Learning from Nature?

A framework to assess the sustainability of biomimicry product design applications

Megan Connolly

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LUCSUS
Lund University Centre for Sustainability Studies

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Abstract

Products and systems form the bridge between production and consumption, helping to shape our society and lifestyles. Biomimicry uses design principles based on those seen in nature, aiming to emulate the natural sustainability seen from the 3.8 billion years of life on earth. However, there is no current measure to determine how sustainable applications of biomimicry actually are. The aim of this study was to develop a sustainability framework to evaluate the sustainability of biomimicry innovations. Innovations would be considered in regards to their technocentric value – their ability to reduce the impact of the innovation itself, and their ecocentric value – their ability to change dominant consumption behaviours and values. Cases of biomimicry applications were taken from the Biomimicry Institute database and subject to thematic analysis using the framework method. Combined with a systematic literature review, typologies of the types of biomimicry applications were developed and the current applications of biomimicry mapped onto the framework. The first typology is *Business as Usual* with innovations focuses on improving existing products giving little attention to either techno- or ecocentric aspects. *Behaviour Solutions* focus on changing how products are consumed, and *Technology Solutions* focus on the product itself to reduce the impact. Finally, *Sustainable Futures* comprise the innovations with the greatest sustainability potential, giving equal consideration to technology and behaviour whilst using radical new design. Currently, most biomimicry applications are contributing somewhat towards achieving sustainability but do not consider the behavioural aspects to have a greater impact. Whilst biomimicry still has some theoretical flaws to address, it has the potential to contribute towards sustainable design. The framework can be used to guide and assess individual biomimicry innovations in their development to help achieve the maximum impact.

Key Words: Biomimicry, sustainable design, evaluation, consumption, technology

Word Count: 10,543

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Corona definitely made the thesis process much more challenging – working in isolation is clearly not my strong suit and this process made me realise just how much energy and enthusiasm I get from my friends and those around me. So, congratulations to my fellow LUMESians for working against the odds and thank you for all the energy and enthusiasm you have given over the past two years, and continue to give for our future endeavours. Studying and working towards sustainability comes with a large emotional toll and fear of the future, but the spirit of LUMES fills me with hope.

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1 Introduction

Achieving a sustainable future will require a considerable shift and overhaul of the current structures of modern society. Economic, power and social systems will have to be redesigned if we are to move away from an unsustainable, ever-growing, carbon-based economy. There is no single product, however well designed, that will create this transition to a sustainable future alone and yet our lives are filled with products which we use passively or actively, every second of every day. Product design helps to shape how we consume, produce waste and use energy. It helps shape how we live our lives.

A new, sustainable world requires a new way of living within it, and with that new products and systems. Nicolis and Prigogine (1989) call for "new innovations" as one aspect to prevent the downfall or "fossilisation" of society (p. 238-242). If we accept that our old way of thinking, of designing our society, doesn't work we will need new principles that will guide this innovation process. Sustainable design is a broad term covering many different practices, including biomimicry. The fundamentals of biomimicry call for us to live by the laws and principles seen in nature which have a proven sustainability of 3.8 billion years. Evolution has resulted in solutions to every problem faced in the natural world, the designs which proved beneficial to life persisted whilst those that were not are now fossils. Biomimicry looks to the design seen in nature and uses this thinking to help solve human problems sustainably. One example of biomimicry is Whale Power (https://whalepowercorp.wordpress.com/), an innovation based on the flippers of blue whales. Lumps, called tubercles, can be found on the leading edge of the flipper and have been found to allow for increased manoeuvrability of these huge animals. When this feature was added to a wing simulation model it was found to both reduce drag and increase lift, a highly desirable design feature (Watts & Fish, 2001). This technology has since been adapted by Whale Power, applying it to devices such as ventilation fans reducing their energy consumption and to windmill blades to increase their efficiency (Fish, Weber, Murray, & Howle, 2011).

Biomimicry envisions a world in which structures and systems at all levels and scales take inspiration from nature and ensure we live within safe natural limits. It has been applied theoretically to macrostructures such as our economic system (Collins, 2014) and also to the design of entire cities and urban living (Zari, 2018) as well as individual products or services. However, the vast majority of current applications remain within the product design level (Ceschin & Gaziulusoy, 2016).

1.1 Relevance to Sustainability Science

Fundamentally, sustainability science seeks solutions through interdisciplinary approaches to the complex sustainability challenges we are facing today and in the future (Jerneck et al., 2011). It focuses on the relationship between nature and society and how they shape one another, recognising the immense complexity of the related sustainability challenges and seeking solutions through the collaboration between not only different research disciplines but crucially between academia and practitioners (Clark & Dickson, 2003).

Spangenberg, Faud-Luke, and Blincoe (2010) have criticised the sustainability discourse for excluding design and ignoring its role in helping to achieve sustainability. In some cases, sustainable design approaches have even been framed as part of the problem. This may be due to the relationship between design and consumption, with an underlying assumption that design does not challenge our consumption systems, instead encouraging increased consumption by making products more desirable. It also may be due to the fact that design, especially on the product level, is seen as working on too small a scale, not being powerful enough to target the true problems of power, inequality and consumption. However, this forgets that design forms the bridge between production and consumption and so has a vital role in changing how these activities occur and their impact. Smart product design can be used to help empower communities, decentralise our systems and completely change our consumption patterns. Sustainable design has the capacity to help change the world we live in and over the past few decades there has been a large increase in different types of sustainable design, for example eco-design, cradle-to-cradle and emotionally-durable design (Ceschin & Gaziulusoy, 2016).

Biomimicry is a solution-orientated sustainability practice, seeking a new perspective on the relationship between nature and society (Mead & Jeanrenaud, 2017). It forces the traditional methods of production and consumption to be looked at and relies heavily on the knowledge of multiple scientific disciplines, namely life scientists and engineers, creating solutions which are being applied today. (Baumeister et al., 2014) It has already been applied broadly using different interpretations of sustainability. Some applications wish to leave a net positive ecological impact, whilst others aim to simply reduce the impact of existing technologies. Some applications focus on completely changing the consumption relationship, whilst others aim to improve the efficiency of existing products allowing them to seamlessly enter our lives. However, as with all sustainability approaches, there is no promise of sustainable results. Therefore, a crucial part of any solution is critical review to ensure it delivers the promised results.

1.2 Research Aim and Questions

Biomimicry takes ecological laws and uses them to create naturally sustainable solutions. However, the process is not as prescriptive as other design methods; not all the principles have to be followed and they can be interpreted and enacted in different ways (Baumeister et al., 2014). Biomimicry has been criticised for its approach to achieving sustainability, specifically that having such loose metrics makes it hard for designers to consider and implement sustainable practice (Faludi, 2019). This results in variable outcomes, two biomimicry responses to the same problem are likely to produce different solutions. For this reason, whilst biomimicry aims for sustainable solutions there is no guarantee of the outcome. Biomimicry runs the risk of naively being used as a label which assumes guaranteed sustainability with it, whilst delivering questionable results, or at worst becoming yet another form of greenwashing (Mathews, 2011).

Whilst the principles of biomimicry are intended as a new philosophy embracing a new way of thinking in practice, there are few examples of it being applied to larger systems thinking yet. Therefore, this thesis will focus on product level innovations.

The overall aim of this research is to critically evaluate the sustainability of biomimicry product innovations. This will be achieved by answering the following research questions.

RQ 1: How can the sustainability of biomimicry innovations be evaluated?

The current evaluative approach for biomimicry simply calls for us to use *nature as measure*, positing that we ask if nature would have come up with the same solution and comparing the results (Baumeister et al., 2014). This leaves substantial room for interpretation and provides no real answers as to how sustainable a solution it is. Current practitioners of biomimicry are forced into taking a very loose approach to the evaluation of sustainability, most just using their own personal perception as existing evaluation tools for sustainable design, such as life-cycle assessment, do not provide meaningful feedback when applied to biomimicry (Mead & Jeanrenaud, 2017). Therefore, it is crucial to be able to critically evaluate the sustainability of design applications to determine how useful the field is for achieving sustainability, and to provide guidance to achieve more sustainable results when being applied. Furthermore, creating an evaluative method helps to create accountability for practitioners, ensuring sustainable action can be achieved.

RQ 2: What typologies of biomimicry product design currently are there?

At present, all biomimicry innovations are viewed somewhat equally. Innovations can be classified based on the type of nature they take inspiration from, either form, processes, ecosystems, however this does little to describe the sustainability potential of an innovation. Being able to create typologies, and linking these typologies to degrees of sustainability, allows for common features to be identified and help distinguish the similarities in the applications which are more successful than others. These notable features can then be factored into the development of future biomimicry innovations.

RQ 3: How sustainable are the current applications of biomimicry in product design?

Once a method to evaluate the sustainability of biomimicry approaches is available, it is useful to be able to understand the state of the field at present. This can indicate how biomimicry is currently being understood and approached, giving an indication for which areas of the concept need to be focussed on the most. Having knowledge of the state of biomimicry sustainability today indicates where it needs to go in the future.

