BIOMIMICRY

Dissertation title:

Biomimetic approaches to design:
Cases of extreme environments

Evangelia Vangeli Margariti

SCHOOL OF ECONOMICS, BUSINESS ADMINISTRATION & LEGAL STUDIES

A dissertation submitted for the degree of

MSc in Strategic Product Design-Industrial Innovation stream

Student number || 1106170031

Supervisor || Dr Dimitrios Tzetzis

INTERNATIONAL HELLENIC UNIVERSITY

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I hereby declare that the work submitted is mine and where I have made use of another's work, I have attributed the source(s) according to the Regulations set in the Student's Handbook.

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Abstract

This paper derived inspiration from recent design studies regarding the habituation of extraterrestrial, extreme environments. The interest in studying life in extreme environments on Earth and the augmenting industrial and research attempts to create knowledge and applications for sustaining life in the extremes is rising. Along with this interest, an abundance of design thinking approaches are stated and explored. The research ponders and take as ground base the two main challenges that torment and ignite our era's scientific and industry world; the new quest for Space exploration and Climate Change deterioration. The first addresses the harshest environment for humans known so far and the latter presents a near future of extreme climatic and ecosystem conditions. Therefore, it was considered interesting to explore biomimicry; a methodology of design problem solving that could perhaps consider both challenges, by diving into the natural world of the extremes, to finding inspiration for product and spatial design solutions for multiple stressors and sustainable applications. Biomimicry as a type of natural analogy method, when executed gracefully, gives great examples of novelty and economy in design solutions. The following research reviewed the current knowledge of nature's adaptations to extreme environments and investigated examples of developed biomimetic technologies for space applications and research from various fields that presented interdisciplinary, sustainable approaches for space and Earth. The specific issues argued by the author are the necessity of advancing biomimetic approaches for space exploration and use them as tools for the emergence of extreme climatic environment on Earth. Under the cause of the study, space-related knowledge gaps were surveyed, a design study of biomimetic ideation was analysed and suggestions for further research of a biomimetic design methodology was formed as an outlook for potential development in biomimetics and product design. By experimenting on a biomimetic-concept design study, the future of design disciplines in the NewSpace and "resources reproaching" era was questioned. Can biomimicry prove itself useful for interdisciplinary collaboration for future design solutions and what aspects can create limitations?

Keywords: biomimicry, product design, extreme environments, space, climate change, space for earth

Evangelia Vangeli Margariti

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Evangelia Vangeli Margariti

To the readers,

A combination of poems and literature from three creative humans that accompanied me while writing this dissertation

We are torn between nostalgia for the familiar
and an urge for the foreign and strange.

Carson McCullers

That we worked here, at the ESA? Justo asks
and I say yes, because even if I never knew the letters for
Those sun-soaked buildings under Spanish skies
I remember the photos of newly built rockets
All those strange machines igniting and
The time we gathered around a too-small screen
To watch the parachute land in a dessert that was not ours
No Sahara or Egyptian plane,
No dunes of sand whose grains we knew,
but the jasper mist of Titan…

DID YOU KNOW, poem by Jessica Kashdan-Brown
Apparently inspired by Titan touchdown by Huygens lander.

Είμαστε των αστεριών παιδιά
και αυτό είναι το δώρο
μίας απίθανης στατιστικής,
στον Χώρο και στον Χρόνο

ΠΑΙΔΙΑ ΤΩΝ ΑΣΤΡΩΝ ,στίχοι Άκης Λούκας

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Introduction

Roots of the Research Problem

After approximately 3.8 billion years of evolution, Nature has become supremely efficient and sustainable by carrying forward what adapts, what is efficient and what lasts. Its numerous patterns, forms and mechanisms, in all scales, encompass a wealth of knowledge having enormous potential of adaption. This adaptation is co-dependent with ecosystem's food chain balance and environmental parameters. Scientists have so far discovered and established the theories and proof for natural selection and ecosystems' balance. By looking deeper, they found the set of elements, which allow life processes to flourish on Earth; carbon, hydrogen, nitrogen, oxygen, phosphorus and sulphur. In fact, the deeper they looked the more certain this case appeared.

At the outstanding depth of 11.000 meters in the sea, at the Mariana Trench, where the pressure is more than 1.000 times the standard atmospheric pressure at sea level and the density of water is increased by 4.96% (Columbia, 2012), life is thriving. Multinucleate, unicellular organisms were found, that extract minerals from their surroundings and use them to form exoskeletons as well as other microbial life forms. Even deeper, excavating at 9.660 meters below the Trench's bottom, inside a mud volcano, scientists discovered tantalizing traces of organic material, which may add to evidence that life can indeed survive in the most extreme of environments. (Plümper, 2017) There are many examples of the evolutionary triumph of life in extreme cases of environments on our Planet and some are selectively stated by the following literature review.

On the contrary, the human organism met few times with biological adaptation since the Cognitive Revolution (70,000 BCE) and maybe the equivalent natural balance for this was the gift of human imagination development(Harari, 2014), allowing man to synthesize ways to maintain stable biotic parameters regardless his environment. Since those times, observing and interpreting some extreme ecosystems cases led to the understanding of natural analogies that are helping mankind innovate and find systematic ways to combine technology and biological mechanisms into design solutions. But this observation, although successful for humans, has not always been of good interest for the rest of the ecosystem.

The challenges of our Era

Exploration of the unfamiliar asks for further knowledge, innovative approaches, trials for adaptation and rigid science. We are experiencing an era where, the scientific community attempts to overcome the previous frontiers of knowledge and likely deploy scenarios for further space exploration by creating an abundance of technological tools and operations. Moreover, globally leading industries and scientific communities are aspiring for man-made extraterrestrial habitats and space resources exploitation which requires a wider perspective between intersecting fields of study and a combinative approach to the challenges in order to be innovative, ethical and sustainable. The result of sending people to space is the increasing need for efficient products, design and settings directed to support life in space, the most extreme environment known so far. Taking advantage of the opportunity that emerged for the private sector, a new commercial market is in the creation, the NewSpace market. Meanwhile, increasing concern on extreme climatic events on Earth and environmental awareness by scientists and citizens has positively motivated a desire to reduce the waste of resources and environmental pollution through eco-efficient design imperatives and has triggered research on industrial product design, biotechnology, urban design & architecture,telecommunications and energy systems. These two challenging frontiers, both addressing life in extreme conditions but from different perspectives, have created an ambiguous debate, questioning the necessity of Space exploration advancement compared to that of Environmental protection. The literature explores a design and problem-solving methodology that could potentially address both challenges and give some intuitive answers to this debate.

Biomimicry as an approach

Biomimicry is a strategic design methodology, which poses a positive attitude towards nature inspiration and sustainable attitude towards ecosystems. The biomimetic solutions vary from clearly morphological patterns to nanoscale operating analogies. Biomimetics, in particular, can be defined as the products of *reverse engineering* ideas and concepts from nature and implementing them in a field of technology such as engineering, design & computing. The natural world contains infinite examples of how to achieve complex behaviours and applications by using simple materials in a clever way. As we begin to exhaust the natural resources we relied on to create our products and infrastructures, designers are turning to nature—where organisms make use of limited materials to survive—for inspiration on how to invent fascinating solutions to everyday design problems.(Kapsali, 2009) However, safe to say, challenges remain in the most critical industry sectors regarding sustainable ways of planning, designing and manufacturing systems and components for demanding or less explored target environments. It is therefore, of interest to see if biomimicry facilitates, as a design methodology, innovative solutions for this era's challenges and if it sets healthy examples for humanity's future civilizations.

Dissertation Focus

Nowadays, the speed with which things are evolving, interacting, derail or accelerate in growth has increased. Space exploration re-emergence and planetary resources sustainability pose two major focus areas for future design, and an opportunity lies where their solutions possibly osculate. In this dissertation, an examination of the factors, which affect the conditions of human viability in extreme environments, will take place. Inevitably, this brings the questions of why so far humans have not managed to understand and coexist with Earth's ecosystem and therefore how humans could live beyond it. Since living, for a human civilisation, inextricably means designing and planning, these are challenges that designers and engineers will soon have to solve. However, they may not do it alone. This hypothesis of a necessary interdisciplinary collaboration based on biomimetic approaches will be tested.The rise of interest in biomimicry in recent years provides a fertile ground for innovation. The research argues that, in the long term, humanity's future in space and on Earth will not necessarily be a sterile, techno-industrial dystopia of the Anthropocene and investigates in what ways biomimetic approaches to designing for this future will bring more STEM, social, economic, philosophical and artistic disciplines in collaboration and involvement.

The review follows a multi-disciplinary literature framework in order to accomplish a dense gathering of comparative information on biomimetic designs. The findings focus both on the areas that have been affected by the application of biomimicry, the opportunities and on the limitations that exist regarding biomimetic approaches to design.

Dissertation Value

Recognized for its value for sustainable competitive advantage and commercial success, strategic product design has an essential role to play in the future R&D demands of the currently evolving technological sector and bio-economy. Extreme global challenges call for the creation of a future where inner wisdom and science work together to address some of the most pressing issues. The industrialization of biology offers far-reaching benefits at global scale. Strategic product design attempts to develop a mindset of approaches in order for the next generation of products and manufacturing to be market-viable but also intuitive, unobtrusive and valuable. The review of literature highlights how biomimetic approaches contribute into driving the innovation economy and sustainable growth. It is of interest to explore if biomimicry will potentially lead to solutions of some of the societal grand challenges of our time, such as helping to deliver clean, affordable and sustainable energy, enabling next-generation manufacturing, space exploration and creating new markets (materials, textiles, electronics, surfaces, energy and more), skills and jobs to benefit the present and future generations. The use of biomimicry as a lens for design and human growth is investigated as necessity rather than option, while new extraterrestrial frontiers or on-earth disruptive technologies ask for insightful research as well as economy in design.

Dissertation Aims & Objectives

Obviously, there are still technological hurdles to overcome until the first humans can set foot on hostile environments as for example Mars, until space tourism commercialize space product design to support long-distance manned missions and design specifications like the ones described and envisioned in this dissertation can take place. However, our era calls for intuitive research and vision for the scientific purpose of explaining how the natural world works and how that can best benefit the collective needs of humanity.

Aims

This research aimed to examine biomimicry in design, focusing in studying the parameters affecting life and the design needs for the most extreme of environments. It presents interdisciplinary examples in order to generate reflection both conceptual and methodological, about the use of natural analogies as support to design projects and problem solving. It yet attempted to investigate the potential of biomimetic applications providing efficient –in the long term- solutions in extreme parameters in comparison with those plainly technological solutions. Finally, the research's root aimed to argue about the future of design disciplines in the NewSpace era and to add knowledge in the discussion around space exploration, which is frequently met with skepticism by environmental scientists and sustainability advocates.

Objectives

1) Connect existing knowledge of disciplines seemingly segregated from product design
2) Investigate factors from extreme environments and the value of their research
3) Explore biomimetic-approached solutions for extreme environments, inspired by natural analogies.
4) Provide insight on whether the biomimetic toolset helps designers contribute in solving today's and tomorrow's demanding challenges
5) Assess the potential interest of further relevant research.

Literature Review

A background check

Outstanding natural phenomena of life adaptation have been observed all around the globe, in fruitful environments but also in extreme ones. From Mangrove forests with waters of high salinity, illumination, and temperature fluctuations, to anoxic hydrothermal vents and the frigid Polar Regions, Nature surprises us with innovative life mechanisms. (Rothschild & Mancinelli, 2001) The natural world adapts and sustains itself over the long term by meeting its own needs through generations of positive natural selection. Embodied technologies can be found everywhere in the optimization of the geometrical form and efficacy of energy and material distribution. (Hu, 2017) Thus, to almost every challenge of environment parameters, Nature provides sustainable remedies in the form of evolution.
Humans, on the other hand, have evolved physically little since our common ancestor; the Homo sapiens walked the Earth more than 150.000 years ago. (McBrearty & Brooks, 2000) We come in a complex, sophisticated package with an extraordinary set of organs, systems and sensors, the human body and brain. However, this evolutionary gift has remained physically similar to that of our ancestors, with few exceptions of further evolutionary changes happening in small civilizations in high altitude mountains – from 3500 to 4200 meters high (Hlodan, 2010)- and some recorded nomadic divers' tribes, fishing up to 60 meters underwater. (Ilardo, et al., 2018) Yet, our surroundings remain exposed to extremely varying conditions and still, we managed to not only survive as a species but also confront challenges in an insightful way. So which attributes situated us on another path compared to the rest of the Hominid family?

Dreaming in another language

Around 70.000 years ago, the Cognitive Revolution gradually took place and Homo sapiens, exhibited flexible and inventive behaviour when in need to cooperate with a substantial number of strangers and form groups and alliances.(Harari, 2014) All other animals use communication tools to describe reality. Humans use it not only to describe but also to invent reality, driven by the incentive of mass scale human cooperation and survival. Early humans relied on nature for the provision of food, shelter and other native innovations for their existence and survival. By mere observation as well as in-depth study of nature, early humans knew local flora and fauna to a holistic extent beyond everyday survival, giving the perception of civilizations cooperating with ecosystems. (Levi-Strauss, 1966) Since then, civilizations and societies grew and scientists and innovators have been able to gather invaluable information about the functions and exploitation of resources. Many of this information led to innovations renowned in the areas of medical and pharmaceutical sciences; shelter architectures; weapons and defense, sensors, and alarm systems; crossing waters; agriculture and processes related to manufacturing. (Murr, 2015) Thus, human imagination, product of a unique intelligence among animals, gave birth to technology and to the collection of applicable knowledge to master or alter the environment and achieve previously impossible goals –resulting in deceleration of humanity's evolutionary process. Areas in which human imagination was measured through time, serving the research's interests are:

- *Architecture & Product design*

Imagination, whichever evolutionary path it was born from, led humans to develop visions of how they wanted to form their stories and strategies in order to achieve them. As the level of knowledge and the sophistication of the tools grew, humans gave birth to ideation, experimenting with usage of materials in further ways than before and scaling up the concept of shelter, transportation, energy storage and community engagement. *"The separation of man from nature is the motivation for the existence of architecture in the first place"* (Kellert, Heerwagen, & Mador, 2011). To interprete those words, built human habitats were created to shelter, to protect one from the outside environment and to enable – socially and economically- necessary interior activities. Driven by the changes in technology by the first and second industrial revolutions, the field of design emerged to specialize in the creation of commercial products. These products appealed to a broad audience and could be manufactured at scale, balancing functionality, aesthetics, ergonomics, durability, cost, manufacturability, and marketability.(Chang, 2015) An increasing urban population had different consumption needs than its rural counterpart, and the industrial manufacture toolset pushed the limits of industrial inventory and human imagination even further than existing technological knowledge. The rise of electronics, telecommunications and computers led to the production of miniaturized materials, which are currently working wonders, most notably to space research and biotechnology. (U.S. Congress, 1991) For industries, this revolution signalled the era of high-level automation in production through programmable logic controllers (PLCs) and robots. Meanwhile, another technological phenomenon took place and continues to evolve, that of digitalization; this time information reading and using came closer than ever into approaching bio-architectures. (OECD, 2017)

- *The notion of Society and Economy*

When human imagination is being put under a microscope we speak per se, for all human inventions – tangibles and intangibles- that may seem archaically established and inherent. From laws, nations and religions to the idea of economy, trade, credit and enterprises. All these started as stories created out of need and imagination and were chosen by prevailing groups of humans. (Harari, 2014)

- *The infrastructures*

Cities and their transportation and energy infrastructures are the largest, most complex artefacts constructed by humans. They are dynamic, spatial and material systems that display phenomena characteristic of complex systems – power scaling, self-similarity across a range of scales, and 'far from equilibrium' dynamics. (Weinstock, 2013) Moreover, cities and the land or waters in between them carry a network of information underneath. The internet consists of fiber optics crisscrossing the globe. (Strickland, 2008) Although artificial, they resemble in analogy some natural networks of energy and information transfer. Networks and infrastructures exist also in orbit around Earth (LEO), in the form of satellites transmitting signals and analyzing data and habituated space stations. (Howell, 2017)

- *Space exploration*

"From the pioneering sailors of the distant past and the covered wagons crossing California in 1800 to the radical engineers and pilots of yesterday, once the first airplane tamed the winds, it barely took seventy years for humanity to stretch even farther and touch another celestial body, the Moon." (Profitiliotis, SGAC, 2018) Not only did human imagination conceived technology that relieved some stressors on Earth and enabled longer generation cycles, but it also facilitated the unimaginable: extending human presence beyond the terrestrial biosphere. The creation of long-term "built" environments in outer space[1], LSS (Life support systems) and tailored equipment like the ones on the ISS (International Space Station), is an example of endless capabilities. (NASA, 2017) The quest continues

1 Outer space is the expanse that exists beyond the Earth and between celestial bodies. Outer space is not completely empty—it is a hard vacuum containing a low density of particles, predominantly a plasma of hydrogen and helium, as well as electromagnetic radiation, magnetic fields, neutrinos, dust, and cosmic rays. (Wikipedia, 2014)

nowadays with one addition; the search for Exoplanets. Exoplanets are planets outside our solar system, which share similar environmental conditions with ours and could potentially be habitable new worlds for the next generations. (Pulliam & Betz, 2019)

(Hu)Man in the mirror

How humans perceive progress and where they place themselves compared to Nature are two questions with much interest to review and debate on. Unlike Levi-Strauss (Levi-Strauss, 1966) and later anthropological studies of native tribal life and knowledge, some recent findings of archaeologists and neuroscientists showed a different view over human intelligence evolution. What they show is that in the last 100,000 years of man species appearance and Homo sapiens' jump to the top of the food chain, humans held the record among all organisms for driving the most plant and animal species to their extinctions. (Harari, 2014) On its own benefit, the human civilization met with large numbers of cohabitation, sophisticated infrastructures, medical and nutritional advancements, judging by the increasing numbers of population. (McEvedy & Jones, 2019) Along with the market-based argument of inherent, fundamental selfishness of the human species, many influential scientists, researchers and enterprises align with the ideological movement known as *New Optimism* (Burkeman, 2017), stating that the global level of wellbeing, flourish opportunities and well ageing is at the highest pick during our century, reflecting humanity's progress. (Pinker, 2018) However, the stories of humanity's choices are also embedded in the material world; resources exploitation and urban heat islands, poverty, garbage and global warming. (Boer, 2019) The consequences of these evidences indicate that earth is becoming less hospitable to our kind by the day. (Bastin, et al., 2019) Thus, Pinker's interpretation of progress has come under fire from scientists and historians for –as they argue- its selective use of evidence. (Hickel, 2019) The United Nations Industrial Development Organization also presented data leading to such conclusions. (UNIDO, 2004) Although it started with Carl Woese's work on horizontal gene transfer in the 70s (Woese & Fox, 1997), recent studies from multiple domains show rigid evidence that Nature succeeds to flourish under coexistence and symbiotic collaboration, rather than the *survival of the fittest*; and humans are also genetically prone to this. (Baumeister, 2018)

Biomimetic approaches to Design

In the past few years, a new method of designing has gained attention throughout different technical disciplines, which requires design thinking[2] by looking to Nature as the solution to sustainability problems. However, the practice is several years old. Leonardo da Vinci and Otto Lilienthal's attempts to develop flying machines based on bat and bird wing morphology named them history's most famous *bio-mimics*. (Pawlyn, 2011) Biomimetic solutions have been around for decades but their systematization through scientific disciplines first became established in the second part of the last century. (Hesselberg, 2007) Moreover, recent advancement in the biological and electronics field caused their true potential to emerge.

