmental friendly solution
Industrial symbiosis	+	+	+	+/-	+	+	+	+

5. Bioactive compounds

The utilization of interesting bioactive compounds is growing in Iceland, especially for medicinal and cosmetic purposes. Probably the first successful example is the research of cod enzymes that started in 1970s and has resulted in marketing of dermatologic and cosmetic products under the names Penzim, Coddoc, and ZoPure serum droplets (www.andra.is). Another established example is Blue Lagoon, which makes products from sea silica, algae and minerals. More recently, UnaSkin, a skin protection cream based on antioxidant activities of seaweed has entered the market (http://unaskincare.com). The biomimicry aspect of these applications is that the natural defense mechanisms of organisms living at harsh conditions can be beneficial to human skin.

Cellulose, chitin and chitosan are the three most common polymers found in nature. Several biomimetic applications of chitosan can be found in the literature, demonstrating the application potential of the compound. Chitosan can be mixed with industrial polyester to create tiny tubes to support repair of a damaged nerve (www.biomimicrynews.com). Also to create fire-resistant nanolayer polymer coating to protect fabrics (Grunlan, 2011) and to make edible form of packaging that encloses food and drinks (www.wikicells.com). The Icelandic company Genís isolates chitosan from the shell of cold-water shrimps. Currently chitosan is being tested as bone healing material, with ability to accelerate bone growth (Gissur Örlygsson, personal communication). This work is still in development.

The company Kerecis applies complete fish skin for tissue regeneration by transplantation. When the fish skin is inserted into or onto damaged human tissue, it is vascularized and populated by the patient's own cells, and ultimately converts into living tissue. Presumably, Omega 3 fatty acids, which are found in high concentrations in fish oil, contribute strongly to the positive effects (www.kerecis.is).

The common denominator of the above-mentioned applications is the use of raw material from the sea, which previously have not been utilized. Both cosmetic and medicinal applications lead to products with large economic potential. This stresses the economic significance of biomimicry in this field and the importance of extended knowledge from marine biology because biodiversity in the ocean around Iceland is largely unexplored with respect to chemical components (Ómarsdóttir et al., 2010). In that context, various organisms other than mammals and fish can be considered. Potential candidates to learn from can most likely be encountered in biodiversity hotspots such as the hydrothermal vents in Eyjafjörður, the cold-water coral reefs areas south and southwest of Iceland, and in the shallow sea of Breiðafjörður Bay.

None of these examples has evolved as a predesigned biomimicry project, although in retrospect they may be characterized as being inspired by living organisms (Table 4.8). However, the line between bio-utilization and true biomimicry design is thin when applying bioactive compounds. Systemic methodologies and more research will increase the potential of their biomimicry applications. The projects are technological innovative and they include more efficient use of resources, although more effort to translate the underlying biological processes into the production practice is needed to create a true environmental friendly solutions.

Table 4.8 Inspections of biomimicry projects: Bioactive compounds

	Inspiration by nature	Mimic biological forms/ processes/ systems	Mimic function rather than merely form	Learning from nature rather than bio-utilization	Interdisciplinary approach	Technological innovation	Energy efficient solution	Environmental friendly solution
Bioactive compounds	+	+	+	+/-	+	+	+/-	+/-

6. Playground equipment

Krumma-Flow is a new design of playground equipment for children. The design promotes and supports the imagination and creativity of children and is inspired by Icelandic nature (http://krumma.org). As a response to the requests from landscape architects for nature-mimicked apparatus, the company has combined novel material and production processes with the required safety and quality regulations. The free form of the structures is created by a an accurate cutting operation, making every item identical, although irregular. The product line resembles lava stones, caves, and spider-webs and is intended to challenge children´s senses and create nature-like environment within the city.

Krumma-Flow products were evaluated on biomimicry criteria and as such fail to fulfill them, basically because Krumma-Flow is mainly inspired by non-living nature, while biomimicry is centered on living organisms (Table 4.9). However, the design is inspired by and builds on learning from nature, contains technical innovation, and to some extent interdisciplinary approach when applying material and techniques of other disciplines. The products themselves do not represent an energy efficient solution, although the production process does consider efficiency of energy use. According to Hrafnsdóttir the manufacturing process is an ongoing project towards more environmental friendly process and material, and the company is incessantly focusing on more efficient energy use. The company´s stated policy is to try as much as possible to use environmentally friendly materials:

> ’The possibility of obtaining recycled plastic was examined but found difficult to get and more expensive than importing new plastic. However, I believe it is a matter of time before it becomes more accessible and economic to use’ (JH).

Table 4.9 Inspections of biomimicry projects: Playground equipment

	Inspiration by nature	Mimic biological forms/ processes/ systems	Mimic function rather than merely form	Learning from nature rather than bio-utilization	Interdisciplinary approach	Technological innovation	Energy efficient solution	Environmental friendly solution
Playground toys (Krumma Flow)	+	-	-	+	+/-	+	-	+/-

7. Pressure retarded osmosis

At the Icelandic Innovation Center a project on pressure retarded osmosis is ongoing (Óskarsdóttir, 2010). This technique mimics the flow of liquid in and out of cells and cell-compartments, where solvent flows over a cell membrane from a less concentrated region to a more concentrated region. Pressure retarded osmosis, sometimes also called blue energy, is available worldwide where fresh water-streams flow into the sea. Salinity gradient energy is retrieved from the difference in the salt concentration between seawater and river water, separated by a semi-permeable membrane. In principle, pressure retarded osmosis generates power with reversed techniques of desalination (purification of sea water) (Post et al., 2007). The first osmotic power plant in the world opened in Norway in 2009 (www.statkraft.com). On global level the technical potential of pressure retarded osmosis is significant and for some countries, like the Netherlands, salinity gradients could become a substantial source of renewable energy (Post, 2009).