2 Biomimicry

Biomimicry is an approach to design based on "the conscious emulation of life's genius" (Benyus, 1997 p. 2). It can be more formally defined as "learning from and then emulating natural forms, processes, and ecosystems to create more sustainable designs" (Baumeister et al., 2014). The entire philosophy, formulated by Janine Benyus, is built upon the understanding that 3.8 billion years of evolution has led to the best design solutions to allow life to prosper and sustain itself. These designs are successful not because they work in isolation, but because they work within and are adaptive to the systems of life they are intertwined and dependent upon. These successful designs share common features which have been identified to produce the principles biomimicry is built upon (Benyus, 1997).

A key feature of biomimicry is its aim to achieve sustainability. This is based on the understanding that with 3.8 billion years of life, nature has proven its capacity to sustain complex life. In nature, the complex web of ecosystems ensures that life lives within its limits, with any overuse eventually resulting in the collapse of that species. However, the assumption that by following the rules in nature results in sustainable results has been disputed numerous times and forms a large part of the critique of the concept (Faludi, 2019; Fisch, 2017; Mathews, 2019; Mead & Jeanrenaud, 2017). These concerns highlight that using these principles, in isolation, on individual products in a system based on different rules, cannot be assumed to yield the same results.

2.1 Life's Principles

There are patterns and consistencies within nature which generally dictate what will survive and what will perish. Benyus initially outlined nine commonalities, labelling them 'Life's principles' (Benyus, 1997) which have been continually adapted and modified by The Biomimicry Institute, resulting in the ten principles shown in Table 1 below, (Biomimicry Institute, n.d.). These principles reflect the commonalities seen in nature and prescribe the actions and considerations to be used by designers in their development process.

Table 1. The commonalities, or "life's principles" which are found in all natural design developed by the Biomimicry Institute (Biomimicry Institute, n.d.). These principles should then be applied to human design to create sustainable innovations inspired by nature.

1	Uses only the energy it needs and relies on freely available energy. *Nature uses low-energy processes due to the high costs associated with the access to energy.*
2	Recycles all materials *Materials and resources are broken down and used by another system or process, with zero waste.*
3	Is resilient to disturbances *The ability to continue functioning in the face of challenges, achieved with mechanisms such as increased diversity and decentralisation.*
4	Tends to optimise rather than maximise *Really valuing resources, using them in the most efficient manner rather than using more*.
5	Provides mutual benefits *Creating relationships with other systems or processes*.
6	Runs on information *The ability to respond appropriately to the environment by being aware of change, both internally and externally*.
7	Uses chemistry and materials which are safe for living beings. *Using materials and processes which do not cause harm, in human design this considers the sourcing, production and transport of materials as well as considering their end of life.*
8	Builds using abundant resources, incorporating rare resources sparingly. *The bulk of materials used should be readily available, meaning they are common and local. This also considers the minimisation of waste, using only exactly what is needed.*
9	Locally attuned and responsive *Being adaptive to local conditions and the changes. For example, if a resource becomes scarce or more common, or a business model which can adapt to changing regulation, economic functioning etc.*
10	Uses shape to determine functionality *Form can be used to maximise function without the increased use of resources, with the role of the form to support the function. In human design this means all aspects of the physical form of the innovation must be considered to support its functioning.*

2.2 Practising Biomimicry

When designers use biomimicry, they aim to use the principles of nature (Table 1), with the majority taking inspiration from one particular aspect of nature. Dependent on the aspect of nature being emulated, the mimicry can be classified into one of three categories -- form, process, or ecosystem -- requiring an increasing depth of knowledge and understanding of nature's principles (Baumeister et al., 2014).

Form is the simplest type, taking inspiration from just the physical structure of an organism or system. This form is mimicry is used by NBD technologies (https://www.nbdnano.com/), creating a fabric coating based on the hydrophobic patterning seen on the Namib Desert beetle.

The second application is *process.* This involves the mimicking of "a series of actions or steps taken in order to achieve a particular end" (Biomimicry Institute, n.d.) An example of this is the movement of cuttlefish mimicked by Undula Tech (https://www.undulatech.com/). Cuttlefish move through the water by undulating their fins, but energy can be harnessed by reversing this process. The company create an alternative method to capture wind energy by creating long fins, which undulate, powering a motor.

The final form is *ecosystem,* is the most complex and could be considered to be the highest form of biomimicry. This requires the study of how an entire system works, including the dynamics within it and how it acts as an entire unit. This has been applied to the treatment of wastewater by understanding the steps and interactions used for digestion in cows. EcoSTP (http://www.ecostp.com/) have created a powerless and chemical-free sewage treatment system by recreating the conditions of the cow's stomach and bacteria.

2.3 Confusion in the field

Biomimicry explicitly strives to achieve sustainable results by taking inspiration from nature. However, it is not alone in its use of nature's principles as inspiration and guidance for human design. These biologically informed principles (BID) include a range of design approaches which crucially "may or may not result in sustainable solutions" (Iouguina, Dawson, Hallgrimsson, & Smart, 2014, p. 203). The wide range of associated concepts are mapped in Figure 1, showing some design concepts linked to biomimicry (Lenau, Orrù, & Linkola, 2018) and their linkages within bio-inspired design (Fayemi, Maranzana, Aoussat, & Bersano, 2014). Their mapping shows the high degree of overlap with another design principle – biomimetics. However, the field of biomimetics developed earlier and independently to biomimicry. First coined in the 1950s, it has since been defined as the "use of mechanisms and functions of biological science in engineering, design, chemistry, electronics" (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006, p. 471). From this definition, it is clear that there is no intention for biomimetics to create sustainable solutions rather just innovations that are inspired by natural principles.

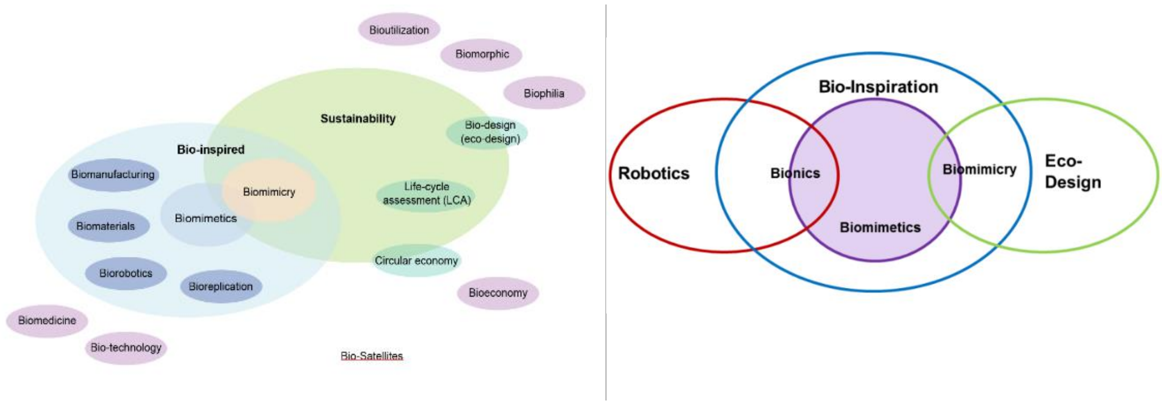

Figure 1. The relationship of biomimicry to other bio-inspired design approaches mapped from two studies. The left schematic taken from Lenau et al. (2018) maps concepts related to biomimicry in the Nordic countries, whilst the right from Fayemi et al. (2014) shows the relationship between bio-inspiration and different design approaches. Both find a considerable overlap between biomimicry and biomimetics, with biomimetics not aiming for sustainable results, unlike biomimicry. This blurring of concepts confuses the aims and can weaken the results of biomimicry.

Despite the key difference between biomimetics and biomimicry, there is some confusion in the field. A survey with 25 practitioners found that for 45% of the respondents the term "biomimetic" was synonymous with biomimicry (Iouguina et al., 2014). Even Janine Benyus herself uses the term interchangeably in her seminal book (Benyus, 1997). Furthermore, whilst there is no legal framework for biomimicry, the International Standardisation Organisation (ISO) has developed a standard for biomimetics. These standards are not legally binding but are often used as a marker and expectation of best practice. Within this standard for biomimetics the ISO, seeing it as a related concept, also define biomimicry making the distinction that biomimicry takes "nature as model to meet the challenges of sustainable development" whilst biomimetics just "solve practical problems" (ISO, 2005, p. 2). But with such a small mention, this distinction is yet again not made obvious and potentially increases the risk that biomimicry will be swallowed by biomimetics, losing the key differentiator of sustainability. This confusion between concepts has been identified as a barrier to their success by blurring aims and goals (Fayemi et al., 2014).

3 Background

Biomimicry explicitly aims for sustainable results; however, the concept of sustainable development is extremely broad creating a multitude of different responses and understanding of solutions. It was first developed in the late 80s with the Brundtland report defining it as “paths of human progress that meet the needs and aspirations of the present without comprising the ability of future generations to meet their needs” (WCED, 1987, p. 8). Sustainability challenges have since been identified as *wicked problems,* being highly complex with solutions that are not only unclear but are at risk of causing other unanticipated problems (Jerneck et al., 2011). It is impossible to ensure sustainable results if there is no way to measure or evaluate the interventions taken. However, as a wicked problem, the solutions are extremely variable making quantifying and assessing extremely difficult. Therefore, there is a need for evaluation tools to be developed specifically for different approaches to achieving sustainability.