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2 Design thinking is a human-centred approach to innovation that draws from the designer's toolkit to integrate the needs of people, the possibilities of technology and the requirements for business success. (Brown, 2018)

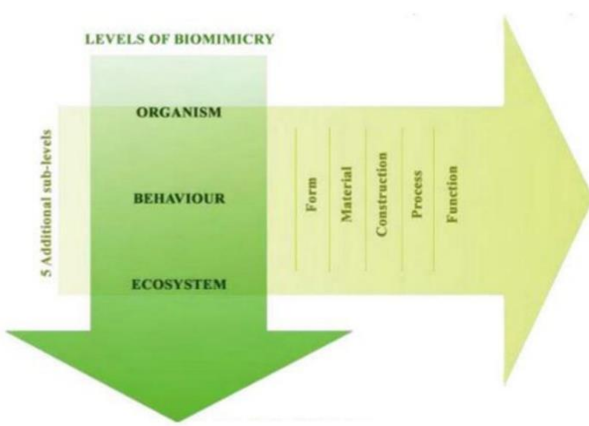
Nature’s library of strategies

Biomimetic design is interdisciplinary and derives inspiration by biological phenomena for solutions to engineering problems. (Helms, Vattam, & Goel, 2009) Biomimetics are the result of applying principles from engineering, chemistry and biology to the synthesis of materials, systems or machine functions and they target complex human problems. (Demirel, 2019) The practice of looking to Nature for new product creation has been documented by a number of studies focusing on bionics, biomimetics or biologically inspired design. (Lenau, Metze, & Hesselberg, 2018) Most approaches claim biomimetics to be the tangible products of the method called biomimicry. (Benyus, 1997) The term “biomimicry” first appeared in scientific literature in 1962 (Radwan & Nouran, 2016) , when the problem of energy shortage along with the high energy demand in buildings and industry was widely introduced.Literature also presents Otto Schmidt, American inventor and biophysicist to have primarly coined the term biomimetics during his practice[3]. (Bhushan, 2009) In the 1980’s it was adopted by material scientists. (Collins, Hunt, & Atherton, 2004) In 1997, Benyus’s book, “*Biomimicry Innovation Inspired by Nature*”, reintroduced the term and broadened its importance as a methodology that analyzes nature’s best ideas and adapts them for human use.

Levels of adaptation

According to Benyus (1997), the inspiration from nature could be drawn from three *levels of adaptation*:

- *The organization level*. At this level, we could mimic the whole organization or certain parts of the whole. (Hu,2017)
- *The behavior level*. At this level, we could learn from the drive of an organism’s function and apply it design. (Hu,2017)
- *The system level*. This level is considered the most difficult level, as it focuses on a functionally difficult issue to mimic.(Hu,2017) Following the categorization in these levels, she stated that, the design is listed as biomimicry in the way it looks (form), what it is made of (material), how it is made (construction), how it works (process) and what its capability is (function). (Aziz & Sherif, 2015) These levels attempted to propose a complete biomimicry approach.



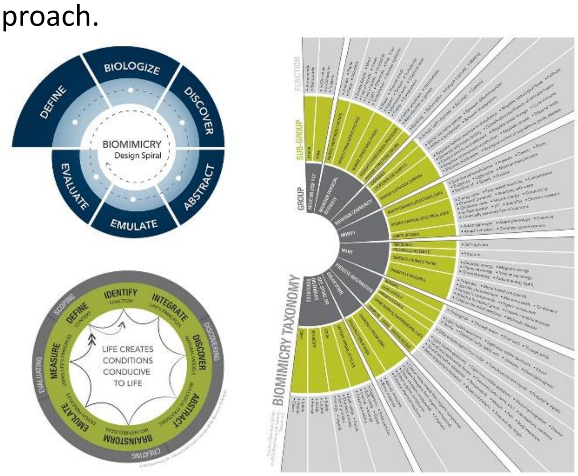


Figure 1The three levels of Biomimicry and five additional sublevels. Figure 2 Clockwise: The Biomimicry spiral of design transfer analogy as defined by the Biomimicry Institute, The Biomimicry Taxonomy for analogy transfer, The circular design process of Nature (Sources: Biomimicry.net and AskNature.org)

3 Schmitt invented or co-invented the Schmitt trigger, the differential amplifier, and the chopper-stabilized amplifier.

Categories of biomimicry design processes

Having established biomimicry as a design process in the past decades, research and practice of engineers, life scientists and inventors recognized two *categories of design processes*.

- *The design referencing biology*.

This is when a human need or design problem is first defined, and then the ways other organisms or ecosystems solve this problem are explored for potential inspiration. Throughout literature review, one can find different names addressing this category, like *problem driven biomimicry.* (Helms, Vattam, & Goel, 2009)

- *The biology influenced design-BID*.

This refers to biomimicry where a particular characteristic, behaviour or function in an organism or ecosystem is identified and is then translated into a human design context. (Aziz & Sherif, 2015) One can also find this category, under the term *solution driven biomimicry.* (Helms, Vattam, & Goel, 2009) Also, some examples of 'bio-utilisation', which describes the usage of living organisms in human systems can be under the BID umbrella although the idea of integrating with ecosystems, so that the man-made form is more compatible with natural ecosystems for the mutual benefit of both, is also not strictly speaking biomimicry. (Zari, 2018).

Figure 3The German developed Bio Intelligent Quotient (B.I.Q.) building system is an example, where live algae farm was used inside the apartments' window façade contributing to its passive energy system. (Wallis, 2013) The algae vertical farm contributes to energy saving system by shading the building, abating street noise and gets harvest to create biofuel and produce heat. (Source: sierraclub.org)

This categorization of biomimetic approaches reveals a broad spectrum of techniques that sometimes are segregated from biomimicry and others blended. Therefore, in order to have quantifiable metrics of the given approach, Wahl (2006) described *three main motives* behind using biomimicry.

A. *Biomimicry for innovation*

Most biomimetic research and patents so far relate to this motivational factor and are concerned with creating new materials and technologies. The motive here is novelty, in increased performance capabilities or increased economic profit margins. (Wahl, 2006) A considerable body of research details experiments and technological innovation particularly in robotics, computing and materials technologies that had no or little focus on sustainability issues in the previous decade. (Allen, 2010,Garrod, et al., 2007,Nakrani & Tovey, 2004) According to Bhushan (2009) the following properties of biology are of particular commercial interest: molecular scale devices, super-hydrophobicity, self-cleaning, drag reduction in fluid flow, high adhesion, reversible adhesion, aerodynamic lift, materials and fibres with high mechanical strength, biological self-assembly, antireflection, structural coloration, thermal insulation, self-healing and sensory-aid mechanisms.

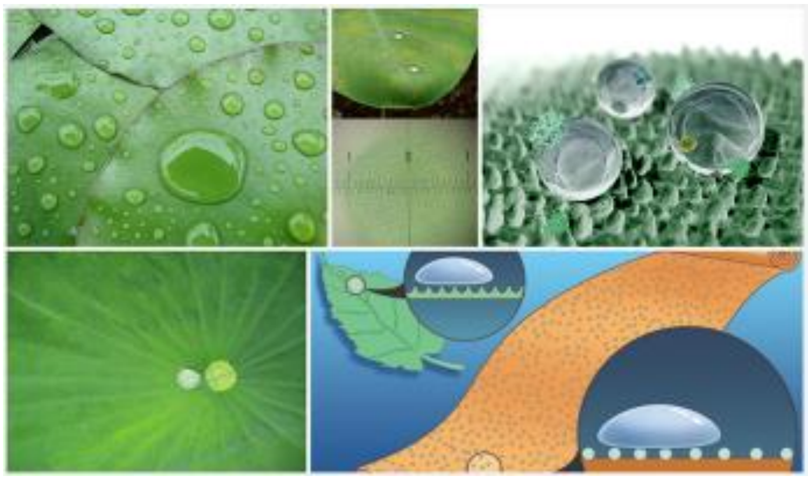


Figure 4 The Lotus plants, an aquatic plant stay dirt-free due to their superhydrophobic surface. Surface coatings were inspired by the self-cleaning mechanism of lotus plants.(Source:AskNature.org)

B. *Biomimicry for sustainability*

There is a rise in interest in the potential of biomimicry as a way to create more sustainable materials, products, built environments, and engineering solutions. So far, there was little quantitative evidence suggesting that mimicking an organism in design is in itself a means to achieve greater sustainability. (Zari, 2018) However, investigations of the past decade observed how biomimicry might contribute to addressing global challenges, including sustainable development, in a 50-year period (Gebeshuber, Gruber, & Drack, 2009)and recent events of climate change deterioration, pollution, overpopulation rates and scarcity of resources have made this a rather 10-year period in demand. (UN, 2019) Biomimetics promise tangible advancement in areas like materials science, energy conversion technologies, energy production systems and recycling systems by improving the ecological performance of human technology.

Figure 5 Innovative Wind Turbines inspired by whale fins, have power harness results increased by 20%.(Sources: Inhabitat.com & Bio-inspiredd.blogspot)

C. *Biophilia*

Another recently increasing motivation for exploring biomimicry comes from researchers and designers who propose a design approach linked to the concept of biophilia. Biophilic design builds on the processes of human psychological connection with the perceivable living world and combines theories from the areas of environmental psychology, evolutionary psychology and neuroscience with architectural and urban planning concepts. Much of the quantitative evidence that biophilic design draws on comes from the premise that the human mind evolved in the natural world, thus survival behaviours and responses related to certain substances, landscapes and natural forms are inherent and affect the human sense of belonging and wellbeing. (Kellert, Heerwagen, & Mador, 2008)

Figure 6 (Source: biomimicry2016.wordpress)

Examples of biomimetic approaches to design

Nature demonstrates an incredible plethora of design solutions and a database of mechanisms that scientists and engineers yet keep exploring. In the post-industrial-revolution's popular imagination, the best-known example is the microscopic "hook" on burrs that inspired the development of Velcro, but there are many more applications, from kingfisher beaks inspiring the shape of bullet trains to shark's skin being used as a model for advanced swimsuits.

Figure 7Velcro was invented by George de Mestral in 1941 and was inspired by the burrs he found on himself and on his dog. Being an engineer and entrepreneur, Mr. de Mestral examined the burr under a microscope and realized the small hooks of the burr and loops of the fur/fabric allowed the burr to adhere exceedingly well. This sparked his idea to mimic the structure as a potential fastener. (USA Patent No. US3009235A, 1955)

Moreover, advancements in computational engineering paved the way for optimization in innovative technologies, in not only the commercial industrial scene but in future earth and space technologies. (Srivastava, Tuteja, Tuteja, & Tuteja, 2013) Novel biomimetics include forisome protein building for smart biomaterials in microfluidic devices (Shen, Hamlington, Knoblauch, & Peters, 2006)or leaf structures duplicates on the surface of photocatalytic PI (thermally stable polyamide) film achieving hydrophobic materials with high mechanical and thermal stability, valuable in industrial flue-gas treatments. (Tseng & Kang, 2018) The research attempted to collect few indicative and state-of-the-art examples for each of the believed to be *design-infused* sectors of tomorrow. (UHY, 2019)

Example in transportation & aerospace product design

The Manta Ray inspired Jet

This vertical take-off and landing, all electrically powered aeroplane – designed by Munich-based Lilium GmbH – is set to revolutionise on-demand air taxi service. Instead of looking to the skies, Nathen turned to the ocean, and the form of the manta ray, inspired by the effortless way they glide. Biomimicry played an important role here, using both the dynamic form and the minimum use of propulsion. Mantas move through the water by the wing-like movements of their pectoral fins, which drive water backwards, creating thrust. With no tail, no rudder and only one moving part in each engine, the *Lilium Jet* embodies this near-natural ideal, while balancing functional engineering requirements. (Nathen, 2019)

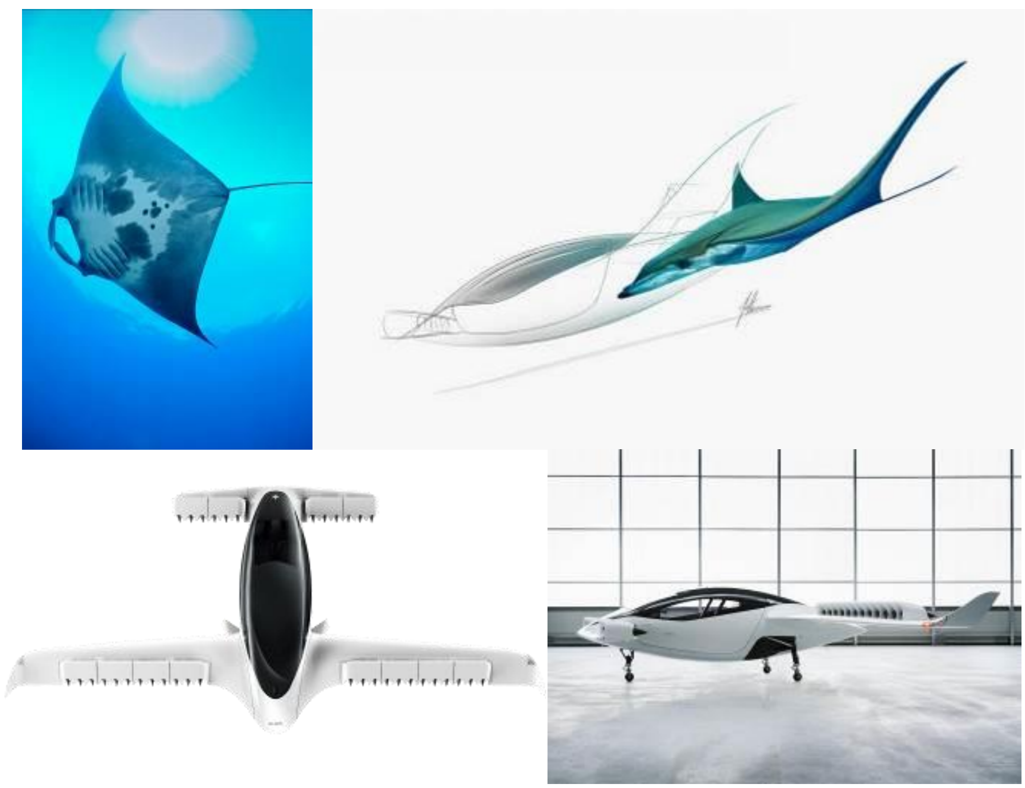


Figure 8The Lilium air flying taxi based on Manta Ray fluid dynamics.(Source: lilium.com)

Example in architecture

The Eastgate Center building

A retail and office building’s interior in Harare, Zimbabwe Africa, was modelled after a termite mound, achieving in maintaining liveable temperatures indoors while wasting less energy. (Hu, 2019)The mound-building termites colonies face record-breaking temperatures from sweltering heat waves and they build an environment that suits them rather than adapting to their arid environment. Their mounds help counteract the problem by maintaining an environment cool and humid. The termites make a living by farming a fungus (*Termitomyces)* in residence, with whom they have a mutually beneficial arrangement, as the fungus break down dead plant and woody material into digestible and nutritious food for the termites. Both the fungi and the termites produce a lot of carbon dioxide in the nest. To battle this, during the day, the outer tunnels of the mound are heated more rapidly than the deeper tunnels and chimneys, pushing air up the outside and down the middle. This creates a circular current that reverses at night as the outer walls lose heat more quickly. As the air flows through the mound, carbon dioxide is flushed outside through tiny holes in the mounds exterior walls, and oxygen enters the mound the same way. (King, Ocko, & Mahadevan, 2015)

Figure 9 The Eastgate Center and termite nest section plan (Source National Geographic)

Examples in energy sector & environmental engineering

Artificial Photosynthesis-A bionic leaf

Following previous attempts to recreate photosynthesis, in order for sustainable energy solutions (Sivaram, 2018), Nathan Lewis at Caltech ,Daniel Nocera at Harvard University and most recently Cambridge University researchers copied the process of photosynthesis, where leaves split water and use carbon dioxide from the air to make sugars into commercially viable *artificial leaf.* (Lewis, 2007) (Sigler, 2019) This process aimed at catalysts development which use solar energy to split water into oxygen and hydrogen, and creation of others that can convert hydrogen and carbon dioxide into an energy-dense fuel. Using nanotechnology, they designed silicon *microwires*, which allow the material to absorb more light. A longer-term goal is to discover catalysts that use carbon dioxide from the air in the production of a liquid hydrocarbon fuel such as methanol. Plants spend much of the sun's energy on growing while contrary; researchers like Lewis are seeking ways to increase the efficiency of converting sunlight to stored energy. One suggested commercial product was to place the fibers on a flexible polymer so that they would resemble a "solar carpet" where they act like tiny trees in a forest.