The greatest challenge for cost effective pressure retarded osmosis is to create strong enough membranes with the required selectivity, allowing the passage of water and retention of ion transport. Specifically for Iceland, most rivers are glacial waters containing much sediment. The effect thereof on membrane permeability is one of the research subjects of Óskarsdóttir and co-workers Improved technical ability and increasing prices of fossil fuels can make this technique more attractive in the near future. The main advantages of pressure retarded osmosis are its scalability, that it can be placed everywhere as long as there is a supply of fresh and sea-water, and that it produces clean renewable energy without any emission of undesirable gases. For Iceland, this type of power plants can be foreseen in the Westfjords, where there is limited geothermal energy and waterfalls.

Pressure retarded osmosis translates a universal process applied by all living cells into a renewable energy source that potentially can be applied in many regions worldwide. There are still several technical difficulties that accompany this alternative, but potentially this is a typical biomimicry application (Table 4.10). The interdisciplinary approach between biologists and engineers is perhaps not strong nowadays but obviously this project builds on earlier biological research.

Table 4.10. Inspections of biomimicry projects: Pressure retarded osmosis

	Inspiration by nature	Mimic biological forms/ processes/ systems	Mimic function rather than merely form	Learning from nature rather than bio-utilization	Interdisciplinary approach	Technological innovation	Energy efficient solution	Environmental friendly solution
Pressure Retarded Osmosis	+	+	+	+	+/-	+	+	+

8. Fin drive propulsion

A project with the purpose to analyze and design a bio inspired alternative marine propulsion system based on the hydrodynamics and locomotion of fishes is currently being carried out at the University of Iceland. Mimicking the highly efficient locomotion of fishes can potentially offer innovative solutions for marine propulsion. The initial studies researches systemically analyzed the movements of Atlantic salmon and Arctic charr under experimental conditions (Ásgeirsson & Unnthorsson, 2012). 'The following steps involve building the equipment to simulate the motions and see how it works. A possible application is a water pump' (RU).

This study is a pure academic project with little financial aid, and so far with no application interest from the industry. However, the approach is quite similar to that of the Australian firm Biopower, which mimics the shape and motion of tunas, sharks, and mackerels to develop its bioSTREAM system, which extracts renewable energy from moving water, as explained in section 2.5.3.

Fin drive propulsion is inspired by and mimics biological form and processes (Table 4.11)., The project includes a technological innovation that potentially results in energy saving and environmental friendly solution, but the outcome thereof is still unknown. The project is in preliminary stages, but so far lacks interdisciplinary approach. It is carried out at the engineering department without collaboration with other disciplines.

Table 4.11 Inspections of biomimicry projects: Fin drive propulsion

	Inspiration by nature	Mimic biological forms/ processes/ systems	Mimic function rather than merely form	Learning from nature rather than bio-utilization	Interdisciplinary approach	Technological innovation	Energy efficient solution	Environmental friendly solution
Fin Drive Propulsion	+	+	+	+	-	+	?	?

9. The Light Trawl ("Ljósvarpa")

The fishing industry is the most important industry in Iceland and therefore relevant to consider its impact on the environment, especially in the context of climate change, depletion of resources, and acidification of the ocean. According to the project leader, Halla Jónsdóttir, the initial trigger for the Light trawl project was primarily her annoyance with the lack of a sophisticated technical level in the fishing industry. Several of the questions that the designers of the Light trawl asked themselves were whether it was possible to avoid the impact bottom trawls have on the sea bottom by catching fish without physical interactions, and how to reduce the energy use of the fishing fleet.

> ’The Light trawl was designed based on the fact that fish senses light. Perhaps this project did not start with biomimicry, but when we were analyzing what could be done to improve the fishing techniques, I went back to my observations as a child feeding fishes in cages. There I was playing with the interaction of light and shadow and the impact it had on fishes. Some of my key partners also had similar experiences’ (HJ).

In nature the skimmer bird, a tern-like bird that hunts for fish at dusk or by night, bases its fishing technique on what Jónsdóttir observed as a child; that fish can be attracted to light. As the skimmer bird flies low across the water, it trails the lower part of its open beak in the water. This creates a line of light in the bird´s wake, which attracts fish. The bird then returns along the same path to pick up the fish (www.asknature.org). This kind of attraction of fishes towards light is the basis for a recent international design award winning innovation of a fish net with luminous rings, or exit portals, strategically placed throughout the net (www.jamesdysonaward.org). The illuminated rings act like an emergency exit sign for the fish and allow young fish to escape. The design is called “SafetyNet” (www.sntech.co.uk) and could help to cut down on the catch and subsequent discarding of juvenile and endangered fish (www.dezeen.com).

The unique characteristic of the Light trawl is, however, that it uses strong lights to scare the fishes instead of attracting them with weak luminous rings as used in the SafetyNet. ’The light looks like a cord in the ocean that the fish sees and consider better to avoid’ (HJ). Instead of using physical net made of ropes to collect the fish into the trawl, a wall of laser light is created. The depth of the light trawl and the direction of the light are under a computer control. The device has been tested in sea and the results were promising at all depths. The Light trawl can follow the bottom without touching it. Hence no physical contact is made with the bottom. This prevents damage to sensitive sites, such as coral reefs. Another benefit of the light trawls above conventional bottom trawl is the lack of resistance of the light. This lowers the oil consumption of the ship considerably because bottom trawls are towed for several hours at a time. It has been estimated that that the area swept by bottom trawling gear per one kg of mixed fish is 1000 m^2 for vessels larger than 2000 kW (Ragnarsson & Steingrimsson, 2003).[3] Not having to pull heavy fishing gear over such a vast area will be of immediate economic and environmental benefit.

The Light trawl project is a collaboration of the Icelandic Innovation Center, The fishing company Hraðfrystihúsið Gunnvör, the netmaking company Fjarðanet, and the Marine Research Institute. ’Depending on the results of further experiments in sea, a marketable version of the light trawl may follow shortly’ (HJ).

In contrast to most other examples, the Light trawl project is systematically designed from the beginning in an interdisciplinary approach to save energy and make environmental beneficial solution by technological innovation (Table 4.12). It is inspired by nature and in many ways is the best example discussed here of a biomimicry approach, but strictly speaking, it does not mimic natural fishing techniques. As explained above, birds use light to attract fish but the

[3] Measured for the time period 1991-1997.