Since its inception, there has been a considerable evolution in the concept, being applied broadly and entering everyday language. The vagueness of the concept allowed room for different interpretations, and from different ontologies and epistemologies emerged different understandings of what sustainability means and what sustainable solutions look like. Hopwood, Mellor, and O'Brien (2005) identify the breadth of views within the sustainability debate and classified them into three categories (Figure 2). The authors consider the views within the status quo category to have the lowest form of sustainable impact, these schools of thought working within and support the current system seeing business as a main driver for sustainable change. Transformative schools of thought, on the other hand, see our relationship with the environment as fundamentally flawed requiring a complete change in our socio-economic structures to be able to cause sustainable action.

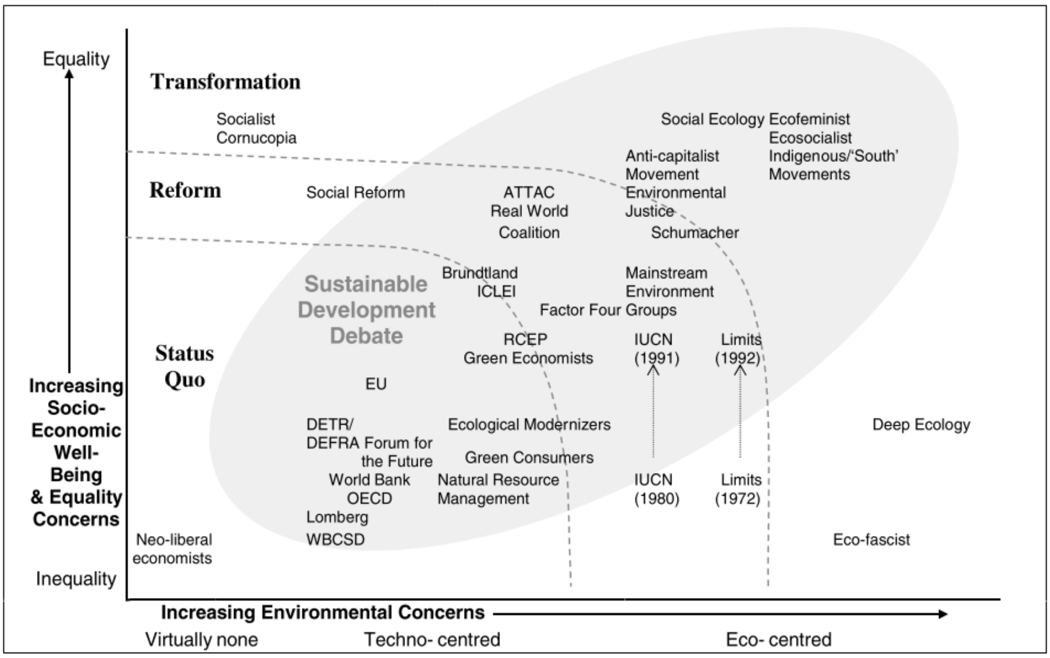

Figure 2. A map of the large number of interpretations of sustainable development through the consideration of environmental and social concerns from (Hopwood et al., 2005). These interpretations are built on different world views and result in different solutions are viewed.

I believe that radical, transformative change is required to achieve a sustainable future. With the IPCC report declaring we have just twelve years, now just 10 years, to remain below 1.5°C global increase (IPCC, 2018), there is simply no time for minor changes. Our current systems simply do not work and require radical change. Therefore, this thesis will be evaluating sustainability in terms of achieving the greatest change.

Biomimicry is still theoretically undeveloped (Mathews, 2011), and due to this, it does not fit obviously within one category in Figure 2. It describes itself as a “radical new approach” and “a revolution” (Benyus, 1997, p. 2) which demands a new relationship between society and nature, clearly aligning with transformative views. However, there is little-to-no consideration of the socio-economic structures which are causing such damage to the planet. It takes a very simple and naïve view of the problems we are facing. Biomimicry views the core problem as being rooted within our relationship to nature, taking an all-encompassing approach that all aspects of society have an equitable impact. Obviously, this is untrue, with far greater negative impact of the global north than the global south having being recognised for decades (Redclift & Sage, 1998). This lack of consideration prevents biomimicry from being able to be classified as transformative for now. However, this does not mean there is no hope for biomimicry to contribute towards more transformative change and therefore should still be judged accordingly. By measuring with an aim towards transformation helps to shape how the concept is viewed and ultimate aims to improve it.

3.1.1 The Two World Views

One crucial deviation in the interpretation of sustainable development is based on how humanity views its relationship with nature. These views can generally be classified into two broader categories, both holding their own interpretation for how sustainability challenges are tackled. Biomimicry does not take a clear stand with either, and so the resulting biomimicry solutions can be seen to have roots of understanding from either side of these world views. This understanding is important as the underlying world views have been found to alter the type and degree of sustainability of different biomimicry innovations (Bensaude-Vincent, 2019).

These views do not form hard, binary categories but instead create a spectrum between them. On the one side of the spectrum there are ecocentric views and on the other are the technocentric. Timothy O'Riordan (1989) developed these polarised categories based on the basic and fundamental different understandings of the relationships between humanity and nature that have developed throughout history and human understanding. These views have since been developed specifically to see how they apply to our understanding of sustainability challenges in a more modern context (Emetumah, 2017), considering our understanding of humanity's relationship with nature and shaping the understanding of what solutions from either side look like. Whilst there are those that steadfastly believe in just one end of the spectrum, the sustainability debate commonly recognises that a combination of the two approaches is required to achieve the best results (Bailey & Wilson, 2009; Emetumah, 2017).

Technocentric

The techno-centric approach fundamentally sees science and technology as having the capacity to solve all sustainability problems. Due to this, there is no need for change in the social, economic or political structures present today (Emetumah, 2017). Whilst this view emerged from ancient times when nature was seen as a battle to overcome or tame, it remains dominant. It is seen in essentially all centrally-planned capitalist economies and has become the default for much of the world (O'Riordan, 1989).

Ecocentric

Ecocentric thinking came about in response to the dominant technocentric view. It saw that humanity has developed far past a time where nature posed a threat to humanity, rather humanity has become the threat to nature (O'Riordan, 1989). Instead, this approach sees value in all aspects of nature, and crucially sees humans as just one species amongst millions. Due to our ecological dominance, humanity needs to become custodians of nature – protecting nature from exploitation. Fundamentally we need a shift in values and change in perspective in how we view humanity in relationship to nature – only then can we return to living within the safe and natural ecological limits (Emetumah, 2017).

Biomimicry does hold a strong ecocentric view on humanity and nature. Firstly, it problematises current dominant views which are seen as "dominating or 'improving' nature" (Benyus, 1997, p. 2) and also calls for "a complete change in core values and belief system that facilitates a new condition" (Baumeister et al., 2014, p. 111). A main principle of biomimicry is living within ecological limits, respecting nature to learn from it and recognising that we are just one species of millions (Benyus, 1997). However, biomimicry takes these ecocentric values and fulfils them using the means of technocentrism; science and technology. This gives the opportunity for biomimicry to achieve the goals of both and falls in line with the belief that the best solutions are found in balance.

3.2 Sustainable Design

Sustainable design is not a discipline such as textile or product design, rather it is a "philosophical approach" which forms the background for various subsets of different design approaches (McLennan, 2004, p. 10). It embodies the values of sustainable development and applies them more specifically to the design process. Just as with sustainable development itself, the broadness of the philosophy allows for wide interpretations and applications. As a result, the field is wide and populated with many different approaches within it. These variable applications align with the different perspectives within the sustainable development debate and are rooted in their base world view (Ceschin & Gaziulusoy, 2016).

Sustainable design practices typically emerged from a more technocentric point of view, and many practices now still maintain roots in this viewpoint (Hofstra & Huisingh, 2014). It is this association with a stronger technocentric point of view which could potentially explain why sustainable design has been criticised within the sustainability discourse (Spangenberg et al., 2010). However, there has now been recognition of the shift towards more ecocentric based design approaches, such as biomimicry.

3.2.1 Two Key Elements; Changing Behaviour and Changing Products

Sustainable design can be seen to focus on two main factors, which align with either side of the world views discussed in section 3.1.1 (Carrillo-Hermosilla, Del Río, & Könnölä, 2010). Ecocentric views, with their call for change in values, structures and society, link with behaviours and production-consumption relationships. Technocentric views see technology as the solution linking with the other design focus of looking at the impact of the product or service itself. These two aims are highly interconnected and a clear distinction cannot really be made from a product itself. However, an innovation can be analysed for its approach to both these factors. Biomimicry design needs to consider both of these aspects if they are to have a sustainable impact.