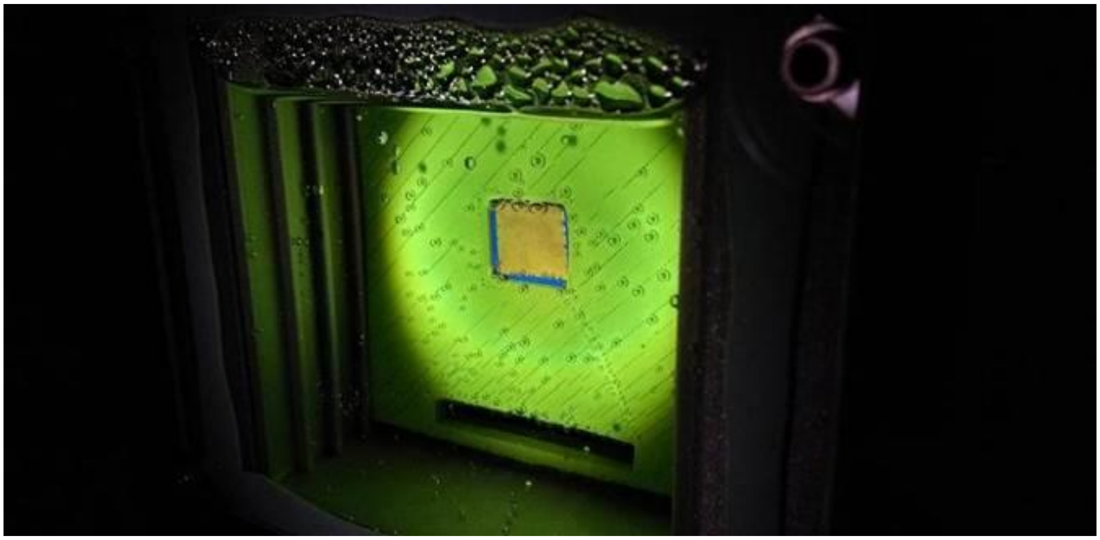


Figure 10 Rather than only create electricity, these fibers are treated with a catalyst to use the sun's energy for fuel production. The catalyst can react with water to produce hydrogen gas, which can be used as a fuel. (Source:cam.ac.uk)

Examples in material science

Sea urchins pricks inspire antifouling boat film wrap

To prevent the growth of algae, barnacles and mussels on the hulls of boats, Dutch inventor Rik Breur designed *Finsulate*, an environmentally friendly antifouling wrap inspired by sea urchins. (District, 2019) These creatures add to the weight of the ship and create drag, increasing fuel consumption. While there are antifouling paints available, these are often toxic and contain heavy metals that can be harmful for marine life. Breur found inspiration for his foil in the sea urchin, which prickly surface repels unwanted settlers. Supplied in rolls like carpeting, the patented material, which consists of nylon microfibers on one side and a self-adhesive film on the other, is free from polluting chemicals and offers a greener and more efficient alternative. (Frith, 2019)

Figure 11 *Finsulate* was a finalist for them European Inventor Award 2019. (Netherlands Patent No. EP1996453)

Self-healing concrete by induced living organisms

Dr Henk Jonkers, a microbiologist specialised in bacteria behaviour, and his team from Delft University have developed self-healing concrete with an inbuilt bacteria-based self-healing agent, increasing the lifespan of any concrete structure. The Delft group found that bacteria were able to produce spores comparable to plant seeds with extremely thick cell walls and remain intact for up to 200 years while waiting for a better environment to germinate. When the concrete started to crack, food was available, and water seeped into the structure lowering the pH of highly alkaline concrete to values where the bacterial spores became activated. (Jonkers, 2011) The self-healing concrete market is expected to grow at a striking pace of 24% CAGR by 2024. (MSF, 2019) Thus, more researchers are developing innovations like microcapsules containing “healing” agents –minerals, epoxy or polyurethane –which can be added to building materials to allow further integration of Nature’s self-healing mechanisms. (Al-Tabbaa, et al., 2018)

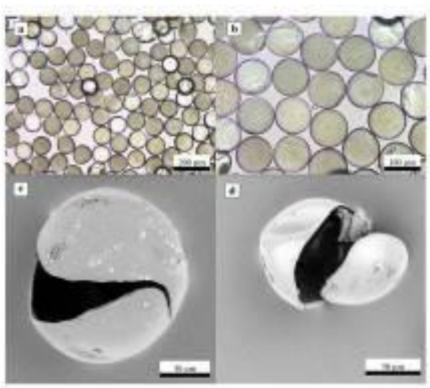
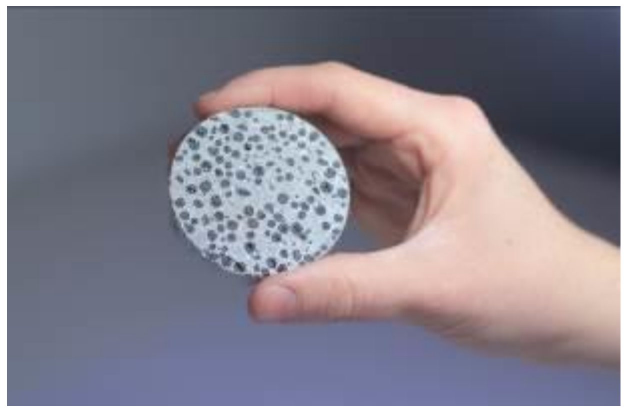



Figure 12 Bacteria spores under microscope. Concrete test sample has self-healing properties(Source:Archdaily.com)

Examples in robotics

Prosthetics & factory robots-Elephant trunk mimicking robotic arm

Engineers have created a robotic limb made using 3D-laser sintering that mimics the features that make the elephant trunk so extraordinary. (FESTO, 2012) While our arms and hands have bones and joints, elephant trunks have something arguably better; 40,000 muscles for incredible flexibility, precision, control and efficient movement. Their tremendous range of motion and eleven degrees of freedom for movement enable them to go from uprooting heavy trees to delicately plucking a blade of grass. The high-functioning and intuitive artificial limbs have shown major progress in the marriage of machines and human interaction, revolutionizing robot factory productivity, unleashing major opportunities for industrial applications spanning agriculture and the automated handling industry. One day, these machines could perhaps be remotely, autonomously printing-building entire buildings and infrastructures. (Biomimicry Institute, 2019)

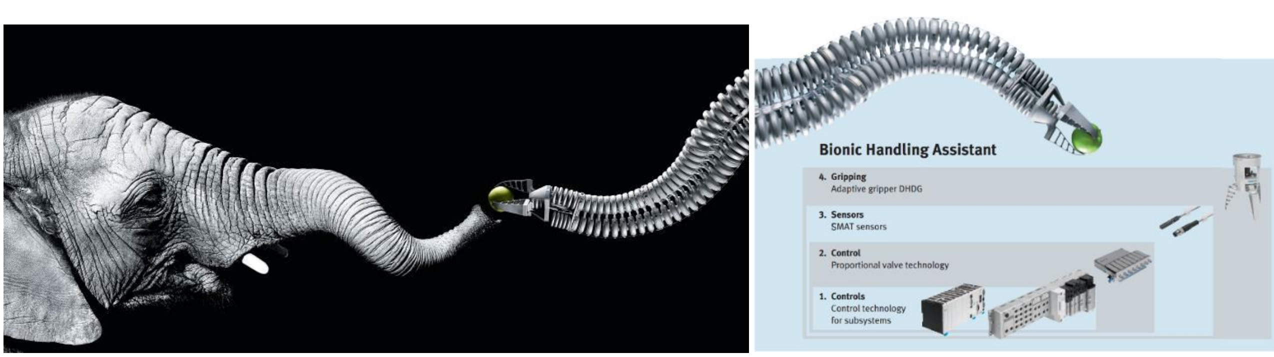


Figure 13 Robotic arm mimicking the elephant trunk. It performs four major actions: Gripping, sensing, controlling its movement, controlling subsystems. (Source: Sciencedaily.com)

Soft robotics inspired from plant roots and insects

Biomimicry has led to the development of a different branch of robotics called soft robotics. This major development in robotics, result of fusing biological systems, electronics and design, have allowed bio-inspired robotic locomotion. Soft robotics or *bio-robotics* can mimic the mechanism of muscles, insects' exoskeletons, animal tactile sensors, worm locomotion, even the squid or jellyfish propulsion and plant root systems. (Olsen & Kim, 2019) (PlantoidProject, 2015) The examples known so far combine software, hardware and mostly additive manufacturing, which allows the necessary level of tiny scale detail and mechanical performance. They are suitable for a variety of tasks like monitoring, exploring, measuring adaptation capabilities in any environment, performing self-adaptively. (Paley, Majidi, Tytell, & Wereley, 2016)

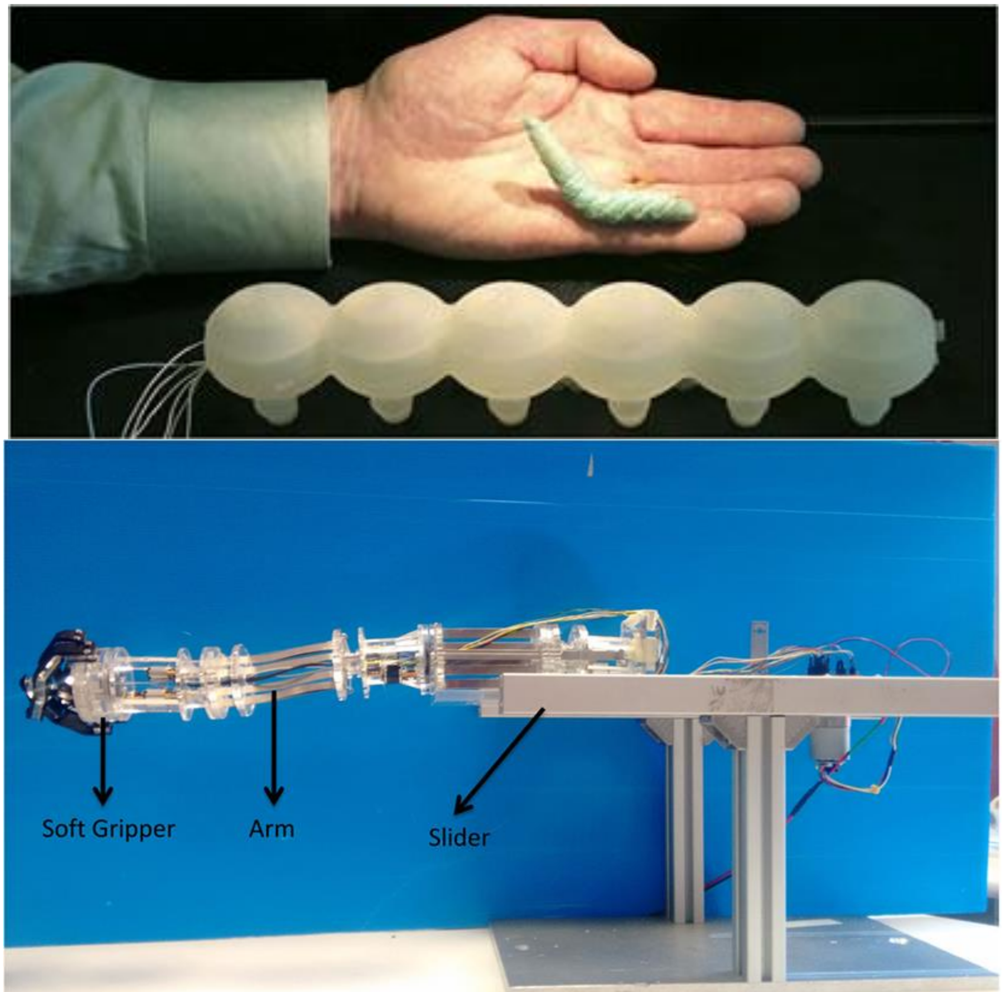


Figure 14 Soft robotics examples mimicking worms and caterpillars (Sources: news.stanford.edu &nytimes.com)

The natural analogies serve as information databases and can be hidden in many environment adaptation parameters. Yet, recent years of biomimicry research -aligned with quest for energy resources, overpopulation management demands, climatic change and space exploration- turn the spotlight onto parameters of environments and ecosystems where human presence is scarcely found in physical, but almost certainly appears in environmental footprint; the extremes.

Extreme environments

Made of stardust

The crucial elements for life on Earth, often called the building blocks of life, abbreviate as CHNOPS: carbon, hydrogen, nitrogen, oxygen, phosphorus and sulphur. (Pearson, 2010) Astronomers have catalogued the abundance of these elements in a huge sample of stars in our Milky Way (APOGEE, 2008) and place constraints on when and where in our galaxy life had the required elements to evolve; a sort of temporal galactic habitable zone. Although humans consider Earth their home and genesis of life, as we know it, there are many places on the planet where environment conditions are hostile for humans as well as other living beings. The study of these extreme environments is an exploration of the limits of life. (Rothschild & Mancinelli, 2001)

Parameters affecting life

Tolerable environments would mean, for example, those with temperatures between 4 and 40°C, with pH values between 5 and 8.5, and salinity between that of freshwater and seawater.(Rothschild & Mancinelli, 2001) However, each of life's many parameters may reach extreme conditions. Most commonly, organisms perform a number of basic functions (homeostasis, metabolism, growth, reproduction) when Earth's water and carbon-based systems are constrained within certain environmental parameters. (Clark, Douglas, & Choi, 2018) Furthermore, living conditions for animals and humans indicate certain levels of psychological convenience and cognition. Extreme environmental parameters can be borderline sufferable for basic functions but abet psychological fluctuations leading in cognitive behaviour changes. (Kring, 2007)

The Basic Parameters causing extremes environments:

1. *Temperature*
2. *Alkalinity*
3. *High Pressure*
4. *Ionizing Radiation*
5. *Salinity*
6. *Humidity*
7. *Oxygen availability*
8. *Toxic Heavy Metals*

The study of abiotic stress tolerance has received much attention because the understanding of how organisms survive and even thrive under extremes can provide valuable insights into evolution, conservation, and biotechnological applications. Few organisms can push these boundaries and thrive in conditions normally inimical to life. (Zhang, 2019) Thus, the concept of "extreme" environment is relative to parameters under which most species thrive. (Boyd, Krell, & Rajakaruna, 2016)

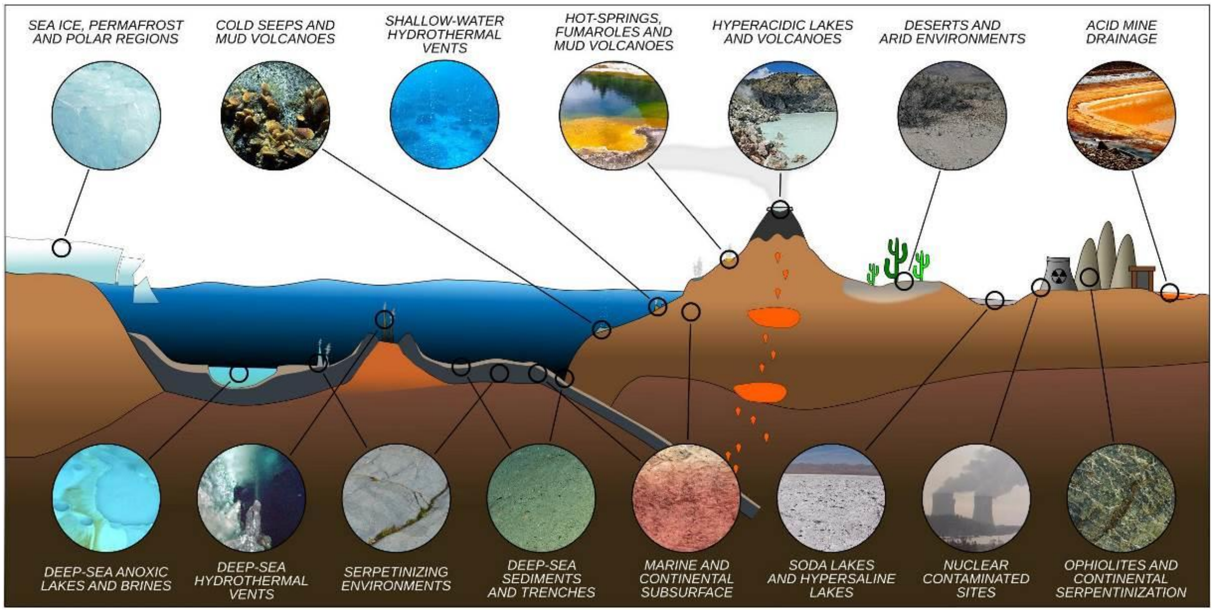


Figure 15 Distribution of places with extreme conditions.(Source:frontiersin.org)

Life thriving in extreme environments

There are many extreme environments where humans cannot operate for extended periods without support. Examples of such environments are observed all around Earth including; the geographical ice poles, hyper dry deserts, volcanoes, deep ocean trenches, high altitude and upper atmosphere, even places contaminated by human pollution as well as -the most multitudinously extreme of all-known so far- outer space.