Light trawl uses light as a herding method, directing the fish into the trawl. The intensity of the light plays a role; low intensity attracts fish but stronger light scares them away.

Table 4.12 Inspections of biomimicry projects: Light trawl

	Inspiration by nature	Mimic biological forms/ processes/ systems	Mimic function rather than merely form	Learning from nature rather than bio-utilization	Interdisciplinary approach	Technological innovation	Energy efficient solution	Environmental friendly solution
Light trawl	+	+/-	+	+	+	+	+	+

10. The Airlocker ("Loftlás")

Humpback whales feed on a variety of relatively small prey species, including schooling fish, such as herring and capelin. Their feeding maneuvers are rather complex. A group of whales expel air underwater to form a vertical cylinder-ring of bubbles around the prey (Wiley et al., 2011). This foraging behavior is called "bubble netting". The whales collaborate to concentrate the fish schools and in this way each whale can trap up to a half-a-ton of herring per day (www.bbc.co.uk).

Build on this feeding behavior of whales, a bubble-net fishing technology, called "Airlocker", was designed and build by the Icelandic fisherman Einar Ólafur Steinsson. 'When I was fishing capelin many years ago, I noticed how whales were producing large air bubbles when they were feeding' (EÓS). The first prototype was tested 2000-2002 and since then, Steinsson has build and sold 4 devices to boats in Iceland, Norway and Chile. The Airlocker is a simple device to prevent migration of herring or capelin out of the nets, which is a well-known problem in herring and capelin fisheries, especially when the net is closing. The Airlocker contains a weight connected to a thin hollow hard-plastic tube with multiple holes on it. By pumping air from the fishing boat through the tube, a wall of bubbles is created that keeps the fish inside the net (www.mbl.is, 2002).

> 'I aimed with my technology to make a better and less destructive method to frighten the fish. For decades explosives have been used to scare fish into the nets, for instance by Norwegians, Danish and Scotsmen in the North Sea. The Icelandic fishermen learned from other nations and gradually started as well to use explosives, even though that is legally forbidden. The use of explosives, commonly known as "Danish fingers" and even dynamite, is a despicable method. The underwater explosion kills much more in the marine environment than you will ever be able to see' (EÓS).

Beside environmental issues, the use of explosives has a security concern, exemplified by an accident on board of a Norwegian boat when a sparkle came in contact with explosives, severely injured one fisherman and the boat had to be pulled back to harbor. This accident was taken up by a maritime court in Norway in 1991 and the use of explosives has been a very delegate matter ever since in Norway, according to Steinsson (www.mbl.is, 2003).

> 'I could not believe my own eyes when I was [working] in Norway. There the Danish fingers were lying in open 20 liters jars just in the storage room where the nets were

> made, amidst all kinds of other stuff. The explosives were already taped with iron rods, batteries and other junk to make them sink. This is a very serious matter' (EÓS).

According to Steinsson, the initial experiments in 2002 with the Airlocker were successful and the users have been satisfied.[4]

> 'I have not heard from the ship in Chile, but the users in Iceland and Norway have been very pleased. They have always used this, every single year as far as I know. I have not heard anything but positive reactions about the device' (EÓS).

Still, only four Airlockers have been sold and Steinsson admits that the appreciation of his invention has been mixed.

> 'Selling new items, it is a matter of a religion. The potential buyer must have faith in the new device. A fisherman knows from experience that explosives can do the job, and that it is easy and simple. It is almost a taboo to try out new things that are not recognized by the hardcore fishermen. Also, you do not see the damage the explosives make under water. People are not willing to discuss this in any earnestness, because they do not want to know about it. But I always say that if we do not know what the consequences are, the animals should profit from the benefit of the doubt' (EÓS).

Currently Steinsson is not working on his invention but he has everything in his own hands and 'it is not impossible that this will be taken up again' (EÓS). An interesting possible application became tangible recently. In an environmental disaster in the fjord Kolgrafafjörður in the west of Iceland more than 50,000 tons of herring got killed in two events, in December 2012 and in February 2013, probably due to lack of oxygen in the fjord. The economic damage is in billions of ISK. (Svavarsdóttir, 2013). At the same time that thorough investigation by the Marine Research Institute may shed some light on the possible causes responsible for the herring death, it is also vital to look for means to prevent this to happen in the future. Steinsson pointed out that bubble net technology could be useful:

> 'The device can easily be modified to scare herring schools away. The fjord´s entrance from sea is quite narrow because of the current bridge and the herring enters the fjord only on high water and when there is little or no current. This situation takes place only a couple of hours per day. Then the bubble net technique can be used to prevent herring to swim into the fjord' (EÓS).

In context of the great economic damage suffered by the massive herring killing and compared to alternative solutions, such as is reconstructing the bridge, or make tunnels for car transportation under the fjord, this relatively cheap biomimetic solutions is definitely worth a consideration, to say the least.

The Airlocker is a true biomimicry project (Table 4.13). The idea for the design came by observing the behavior of whales and the product is an advantageous alternative to illegal practices of underwater explosives. Although the Airlocker is designed and produced by one man, strangely enough, the project can be characterized as interdisciplinary. In the Airlocker, Einar Steinsson combined his interest in nature, experience as a fisherman, concern about

[4] This was confirmed by Bergur Einarsson, the captain on Hoffell SU 80, in a telephone interview on May 8th 2013. The crew of Hoffell uses the Airlocker when fishing herring at a considerable depth. At those conditions, closing the ring net takes a long time and the Airlocker functions nicely to prevent the escape of herring out of the net. It also prevents herring to get stuck in the trawl itself where it dies but the fishermen cannot reach it.

environmentally damaging practices and his skills as a craftsman to build the device. However, for a more successful admittance to the market and acceptance by the fishing industry, governmental support, financial aid and greater awareness in the society about illegal practices in sea are a prerequisite.