Ecocentric; Changing Behaviour

Changing behaviour relates to reducing consumption. This can be achieved by designing for more efficient resource use or extending the life of an innovation (Cooper, 2005), thus altering the production-consumption systems. Further, sustainable consumption can be encouraged by considering three factors (Spangenberg et al., 2010). Firstly, the individual must be armed with the correct information and motivation to behave more sustainably. Secondly, this behaviour change will have to fit into their social context, for example being accepted by their peers and community. Finally, they must have the ability to choose a more sustainable product through price and availability of the product

Furthermore, design can focus on making sustainable choices more desirable or by making it harder to make unsustainable choices (Kuijer & Bakker, 2015). However, consumer choice is a lot more irrational than economic or predictive models may suggest, as feelings associated with a brand or purchase play a large role in consumer choice and this can be almost impossible to. Therefore, innovations have to consider the emotional link they make with the consumer (Page, 2014).

Technocentric; Changing Products and Services

The design of a product determines the materials used, waste produced and energy used. These aspects have a significant impact on the ecological footprint of a product and need to be considered from the production phase through to disposal phase (Tang & Bhamra, 2009). Small reductions in impact can have a large impact when seen in the big picture. For example, an LED bulb provides a 50% minimum energy reduction when compared to conventional bulbs, for one light bulb, this has no impact however lighting is estimated to use almost 20% of global energy (Muneeb, Ijaz, Khalid, & Mughal, 2017). Small design improvements can have a large impact.

4 Conceptual Framework

To determine how sustainable biomimicry innovations actually are, an evaluative tool needs to be developed. Sustainability frameworks have been developed to assess the sustainability of design interventions such as the Design for Sustainability evolutionary framework (Ceschin & Gaziulusoy, 2016), or to analyse sustainability-orientated innovations (Adams, Jeanrenaud, Bessant, Denyer, & Overy, 2016). However, there is no such framework to evaluate the sustainability of biomimicry innovations. To build this tool draws upon the work of Dusch et al. (2010) with their framework developed to assess the sustainability potential of broader sustainable design activities. A key commonality with all these frameworks is the view of sustainability as a continual movement, sustainability is never achieved, rather it is continually sought after.

4.1 A Sustainable Design Framework

The framework of Dusch et al. (2010) draws upon previous models formulated in sustainable development, sustainable design, and innovation. In their own words the framework aims to view "sustainable design in the context of sustainable development" (p.7). The resulting product indicates the true sustainability of innovations by judging them through two main factors; how the innovation changes behaviours and how the innovation changes the products and services themselves.

A picture and frame analogy is used by the authors to illustrate the framework. The *frame* represents the different degrees of sustainability moving from the least to the most sustainable towards the top right corner. The *picture* represents the categories of sustainable innovations, creating four typologies.

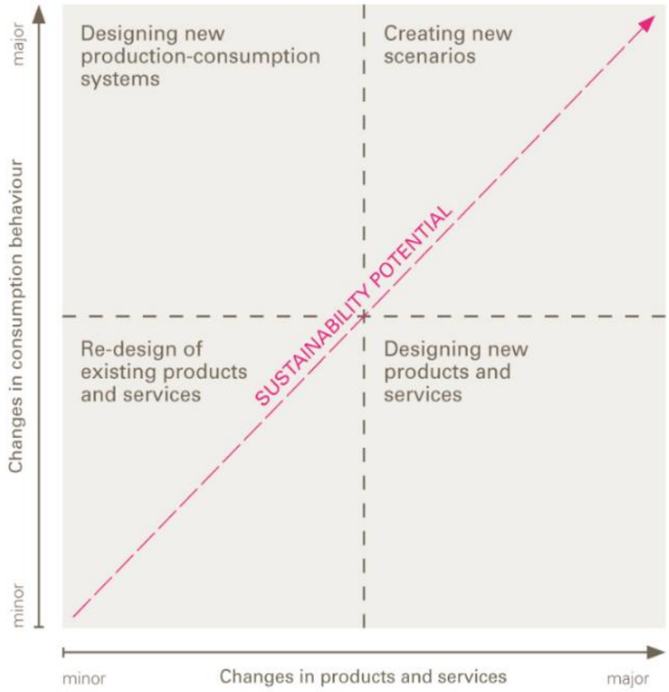

Figure 3. The sustainability framework from Dusch et al. (2010) to evaluate sustainable design activities. This forms the basis for the framework in this thesis, being adapted for use specifically for biomimicry design.

4.1.1 The Frame - Sustainable Development

The frame considers the ecocentric and the technocentric values, capturing the two key elements of sustainable design as described in section 3.2.1. The framework views the greatest sustainability potential in the innovations which maximise both of these factors – the innovations which change our behaviour and are designed to be low-impact.

X-axis; Technocentric

The x-axis focuses on the product or service itself – the *technocentric* side. With a technocentric view placing high value on science and technology, this aspect considers features such as how the product is made, the materials it is made from and the purpose it fulfils. Products with a low technocentric score remain within the status quo, and are not massively innovative giving little consideration to the environmental impact of the product. Whilst products with a higher potential will re-think current products and systems to actively reduce their impact.

Y-axis; Ecocentric

The y-axis tracks the level of change in consumption behaviour related to the innovation, or how *ecocentric* it is. In line with ecocentric views, innovations which actively encourage a change in consumer behaviour, for example through shared ownership or modular design for easy repair, have a higher ecocentric value and a greater sustainability potential than those which reinforce existing high consumption patterns.

4.1.2 The Picture – Sustainable Design

The *picture* forms the four typologies of sustainable design. The sustainable potential, shown in Figure 3, indicates how sustainable each typology is in relation to each other. The features of each typology are described below in Table 2.

Table 2. Categorisations of different sustainable design activities dependent on the degree of ecocentric and technocentric values by Dusch et al. (2010). The degree of sustainability increases as seen in Figure 3.

Designing new production-consumption systems The innovation pushes the consumer to behave more sustainably by focusing on how the product is used, but not giving much consideration as to how it is made.	**Creating new scenarios** These innovations utilise sustainable design and production techniques, whilst altering how the product is used to reduce consumption.
Redesign of existing products and services Not much change from existing innovations, working with and reinforcing current systems.	**Designing new products and services** The technology itself is more radical and environmentally focussed, but it does little to change existing consumption behaviours.

5 Research Design

This evaluative study takes a mixed-methods approach to evaluate the sustainability of biomimicry design. Firstly, to understand how different cases understand and apply concepts discussed in this paper a qualitative approach was taken. Cases of biomimicry innovations were selected and data collected from their websites for analysis. The framework method with a thematic analysis approach allowed for a more interpretative understanding of the data, linking patterns between cases (Ritchie, Lewis, Nicholls, & Ormston, 2013). Following this, a quantitative approach was used to score each innovation based on the themes emerging from the earlier analysis, allowing for a more precise evaluation to occur.

5.1 The Framework Method

The framework method forms the key design process used in this thesis. It was developed for "defining concepts, mapping the range [of phenomena], creating typologies, finding associations, seeking explanations, and developing new ideas", and is rather prescriptive requiring five key stages to be sequentially completed and data to be synthesised into a matrix allowing for easier cross-case comparison (Ritchie & Spencer, 1994). Having originally designed it for applied policy research, it has since been adapted and expanded for studies outside policy research, such as health research (Gale, Heath, Cameron, Rashid, & Redwood, 2013) making it appropriate for this study.

Ritchie and Spencer (1994) defined the five stages as follows:

1. FAMILIRISATION

   Once the data has been collected, the researcher needs to understand the data and to remove pre-conceived ideas about what the data might show. Depending on the volume, either all the data is reviewed or a diverse selection to show initial themes or patterns emerging.

2. IDENTIFYING THE THEMATIC FRAMEWORK

   The data is now looked at with more of the specifics of the original research questions and *a priori* research to develop the thematic framework through which the data will be analysed. Codes are developed to capture the relevant aspects of the data.

3. INDEXING

   The framework is now applied to the entire data set with software such as NVivo.

4. CHARTING

   The data is organised into a matrix; unlike other qualitative methods, the data are summarised to their essence rather than the whole coded passage to present the core message of the data.

5. MAPPING AND INTERPRETATION

   Looking at the data as a whole, dominant themes and patterns are found and cases compared to find key differences and similarities.

5.1.1 Case Selection

There is no definitive list of all biomimicry innovations, however, the Biomimicry Institute has compiled a database showcasing examples and case studies. The institute was deemed appropriate as the source of cases due to it being the leading organisation and global developer of biomimicry. A systematic review of these cases was completed along with purposeful sampling to select cases which met all the criteria of the study. The data was taken from two sources within the institute; Asknature.org and Launchpad.

AskNature.org

AskNature.org (https://asknature.org) is a database developed by the Biomimicry Institute to inspire and facilitate the application of biomimicry. It lists cases which have used biomimicry principles with a description and link to a website for the innovation. To date, 197 cases have been uploaded, from fully-fledged products being sold to others remaining in earlier stages of development.