Organisms that live in hostile environments are usually archaea and bacteria (Woese & Fox, 1997), but study has it that other groups of organisms also have members that live in stressful habitats.(Boyd, Krell, & Rajakaruna, 2016)

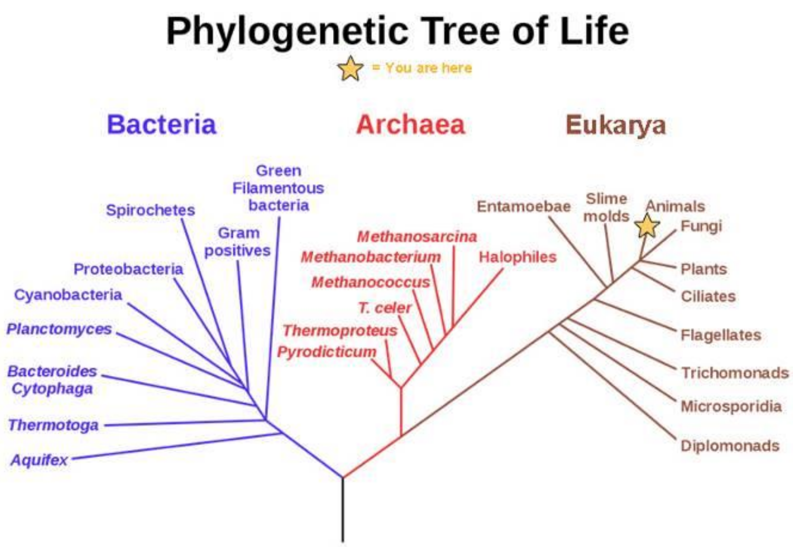


Figure 16 The phylogenic tree of living organisms.(Source: Lumen learning)

Examples on our planet and known solar system

- Extreme Ph and high temperature-Microorganisms Variete

An organism that withstands an extreme environment is an *Extremophile*; one that resists multiple extreme stresses is a *Polyextremophile*. Examples of the latter would include *Sulfolobus acidocaldarius,* an archaea (unicellular organism) that flourishes at pH3 and 80˚C, at the Yellowstone National Park of Wyoming. (Rothschild & Mancinelli, 2001) Natural habitats of similar organisms are solfataric fields in five continents. Their unique extreme thermo-acidic tolerance brought them to attention of biotechnologists looking to expand the thermal range of industrial biotechnological applications,facilitate removal of volatile products, and eliminate cooling costs. (Quehenberger & Spadiut, 2017)

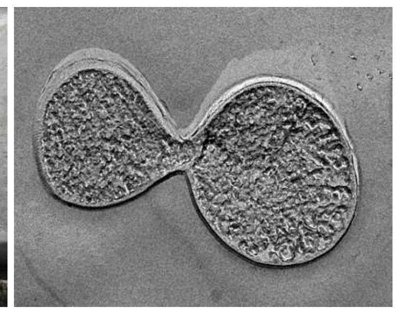
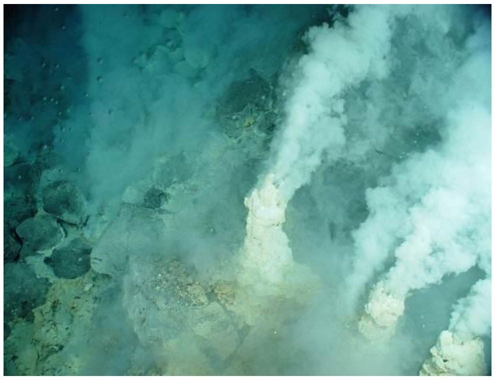


Figure 17 Yellowstone National Park's Congress pool hot spring forms a sulphuric lake with a temperature range of 65˚C->95˚C and pH3. Geothermal activity rumbles on beneath the surface, fuelling the spewing geysers and hot springs that make the site so famous. The rings of color each represent different microbial communities. Figure 18 In the last photo one can see *Sulfolobus acidocaldarius. (Sources:commons.wikimedia.org &sulfosys.com)*

- Extreme heat, acidity and heavy metals- Snails, crabs, fish and octopus

In the ocean depths, there is little oxygen to breathe and the crushing pressure increases the deeper you go. The sunlight cannot reach, so it gets pitch dark and cold.Eruption of volcanic rocks at the midocean ridges is the major mechanism by which heat is lost from the interior of the Earth. Seawater interaction with these underwater volcanoes, at near 400°C, results in substantial chemical flux and contributes to buffering the composition of some elements in seawater. The hot, acidic altered-seawater releases mineral-rich fluids and tall, thin vent chimneys are created on the sea floor from these precipitated metallic minerals deposits (Fe, Mn, Zn, Cu and more). (NationalGeographic, 2019)An ideal place to live or some of the most hostile habitats? Indeed, huge red-tipped tube worms, bacteria, ghostly fish, strange shrimps with eyes on their backs, sponges, iron-shelled snails, crabs and octopus thrive in these extreme ecosystems.(SmithsonianInstitution, 2010)



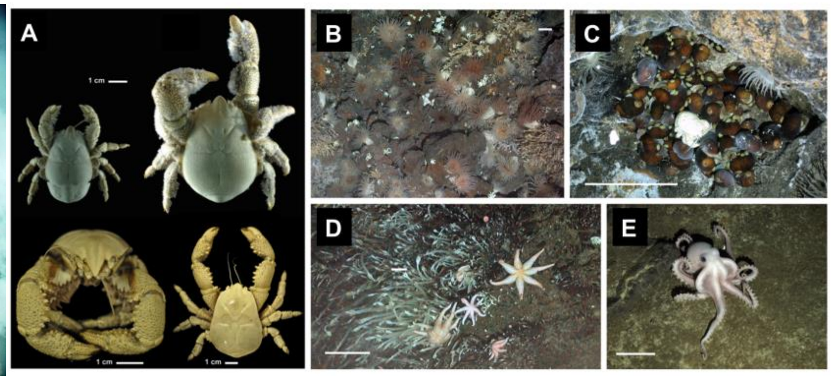


Figure 19 Hydrothermal vents extreme ecosystem (Source: famouswonders.com)Figure 20 a)Crabs, b),d) echinoderms, c)snails and e)octopus, are some of the creatures thriving near the vents.

- Toxicity-Hungry Fungi

The research on pollution of the marine environment by man-produced products like plastics is a cause gaining ground each day the past decade. However, recent studies found that plastic trash, through production and lifecycle journey, allow toxic heavy metals –like cadmium, zinc and lead- latch onto their surfaces and enter the marine environment and food chain. (Munier & Bendell, 2018) Therefore, the discovery in 2011,in the Amazon forest of Ecuador, of a fungus of genus: *Pestalotiopsis,* species: *microspora*, that can survive anaerobic conditions, eating only polyurethane (found in fabrics, foams, shoe soles) was met with awe. (Russell & Strobel, 2011) This discovery, adding to knowledge that mycelium, the vegetative parts of a fungus, are natural decomposers, led to a series of >50 more similar species discovery and cultivation. It is still helping, according to Tom Prescott Senior Researcher at Kew Gardens, understand adaptations of life in ecosystems and design household recycling devices or building materials.

Figure 21 *Pestalotiopsis* species are known as plant pathogens. The surprise was they also decompose some plastic types.(Source: smithsonianmag.com)Figure 22The biomimetic, home-recycling device is called *Fungi Mutarium* and is a combination of creativity, science and design. (Source: smithsonianmag.com)

- Permafrost and polar temperatures – Polar bear skin

For polar bears, the insulation provided by their fat, skin, and fur is a matter of survival, in order to endure the frigid Arctic temperatures of - 40°C. Scientists study how they manage to keep internal body temperature at a steady 37 °C. Except for the tip of the nose, polar bears are covered in a very thick undercoat, which scientist tested with thermal cameras and microscopically. They found the hairs of the fur to be hollow and waterproof, with each having a long, cylindrical core directly through its centre. The hairs appear to be very effective at absorbing infrared radiation; thus heat. (AskNature, 2020) It is the shape and spacing of such narrow cavities that provides their unique body-heat holding capacity and water resistance, as well as stretchiness, characteristics that are essential for a thermal insulator. (Donaldson, 2019)

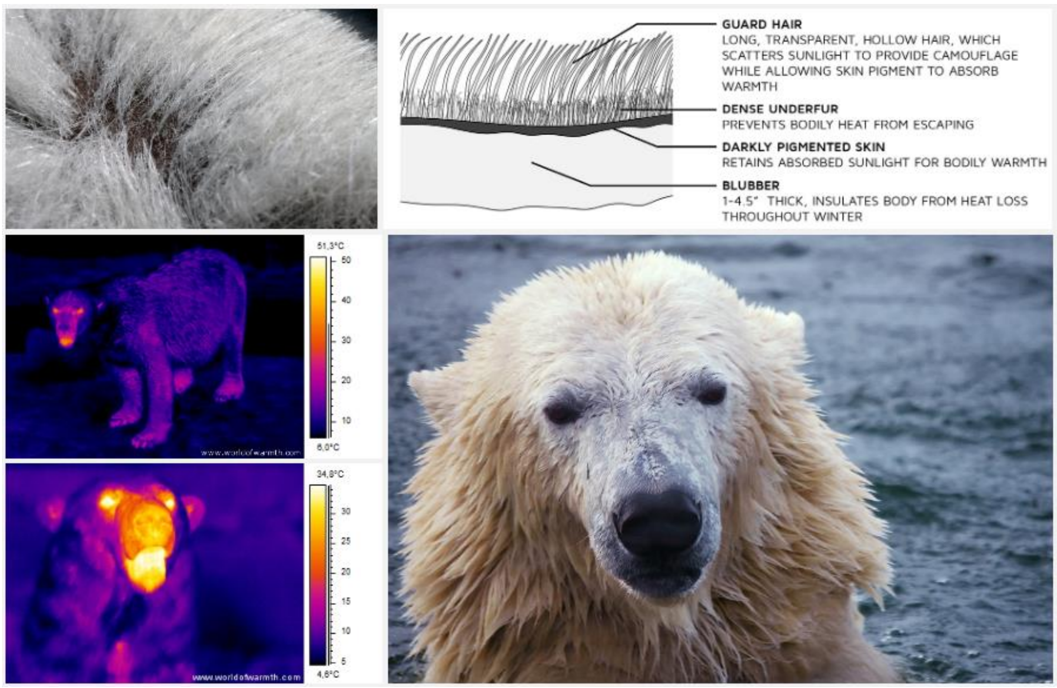


Figure 23 The images above show the findings on polar bear fur insulation, examining it with microscopy and thermal camera. The results have already led to a marketable product.(Source:AskNature)

- Dense urban environment –Weed plants

Cities are, in many ways, extreme environmental habitats. Dense cities of our century and their transportation networks, present urban heat islands. They have poor air quality and they are noisy; they use artificial light; and there is concrete everywhere. (Imhof, Mohanty, & Fairburn, 2014) When it comes to natural seeding plants, the only way to survive in the cities is if they can germinate and create seed in a short space of time and with maximum efficacy. The weeds called Hawk's-Beard plants, that grow in little patches of soil around trees that are planted along city streets of the French city of Montpellier are an example of natural adaptation to the extremely barren cities. These plants make two kinds of seeds, big seeds and small ones. The small ones have little parachutes that they use to float on the wind. French researchers found that these small-sized seeds are disappearing. That has to do with the fact that in the city those drifting seeds will probably land on tarmac and will not be able to germinate. Therefore, the plant's genes invest more in the heavy seeds, which fall to the floor and germinate at the foot of the parent plant.(Dubois & Cheptou, 2017)

Figure 24 This humble weed is a different kind of an extreme environment survivor.(Source:Nature.com)

- Space vacuum-Tardigrades

Another example of a *Polyextremophile* species is tardigrades, water animals also called the *water bears*. At roughly 0.1 to 1 millimetre in size, tardigrades are found in liquid environments around the world—including mountainous and Antarctic seawaters. They are documented for having remarkable abilities to survive extreme conditions, from dangerous cosmic radiation levels to frizzing temperatures like the vacuum. (Schill, 2018) They were launched into space as part of a project to transfer life forms to the moon (on the *Beresheet* lander spacecraft, which crash-landed there, posing planetary pollution discussion). (Oberhaus, 2019) Previous studies identified a Damage suppression protein (Dsup), found only in tardigrades. Intriguingly, when Dsup was tested in human cells, it protected them from X-ray damage. Recent molecular explanation of this impressive feat of the protein is that it has two parts; one that binds to chromatin and another forming a kind of cloud that protects the DNA from hydroxyl radicals. Scientists suggest that this survival mechanism against hydroxyl radicals evolved in the mossy environments where tardigrades inhabit. When heat dries up the moss, they shift into a dormant state of dehydration, called "anhydrobiosis," during which Dsup protection helps them survive. (Chavez, et al., 2019)

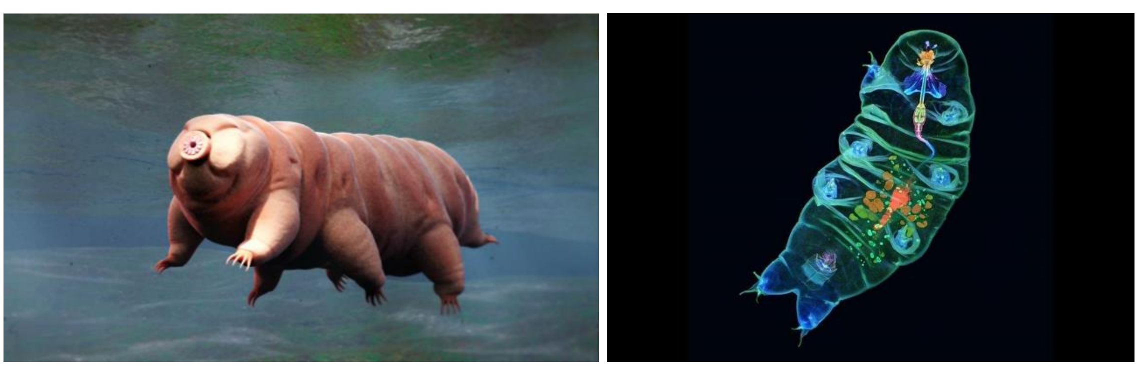


Figure 25 These tiny creatures live just about everywhere: in moss and lichens, bubbling hot springs, Antarctic ice, deep-sea trenches, Himalayan mountaintops and even survived space environment.(source:americanscientist.org) Right: an artistic microscopic representation of the creature's structure through multiple layers of fluorescent illumination. (source:livescience.com)

Adding to the existing knowledge, the BIOMEX (ESA) space experiment placed and exposed several hundred samples of Earthly microbes, including bacteria, archaea, mosses, lichens, fungi and algae, attached to the outside of the Russian Zvezda module on the ISS, to the vacuum of space. After almost 18 months, many of them managed to survive the extremity of the vacuum. The experiment helped define what kinds of biosignatures we should be looking for on Mars and other planets or moons. (Vera, Alawi, & Zucconi, 2019)

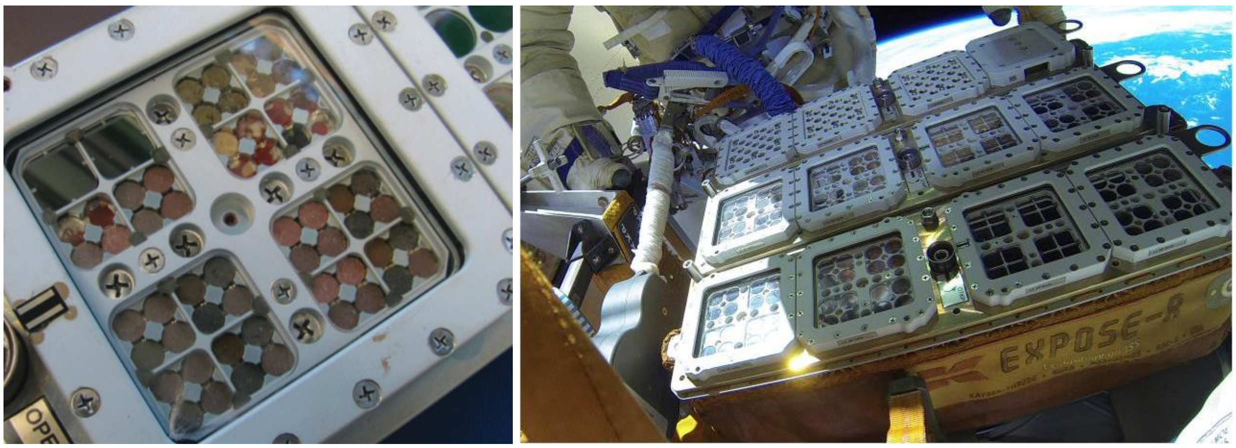


Figure 26 Photos of the BIOMEX microorganism samples, hanging from the ISS, which underwent the 18-month stress test in space ,including exposure to vacuum, ultraviolet radiation, heat& cold (source: dlr.de-German Aerospace Center)

It is wise to note the clear difference between living under extreme conditions and tolerating (usually by hibernation/dehydration) extreme conditions, but both situations are rich sources of information on how life responds to environmental challenges.