Table 4.13. Inspections of biomimicry projects: Airlocker

	Inspiration by nature	Mimic biological forms/ processes/ systems	Mimic function rather than merely form	Learning from nature rather than bio-utilization	Interdisciplinary approach	Technological innovation	Energy efficient solution	Environmental friendly solution
Airlocker	+	+	+	+	+	+	+	+

4.3 The prospects for biomimicry in Iceland

The concept of biomimicry is largely unknown in Iceland, which somewhat can be explained by the fact that the discipline is relatively young. However, the examples discussed above show that biomimicry potentially provides interesting solutions and profitable products. The second aim of this research was to study how future application of biomimicry could be beneficial for the Icelandic society. When asked about the prospects of biomimicry in Iceland, most interviewees expressed the view that the use of biomimicry will expand, but at the same time they were hesitant in predicting the results thereof:

> ’I really don’t know if biomimicry will increase in the near future, although I find it more likely than not that people will start to look more into this possibility’ (BS).
>
> ’The development is fast and biomimicry will be one of the pillars that people will proceed with, but I do not know where it will lead us’ (HBJ).
>
> ’Doesn´t one just has to be positive and say that it will increase?’ (HJ).
>
> ’Perhaps, the underlying trend is that people are evolving in this direction and follow ideas from nature. In other cases, one sees both; the applications are only found in retrospect’ (TÞ).

Reynir Sævarsson and Sigurður Thorlacius at Efla see a great opportunity for biomimicry in the development of innovative solutions for wastewater treatment that are both cheap and simple and offer an affordable option for proper wastewater management by small communities in Iceland.

> ’I just know that such simple and efficient biomimicry approaches as we are now starting are solutions for the future and one has to get the opportunity to get them established. Someone must step up and say that we need to find new and inexpensive solutions to waste problems in Iceland and simultaneously be given the opportunity to test them. That is what we want to do. Then, others will follow’ (RS).

Recently (spring 2013), Sævarsson and Thorlacius were awarded funding from the Icelandic

Student Innovation Fund to explore suitable new ways for waste management in Iceland based on their concept of biomimicry. Noteworthy, this is the first time a project with “biomimicry” in the title or as a keyword is supported by Rannís (The Icelandic Centre for Research). Time will tell if this is the first of many projects with a “biomimicry label” to receive funding.

While the above-mentioned use of biomimicry for wastewater management actually comes forth from the motivation to move away from complicated and expensive technical man-made solutions to more natural ones, potential future biomimicry applications were connected by several interviewees to the increased possibilities for manufacturing as a result of contemporary technological improvements. This does not have to be in contradiction to each other as greater technical options may lead to more simple solutions:

> ’New production methods, such as 3D printing, allow material to assemble layer after a layer and give designers much more freedom. The object is no longer made exclusively from a mold, but can grow and hence designers can make things that are organically shaped’ (GG).
>
> ’Devices are getting smaller and smaller, so now we are approaching the situation that the technical attributes fit into the physical systems. The next challenge is the integration of both systems (FÞ).
>
> ’Technology will solve a lot of problems. But you need to use 21st century technology, not the 20th century solutions. The awakening in biomimicry is tightly connected to rapid advances in information technology. Improved software allows us to design things with high accuracy that was not cost effective before. Indeed, people start to look for answers from nature as they become able to simulate features of organisms. This is also a part of the discussion of sustainability; how we can become sustainable, how we can create renewable components.’ (ÓAR).

Interestingly, the founder of biomimicry, Janice Benyus, also shares this idea of a sustainable application of modern technology. In a lecture she gave at The Circular Economy 100 Annual Summit in London in June 2013, Benyus explicated *e.g.* how 3D printing reduces waste because it builds to shape, similar to nature, while current technology is of a subtracting nature cutting and grinding to take away parts from a bulk material, leaving much waste behind (Benyus, 2013).

So, if technology is (becoming) available, what about the position biomimicry has with regard to general interest and financial funding in Iceland? Here, the interviewees were less optimistic:

> ’Unfortunately, we will have to look to the far future before biomimicry will be a common application. The facts suggest that people do not do anything until it is absolutely necessary to exert’ (KRÞ).
>
> ’When you move away from the industrialized production processes, small enterprises and individuals can use creativity to make things. Suddenly, people can create what they see in nature. This is a basis for biomimicry. I just think that this is not happening so much’ (ÓAR).
>
> ’The reason why biomimicry projects are not more profound within my research is not because of a lack of interest on my behalf; rather because of lack of interest from

others. There must always be a practical application for funding and it is difficult, almost impossible, to start something alone' (RU).

It seems apparent that progressing biomimicry applications is dependent on more awareness and attitude changes. One of the revolutionary aspects of biomimicry is its interdisciplinary approach. This consists of consultations between disciplines and realization of well-thought strategies aiming at sustainable solutions. This approach may clash with the current educational system, which was heavily criticized by several interviewees:

> 'You are trained to be a lawyer, biologist, or geologist. Today, the connection between disciplines is much more important. That is what is lacking and what businesses are asking for. Similar to information technology, biomimicry needs to touch many fields and requires much more integration than the current educational system is giving' (ÓAR).

> 'Old thinking is prevailing in the education system. All sectors have changed dramatically the last 50 years, but one of the few that has not changed is education. At the university level, we have the duty to make sure that when students graduate they have some understanding of their position in society; that they can reflect upon our position in the world and the future. With education, you can change the mentality and fully implement these ideas, and we should teach this on the same basis as we use mathematics and philosophy to explain science. What we actually need to combat is professional narrow mindedness. The system has already created too much "professional idiots". Science has largely isolated itself from the remaining of the society, using language more or less no one else understands' (KRÞ).

A practical example of lack of interactions between departments was given:

> 'At the department of engineering almost nothing is taught about biological processes. You have to chase it up yourself. Sometimes connection is formed by people who know people, but there is no sign that the departments of engineering and biological science are really talking together - or any other departments, for that matter' (RU).

The necessity to change the prevailing attitude outside academia was also mentioned:

> 'There is too little development within the building industry in Iceland. We do not take time to sit down and rethink how houses are build; instead it is always a copy and paste of the previous design' (BM).

> 'We do not achieve sustainable fishing as long as people always feel the need to expand the fishing gear more and more to increase their margin. As long as people think it's okay to spend millions of IKR on oil for each fishing trip and while businesses are run such that a small percentage drop results in finishing off the industry not much will happen. For something to do occur, the changes must come from inside. We need a policy – and not only in fishing matters, but in all resource management' (EÓS).