Launchpad

The Biomimicry Institute also hosts *Launchpad,* a programme designed to incubate start-ups using biomimicry. Every year teams apply and are then mentored for 10-weeks to improve the innovation and business itself, all based on the biomimicry principles. The teams and their innovation are listed on the website (at https://innovation.biomimicry.org/launchpad/) from the years 2016, 2019 and 2020.

A systematic review of all cases (n=211) was completed to determine if they reached the criteria relevant to this study, shown in Table 3. Only 20 cases were identified to meet all the criteria, with a full list in Appendix I. Ten were taken from Launchpad and ten from AskNature.org.

Table 3. The criteria for case selection, resulting in 20 cases remaining from a total of 211.

Criteria	Description
Initial	211 Cases
Development Stage	Innovations were at various stages of development, with some just an idea with others already applied and on sale. The innovations were classified into four categories; research, concept, developing, and applied. Only applied cases were selected as they are proved to be a viable innovation.
Information available	Only innovations with developed websites were included, in order to provide enough information for analysis.
Use of Biomimicry	Not all innovations described their design process or principles, therefore all sites which did not mention "biomimicry" in the context of a design principle were excluded. Due to the industrial confusion between "biomimetic" and "biomimicry" (Iouguina et al., 2014), any sites which listed "biomimetics" were also included.
Final	20 cases

To capture the data for each case an offline copy of each website, or relevant pages, .pdf files were created directly from each site. NVivo (QSR International Pty Ltd., 2018) was used to both code the data and build the matrix.

6 Analysis

6.1 Familiarisation, Thematic Framework, Indexing and Charting

Of the 20 cases, ten were selected to be familiarised with. The cases were selected with reference to the innovation type, aiming for a diverse and representative sample. This process gave an indication on the amount and type of data available including the general themes, how biomimicry was presented, the nature of the innovation, the motivations of the company and their core values.

To develop the thematic framework, the research questions and *a priori* research were revisited to determine what was really needed to be asked. From this it was clear that firstly there needed to be an understanding of how each case understood and applied the biomimicry principles, and what role sustainability played in each case. In order to be able to evaluate the sustainability using the framework based on Dusch et al. (2010) and understanding of both the ecocentric and technocentric aspects was required too. Several draft frameworks were created and tested on a sample of cases, resulting in the framework shown in Table 4.

Table 4. The thematic framework with codes grouped by category. The left hand-column shows the code name, whilst the right column describes what kind of information was gathered.

Biomimicry	Importance	How important is biomimicry to the values of the company? Is the whole company centred around the principles, or do they just apply it to an innovation? Is it the main design principle or just one aspect?
	Biomimetic	Do they use this term? Is it used synonymously with biomimicry?
	Biomimicry definition	How is biomimicry defined?
Innovation	Product description	What is the product? How does it work? Who is it for? What problem is it solving?
	What nature	What aspect of nature inspires the product and how is it applied?
	FPE	Does it emulate form, process, ecosystem? Or a combination?
	Company motivation	What motivates the company to use biomimicry? What was their motivation for developing the innovation?

Ecocentric	Ecocentric	How does the innovation target consumption behaviours or values? For example, anything related to: - Reducing consumption behaviour - Improving accessibility to sustainable innovations - Increasing knowledge to make sustainable choices - Specifically targeting behaviours - Focus on the social acceptance of the innovation
Technocentric	Technocentric	How does the innovation use technology to solve sustainability challenges? How does the innovation fit in with existing values? For example, anything referring to: - Materials used - Closing production loops - Energy used How it fits in with our lives today
Sustainability	Sustainability	How is sustainability is understood? What context is it placed in? How important sustainability is to the innovation or company?

The data was then indexed and organised into a matrix using NVivo. The matrix created a table with each case on the left-column, and the different codes along to top row, creating a summary of the content for each cell.

6.2 Scoring

The Dusch et al. (2010) framework provided the template and structure to evaluate sustainable design applications but it did not provide the tools to be able place an innovation within this frame. In order to place the cases accurately, twelve questions were formulated to measure the ecocentric technocentric values respectively. The questions were developed based on the values of both views discussed in section 3.1.1, and how these views would translate to product design. The aim of sustainability was also considered.

6.2.1 Technocentric Scoring

In brief, technocentric views see science and technology as the fix to sustainability problems without a need for any change in values, or social, economic or political structures (O'Riordan, 1989). When translating these views to product innovation, the focus is placed on the impact of the technology itself and how it fits in with dominant values today. Questions related to the direct impact covered the materials used, energy, how waste is handled, and the life-time of the product. As the technocentric world view is currently dominant and does not need a change in values or behaviours (Emetumah, 2017), innovations were also asked if they fit in with our lives today.

Table 5. The questions developed to score the degree of technocentricity of biomimicry product design. A point Is earnt if the innovation can answer in line with the right-hand column. A maximum of six points can be earned.

	Question	Point Awarded For
Technocentric	Does the innovation consider the choice of materials in terms of pollution, source and end of life?	Yes
	Does the innovation consider the energy use or source during the production of the product or in its life time?	Yes
	Does it consider entire the lifetime of the product? *For example, in terms of durability or disposal.*	Yes
	Does the innovation fit in with our lives today? *Innovations which do fit in do not challenge existing views or processes too much, they let the innovation do the work to achieve sustainability.*	Yes
	Does the innovation consider the minimisation of waste in production or use?	Yes
	Is it a new innovation or is it just a re-design of an existing product or service? *A re-design is a simple improvement of an existing innovation, for example improving the energy efficiency, whilst new design focuses on tackling the problem itself with new solutions.*	New Innovation

6.2.2 Ecocentric Scoring

Ecocentric views call for a change of values in society, valuing all aspects of nature and returning to living within safe ecological limits for the sake of all life (O'Riordan, 1989). To capture this view within product design focus was put on consumption behaviours and targets for values. Questions related to reducing consumption, and increasing the capacity of humanity to be custodians of nature. They also looked at how innovations impact behaviours on a longer term, questioning the behavioural changes required to use the product as continual behavioural change can help to reinforce these new vales (Mathews, 2019).

Table 6. The questions developed to score the degree of ecocentricity of biomimicry product design. If the question can be answered "yes" then a point is awarded. A maximum of six point can be earned.

	Question
Ecocentric	Is it designed to reduce consumption?
	Does the innovation reduce the consumption of other products associated with it?
	Does it actively encourage society to protect or conserve nature? *For example, innovations which make it easier to regenerate or care for nature*.
	Does it require an active change of behaviour to use the product, beyond the purchasing decision?
	Does it make a sustainable choice more accessible? *For example, does it consider the price in comparison to alternatives which do not consider sustainability.*
	Does it increase the knowledge about sustainable innovations? *Some products raise the profile and awareness of sustainable innovations by being visible for example, an indoor plant propagator, whilst others such as energy efficiency software can operate unknowingly.*

6.2.3 Sustainability Scoring

The motivation for the innovation development was also considered. Some innovations are developed explicitly with the goal of achieving sustainability, whilst others take it into consideration but not as a core aim. Innovations were asked *"Is an explicit aim of the innovation to help achieve sustainability?".* Innovations which aim for sustainability operate with a different way of thinking, a crucial step to achieve sustainable results (McLennan, 2004). With this mindset comes a greater assurance that a more holistic approach is taken, that design choices are made because they are the most sustainable rather than convenient, and that choices are made with intention rather than assumption. It also looks to the future development of that innovation, with sustainability as an aim there is hope that the innovation will continue to strive for sustainable results rather than following trends.

6.3 Developing Typologies

The matrix was used to develop the typologies of biomimicry design. After each innovation had been scored, they were plotted onto the sustainability framework determining which quadrant they fell into. The cases from each quadrant were then grouped and compared finding the key similarities of practice.

7 Results and Discussion

Biomimicry innovations can be evaluated by scoring both the technocentric and ecocentric values and then comparing these values using the framework developed by Dusch et al. (2010). This evaluation allowed for the development of typologies of applications based on whether either aspect was incremental or radical. After scoring current biomimicry innovations, these typologies could be further developed to determine what features specific to biomimicry can be associated with each typology. The process of developing the typologies and determining the sustainability of current evaluations was an iterative process, with both steps influencing the other. This produced the four final typologies; Business-As-Usual, Technology Solutions, Behaviour Solutions, Sustainable Future. Innovations can be classified into a typology allowing for a greater understanding of what features to focus on in order to increase the sustainable potential of the innovation. Scoring current applications of biomimicry showed that currently, biomimicry design is producing somewhat sustainable product innovations. These innovations rely more on technology to produce sustainable results and could become more sustainable by giving greater consideration to the consumptive behaviour they influence.