Design needs when dealing with *the extremes*

Extreme conditions are intriguing for engineers and design strategists because of the way that they exaggerate aspects of the design process and can lead to atypical architectural responses. While inhospitable to humans, extreme environments present many activities that may warrant a human presence**.**

Categories of extreme cases that require integrated design

Category #1. Resources exhaustion - Climate change deterioration

The only hospitable for human kind planet on our solar system is becoming less and less tolerant to our presence by the day, presenting environmental and biological conditions that resemble extreme environmental parameters. Waters are contaminated with toxic chemicals, agricultural contaminants and microplastics beyond the point of nature's ability to balance it; earlier fertile regions are now barren, wild landscapes deforested, water cycle hindered and the biodiversity loss is here to stay. (AmesResearchCenter, 2019) Even away from Nature, inside the dense urban blocks humans are suffering the extreme climatic conditions with floods, droughts, poor air quality and heat waves. The stated facts put to question the strategic design of urban, food, agricultural, marine and air activities of humanity and call for constraints-based design and modelling, circular manufacturing and mitigation of the climatic extremity. (UN, 2019)

Figure 27The 17 Sustainable Development Goals table, as defined by the UN 2030 agenda.(Source: un.org)

Category #2. Rescue missions and extreme contamination conditions

Close enough to the previous category; disaster zones, both natural and manmade, and epidemic diseases spread frequently pose risks especially to first responders and relief personnel. One of the first tasks of responding personnel is to establish safe staging areas, which can be difficult when facing environmental hazards, rigidness and obsolescence of fundamental infrastructure. (Zibulewsky, 2001) It was observed that previous design of emergency structures, health treatment spaces, rescue mission tools and equipment lacked the dynamic variables of the changing environmental conditions of the planet. (Tenenbaum, 2020)

Figure 28 Indonesia erathquake and tsunami disaster zone scene from 2018. (Source:time.com) Figure 29 The COVID-19 world pandemic showcased the need for universally intuitive design of equipment and is also raising questions regarding products and materials lifecycles.(Source:cidrap.umn.edu)

Category #3. Terrestrial/Environmental Analog Sites

The design of spaces dedicated to experiments in preparation for future spaceflight (known as analogue simulations) place human subjects in extreme environments (known as analogue sites) that closely resemble the operational environments on other solar system bodies, like the Moon or Mars. Analogue site studies are necessary because they help to understand geological processes, which can be extrapolated to other solar system bodies, with minimized costs and risks, in order to interpret and validate the data received from equipment in orbit or assisting space rovers. They also help to optimize scientific processes, technological design needs and exploration strategies for space missions. (Foing, Stoker, & Ehrenfreund, 2011)

Figure 30 EDEN ISS is a greenhouse in Antarctica that aims to advance controlled environment agriculture technologies in extreme environments, to support autonomous plant cultivation in future human explorations to unknown worlds. (source:eden-iss.net)

Figure 31 An analog Mars mission at the HI SEAS, semi-portable Mars analog Habitat (Hawai'i Space Exploration Analog and Simulation).The crew member in the photo spent one year in confinement at the habitat.(source: HI-SEAS/C. Heinicke).

Figure 32 The EBIOS project, from Interstellar Labs studio is a recent milestone from engineers and scientists to create an Environment Controlled Life Support Solution (ECLSS), for space settlement on Mars. It will include systems for water treatment, waste management, and food production, guaranteeing a zero carbon footprint, zero waste and nature conservation.(source:interstellarlab.earth)

Category #4. Scientific exploration in extreme places

Researchers and industries frequently demand the entering to extreme environments for experimental exploration, testing or for maintenance of data collection apparatus. This form of design roots from the early pressure resisting diving chambers and comes all the way to present architecture of freezing Antarctica stations, the ergonomics of the ISS Space laboratory and product design of autonomous, orbital labs inside nanosatellites; floating through meteors and ionized radiation. (USB, 2014)

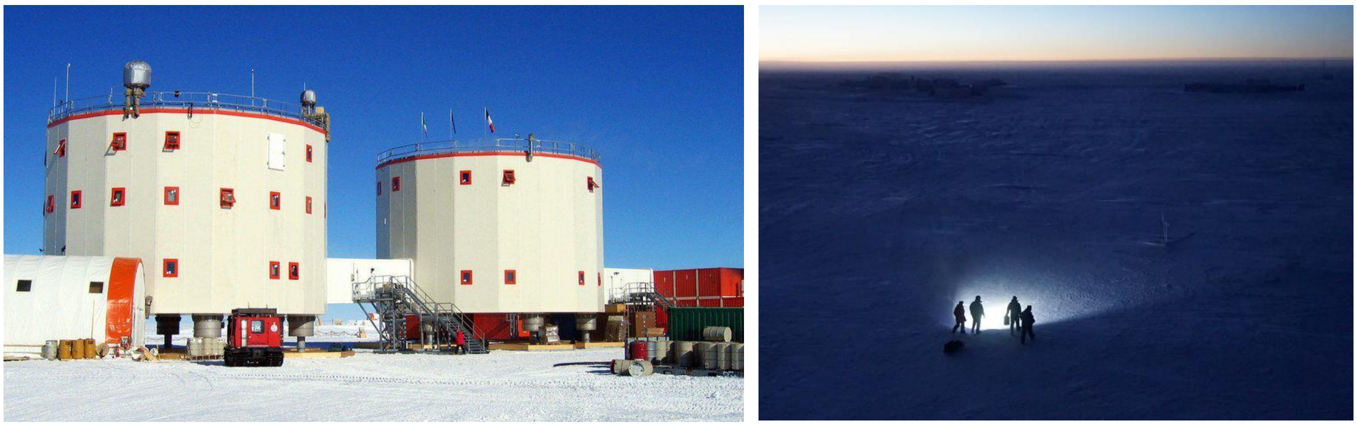
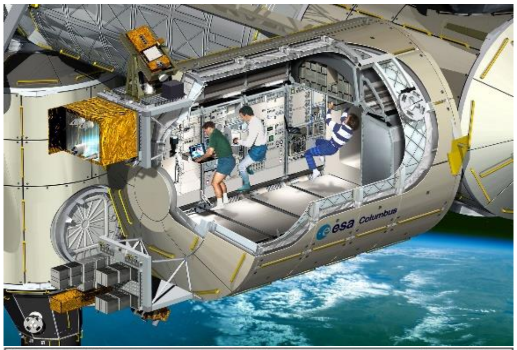


Figure 33The French-Italian Concordia research station is one of three year-round stations and is located on Dome C, secluded from the world in inhospitable conditions, the crew stationed there tackles temperatures that can drop to –80°C in the winter, with a yearly average temperature of –50°C. (source: esa.int, institute polaire français Paule-Emile Victor)

Category #5. Space missions, commercial space and future colonization

Right as these lines are being written, there are 9 people living on the ISS (Expedition 60), in Low Earth Orbit; a record of a number of humans living outside in the extreme environment of vacuum. (Urrutia, 2019) For this condition to be made possible, the design needs include engineering, products and architecture for microgravity, insulation and clothing for extreme temperature fluctuation, system design for air filtration, water sanitation and waste circulation, manufacturing with in-situ resources, protection of humans and materials from ionized radiation, packaging design for food and medicine, and more. (Finckenor & Groh, 2015)(Nixon, 2017) Future human missions will include establishing a sustained extra-terrestrial human presence beyond low Earth orbit, involving an increase in mission length and upgrading the significance of design beyond the performance of machines and labs. (Fleeter, 2000) (Niarchos, 2018) Furthermore, commercial trips, permanent colonization are already under research and new challenges and questions regarding the influence of psychological and physiological factors. (NationalResearchCouncil, 1997)



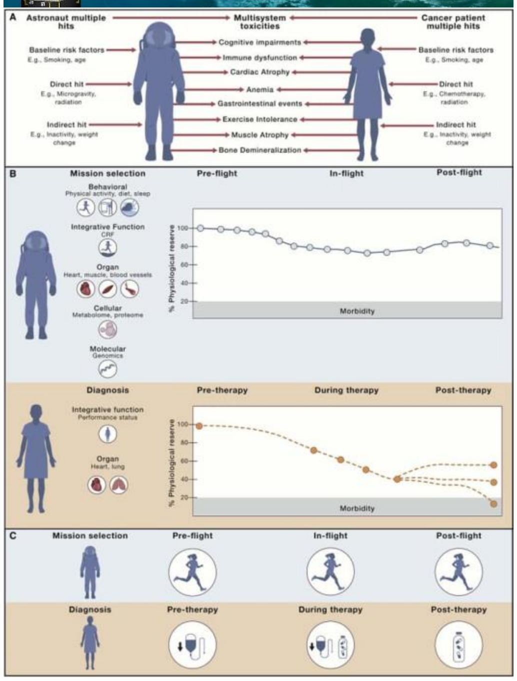


Figure 34 A section of 3d visualization of *Columbus*, the European laboratory module of the International Space Station(source:esa.int). .

Figure 35 The Dannish architecture studio SAGA developed a folding geometry lunar habitat , the *Lunark*,and is going to test it in the remote landscape of Greenland next year.(source:lunark.space).

Figure 36 Extreme environment conditions in space and the effect of cosmic radiation on the human body are examined in this comparison that helps scientists find ways to help multisystem toxicity in cancer patients.(source: sciencemisssion.com).

Figure 37 Technologies in product development based on extreme parameters on planet Mars and the human factors.(source: luonacai.com-NASAWorkstation).

Target Destination	Radiation (krad/day)	Heat flux at atm. entry (kW/cm^2)	Deceleration(g)	Pressure (bar)	Low temperatures (°C)	High temperatures (°C)	Rotational period (Earth days)	Chemical corrosion	Physical corrosion
High temperatures									
Venus		2.5	300	92	482	243		Sulfuric acid clouds	
Jupiter (upper atmosphere)		30	228	22		230	0.4		
Low temperatures									
Lunar permanently shadowed regions					−230				Dust
Comet (nucleus)		0.5[a]			−270				
Titan		0.01	15	1.5	−178		16	CH4	
Enceladus (equator)					−193				
Enceladus (south pole)					−188				
Low temperatures and high radiation									
Europa (orbit)	40								
Europa (surface)	20				−180		3.6		
Europa (sub-surface)	0.3 at 10 cm				~0 at 5 km				
Thermal cycling									
Moon					−233	+197	27		Dust
Mars		0.05 −0.1		0.007	−143	+27	1		Dust
[a] refers to Earth return									

Figure 38 Table of extreme environmental parameters observed on celestial bodies of our solar system.(source: (Balint, Cutts, Kolawa, & Peterson, 2008)

Design education and processes have long studied the *design for the remote,* predominantly through the systematic approach and prefabricated construction, but extreme environments present more complex, environment-specific challenges. Adding to this fact, when the design needs surpass a mission design to the extremes and call for long-term life-sustaining systems things get more perplexed. (Bannova, 2014) Thus, engineers and designers are faced with two primary tasks:

1) To study the aspects of building in a dynamic extreme environment.→ To understand the extreme.

2) To find methods of countering the major physiological and psychological problems faced when attempting to maintain life for long periods in extreme cases. → To explore dynamic approaches. (Arnhof, 2016)

Biological systems have developed numerous optimized (while constraints-based) subsystems respecting the *least energy principle*. In addition to genetic evolution, this principle is considered as an objective attribute that guarantees the development of living creatures. The biological *least energy principle* is translated in design as minimum resource utilization, least cost, maximum efficiency and autonomy. (Ayre, 2004) All four design characterisics are affected by multiple stressors in an extreme environment. It seems likely that biomimetic approaches, interpreted in engineering and implemented for designing in the extremes could lead to solutions suitable for dynamic problems.

Biomimetics for extreme space applications

Space architecture and space technology applications are already facing extreme environment design parameters and biomimicry is of rising interest regarding their design toolset. At this point,the rearch reviewed three novel examples of biomimetic design for space, including a bio-utilization example, a solution-driven biomimicry example and a system level biomimicry example.

Examples

- SOLAR BLACK Thermal coating

The US and European Space Agencies, launched the *Solar Orbiter* spacecraft this February, in a mission to explore our sun's poles. This exploration is expected to provide knowledge about the development of planents and the emergence of life in solar systems. The requirements of the mission include, among others, for the spacecraft to go close to the Sun (within 0.3 AU); meaning its surface materials to withstand temperatures greater than 550˚C on the side observing the Sun and below -200˚C on the opposite side, whilst protecting the sensors and equipment and being as light as possible to launch. Scientists calculated that the surface made from titanium, had to be black on the outer layer to release heat to space (ESTEC, 2010)For such requirements, the ENBIO company developed a biomimetic thermal management coating that stayed the same colour and did not melt, peel or degrade in these extreme conditions; the *Solar Black.* ENBIO faced the challenge of mission-critical surface requirements, by using bio-utilization from powdered baked animal bone to create the coating technic. A technic with roots back to the Stone Age painting. (Twomey, 2019)

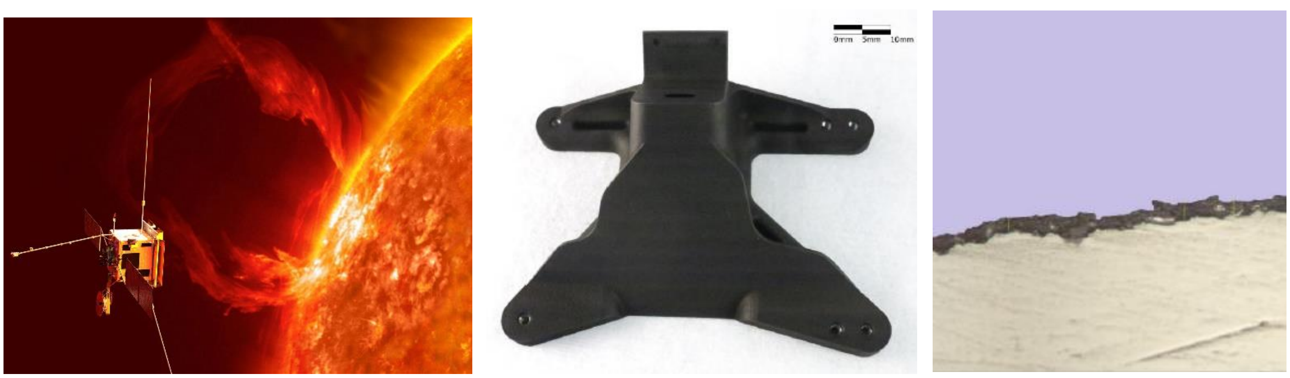


Figure 39 From left to right: The Solar Orbiter Spacecraft (source: esa.int) The Solar black thermal coating on a component of the Solar Orbiter and micro-image of surface layer thickness at 7.8 μm ±1.6 μm (source: ENBIO-GSTP ESA workhop presentation)

- DOVES energy autonomy with deployable nanosatellite sollar panels

Doves are series of nanosatellites with foldable solar panels, resembling the dove wings. (PlanetLabs, 2019) The necessity of hydraulic-like foldable or self-deployable structures in space lies on the lightweight,low cost launch needs, on the need for maximum surface for energy transformation and on the lack of air friction in vacuum, causing any high jitter of deploying mechanisms to create turbulence and affect orbital calculations. (NASA, nasa.gov, 1993) However, although morphologically resembling wings and flexible structures of animals and plants, this example was stated as design-inspired by the Japanese origami folding technic. (Lienhard, 2015) Some researches although argue origami-like unfolding is observed both at molecular level folding of DNA packaging as well as cellular and tissue level in plants pollen protection,photosynthesis and animals organ development. (Hunter P. , 2015)