> 'It is a very strong in our profession of engineering that if something is difficult to measure then it is rejected. If you cannot get a machine that cleans the wastewater and measure the results thereof, then everyone just panics. Still, it is evident that nature is fully capable of cleaning the water in ponds via its own chemical factory' (RS).

The people responsible for nature-inspired projects like the Light trawl, Airlocker, and Fin drive propulsion, agreed on that funding their project has been challenging in the past:

> ’It was a great struggle to get the idea through. First with my supervisors and later at the Technology Development Fund’ (HJ).

Financial aid of biomimicry projects in the time to come will be dependent on political will. Radical changes are not expected to take place: ’Minor gradual changes are more likely to happen than sudden transformations’ (SB). In this respect, is interesting to look to the development in Europe, where things may be moving more quickly into the direction of promoting biomimicry projects. Icelandic scientists actively participate in applying for European funding and next year, 2014, we will see the start of the European Union’s new funding program for research and innovation, called Horizon 2020. Noteworthy, at the Industrial Technologies 2012 Conference, a meeting supported by the European Commission Directorate General for Research & Innovation, biomimicry was qualified as one of the 10 hot topics of innovations. The meeting was visited by more than 1000 representatives of the fields of cutting-edge nanotechnology, advanced materials, and innovative production technologies, discussing how to develop Horizon 2020 in order to ensure that the program supports industrial innovation (www.industrialtechnologies2012.eu). The emphasis on biomimicry by these important players foresees its integration into future European Commission´s strategy towards sustainable use of renewable resources (http://ec.europa.eu, 2012). The role biomimicry plays within the European policy will without doubt influence future Icelandic research projects and innovations, only the time frame for that to happen is uncertain.

5 Discussion

The thesis defines the concept of biomimicry and analyzes its current status in Iceland by interviewing various players active in research, academia, engineering and design. Biomimicry is a relatively young discipline that aims at environmentally sound businesses. Its fundamental concept was put forward in the last decennia of the twentieth century by the American biologist Janine Benyus. Since then, the idea behind biomimicry has increasingly gained recognition, first within the United States and more recently worldwide. The propagation of biomimicry is mainly the result of the activities by Benyus and co-workers of Biomimicry 3.8. In connection with the Missoula, MT based organization, more than 30 regional networks of biomimicry have emerged both inside and outside USA. The most active offices are found in seven different US cities, and in Mexico, Canada, Netherlands, and South Africa (http://biomimicry.net). Furthermore, Biomimicry 3.8 consults and collaborates with numerous multinational companies regarding sustainable design and Benyus is a highly appreciated speaker on international conferences, including the prestigious TED Conference (www.ted.com). From the literature search of this thesis, it can be observed that in the 16 years since the publication of the book "*Biomimicry: Innovation Inspired by Nature*" the concept has obtained a certain standard by academia, architects and designers in the USA, Europe, and elsewhere, as well as is moving its way into the board rooms of companies and decision makers. Still, Benyus´ theory is largely unknown in Iceland. A possible explanation for this could be a relative late environmental awareness in Iceland compared to the neighboring nations (Sigurbjörns-Öldudóttir, 2013). Furthermore, an increased interaction between biological, technical, and creative fields seems needed for a successful integration of biomimicry into Icelandic businesses.

An overview of the background of biomimicry and other green and bio-inspired concepts that are linked with biomimicry is presented in this thesis. Undoubtedly, biomimicry somewhat overlaps with ecological design, green chemistry, cradle to cradle, and bionics. However, it can be argued that the outstanding quality of biomimicry is to integrate bio-inspiration and innovation for sustainable design and businesses. Its driving force is the fundamental love of the beauty of living systems and the urge of changing how material is synthesized, used and wasted. Like traditional environmental movements, which have roots in the nature preservation movement of the 19th century and the nature conservation movement of the early 20th century, biomimicry aims at maintaining biodiversity. Furthermore, biomimicry incorporates the principle of sustainable development, which integrates environmental protection and human and economic development. The cornerstone of the design philosophy of biomimicry is to take inspiration from natural designs and processes to solve human problems, instead of building on what can be extracted from nature; "*to use nature´s ideas, not necessarily nature´s material*" (Benyus, 2013). As such, biomimicry is a true environmental discipline, aiming at sustainable use of resources. Still, biomimicry has obtained criticism, also within the environmental field. According to the Australian philosopher Freya Mathews, the success of biomimicry can be hampered by its relatively *ad hoc* approaches and its need of a deeper philosophy (Mathews, 2011). It is true that biomimicry is more a pragmatic discipline rather than a deep philosophical field of environmental study. Whether that makes it less likely to be successful for environmental benefit is however questionable. Biomimicry has also strong roots in science and technical field, propagating innovation and high tech solutions. From those sectors, criticism can also been heard. For instance, from the field of material science the view has been put forward that biomimicry and other bio-buzzwords have the pitfalls of assuming that nature's designs are always the best (Reed et al., 2009). Clearly, biomimicry is rapidly evolving and criticisms like these are therefore not carved in stone. Literature research revealed no evidence that Benyus or other staff of the Biomimicry 3.8 Institute participate in such debates. They seem to prefer to keep on explaining their ideas and providing increasing amount of biomimicry examples. This typically represents the pragmatic character of biomimicry. Currently, the main focus of the Biomimicry 3.8 Institute is to train, connect and equip people with biomimicry tools. Biomimicry 3.8 organizes study programs, conferences and workshops, consults companies, maintains global networks for education and experts, and provides an open database with ongoing list of biomimicry ideas organized by design and engineering function (http://biomimicry.net).