7.1 RQ1 - How can the sustainability of biomimicry innovations be evaluated?

The sustainability of biomimicry evaluations can be determined by considering both the technocentric and ecocentric aspects. This captures both the impact of the product itself and the impact from consumption patterns, allowing an innovation to be placed on a framework based on the one developed by Dusch et al. (2010). To accurately place an innovation on the framework, it can be scored using a list of questions. One point can be received per question, with the number of points then determining the position along the x and y-axis. Each axis has a maximum value of seven, and is split evenly in half to indicate whether an innovation is incremental or radical. Innovations which score a value smaller than four are incremental, with those over being radical. A maximum of six points can be received for either axis, to achieve the maximum seven points then an innovation also has to explicitly be developed to be sustainable. If the sustainability point is achieved, then another point is added to both the techno- and ecocentric scores. Once a score is assigned to an innovation it can be plotted onto the sustainability framework shown in Figure 4. The x=y transect, shown in orange, indicates the sustainability potential with an upward increasing sustainability towards the top right quadrant. To achieve sustainability, a balance between both the technocentric and ecocentric is required (Bailey & Wilson, 2009), therefore innovations falling closer to the transect can be considered more sustainable.

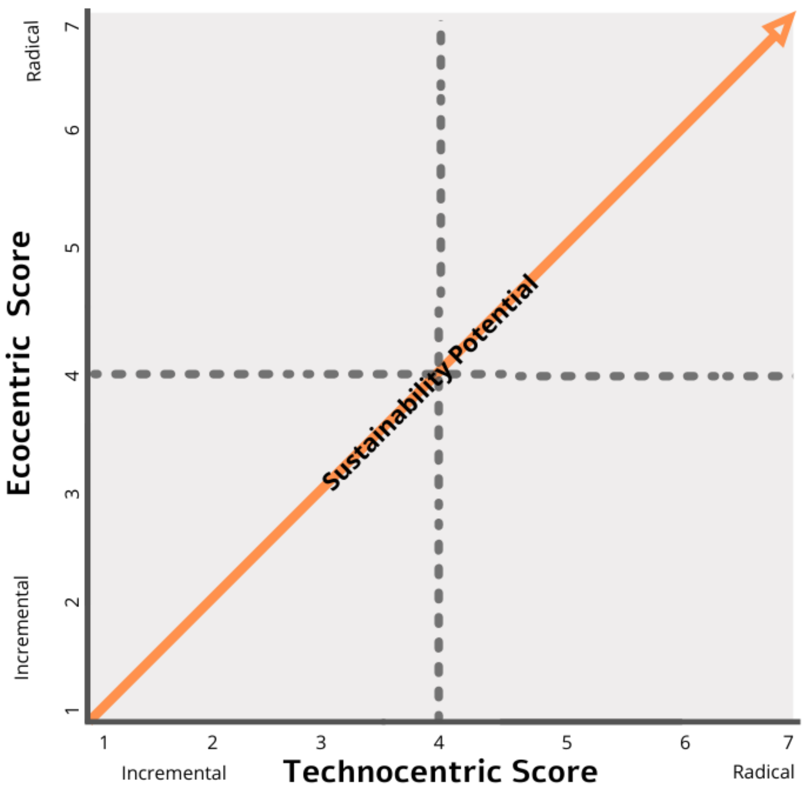

Figure 4. The framework used to evaluate the sustainability of biomimicry product design. Innovations are scored for both axes, using pre-defined questions which determines their position and typology. Innovations with the highest technocentric and ecocentric values are the most sustainable, and innovations which utilise a more even balance of both aspects having a higher sustainability potential. Adapted from Dusch et al. (2010).

The position of the innovation in the framework also indicates the typology of the innovation by identifying what quadrat it falls within. The typologies developed from the original framework were based on more general sustainable design innovations, therefore typologies for biomimicry applications were developed and are presented in section 7.2. Awareness of the typology contributes to the ability to be able to evaluate the sustainability of an innovation, more importantly it highlights potential areas of focus to make an innovation more sustainable.

7.2 RQ 2 – What typologies of biomimicry product design applications are there?

Based on the approach to sustainability, biomimicry innovations can be classified into four typologies. These typologies build on those developed for more general sustainable design by Dusch et al. (2010) who identified how radical an approach each innovation takes in regards to ecocentric and technocentric values. They also incorporate the classifications from Adams et al. (2016) based on whether innovations aim to just minimise harm or to do good, whether they are doing new design or just re-designing, and also how they work with other designs. Based on the cases analysed here, the typologies include how innovations use biomimicry and their approach to sustainability.

7.2.1 Business-As-Usual

These innovations have the weakest sustainability impact, with little change from existing product innovations. Crucially these innovations take sustainability into consideration but it is not their main focus or aim in development. Biomimicry may be assumed to automatically provide sustainable results, a dangerous assumption due to the complexity of sustainability issues as wicked problems. They aim to make better products, for example by increasing the efficiency, but not necessarily creating new innovations which have a greater focus on the real problems. This aligns with the Adams et al. (2016) classification that less sustainable level innovations will aim to "do less harm", rather than create a positive impact. These innovations can be considered add-ons, relying on other products in order to be functional, such as increasing durability of another product. These innovations have limited capacity to create change as they are heavily reliant on existing products and systems. Additionally, these cases are highly likely to easily fit into our lives today as they do not require any change in lifestyles or values to use. Furthermore, as these innovations are not providing new designs, rather just improving the sustainability of existing designs, they rely more on the individual consumer to continually make the sustainable choice in competition with 'regular' products, weakening their impact (Vezzoli & Manzini, 2008).

A more simplistic application of biomimicry is used, with these innovations likely to only emulated nature at the level of *form*. Further to this, biomimicry design principles are isolated to the innovation itself, and not applied to how other aspects of the company may be ran. The use of biomimicry in these innovations is more similar to that of biomimetics; taking designs from nature and applying them to existing innovations without considered focus to sustainability issues. Interestingly, these innovations are also more likely to use the term *biomimetics* synonymously with biomimicry. This application of biomimicry is recognised as weak -- "mimicking form alone and using the same old unsustainable, life-unfriendly practices to do it" (Baumeister et al., 2014, p. 79).

7.2.2 Technology Solutions

These applications place the highest consideration on the technological aspects to create change, with an intermediate sustainability potential. These innovations emulate nature broadly, drawing on inspiration from form, processes and ecosystems, and frequently in combination. The use of more complex aspects of nature is likely to push them slightly closer to systems thinking and expand their capacity to act sustainably. Seeking to create positive impacts (Adams et al., 2016), these innovations actively aim to produce sustainable results, considering it a core value in development rather than an inherent aspect of biomimicry. Despite this aim for sustainability, these innovations are still likely to view biomimicry and biomimetics synonymously.

Whilst these innovations focus on the impact of the product itself by offering a new solution, they do increase the accessibility of sustainable alternatives supporting -- but not targeting -- behavioural change. However, once the initial choice to use that innovation occurs the product quietly does the rest. This means that sustainable behaviours are not continually reinforced and changes to current lifestyles are not required, reducing their impact (Mathews, 2019). Similar to the "Business-as-usual" typology, these cases fit into the current system and way of thinking, this also links to their understanding of sustainability with less radical and more neoliberal views of sustainability.

7.2.3 Behavioural Solutions

These innovations share a similar sustainability potential with *Technology Solutions,* but instead rely almost entirely on behavioural and value change to reduce consumption. Only one case analysed in this thesis could be categorised into this typology making the themes within this typology more uncertain and so should be treated as more of an outline, requiring further development.

It can be assumed with some certainty that these innovations will explicitly aim for sustainable solutions in their development due to their radical score. Due to their focus on changing behaviour, these innovations may be more likely to emulate processes or ecosystems due to the interrelatedness and systems thinking. A lack of focus on technology makes these approaches unlikely to see biomimetic and biomimicry as synonymous.

7.2.4 Sustainable Future

By maximising new, low-impact technologies and focussing on reducing consumption behaviour, these innovations achieve the greatest sustainability potential. These innovations facilitate sustainable behaviour but crucially do not work passively, instead continually reinforcing sustainable behaviours. Unsurprisingly, they explicitly aim to be sustainable, and often have a more developed understanding and interpretation of sustainability compared to the other typologies. These innovations are unlikely to use *biomimetics* synonymously with biomimicry, perhaps indicating a deeper understanding of sustainable design applications. Further to this, the biomimicry design principles are less likely to be isolated to just the product innovation, instead they applied to the entire running of the company. They apply the most complex type of biomimicry through the emulation of ecosystems, giving a greater systems approach. These innovations also focus on creating a positive impact as Adams et al. (2016) suggests, but with a greater sustainability potential the impact is likely to be higher than other typologies. Therefore, the innovation may be regenerative, focussing on how to help restore and protect nature rather than just focussing on the resulting problems. This facilitates an increased connectedness between society and nature, specifically by increasing the capacity for society to be custodians of nature.

7.3 RQ3 - How sustainable are current applications of biomimicry in product design?

Overall current applications of biomimicry do appear to be achieving sustainability to some degree however there is considerable room for improvement. The majority of cases focussed more on the impact of the product itself, with little consideration to how it impacts consumption. Figure 5 below shows the distribution of innovations across the framework, with a clear trend towards more technocentric approaches. However, there are innovations which take either a more balanced approach, or a more ecocentric approach. The cases also covered a broad range of innovation types for example textiles, energy production, water management and food production, indicating the scope of biomimicry design.