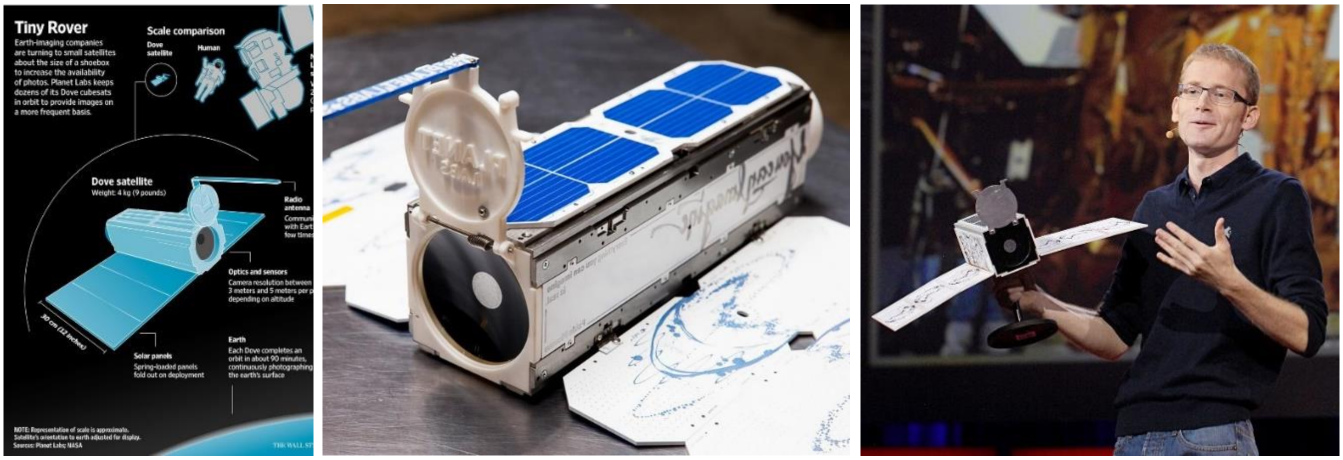


Figure 40 The Planet Labs cubesat satellites series with deployable solar panels and oprtics called the DOVES, so far is leading the nanosatellite constelation-in-orbit race.(source:planet.com)

- MELISSA Closed ecological systems

The MELiSSA (Micro-ecological life-support system) biomimetic project is designed as a tool to explore the function of closed life-support systems. The support systems of space architecture, scaling from a manned spacecraft, to a space station and to an entire colony or deep sapce travel, generally consume a lot of energy and need to be sufficient and autonomous. (Escobar & Nabity, 2017) The autonomy regards energy and food production, air filtration and manufacturing resourses, even pychological human factors. (Lasseur, 2008) According to Lasseur (Lasseur, 2008) "*MELISSA loop and the choice of the several microbial processes has been done to simplify the behavior of this artificial ecosystem and allow a deterministic engineering approach. MELISSA has five major compartments colonized, respectively, by thermophilic anoxygenic bacteria, photo-heterotrophic bacteria, nitrifying bacteria, photosynthetic bacteria, higher plants, and the crew*".

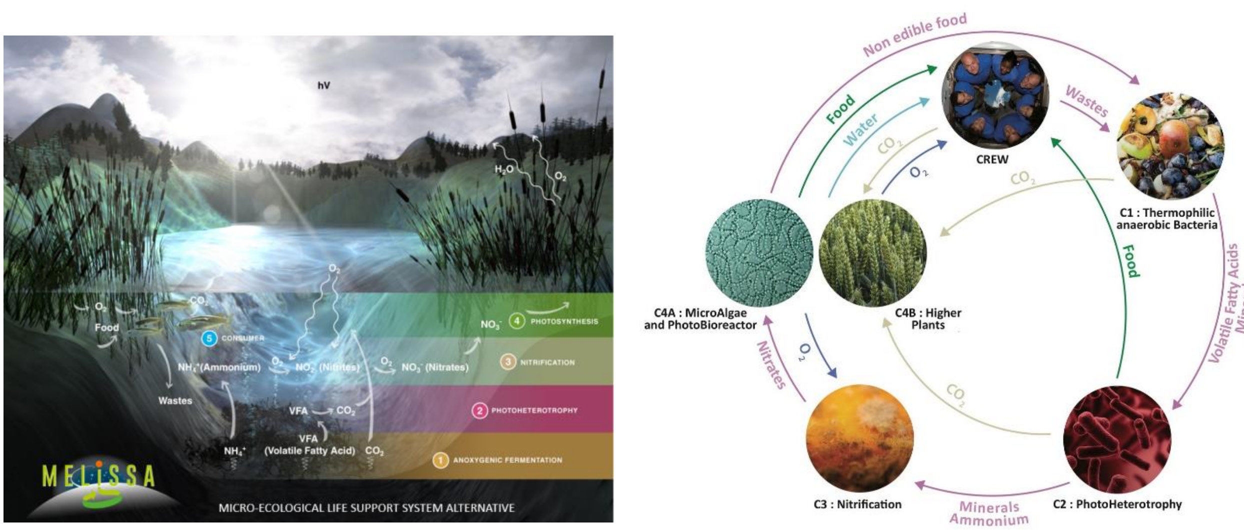


Figure 41 MELiSSA is internationally recognized as an advanced on-going effort to develop closed loop life support systems and around 50 organisations (e.g. universities, research centers, space industries, terrestrial companies) and 15 partners are involved in the project.(source: melissafoundation.org, esa.int)

Research question

Research question:

-How can biomimetic approaches to design for space – an extreme environment- help as ideas for mitigation of the extreme climatic stressors on Earth?

The summary of the main concepts examined in the literature review has led to the following hypotheses, which will be investigated through the data analysis and conclusion extraction process.

Hypotheses of the research:

- It is likely that the design guidelines of modern cities, systems and products, need to start resembling that of outer space living.
- Biomimicry, as an interdisciplinary collaboration, has limitations because of different drives of sciences and different life scale understanding.
- Biomimetic design is not by definition an effective, sustainable approach to human problems, as it is highly influenced by economical,political and societal choices.

Methodology

Shaping research strategy

Following the research question, "*How biomimetic approaches to design for space – an extreme environment- can help as ideas to mitigate the extreme climatic stressors on Earth?"* the methodology strategy provides an outline of the architecture used for data collection and evaluation.

Research Design and Rationale of mixing research methods

Due to the interdisciplinary nature of the biomimicry, the shape of the research question and the mostly literature review sample of the research, the architecture was based on the *descriptive research* method; a method, which aims at answering the questions like *how* when a research has limited sample resources for quantitative analysis. Data collection came mostly from extensive, state of the art literature on biomimetic approaches and extreme environment challenges. In the data evaluation process, the author critically analyzed the collected data with industry reports and discussed milestones with experts from five fields:

1. Space tech and bioastronautics sector
2. Biology field
3. Agricultural and environmental sector
4. Planetary protection and bioethics field
5. Material industry and industrial product lifecycle operations

The selected fields were believed by the author to have tangent environmental challenges today with that of future Product Design field. The criteria for the analysis were based on the potential of *Space for Earth* mentality, meaning space technology and exploration overview being of use for climate change action.

Furthermore, the author aimed in experimenting with the length of interdisciplinary collaboration potential that biomimicry poses and with the argument that biomimetic design can serve as stressor relief for both space and earth extreme environment challenges. Thus, one more research method was combined, that of *qualitative research* through a relevant design study observation. The design study experimented with biomimetic approach in product design addressing extreme climatic environment needs and future concepts of in-situ manufacturing methodologies in space.

Limitations of the methodology

While a variety of cases of biomimetic design are reported in literature, little is openly reported regarding the analogy transfer processes used. The transfer processes help understand the design outcomes. Thus, the design study aimed to add to the analysis by providing content on transfer process and interdisciplinary design thinking. For the qualitative research, ideally, a series of design experiments would have been carried out to evaluate these guidelines by comparing the performance of designers collaborating with life scientists and the quantitative results of the biomimetic outcomes. However, this was not made possible during this dissertation and is noted for recommendation for future relevant research.

Data Analysis

Data analysis from Literature Review

Connecting qualitative data from different field backgrounds

- Engineers and product designers are asked to be adaptive problem solvers. Especially when dealing with biomimetic approaches, the need to train into analogical thinking appears crucial.
- Nature's goal is to preserve life, therefore reproduce with genetic fitness in any given environment. Paralell to that, Nature has optimised subsystems that multitask and corelate,ensuring least energy consumption with maximum results.
- The genetic propagation drive or the habitat conditions of an organism are not usually a suitable analogy for human engineered systems. Most reviewed examples of biomimicry for Earth challenges focus on performance integration and durability.
- There has been continuous debate regarding the inherent competitive mentality of Humans.Yet, recent studies from many different fields reveal cooperation to be the driven force of adaptation and survival of all living things, rather than competition.
- Environmental sudies showed the human footprint to be higher than it was assumed.Evidence showed ingested microplastics in marine creatures samples at ocean depths up to 10890 m (Jamieson, et al., 2019)
- The practical abilities of knowledge, sciences and practices and their outputs -design included- represent the prevailing contradictions of our era; Nature's destruction and recklessness towards ecosystems.
- Biomimicry, sustainability and eco-friendly thinking are terms that began to spread from urban transportation, building technology, energy and industrial packaging to the fashion and food industry, medicine and education, broadening design specifications.

Observations on the review of the examples of biomimetic design approaches

- Considering the Eastgate Center and contrary to the popular assumption, architecture that is biomimetic does not necessarily translates into a new design aesthetic. The process of biology transfer into architecture can differ from morphologically organic design, similar to the organisms themselves, but rather share the level of function.
- Design that mimics nature for the sake of sustainability, tends to consider the working systems of the built environment and their relationship to the wider urban setting in which they are situated. Biomimicry for sustainability calls for a holistic or combinative emulation of natural analogies
- Here lies a distinction between the broad biomimetic approach and a specific bio-inspired design solution. The design solution can be a process of learning from nature and designing a mechanism that is simpler and more effective than the system observed in nature, for the mere reason that one needs to integrate one result, not replicate the entire, multipurpose natural system.

Observations from extreme parameters and design needs review

- We explore extreme environments to learn about our history, the history of other living things, and the history of Earth itself.
- Recent discoveries have shown significant progress in understanding the fields of evolution, metabolism and function of archaea, which stand at the intersection between life sciences and earth

sciences. Archaea were thought to live solicited in extreme environment but past decades studies proved they are everywhere life is found; in deep-sea vents, in ice, in salt flats, in seawater, in soil, and in our body's microbiome (sharing similarities in information processing processes with eukaryotes). (Chaban, 2006)

- The different colors in the rings of the Yellowstone park pools are a result of different kinds of microbial life. Sequentially, entire food chains depend on microorganisms that live in the near-boiling water pools made from the geysers and hot springs. The color-creating bacteria that cover the wet rocks; are dinner to flies, which carry mites, and the flies are food for predatory wolf spiders.
- Field researchers on extremophiles, moving from the hot and wet to the dry and cold need to take the laboratory with them and have it be adaptable too.
- From Antarctic ice and ocean to hydrothermal vents and acidic geysers, the study of life in extreme environments confirms that liquid water is the fundamental element of life on Earth, and arguably any life in our Solar System. Scientists across the country and around the world are diving into origin-of-life, adaptation in extremes and life-beyond-Earth issues and developing exciting and cutting-edge work.
- In a way, for life to survive in space, it demands a vigil approach much like life on Earth's extreme environments. Recent studies and explorations indicate that what life on Earth is now, may have been or still is life on other places in our Solar system too.
- Analogies transfer from extreme environments on Earth to space exploration issues include molecular *flexibility* for alteration, mechanisms for insulation and protection against temperature/pressure, radiation or pH fluctuation and collaborative, or codependent behavior's inside an extreme ecosystem.
- Some extreme environment parameters on celestial bodies do not have direct analogies on Earth. For example, the sharp Moon dust particles levitating from the Moon's surface without wind or atmosphere, a methane cycle instead of a water cycle on Titan (Saturn's largest moon) and Jupiter's clouds made from ammonia.

Evidence from experts & industry reports

For the cause of analyzing the literature review data, the author contacted experts, and advised industry and organisational reports. Most experts who were consulted at this stage of the research are stated at the acknowledgment section.

Facts regarding the biomimetic approach

- A latest example is a diving expedition off the coast of Western Australia, where scientists discovered approximately 30 new species. (Irving, 2020) After centuries of exploring our planet's oceans we have still just scratched the surface of what lives down there and how they succeeded to adapt in sun deprivation, pressure, temperature and chemical environment.
- Institutes, scientific researchers and practitioners claim that biomimicry is a spectrum methodology whose design output is not supposed to exclude any discipline affected by present environmental and economic aspects.
- There are ongoing efforts to incorporate biomimetic system examples into business matrices, in the search for viable business solutions.

- So far, research on biomimetic approaches for complex problems has been optimistic, but has also shown that biomimetic applications do not always perform better than plainly technological solutions. Sometimes, there is simply not a known, similar problem analogy in the natural world.
- An important part of the scientific community has unofficially declared the geological epoch of human impact on Earth's geology, atmosphere and ecosystems as the Anthropocene. A name that indicates the level of forming that humans subject their environments into, many times in a negative aspect and lately linked to the anthropogenic climate change.
- Another set of discourse data, regarding the analogies, states that the era of the Anthropocene addresses problems in such an anthropogenic way that does not comply to the natural world solution processes. For example, a technical solution can be for a narrow field application and nature's response to similar problem is much more complicated and interdependent in systems and outputs.

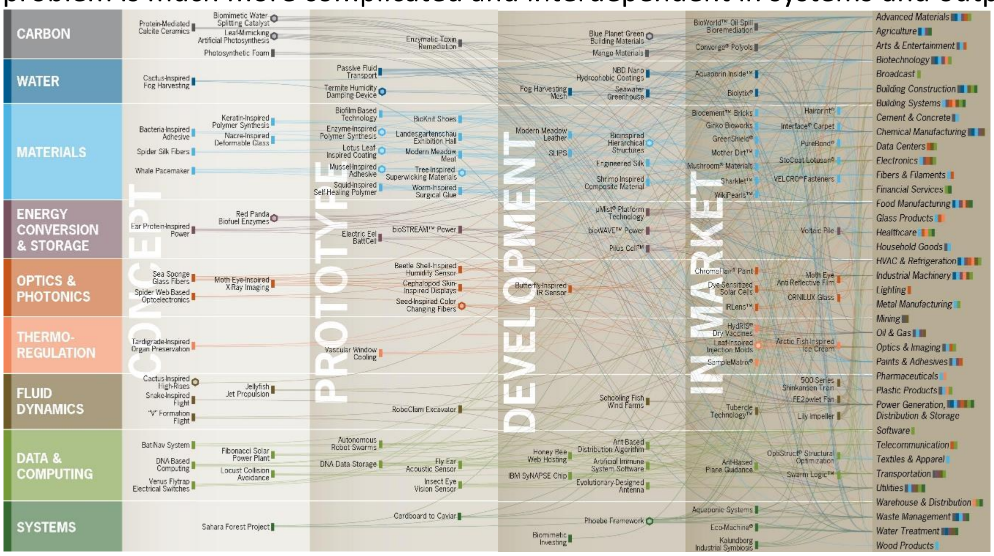


Figure 42 Table diagram of the market segmentation of biomimetic concepts and their resent marketability into products (pro-COVID19), based on the technology researched.(source: industryresearch.biz/)

Facts regarding the Newspace era

- There is no agreement among scientists, over the role that private enterprise ought to play in human spaceflight. Yet already, companies help build the machines that carry astronauts into space. In fact, investor-financed commercial enterprises already surpass the expenditures of governments on space objects.
- This year is the first time in history that a space manned launch to the ISS will take place from a private company and not a state space agency. This event marks a new era of space sector development and discussion is on the table regarding the pros and cons.
  - According to *Spaceworks* industry report, in 2020 there will be between 298–369 nano/microsatellites (1 – 50 kg) launched. From these only a minority will be testing new materials and components in extreme environments and the majority will deal with commercial imagery data transmission, telecommunications and exploratory missions.
  - An interest was established by various countries to proceed in building lunar bases the following years and a number of exploratory autonomus missions is in progress. However, according to space law expert, a lunar building code does not exist. For most purposes, national design codes can be applied

to help the structural engineer, with respect to the different ground acceleration g because all existing design codes only address the gravitational conditions on Earth.

- In light of the rapidly growing NewSpace Economy, the landscape of space exploration and development activities will certainly become much more complicated year by year, requiring definitions of technological approaches, laws and completely new regulatory and operations bodies. (Profitiliotis & Loizidou, 2019)
- *Departments of the European Space Agency design equipment, facilities and environments for long-term missions inspace and explore* self-replicating or in-space manufactured hardware. Furthermore, state and private agencies are doing research on space agriculture and are looking into space agro-technologies that promote agricultural sustainability on Earth as well.
- NASA open source data show immense possibilities in the use of in space-aquired data on Earth problems' applications.