In the US and Europe, biomimicry is moving its way into various levels of the society. It is already present in design and engineering but gradually is also entering policymaking and the boardrooms of both small and multinational companies. Harvard University has initiated the Wyss research institute, focusing completely on bio-inspired solutions. The concept of biomimicry may not be mainstream yet, but it has a rapidly growing group of supporters, presumably because it converges with the urge felt by many in these countries that recent human behavior is a threat to future life on earth. Apparently, biomimicry ideas are flourishing most in circles enlightened about environmental concerns and those caring about sustainability. Issues of sustainable development have already made their way into international agreements and are on the table of global leaders everyday now. Having "innovation inspired by nature" pointed out as one of the ten hot topics of smart solutions to improve the European innovation environment during the Industrial Technologies 2012 Conference (www.industrialtechnologies2012.eu) could therefore be of a significant importance for the development of biomimicry in Europe.

It is not easy to define biomimicry in simple terms. The philosophy behind it can be viewed as a revolutionary concept, but at the same time refers in many ways to common sense. It has synergy with several other green movements, as explained in this thesis. It is build on ancient values but relies on high tech methods and intelligent solutions. It is closely associated to entrepreneurship and innovation and aims at practical and profitable solutions, but is build up from an idealistic vision about sustainability and biodiversity conservation. Biomimicry brings to life a new type of profession: "the biologist at the design table". A biologist, who works with product designers, architects, engineers, chemists, material scientists, and city planners to persuading them to look to the natural world for inspiration to do new things. This emphasis on the interdisciplinary collaboration between biological scientists and designers is very strong in the biomimicry concept, compared to other environmental disciplines.

The two research questions dealt with in this thesis were centered on the present status of biomimicry in Iceland and its potential future importance. To answer those questions, interviews were performed with representatives of academia and industry. The largest part of this thesis deals with the first research question; the present status of biomimicry in Iceland, while answers to the latter research question on how biomimicry can benefit Icelandic society in the future are less obvious. In general, the interviews revealed that biomimicry is largely an unknown concept in Iceland and that true biomimicry applications in Iceland are relatively rare. However, the attitude towards the idea behind the concept was positive by all interviewees, once they learned about it. With that in mind, increased focus on biomimicry solutions in the future can be anticipated. Such potential change must start with increased awareness about biomimicry and will require structured approaches. Biomimicry is an emerging discipline in US and several European countries and the current development there could find followers in Iceland. To achieve that, more information about the concept; its multi-disciplinary characteristics; its associated economic benefits in terms of more efficient processes; and its sustainable solutions, is clearly needed. Effective biomimicry solutions will presumably increase with stronger environmental concern in Iceland. Furthermore, stimulation for innovative material techniques and environmental friendly processes is required. Finally, integration of diverse fields; technical, intellectual and production-wise, is necessary.

The thesis analyzes ten examples of potential biomimicry applications in Iceland in some detail. These cases show a representative status of biomimicry in Iceland, although it should be mentioned that this list is not conclusive for biomimicry examples in Iceland. The interviewees where carefully chosen based on their participation in potential biomimicry projects, knowledge on the subject, and/or having an overview on the current status in academia and industry. Obviously, the outcomes may be dependent on the choice who where interviewed. However, the results present not merely the personal view of the interviewees, but a combination of multiple interviews, categorized around common topics that where analyzed along pre-developed themes. The reason to finalize the interviews after having talked to 22 people was mainly taken on basis of practical reasons and time frame, but it was evident that as the number of interviews grew, less new information about the status of biomimicry emerged. Therefore, the researcher is confident that the material gathered during the study provides sufficient material for substantiated analysis on the current status of biomimicry in Iceland.

The biomimicry examples studied are very diverse but they are all innovative. Some of these examples are small and still in an experimental phase, while *e.g.* the company Össur relies on biomimicry for most of its products. The projects all mimic and/or are inspired by nature. At least five applications: Urban water management, Industrial symbiosis, Pressure retarded osmosis, Light trawl, and Airlocker result in environmental-friendly solutions. However, the perception that these approaches can be considered a part of an environmental platform was largely absent from the answers of the interviewees. Even though performing biomimicry, the interviewees were unaware of the philosophy of Benyus and the presence of the Biomimicry 3.8 Institute. The structured approach of the design process, recommended by the biomimicry thinking: Scoping – Discovering – Creating – Evaluating (depicted in Fig. 2.4) was apparently not applied in any case. Still, the approach by the interviewees towards biomimicry was positive and, overall, the idea that the number of biomimicry applications will increase in the future prevailed.

As mentioned earlier, various definitions of biomimicry are present in the literature. Also, different views on what biomimicry includes were observed amongst the interviewees. The fact that most people in the beginning of the interview were uncertain of the definition of biomimicry and how to classify a project as a biomimetic one, stresses the importance of the method of an one-to-one semi-open interview, as performed in this study. Only gradually, during the interviews more awareness of the matter became apparent and hence more details became available. Other methods, like questionnaire or e-mail requests, would not be as successful in collecting information. This became evident in the e-mails sent to the seven managing directors of University Research Centers throughout the country. This approach did not reveal any possible biomimicry projects, although several of the examples mentioned in the thesis are present outside the capital area. Presumably, the observed responses were influenced by the method. One cannot exclude that the knowledge of these and other biomimicry projects would emerge by the managing directors during a conversation.

However, the lack of positive responses about local biomimicry projects tells a story about the position of biomimicry in Iceland. Apparently, the comprehension on biomimicry and its potential is not strong.