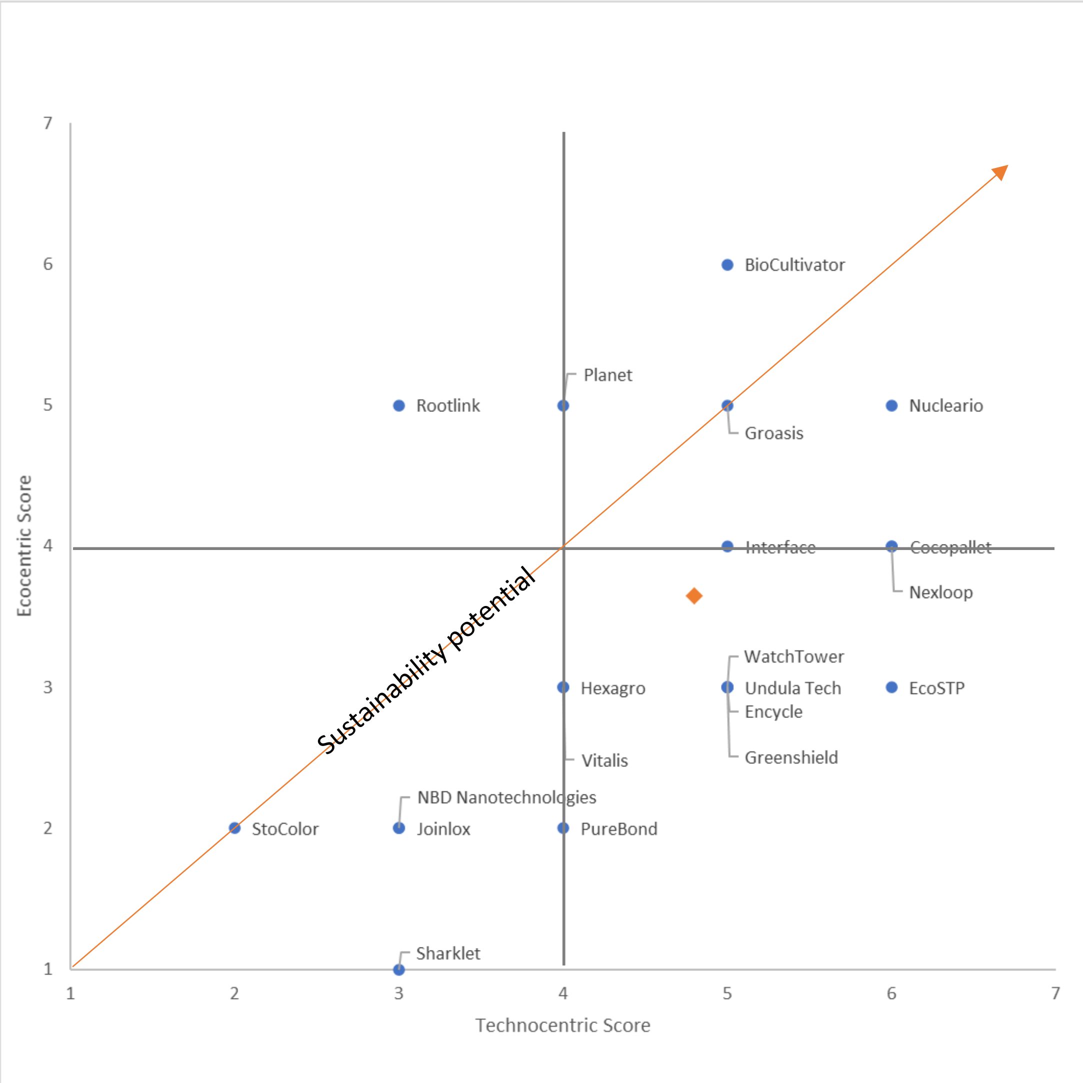

Figure 5. The sustainability of current biomimicry applications. Twenty cases were analysed based on their approach to sustainable solutions, with the majority of cases favouring a techno-centric viewpoint. The quadrants show the different typologies of design applications, with the average score indicated by the orange diamond.

7.3.1 Scoring Trends

Themes and trends appeared when scoring each innovation. Encouragingly, most cases did aim explicitly for sustainable results, with 75% of cases including sustainability as a core aim of the development of the product. The five cases which did not explicitly aim for sustainability did not achieve a high sustainability potential, remaining within the Business-as-Usual typology. The majority of cases also increased the accessibility to sustainable innovations (95%), for example by considering the cost or how to make it available to more people. This creates an opportunity for a sustainable choice to be made, however does not guarantee it will happen. There are three types of consumers; those who wish to make sustainable choices, those who are open to them, and those who do not wish to use them (Kuijer & Bakker, 2015). The majority of people cannot be assumed to fall within the first category and so making sustainable choices available is just the first step to their uptake. Another popular trend was the focus on waste, with 85% of cases giving consideration to the minimisation of waste with their innovation, either through the use of a waste product or by minimising the amount of waste the innovation itself produced. Targeting waste at the design stage is especially important for achieving sustainability as this helps create the shift from waste *management* to waste *prevention* (Corvellec et al., 2018). The focus on waste also may be related to the prevalence of other sustainable design approaches which give heavy consideration to the product lifetime, such as cradle-to-cradle design (Ceschin & Gaziulusoy, 2016).

The least popular areas of design focus were all found in the ecocentric criteria, specifically on the focusing of challenging values. Only a quarter of innovations required an active change in behaviour to use the product, and again only a quarter of innovations encouraged the protection of nature.

7.3.2 The Quadrants

Of the 20 innovations, 13 fell into clear typologies whilst the remaining seven fell on the border of two quadrants. The majority of innovations achieved a radical technocentric score but struggled to move past incremental ecocentric design. A description for each quadrant and an innovation example is given for each.

Business-as-Usual (4)

A fifth of the innovations created incremental change, with most of these cases related to materials design. These products generally aim to increase the durability or functionality of other products limiting their capacity to make change beyond that one product relationship.

One innovation of this typology is Sharklet (http://www.sharklet.com/), a bio-film based on shark-skin which prevents the growth of bacteria through structure alone, preventing the use of harsh chemicals. Whilst this innovation uses new design, it lacks basic considerations such as the materials used or energy source. Crucially it ignores all almost all ecocentric aspects, only reducing the consumption of cleaning chemicals. As it is designed to be used on medical equipment and in hospital settings, the awareness of the innovation is likely limited to the initial purchase rather than a reinforcing action.

Technology Solutions (5)

The majority of cases provided *Technology Solutions*, with radical technocentric approaches but little consideration to behaviour and consumption. The total average score fits into this typology, which is perhaps unsurprising due to the technological focus of product design (Hofstra & Huisingh, 2014).

An example of *Technology Solution* innovation is EcoSTP (http://www.ecostp.com/) a sewage treatment system based on the process of cow's rumination and digestion. It allows for the treatment of all sewage waste without the use of either energy or chemical inputs. Once the choice is made to use this system over other systems, such as a septic tank, no other behavioural changes are really required with the system working quietly in the background.

Behaviour Solutions (1)

Only one innovation could be considered to provide a *Behavioural Solution*, reinforcing the lack of attention paid to this area by current biomimicry innovations.

Rootlink (https://www.therootlink.com) is a digital food web designed to link farmers with local consumers to reduce food miles, packing and wastage. There is no physical product, instead using technology is used to facilitate the main goal of changing production-consumption systems.

Sustainable Future (3)

Promisingly, three innovations could be classified as achieving the greatest sustainability potential. The three innovations analysed all placed a large focus on assisting society to be greater custodians of nature with regenerative approaches.

Nucleario (https://www.nucleario.com/en/) is a device used to help with the reforestation of native forest in South America. When a sapling is planted the device helps protects the plant until it is mature enough to resist against threats, after which the device biodegrades. It encourages replanting by making the process much easier, cheaper and effective whilst also reducing the consumption of materials normally required for the process.

7.4 The Final Framework

The complete evaluative framework includes the questions from tables 5 and 6, allowing an innovation to be placed on the framework below. The placement will determine the typology and can be used to indicate how to improve the sustainability potential of innovations.