Knowledge gaps

- In the case of long-term space exploration scenarios and planetary habitats, the scientific community bases its technology research on simulations of extreme environments. In order to know for good which approaches are of best interest it will eventually need *ground truth* of the extremes of space bodies.
- Regarding revisiting the Moon, it is still unknown what levels of dermal and ocular toxicity can lunar dust cause.Also, due to microgravity and dust levitation, the protection of systems has to be kept in mind. Medicine, food and practice are also some of the most important aspects of human life that will be tested on the Moon's 1/6g gravity.
- Although there have been conclusions on the effects of cosmic radiation on plants and mamalians , in case of long-term human exposure, it is still unknown how much it affects sensimotor function,cognitive behavior, hereditary conditions and fertility.
- Researchers, engineers and designers are searching for the optimum shielding approaches against irradiation and MMOD anticipation and resistance of space based habitats.
- Studies are looking into the design of space suits which will allow size-fluctuation and optimum fit between different planetary bodies, keeping in mind the bone and muscle atrophy that will occure in long-term spaceflight and in different gravity environments.
- As exploration missions extend farther from Earth, EVA suits will need to incorporate real-time sensors and intuitive design to provide astronauts with the necessary operational autonomy, as well as biofeedback and life support information.
- There are ongoing efforts to design and construct a closed loop ecosystem, a biosphere, that will sustain human life based on its autonomy, much like what earth ecosystems do on a local level.The goal is to be able to fully sustain life on remote planetary bodies in the future, without relying of cargo shipping.
- Finally, there is yet much to know about the extent of biophilic design and in which aspects it could be used to relieve or enhance human living in the extremes and under pressure.

Observation of a design synthesis study

The design study examines, in an exploratory approach, how the designer perceives biomimicry in product eco-design practice. The process of the biomimetic approach was to: *define a need - search for biological analogues - analyze the biological analogues - transfer the findings to the design process.*

The need

Exploitation of resources in the construction industry is widely acknowledged. On top of it, debris from old construction, new urban planning or building renovations usually end up in landfills at best. With the current knowledge regarding environmental pollution, resources scarcity and energy sources reformation, rises the need for a more circular economy that adds value to discarded construction materials while addressing urban problems. Another great source of pollution is marine plastics, as mentioned in the literature. Recycling plastic debris from ocean waters is not a new concept. However, putting it to work in providing low cost, efficient material for printing could be a solution compatible with an attempt to design eco sustainable products. Thus being seen, it is interesting to investigate if it could either be directly combined with ceramic materials or join forces to form layers inside a perplexed mix of the two.

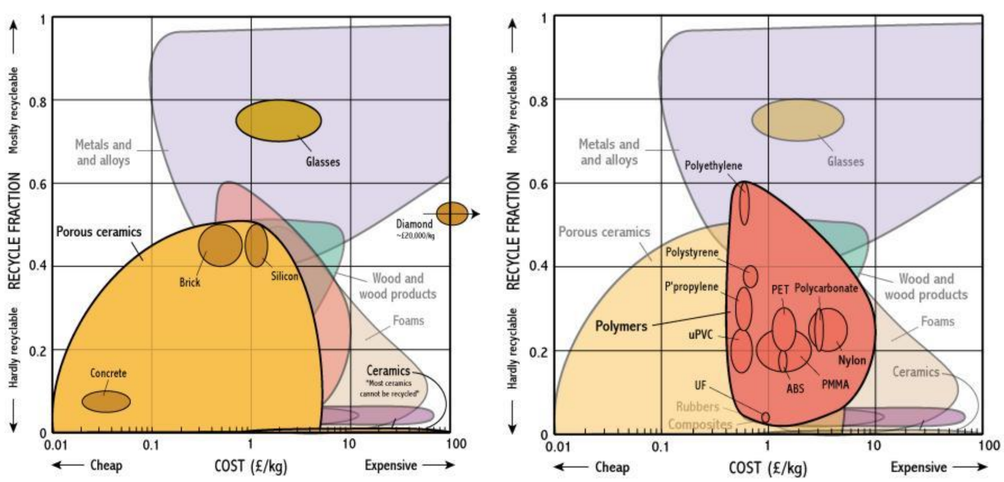


Figure 43 Recycle fraction charts displays the cost over recyclability of porous ceramics like the ones found in construction waste and in polymeric commercial materials.(source: http://www-materials.eng.cam.ac.uk/)

The design study followed a biomimetic approach and observed a case of an insect species whose larvae build nests and food traps underwater, while it considered why this could be a good inspiration for designers. To explore so, it studied two levels of the larvae case construction, the organism level and the behavioral. The first was based on observing the form of the organism, analyzing how it functioned; and choosing to mimic a part of it. The second, involved the imitation of how an organism interacted with its immediate environment in order to build a structure that can fit in without resistance in its surroundings.

The Caddisflies larvae

The study investigates the Caddisflies, order Trichoptera, a species of insects with aquatic larvae and terrestrial adults. These larvae are important in the understanding of freshwater fauna and of critical use in biomonitoring. Most related to moths and butterflies, there are some 14,500 described species of caddisflies. Caddisflies are found worldwide, with the greater diversity being in warmer regions. Their aquatic larvae are associated with a wide variety of habitats of freshwater and other temporary bodies of water. From the two most known groups of Caddisflies; Integripalpian larvae construct a portable casing to protect themselves as they move around looking for food, while Annulipalpian larvae make themselves a fixed retreat in which they remain, waiting for food to come to them. (Wiggins, 2015)

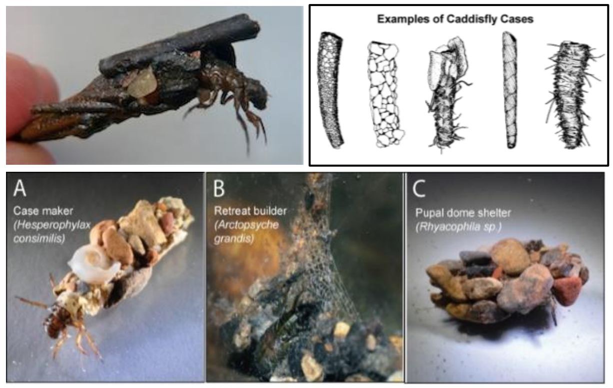


Figure 44 Caddisflies larvae sorted by their cases type and net building.(source:projects.ncsu.edu/General Entomology)

The phenomena of the cases

The Caddisfly larvae - a collector and underwater architect uses silk to make protective cases, which are strengthened with incorporated gravel, sand, shells, bitten-off pieces of plants, or other debris. The debris are neatly arranged and stuck onto the outer surface of the silken tube. The result is a case with both ends open. As the larva grows, more material is added at the front, and the larva can turn round in the tube and trim the rear end so that it does not drag along the substrate. (Wiggins, 2015)

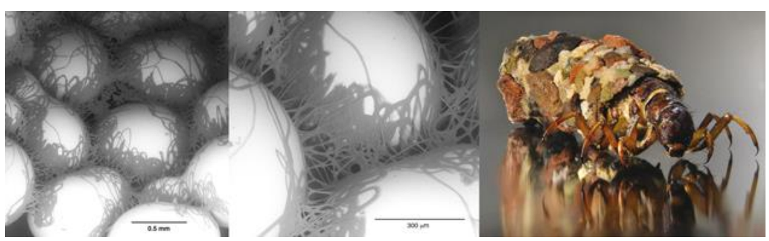


Figure 45Microscopic view of the bonds between silk protein and sand (source: researchgate.net)

The mechanism analysis

Organism level

Silk fiber produced by the larvae of Trichoptera (caddisflies) persists in water and contains homologues of H-fibroin (>500 kDa) and L-fibroin (25 kDa). The amphiphilic nature of H-fibroin and its high content of charged amino acids probably facilitate the secretion and storage of a covalently linked L-fibroin/H-fibroin dimer in the absence of P25. (Yonemura, Sehnal, Mita, & Tamura, 2006).A close look at the Caddisfly larvae cases shows a difference in layers between a denser and perplexed, water resistant, silk composition on the inside of the case and the bondage composition of silk alongside solid debris materials on the outside. Silk fibroin, mostly *dry* silk from moths, is studied as a protein polymer for biomaterial applications. It has remarkable mechanical properties when formed into different materials, demonstrates biocompatibility, has controllable degradation rates from hours to years, and it can be chemically modified to alter surface properties or to immobilize growth factors. (Rockwood, et al., 2011)

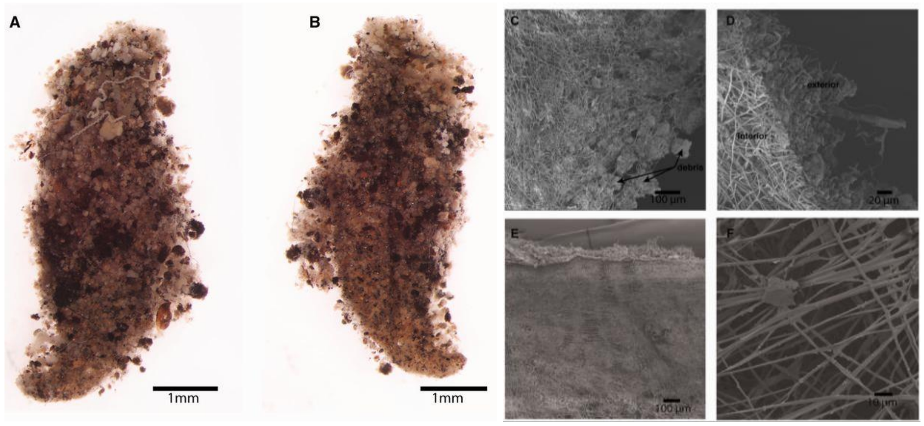
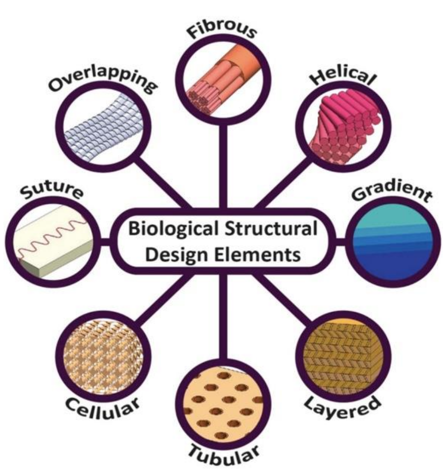


Figure 46 The inside and outside of a larva case with the differences of silk and debris bondage. (source: researchgate.net)

The substantial difference of aquatic larvae *wet* silk filament is that its silk proteins are heavily phosphorylated and have a large number of positively charged amino acids, thus making it water resistant and adhesive underwater. (Stewart & Wang, 2010) A variety of aqueous or organic solvent processing methods can be used to generate silk biomaterials for a range of applications. (Rockwood, et al., 2011) .Regarding the organism level of biomimicry, the caddisfly larva produces and spins adhesive silk underwater to construct protective shelters with adventitiously gathered materials. To top that, the nests are compatible with water. With the advancing technology of free form 3D printing, complex structures with microscale resolution can be created in arbitrary geometries and without the limitations found in traditional bottom-up or top-down additive manufacturing methods.



x	3D Priniting	CnC	Laser Cutting	injection moulding	extrusion	modular assembly	coating	weaving	casting	welding	etching	themal treatment	glue	pre-tension treatment	laminating	matting
Fibrous	x				x		x	x								
Helical	x				x	x		x						x		
Gradient	x					x	x			x		x	x		x	x
Layered	x			x	x	x	x	x					x		x	
Tubular	x	x	x						x		x					
Cellular	x	x	x	x				x			x					?
Suture		x	x	x				x		x						
Overlapping	x							x		x			x		x	x

Figure 47 Diagram of most common Structural Design Elements in biological materials (source: (Naleway, Porter, McKittrick, & Meyers, 2015)) Figure 48 Table chart of Structural design achieved by various manufacturing technics.

Behavioural Level

The rhythm with which the Caddisfly larvae collect materials for their cases' construction has made them known for quite the collectors. Regarding the behavioural level of biomimetic design research, Caddisfly larvae, although lacking a nest made from their parents, present an admirable neuro mechanism, that drives them to collect water debris and make them useful materials for nest construction and rigidity. People can learn from them as to collect what is seemingly waste and give it new purpose.

The idea transfer

After observing the larvae, the case study design idea that was inspired by this little insect was to use recycled plastic waste fiber or microfiber along with ceramic construction waste materials – like casting sand and construction sand and gravels- and create circular-economy products. Urban environments nowadays deal with one more parameter, that of climate change-rooted weather phenomena. Dense cities like Athens, Greece, with weak infrastructure against floods or dry seasons, could benefit from a potentially eco-friendly product solution. Based on current possibilities provided by 3D printing technology and material waste management systems (Seghiri, Boutoutaou, Kriker, & Hachani, 2017), the concept study suggested a tile that is water and heat resistant which could benefit both the material industry by giving new life to construction and plastics waste and simultaneously help manage urban rainwater and make use of it in dry seasons. A solution like this could be a parallel solution to water management of urban landscapes taking advantage of the unstable weather in the Mediterranean.

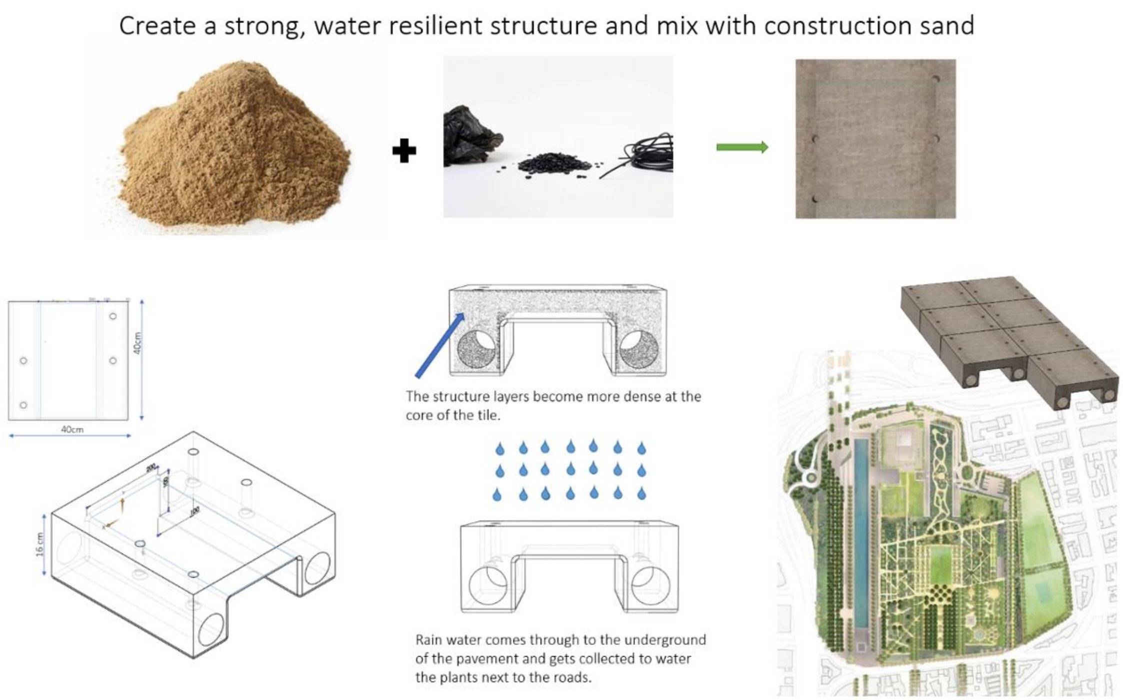


Figure 49 The LARVTile, an outdoor pavement tile made from recycled plastics and recycled construction sand. It is suggested as solution to rainwater management of urban-planted landscapes. Original concept,created in SOLIDWORKS and supported by Blue Cycle Lab, Aikaterini Laskaridis Foundation.

Findings & Discussion

Findings

Present knowledge gaps and opportunities in the biomimetic approach

For approaching biomimicry

Biophilia and bio-utilization were found in review to contradict the biomimetic approach but were includes in the biomimicry motives. This contradiction was found to be based on the approach with with product development was using biomimicry and not on the focus, that biomimicry wants to bring front. Further findings regarding the motives behind using biomimetic approaches in design showed that biomimicry-for-sustainability tends to recognize the importance of mimicking not just organisms but also the underlying processes and functions of ecosystems, to lead to more sustainable outcomes. Results of this motive surpass the sake of a novel technology and pave the way for alteration of the design thinking foundations that were set so far.

Another finding worth mentioning was the locality that characterizes nature's ecosystems, thus the database of biomimetic design, in contrast to the global notion of human needs and economy. The systems and modern urban technologies, like transportation, industrial manufacturing and energy, from which the need for more sustainable approaches was raised are simultaneously influenced by locally and globally affecting aspects. This realization poses both as an ambiguous gap and as a promising opportunity for the development of biomimicry at the same time.

For extreme environment cases

The research's investigation of life in extreme environment examples revealed an important finding. The example of the Yellowstone Park, as reviewed in the literature, appeared hostile in its extreme life condition and known for its colourful pools. However, these colours are all result of different yet co-dependent living organisms. At the extremes, still a loop of energy transfer is found and is balancing all parameters in order to sustain life. This particular finding, linked with the research question, in the quest for biomimetic inspiration from extreme environments.