The interviewees made several suggestions about plausible reasons why biomimicry is an uncommon practice in Iceland. Most noteworthy, zoning of the educational system, lack of funding for experimental research, and lack of structured governmental policy were put forward by the interviewees. Segmentation of the educational system and a lack of communication between different scientific fields emerged from many interviews as an Icelandic reality that hampers the creation of an interdisciplinary approach as suggested by the founders of biomimicry. Some categorized the University system as old-fashioned and not in touch with the need of businesses and innovation. Although such discussion is beyond the scope of this thesis, it is the view of the researcher that integration of disciplines within Universities and interaction with industrial activities outside the educational institutes will profit the progress of new and exciting ideas, including biomimicry. Lack of funding experimental projects with uncertain outcome may, at least partly, be responsible for the relatively small number of biomimicry projects. Funding of fundamental research, which more often than not forms the basis of true innovation, is difficult to obtain in a system that is built up by a couple-of years support each time. On the other hand, biomimicry projects are hands-on and solution oriented. Therefore, they should have a reasonable chance of getting funded, as long as they are well substantiated. In connection with the third option; lack of structured governmental policy one can think of lack of strategies, not only for environmental matters, but also for social and economic issues and as such this argument relates presumably to ever changing political reality at each time. A long-term vision is less likely to occur in instable political and economic periods and a stable governmental policy aiming at sustainable development and likewise financial support would clearly pave the way for biomimicry, as biomimicry pursues sustainable solutions. It is a relatively new discipline, and as such requires sufficient financial input for its introduction, for more research, and for the start-up of innovative companies in this field. Having said that, it is equally important that the infrastructure of biomimicry projects becomes more organized. A systemic design centered on the design principles explained by Benyus and co-workers is lacking in Iceland. It is the opinion of the researcher that integration of life principles to the early stages of the design process where designers, biologists, and project planners ask themselves the question: “How would nature solve this?” and subsequently aim at sustainable and environmental friendly solutions at all level of the process is vital for effective biomimicry undertakings. Such an approach will deepen the understanding of the biomimicry concept, strengthen the involvement of science and businesses to it, and increase the success of biomimicry projects.

There are multiple benefits of increased assimilation of biomimicry into academia and industry in Iceland. Biomimicry aims at sustainable businesses and restores the connection between people and nature. The need for environmental sound solutions is becoming stronger, here in Iceland as elsewhere, and biomimicry can contribute to such solutions. Biomimicry is a revolutionary concept, which makes us look differently at the material processes and material use. It tells us to learn from 3.8 billion years evolution of living organisms on earth and use that knowledge for innovative solutions. It propagates nature´s way of building to shape, resulting in reduction of waste. Those interested in developing and performing biomimicry can amongst other things be inspired by the following argumentations:

- Biomimicry aims at simple and economic favorable solutions that avoid the requirement of complicated man-made structures, with examples such as waste management and urban water management.

- Biomimicry aims at energy efficient solutions. It makes use of renewable energy resources, like water (*e.g*. power by pressure retarded osmosis and tidal power inspired by thunniform swimming species), wind (efficient wind power systems mimicked by the irregular bumps on the flippers of the humpback whale), and sunlight (solar cells inspired by the photosynthesis of green plants). The use of these renewable energy sources instead of fossil fuel is an important step for combating climate change.
- Biomimicry aims at environmental favorable solutions such as reducing the use and emission of polluting chemical components. Examples are the self-coating paint without any detergents, which is inspired by the super hydrophobic surface of lotus plants, the flexible carpet tiles with their simple installation system that prevent the use of glue, and biomimicry solutions inspired by microorganisms capable of utilizing H_2S, CO_2 and H_2. The last example is a promising method to clean unfavorable emission of Icelandic geothermal power plants and turn these substances into valuable products.
- Biomimicry aims at common-sense solutions that people can relate to. This may be beneficial for funding like Össur has already experienced in several international collaborations (see section 4.2.4).
- Biomimicry aims at efficient use of resources, mimicking natural ecosystems, wherein everything gets recycled. Industrial symbiosis, a subset of industrial ecology, which has a particular focus on sharing of services, utility, and byproduct resources to reduce costs, shares this philosophy. Interestingly, one of the focal points of innovation in Iceland concerns more efficient utilization of natural raw material. Biomimicry applications and projects have a great potential in this area.
- Biomimicry aims at reduction of material use. Biomimetic design based on bone and tree structures show that lighter structures can be equally strong. Economic benefit is predictable for architecture and industrial design if rethinking design along biomimetic principles.
- Biomimicry is a modern concept that relies on advanced technology and embodies innovation and creativity. Biomimicry solutions flourish by recent improvements in information- and nanotechnology and at the same time contribute to the sustainability of these technologies by providing environmental friendly applications.
- Biomimicry is the business link to biodiversity. Biomimicry can justify and increase research of the largely unknown marine biology around Iceland as well as the biology of sensitive terrestrial ecosystems. More knowledge of bio-organisms and ecosystems makes innovation and technical progress possible and at the same time supports protection management of important areas and species.
- Biomimicry fits into the framework of the new Horizon 2020 and the emphasis of the European Union on sustainable development and renewable energy policy. Noteworthy, biomimicry was rated as one of the ten hot topics for innovation at the Industrial Technologies 2012 Conference. This adds to the odds of obtaining European funding for those Icelandic researchers and scientists working on biomimicry and simultaneously will increase the awareness on biomimicry in Iceland.

This thesis is the first outline of the status of biomimicry in Iceland. As the discipline is worldwide in a rapid development, the researcher realizes that the current discussion can only be a snapshot of the situation as it emerges in the year 2013. Future changes will take place and how biomimicry in Iceland will evolve depends both on international development and domestic factors. Prompt improvements in electronica, nanotechnology, and 3D printing make changes in how we design, produce, and discard stuff plausible. Furthermore, the urge for reducing human impact on the environmental is becoming increasingly critical. These are international considerations but play a role in Iceland as well. In the coming years, the fate of those Icelandic biomimicry projects described in this thesis will become visible. Their success may influence the future progress of biomimicry in Iceland. However, incidental successes of individual projects are not sufficient. Coherent awareness of biomimicry as a concept by those executing biomimicry projects, as well as policy makers, is more likely to fuel its prospective. As biomimicry in Iceland is still at early stages of development, much can be gained in the coming years to improve its significance. Future research should follow carefully international development and introduce well-proven nature´s ideas for economic, social, and environmental advantages in Iceland.

6 Conclusion

In conclusion, the data collected in this thesis shows that biomimicry in Iceland is just emerging. So far its importance in Icelandic academia, engineering, design, and businesses is somewhat limited and biomimicry projects are incidental. No structural approaches or policy are available. On the other hand, the concept behind biomimicry seems appealing to most interviewees and all agreed on that biomimicry has a potential benefit for the future. The advantage of biomimicry for the Icelandic society relates to stronger environmental awareness, more efficient use of natural resources, and innovative applications. Biomimicry promotes interdisciplinary research and can result in economic favorable solutions.