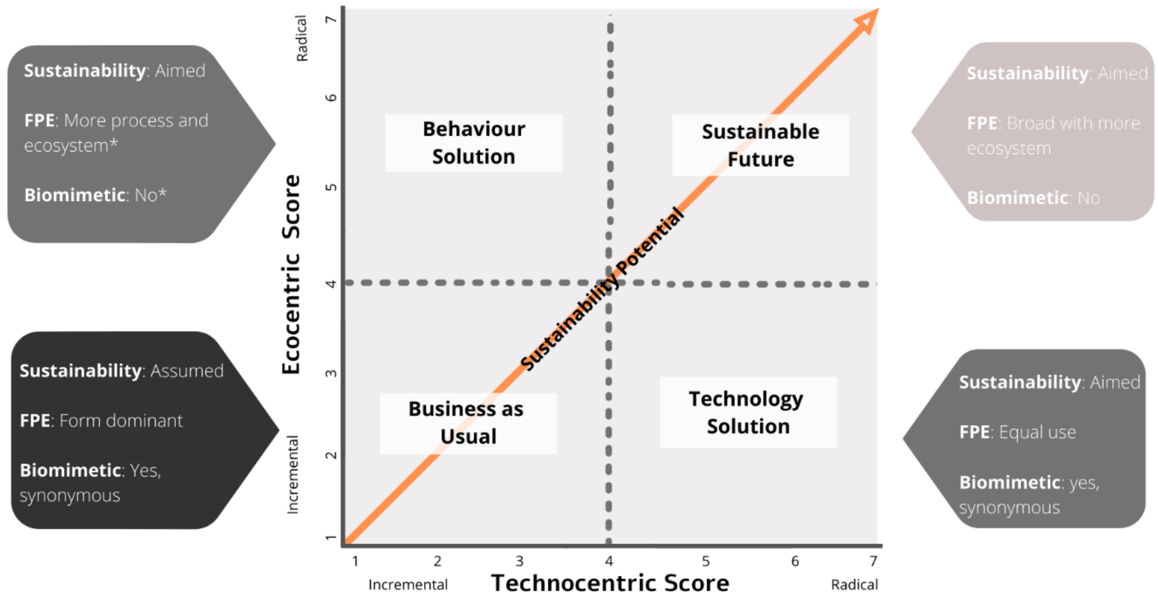

Figure 6. The full evaluative sustainability framework for biomimicry product innovations. Innovations are scored on the extent of their ecocentricity and technocentricity, placing them within a typology. The balloon labels indicate the common features of that typology: - whether sustainability is assumed to accompany biomimicry or whether it is an explicit design goal; the type of nature emulated (form, process or ecosystem); and whether biomimicry and biomimetics are frequently understood as synonymous. The asterix indicates lower certainty in the categories due to a lack of data.

7.5 Limits to Sustainability

Whilst biomimicry does contribute to achieving sustainability, it does still hold some significant theoretical flaws which need to be addressed if the concept is to have a higher impact. Firstly, biomimicry views sustainability as largely an environmental issue. This massively simplifies the problems at hand, ignoring the huge socio-economic aspects of sustainability (Mathews, 2019). Similarly, it does not address issues of environmental justice. The framing of the imbalance of humanity with nature implies all of humanity has an equal impact on the destruction of our planet, when in reality the rich minority should be held up as the problem. Another key issue is that biomimicry is currently generally limited to product innovation, not yet evolving to the higher levels of system design required to create a larger impact (Ceschin & Gaziulusoy, 2016). However, if biomimicry is to be scaled up it needs to address the limitations mentioned above in order to ensure an optimal outcome.

8 Concluding Remarks

8.1 Limitations

This study aimed to provide a comprehensive overview of the sustainability of biomimicry design approaches however, this study does face some limitations. Firstly, due to the nature of the current research in the field, the framework used to evaluate sustainability takes a very strong focus on the environmental aspects of sustainability with little consideration to the socio-economic aspects. Secondly, the typologies were built on limited numbers of cases. Confidence in the categorisation of the typologies would be higher with a greater number of cases, especially in the case of *Behavioural Solutions.* Finally, similar sustainability frameworks confirmed their results and applicability with practitioners strengthening their potential usefulness (Grover, Emmitt, & Copping, 2019). Unfortunately, this was not possible in the time constraints of this thesis.

8.2 Impacts and Implications

Being able to evaluate the actual sustainability of biomimicry innovations addresses the previous ambiguity highlighted by (Mead & Jeanrenaud, 2017), where the lack of measurement meant there was no accountability for practitioners. It also helps to shape how sustainability can be approached within the design concept, making explicit the need for a focus on the consumption systems during development.

8.3 Conclusion

Biomimicry is contributing to the field of sustainable design, but there is still room for improvement. Generally, current applications do not give enough consideration to the impact from the use and consumption of the innovation, instead focusing more energy on improving the technological aspects. The sustainability of biomimicry applications has also been held back by the lack of evaluative methods for review (Faludi, 2019; Mead & Jeanrenaud, 2017). With hope the creation of a formal evaluative process helps to counter this issue by creating accountability for practitioners as well as greater guidelines for the factors to consider when aiming for sustainability. Biomimicry design applications can now be classified into one of four typologies based on their approach to sustainability solutions, giving a greater understanding of how to improve the sustainability of innovations. The concept does still have limitations and theoretical flaws which need to be addressed before it can be scaled up to large systems design, namely a greater recognition of the socio-economic aspects of sustainability. The association with *biomimetic* design is also potentially hindering the sustainability potential of applications, and so measures need to be taken to distinguish the two. Despite these challenges, biomimicry still contributes to the field of sustainable design and can help the transition to a more sustainable future. Although product design will not transform the world on its own, it should be viewed as one piece of the puzzle.

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10 Appendix List

Appendix I: Cases

Case	Website
Encycle	https://www.encycle.com/swarm-logic/
StoColor Lotusan	https://www.stocorp.com/lotusan/
Interface	https://www.interface.com/EU/sv-SE/sverige?r=1
Joinlox	http://www.joinlox.com/
Vitalis	https://www.logoplaste.com/case-studies/vitalis-case-study/
Groasis Waterboxx	https://www.groasis.com/en
NBD Nanotechnologies	https://www.nbdnano.com/about-us/
Sharklet Technologies	http://www.sharklet.com/
PureBond	https://www.columbiaforestproducts.com/product/purebond-classic-core/
GreenShield	https://greenshieldfinish.com/
CocoPallet	https://www.cocopallet.com/
EcoSTP	ttp://www.ecostp.com/
NexLoop	https://nexloop.us/
Nucleario	https://www.nucleario.com/en/cause/
Rootlink	https://www.therootlink.com/impact
WatchTower	https://www.wtrco.com/
UndulaTech	https://www.undulatech.com/
BIOCultivator	https://www.bio-cultivator.com/
Hexagro	https://www.hexagrourbanfarming.com/
Planet	http://planet.wemimic.it/mangrove-still/

Appendix II: Scoring per case

	Technocentric						
	Does the innovation consider the choice of materials in terms of pollution, source and end of life?	Does the innovation consider the energy use or source during the production of the product or in its life time? (if 0 energy then Y)	Does it consider the lifetime of the product? (Durability, modular, end of life)	Does the innovation fit in with our lives today?	Does the innovation consider the minimisation of waste in production or use?	Is it a new innovation or is it just a re-design of an existing product or service?	SUM
1 : BioCultivator	1	1			1	1	4
2 : Undula Tech	1	1		1	1		4
3 : Hexagro	1			1	1		3
4 : Planet		1		1	1		3
5 : Rootlink					1	1	2
6 : WatchTower		1		1	1	1	4
7 : EcoSTP	1	1	1	1		1	5
8 : Encycle		1	1	1	1		4
9 : StoColor			1	1			2
10 : Interface	1		1	1	1		4
11 : Joinlox	1			1	1		3

12 : Vitalis	1			1	1		3
13 : Groasis	1	1	1		1		4
14 : NBD Nanotechnologies			1	1	1		3
15 : Sharklet				1	1	1	3
16 : PureBond	1		1	1	1		4
17 : Greenshield	1		1	1	1		4
19 : Cocopallet	1	1	1		1	1	5
20 : Nucleario	1	1	1		1	1	5
21 : Nexloop	1	1	1	1		1	5

	Ecocentric						
	Is it design to reduce consumption?	Does the innovation reduce the consumption of other products associated with it?	Does it actively encourage society to protect or conserve nature?	Does it require an active change of behaviour to use the product, beyond the purchasing decision?	Does it make the sustainable choice more accessible?	Does it increase the knowledge of sustainable innovations?	SUM
1 : BioCultivator	1		1	1	1	1	5
2 : Undula Tech		1			1		2
3 : Hexagro					1	1	2

4 : Planet		1		1	1	1	4
5 : Rootlink		1		1	1	1	4
6 : WatchTower		1			1		2
7 : EcoSTP		1			1		2
8 : Encycle	1				1		2
9 : StoColor	1				1		2
10 : Interface	1				1	1	3
11 : Joinlox		1			1		2
12 : Vitalis	1				1		2
13 : Groasis		1	1	1	1		4
14 : NBD Nanotechnologies	1				1		2
15 : Sharklet	1						1
16 : PureBond	1				1		2
17 : Greenshield	1				1		2
19 : Cocopallet	1		1		1		3
20 : Nucleario		1	1	1	1		4
21 : Nexloop		1	1		1		3

Sustainability: Is the innovation designed to explicitly be sustainable?								
1 : BioCultivator	2 : Undula Tech	3 : Hexagro	4 : Planet	5 : Rootlink	6 : WatchTower	7 : EcoSTP	8 : Encycle	9 : StoColor
1	1	1	1	1	1	1	1	0
11 : Joinlox	12 : Vitalis	13 : Groasis	14 : NBD Nanotechnologies	15 : Sharklet	16 : PureBond	17 : Greenshield	19 : Cocopallet	20 : Nucleario
0	1	1	0	0	0	1	1	1