By exploring and by understanding more about the chemical makeup of our planet, by testing for habitability and design on missions in extreme places, biomimicry comes one step closer to mastering life's mechanisms.

Findings from data investigation show that environmental degradation is here already and global efforts to alleviate the conditions and the following crisis have so far not much success, mostly because of belated action and non-alignment with global goals and unsynchronized efforts. The result is the urgent rise of extreme conditions for all life on Earth.

For space environment

Humans rely on design in order to stage areas to live in any environment. When it comes to space, the construction of such safe areas in an extreme environment can be incredibly costly, time consuming and risky for humans during the construction period. The research found that this difference in design codes between Earth and space environment, created by the extreme parameters in space,is welcomed by some biomimics. These designers and scientists focused on insects and animals that defy gravity on Earth. Findings also showed that there is a gap for further investigation upon a co-beneficial standardization of biomimetic design methodologies for both space and earth applications. The drive of this finding lied on the realisation that life on Earth is evolved to be easy or at leat balanced. In order to be able to consider space as a future habitation area, it should become more comfortable and balanced.

Here, the research concludes that biomimetic design could dig deeper that the solution and into the needs that are binded with the existense of life and with human consience.
The presence of micrograwity conditions deeply affects the human body functions at the systemic, organ and cellular levels as well as the psychology.
The findings from industry data revealed a gap of laws, codes, decisions and tools regarding the attitude towards planetary protection of extraterrestrial bodies from human activity. For example, data showed that for the need of future construction on Mars, polyurethane and other polymers can be made from ethylene extracted from Mars's carbon dioxide-rich atmosphere. Therefore, the research reviewed and found that current state of science suggests to bring the most likely "easy" knowledge into these future attempts. Meanwhile, on Earth, the discussion around a circular economy is on the table and under reformation.The Martian regolith has relative equivalent geological analogs on Earth and a methodology to design, stress and repurpose showed new frontiers for product design and biomimetic approaches, given that biomimicry is circular *by design*.

Limitations of the biomimetic approach in problems of the extremes

The biological analogue

Important realization was that the biological world does not necessarily provide an accountable analogy transfer for human needs, in order for an analogy to be considered strategically directed and successfully biomimetic. The genetic propagation drive or the habitat conditions of an organism are not usually a suitable analogy for human engineered systems. Most reviewed examples of biomimicry for Earth challenges focus on performance integration and durability, while space related examples focus both on performance and circularity, due to the high cost and risk of transportation to the remote. There is though, the opportunity for further research of parameters correlation and quantifiable results and for a deeper search into the biomimic's perspective of the world.

The collaboration aspect

The research explored the designing for extreme environments and a literature scenario of a human-made closed ecosystem against a hostile environment. The opportunity to communicate the analogies between biology and engineering were obvious, however data showed that an attempt like that did not succeeded so far. The findings underline the already known complexity of the matrix that has to take place for policymakers, scientists, business investors, engineers, architects, designers, educators and other innovators to consult and translate natural design principles for the development of such big-scale structures, processes and systems that create conditions conducive to Life. This collaboration aspect, which is nurtured in biomimicry, asks for some changes in how the scientific world collaborates.

The mentality aspect

Modern cities, infrastructures and rural or industrial landscapes proved to follow an unsustainable dualistic separation of nature and culture. In space architecture, circularity and optimum use of resources is a vital key. Of course as investigated space habitation concepts are also lacking a sustainable perspective in the long-term, proof is the space debris orbiting Earth. Yet, it is a field in which circularity has come to the spotlight and technologies are advancing. The minds that form design approaches and economic decisions are the same. Findings show an increase to the voices from both the scientific world and society, that support a change in mentality towards design. These voices state that humans live within ecosystems as integral parts and are entirely dependent upon them for survival. A denial of this is reflected into poor design, unsustainable approaches and in extreme climatic transformation.

The design study example

Interestingly enough, the design study showed three main findings relevant to the research question and hypotheses:

1. Recycling involves returning the material to its raw form, but re-using materials is sometimes more innovative as its applications can connect with more systems that have been developed around its the original state. Such is the example of pavement tiles that reuse the materials and correlate with the already built environment by providing watering and structural solution.
2. However, the study showed also that an eco-friendly concept approach does not necessarily have an eco-friendly manufacturing process. A sustainability report could show whether the tiles' production cycle is within the desirable co2 emissions range.
3. How the larvae act in building the nests resembles the concept for space in-situ resources utilisation (ISRU). With further proof of concept and R&D there might be a potential of a shared engineering methodology of sustainable building and ISRU for building on another planet in a similar design approach.

Discussion

Humans' withdrawal from Nature

During the last centuries of population growth and civilization prevalence, humans have transformed the earth geologically, chemically, and ecologically in such significant ways that some researchers defined the start of a new geological era: the *Anthropocene*. The true consequences of these anthropogenic actions have been revealed only in recent decades. The literature argued upon the secession of human from Nature for the cause of creating tangible and intangible frames of civilization. Following this social need, design appeared and is still evolving. However, it appeared that humans forgot that they are part of Earth's ecosystems. The research concluded that current economic models and processes, even design thinking, today are built on the premises that resources are abundant and people are scarce. On the contrary, Nature is scarce and like humans depend on its air, water and food, Nature depends on them to be mindful of its limits. Learning from Nature, has revealed more consistent, efficient and collaborative ways of humans working with each other and developing ideas. Biomimicry is based on values that can help lead to such direction, but is sometimes outshined by obsolete processes.

Regarding the biomimetic choice of approach

Approaches like biomimicry arise. Discussion about biomimicry is enthusiastic about its potential to increase sustainability outcomes, and its novelty in using inspiration from the natural world, but is often uncritical in its investigation of measurable successes or failures of the concept. This could lead sometimes to biomimicry being criticized as a potential *green-wash* mechanism and in results that soon pile up with the rest obsolete industrial remnants. As beneficial as any improvement in energy efficiency,monitio or durability may be, it needs to be considered in a broader context. For any typical product to be developped and to function, energy is still expended, noise is made, and natural habitats are disrupted for resources and space. Therefore, when it comes to the debate *biomimicry for innovation* or *biomimicry for sustainability*, the answer could be a starting point for a desirable merging. An example to support this discussion is the well-promoted Kingfisher beak as inspiration for Japans highspeed bullet train. The publicity it gained was based to the claim that the train's energy efficiency was attributted to biomimesis, however, scientists stated there was no evidence that the kingfisher is energy-efficient due to its beak. Perhaps, it is safe to assume that the design incorporated a biological morphology on the bases of its own product design goals and the prevailing infrastructure type. A merging of the sustainability and innovation goals, under a biomimetic approach, could provide a mean for a shift in design thinking. Through biomimicry, human-centered design and its relationship with planetary resources and ecosystems could fundamentally change and avoid the perils of design greenwashing. Of course the discussion needs to ponder on who benefits from innovation and progress. There are without doubt limitations to the biomimetic approach, as not every problem has an analogy, but the motivation on which design is based upon, is subjective and deeply rooted in economics.

The importance of the extremes

The past twenty years, the research of environmental and life sciences have seen great progress in understanding the world of extremes and the ecosystems' balancing relations. Understanding the mechanisms governing ecosystem stability is essential for predicting the consequences of global environmental changes on ecosystem functioning and sustainability. Extreme environments present a remarkable potential in understanding systems' stability under extreme stressors. Crossing the age of climate change and NewSpace race, extremes seem more and more conceivable by disciplines like design and engineering. An enormous body of science has already been assembled to analyze and explain the origins, characteristics and possible extraterrestrial dimensions of life and another one looks deep into Erath's oceans, volcanos and core. Through this exploration, humans may understand their present and future and it is of interest to see where it will lead. For example, tardigrades in biotechnology may offer knowledge that could be used to increase the durability and longevity of cells as well as irradiation resistant fungi and lichen. Both are organism that are at the center of the space industry attention.

Mechanisms in Nature have a reason for their existence and it drives from Nature's engineering of adaptation to environmental parameters. We still have a lot of ground to cover regarding the knowledge gaps and hypotheses in the space exploration advancement. At the same time, space industry determines ADCS (Attitude Determination Control System) as a crucial subsystem of a spacecraft or satellite and is in need of AI development to accurately determine data and ensure mission success. Current NASA & ESA experiments test AI color coding detection for intuitive ADCS decision making for navigation, data detection and stability correction of flying space structures. A job suitable for engineers, physicists and developers. Yet, biologists have already found that the honeybee's extra set of eyes –the *ocelli*- is feeding information into the key-colour processing areas of the bee brain and the two main compound eyes. In a *biologically validated* mathematical solution, the ocelli allows the honeybee to assess colour accurately and to identify correctly the necessary data (the food source) by calibrating for constant changes in light conditions. Thus, perhaps a closer collaboration of disciplines through the biomimetic prism could lead to insightful solutions**.**Firmly believing that astronauts and future humans should really live in Space instead of simply surviving, some product design students from Italy created multifunctional kitchen tools that could help prepare and eat meals in space easily. While making space comfortable, the study for the extreme environment of space could become relevant to the extreme climatic stressors on Earth too and the sustainability goals. The previous discussion regarding the motives applies here too. The application of biomimicry with collaboration, respect and circularity is contrary to the motives that pollute space with debris. The biomimetic design process helps understand and master extreme environmental stressors on Earth and beyond. What we need to bring on Mars to sustain life is what we need to protect on Earth right now. On an urban and global scale, biomimetic approaches like circular systems of space LSS, could be a valuable tool into thinking about resource and waste management, contemporary forms of working and personal engagement; compact and multifunctional spaces, public-private relation, alternative energy harvesting, health management and inclusion of nature into the built-up environment. Much like astronauts do on the ISS and the future concepts of planetary greenhouse habitats. It is likely that the design guidelines of modern cities, systems and products, needs to start resembling that of outer space living where sustainability is not only about recyclability, but also about extending a product's lifespan through its ability to adapt to dynamic environments.

Ways to learn from biology

As the knowledge of biological systems increases, humans in turn become increasingly aware of the remarkable set of engineering principles that natural systems employ. The world that surrounds us (perceivable by the human eye or not) is a dynamic framework in constant flow. It is a flow of energy, objects, people, capital, information, ideas and means. However, the technically built environment remains rigid against current crisis. In biology, a system or group of elements is an evolution-success only when they possess the power to adapt through variations of their characteristics and properties. This adaptation is linked with collaboration and responsiveness to changes of conditions and leads to balance. Learning from biology could give birth to design approaches that treat the built environment not just as a shell or breathing façade, but as a highly interactive component that could be transformed according to user and energy needs or maintenance. A design approach like biomimicry, if orchestrated bravely, could also lead to the amplification of the users' perceptual range and connection with the surrounding world, an attribute that is of need for a new connection of human with Nature's systems.

What design reveals about our present and our future

Perhaps how humans designed until today shows how separated or how related humans in each historical era felt from Nature. Biomimicry, like any methodology, especially an interdisciplinary one, has limitations because of each era's different drives of sciences and different life scale understanding. Therefore, biomimetic design is not by definition an effective approach to all problems, as it is highly influenced by economical and societal choices.It will be wise to note that even the way we look for analogies in the natural world database and the way we approach human problems is entangled with the existing schemes of history, society and economy. However, today's designers seem to be moving far beyond these historical origins. New frontiers and challenges in design expressions have advanced innovation in construction techniques, while new fabrication technologies have inspired designers and engineers to push further the envelope of design. This time based on a critical moment in the planetary history, which humanity witnesses. The distinction between fabrication technologies that merely make the construction process more efficient and others that fundamentally transform the way of thinking about building is widely obvious in the field of biomimicry. Although the number of patents for explicitly biomimetic technologies has risen from fewer than 500 in 1997 to almost 7,000 by 2017, most of those patents are not expressing gratitude to their non-humans co-inventors in the long-term. The crucial problems for which biomimicry seeks inspiration from biological mechanisms should ideally form an understanding of the ecosystems and align in protecting natural habitats. This redistribution of *wealth* may be the ultimate value of biomimicry. However, economics state that *the social systems that make production possible are maintained by the continued use of the given product*. Thus, usually, biomimetic products created through a resources exploitative system are exploitative all the way down. So the key matter is not only the method of choice in order to be sustainable, bioethical and non-exploitative, nor is it the range on which planet we choose to act upon. The key role is in the motives and purpose of the decisions. If a purpose is not given enough time and effort to be established, then the result maybe having an innovative method but ending up solving the wrong problems. Increased pressure for societally relevant results and climatic stressors response are also likely to further tighten the relationship between science, design, politics and industry. Strategic design may have a role to play and biomimetic approaches could reset the position of humans towards Nature and towards their drive for progress and exploration.

Conclusion & Recommendations

Summary

The dissertation derived inspiration from recent design studies regarding the habituation of extraterrestrial, extreme environments. Space presents extreme environmental parameters for life.

The interest in studying life in extreme environments on Earth and the augmenting industrial and research attempts to create knowledge and applications for sustaining life in the extremes is rising. The research pondered on the two main challenges that torment and ignite our era's scientific and industry world; the new quest for Space exploration and Climate Change deterioration; two challenges both accompanied with extreme conditions for life. It was considered interesting to explore biomimicry; a methodology of design problem solving that could perhaps consider both challenges, by diving into the natural world of the extremes, to find inspiration for product and spatial design solutions for multiple stressors and sustainable applications. Biomimicry, as a type of natural analogy method, was investigated in order to provide insight on novelty and economy in design solutions. The research reviewed the current knowledge of nature's adaptations to extreme environments and investigated examples of developed biomimetic technologies for space applications and research from various fields that presented interdisciplinary, sustainable approaches for space and Earth. The specific issues argued by the author are the necessity of finding analogies of biomimetic approaches for space exploration and use them as tools for the emergence of extreme climatic environment on Earth. The final step concluded by consulting experts of the field, investigating the factors and considerations missed. The findings showed that there is some relevance between designing to sustain life in space and designing for climate action on Earth. Furthermore, they showed that existing biomimetic space applications and research goals can also be useful if applied to address the extreme climatic changes on Earth. However, the biomimetic approaches are still a field that needs to incorporate quantifiable sustainability metrics and ecosystem mentality in order to create radical change.

Conclusions

Can biomimicry prove itself useful for interdisciplinary collaboration for future design solutions and which aspects can cause limitations? It is not possible to exhaustively discuss the many topics and disciplines that must be understood and applied to the design of livable conditions in extreme environments. The dissertation endeavored to summarize a few such topics of relevance, but recognize that many important topics have been omitted. References were made to literature that can point the interested reader to sources with many additional references.

Recommendations

A question upon decision, which this research gave birth to is -are we eventually going to be a spaceflight species? Meaning, are we going to drop the short mission mindset, expand at interplanetary colonies, and adjust to extraterrestrial conditions? If yes then we may need to start designing with the extremes as guideline and form a universal, ethical approach to what sustainability means for life's continuous existence. The author suggests further research in three main directions:

1) How can we efficiently quantify sustainable biomimetic design results and form guidelines for many disciplines
2) Which space challenges can be commercially translated through biomimicry into sustainable products on Earth
3) How can education from an early age introduce biomimicry in complex problem solving.

Hopefully, this review is a starting point as well.

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Background Research Bibliography

Areas of broad research: Biology, Industrial design, Space sciences, Bioastronautics, Anthropology

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APPENDIX

Terminology Used

Although some terms are common to many different fields and sub-disciplines, certain features in the subject of this dissertation warrant specific explanation.

Bio-inspired: Any process of design ideation that digs into nature's *library of strategies*.

Biomimicry: One such design approach that emulates or takes creative inspiration from natural systems, by applying either structural or behavioral mechanisms. This approach is referred to as biomimicry.

Biomimetics: It is the term for the translation of natural models in technology innovation and such technological products.

Bio-utilization: Bio-utilization is to, directly, leverage organisms or biological materials into product design and manufacturing

Biophilic/biophilia: With the Greek deriving suffix –*philia*, meaning creating affinity, biophilic design is a concept used within the building industry to increase occupant connectivity to the natural environment with the use of direct or indirect nature in the built environment.

Bio-morphic: It mimics natural forms and patterns without necessarily having adherence to biological principles, resulting in designs that often do not perform better or are simply not sustainable.

Design thinking: It is a process, applicable to many fields of work, of developing innovative ideas and solving problems.

Ecologize: The recent commercially and philosophically driven action of infusing education, research and political decision with urgent filtering through environmentally friendly mindset.

Extreme environment: It is a habitat that is considered very hard to survive in due to its considerably extreme conditions, which could be; temperature, accessibility to different energy sources, radiation, under high pressure and more.

Humankind: Author's Yuval Harari definition of humanity is used critically in this research, based on the intention of presenting the biological and social evolution and unification of Homo sapiens into the future global civilization that is possibly to come.

LSS: Life support systems is a group of systems and devices that allow a human being to survive in space.

Natural analogy: A comparable metaphor between natural processes and design, industrial implementation techniques.

NewSpace: One –still open to discussion- definition is of an emerging market directed to space technology advancement, followed and driven at the same time by both recent discoveries, space exploration fever rejuvenation and financial market opportunities for the private sector.