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Appendix I Short definition of biomimicry

The e-mails sent to potential interviewees included a short introduction to biomimicry (in Icelandic)

Örstutt skilgreining á lífhermun

Á þeim 3.8 miljörðum ára frá því að líf kviknaði á jörðinni hafa lífverur þróað með sér form og ferli sér til framdráttar sem gera þeim kleift að takast á við hættur sem að þeim steðjar. Ef vel er að gáð geta þessi form og ferli verið umhverfisvænar lausnir fyrir mörg þeirra tæknivandamála sem við mennirnir stöndum frammi fyrir. Kosturinn við að nýta sér þær lausnir sem lífverur hafa tileinkað sér er t.d. fólginn í að (1) ferli lífvera leiða til hringrásar í stað óhemjumikils úrgangs, (2) lífverur nota vatnslausnir í stað mengandi leysiefna og (3) framleiðslan fer fram við tiltölulega lágt hitastig í stað orkukrefjandi meðhöndlunar efna við hátt hitastig.

Lífhermun (e. *biomimicry*) byggir á þeirri hugmyndafræði að náttúran sé innblástur fyrir vísindamenn, hönnuði og verkfræðinga. Reyndar tengist lífhermun öðrum hugtökum eins og "græn efnafræði" (e. *green chemistry*), "frá vöggu til vöggu" (e. *cradle to cradle*) og "vistvæn verkfræði" (e. *ecological engineering*). Lífhermun tengist einnig mjög náið hugtökum eins og "*bionics*" og "*biomimetics*" og stundum eru þessi hugtök: biomimicry – bionics – bimimetics notuð sitt á hvað.

Lífhermun byggist á því að maðurinn tileinki sér náttúruleg form, ferli og samskipti lífvera í vistkerfum og yfirfærir þau sér til hagsbóta. Náttúran er allt í senn fyrirmynd, leiðbeinandi og mælikvarði ("*model, mentor and measure"*) fyrir sjálfbæra hönnun. Kjarni þessarar hugsunar er að við mennirnir lærum af miljarða ára langri þróun lífs á jörðu og noti til þess okkar eigin þekkingu, færni og tæknikunnáttu. Mikil áhersla er lögð á samvinnu vísindamanna, tæknisérfræðinga og hönnuða í þessu samhengi.

Upphafsmaður og helsti talsmaður lífhermunar er bandaríski líffræðingurinn Janine Benyus sem skrifaði bókina *Biomimicry: Innovation Inspired by Nature* árið 1997. Benyus hefur bent á að hægt sé að flokka lífhermun í þjú stig:

(1) Nota náttúruleg form sem fyrirmynd.
(2) Nota náttúruleg ferli sem fyrirmynd.
(3) Nota vistkerfi og samskipti innan vistkerfa sem fyrirmynd.

Hún bendir á að þegar vara er hönnuð eingöngu samkvæmt fyrsta stiginu leiðir það ekki sjálfkrafa til sjálfbærra lausna. Hins vegar er á öðru stigi farið að huga að því hvernig varan er búin til með sjálfbærni að leiðarljósi, til dæmis með því að nota ekki eiturefni eða orkufrek framleiðsluferli. Á þriðja stigi lífhermunar er síðan allt lífsferli vörunnar skoðað. Hönnun hennar og flutningur, viðskipti með hana og endurvinnsla við lok lífstíma; allt skal þetta vera hluti af kerfi sem í heild sinni miðar að því að koma í samt lag aftur og viðhalda auðlindum jarðar, líkt og náttúruleg hringrás vistkerfa gerir. Þriðja stigs lífhermun hefur stundum verið nefnd *djúp lífhermun*.

Þó svo að lífhermun og sú hugmyndafræði sem hún byggir á njóti æ meiri vinsælda erlendis er hún næsta óþekkt hér á landi. Þó má telja líklegt að ýmis konar starfsemi sé til staðar innan menntasamfélagsins og atvinnulífsins sem tekur á einn eða annan hátt mið af þeim gildum sem lífhermun stendur fyrir. Vistvænar byggingar eru reistar sem hugsanlega byggja á náttúrulegum formum og ferlum; lögð er áhersla á klasamyndun bæði á þekkingarsviði og í framleiðsluferlum sem ef til vill má líkja við vistkerfi þar sem samlífi ólíkra tegunda er báðum aðilum til hagsbóta; unnið er að umhverfisvænni orkunýtingu sem leiða má líkum að auki skilvirkni í líkingu við þá staðreynd að í náttúrunni er úrgangur einnar lífveru orkugjafi annarrar; og svo mætti áfram telja.

Appendix II Interview questions

Viðtalsspurningar

1. Þekkir þú hugtakið lífhermun?
2. Á hvaða hátt vinnur þitt fyrirtæki / þín stofnun / þinn rannsóknarhópur að lífhermun?
3. Hvaða dæmi úr þínum bransa / af þínu fagsviði getur þú nefnt mér um verkefni sem snerta lífhermun á einn eða annan hátt?
4. Sérð þú fyrir þér að lífhermun geti nýst þínu fyrirtæki / innan þíns fagsviðs?
5. Sérð þú fyrir þér að lífhermun geti hafa efnahagslegan ávinning hjá þínu fyrirtæki / á þínu fagsviði? Hvernig? Einhver annar ávinningur sem þér dettur í hug frekar en efnahagslegur?
6. Hvað finnst þér spennandi við lífhermun fyrir þitt fyrirtæki / þitt fagsvið?
7. Hvaða tækifæri sérð þú fyrir lífhermun hjá þínu fyrirtæki / í þínum bransa / á þínu sviði?
8. Veist þú um einhver ákallandi verkefni eða áskoranir í þínu fagi sem erfitt er að leysa í dag en hugsanlega væri hægt með því að nýta sér þekkingu frá náttúrulegum formum eða ferlum?
9. Setur þú lífhermun í samhengi við umhverfisvernd? Er lífhermun umhverfisvæn leið?
10. Hvað mælir helst með því að innleiða lífhermun í tækninýjungar og hönnun?
11. Getur þú bent mér á einhvern sem gott væri fyrir mig að tala við um lífhermun?