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Energy saving potential of biomimetic building's skin.

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Layacha Sarah Thesis

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As I like to dedicate this thesis to them.

To My Beloved Family

Layacha Sarah Thesis

Contents

Theoretical Part

Chapter 1: Biomimetic Architecture

Chapter 2: Biomimetic Building Skin

Layachia Sarah Thesis

Practical Part

Chapter 3: The case study

Chapter 4 : From idea to design

Layacha Sarah Thesis

Chapter 5 : General Conclusion

Layacha Sarah Thesis

List of figures

Layacha Sarah Thesis

Layacha Sarah Thesis

Layacha Sarah Thesis

Layacha Sarah Thesis

List of Tables

Layacha Sarah Thesis

ABSTRACT

Since 1970, a major problem worldwide is energy shortage along with the high consumption of energy in buildings. Architects are attempting to find solutions for managing buildings energy consumption. One innovative approach is Biomimicry, Which is defined as the applied science that derives inspiration for solutions to human problems through the study of natural designs, systems, and process too.

A subcategory of biomimicry is building skin which forms the entire exterior of the building. It is the boundary through which the buildings interaction with the environment occurs.

Proper management of the building skin can significantly reduce the building's energy demand. The main objective of this research is to investigate the ability of reducing energy consumption by applying the biomimicry approach on buildings skin design. In order To achieve this aim, a research methodology has been designed to accomplish four objectives. First, it will carry out an in depth research on biomimicry, skin, and biomimicry in building skin through the study of existing literature. Second, international case studies will be presented and analyzed in terms of usage of biomimicry, in addition to, the impact it had on reducing the buildings energy consumption. Finally it will conclude with guidelines for building skin biomimicry design for more efficient energy consumption in buildings.

Keywords: Biomimicry, building skin, energy efficiency, architecture, investigation.

Layacha Sarah Thesis

Résumé:

Depuis 1970, un problème majeur dans le monde entier est la pénurie d'énergie et la forte consommation d'énergie dans les bâtiments. Les architectes tentent de trouver des solutions pour gérer la consommation d'énergie des bâtiments. Une approche innovante est la biomimétisme, qui est définie comme la science appliquée qui tire son inspiration pour des solutions aux problèmes humains à travers l'étude des conceptions, des systèmes et des processus naturels.

Une sous-catégorie du biomimétisme est la construction de la peau qui forme l'ensemble de l'extérieur du bâtiment. C'est la frontière à travers laquelle l'interaction des bâtiments avec l'environnement se produit.

Une bonne gestion de la peau du bâtiment peut réduire considérablement la demande d'énergie du bâtiment. L'objectif principal de cette recherche est d'étudier la capacité de réduire la consommation d'énergie en appliquant l'approche de biomimétisme sur la conception de la peau des bâtiments. Afin d'atteindre cet objectif, une méthodologie de recherche a été conçue pour atteindre quatre objectifs. D'abord, il mènera une recherche approfondie sur le biomimétisme, la peau et le biomimétisme dans la construction de la peau à travers l'étude de la littérature existante. Deuxièmement, des études de cas internationales seront présentées et analysées en termes d'utilisation du biomimétisme, en plus de l'impact qu'il a eu sur la réduction de la consommation d'énergie des bâtiments. Enfin, il conclura avec des lignes directrices pour la conception de biomimétisme de la peau pour une consommation d'énergie plus efficace dans les bâtiments.

Mots-clés: Biomimétisme, peau de bâtiment, efficacité énergétique, architecture, investigation.

Layacha Sarah Thesis

ملخص :

منذ عام 1970 ، مشكلة رئيسية في جميع أنحاء العالم هي نقص الطاقة جنبا إلى جنب مع ارتفاع استهلاك الطاقة في المباني. يحاول المهندسون المعماريون إيجاد حلول لإدارة استهلاك الطاقة في المباني. و أحد الأساليب المبتكرة هي تقليد الطبيعة، والذي يعرف بالعلوم التطبيقية التي تستمد الإلهام لحلول المشاكل البشرية من خلال دراسة التصميمات والأنظمة الطبيعية والعملية أيضًا.

وهناك فئة فرعية من المحاكاة الحيوية هي بناء الجلد الذي يشكل الجزء الخارجي الكامل للمبنى. إنه الحد الذي يحدث من خلاله تفاعل المباني مع البيئة.

إن الإدارة السليمة لبشرة المبنى يمكن أن تقلل بشكل كبير من الطلب على الطاقة في المبنى. الهدف الرئيسي من هذا البحث هو التحقق من قدرة تقليل استهلاك الطاقة من خلال تطبيق نهج المحاكاة الحيوية على تصميم المباني في المباني. من أجل تحقيق هذا الهدف ، تم تصميم منهجية بحث لتحقيق أربعة أهداف. أولاً ، سيجري بحثًا معمقًا حول التقليد الحيوي ، والجلد ، ومحاكاة الطبيعة في بناء الجلد من خلال دراسة الأدبيات الموجودة. ثانياً ، سيتم عرض وتحليل دراسات الحالة الدولية من حيث استخدام المحاكاة البيولوجية ، بالإضافة إلى تأثيرها على تقليل استهلاك الطاقة في المباني. وأخيرًا ، سيتم اختتامها مع إرشادات لبناء تصميم محبة تقليد حيوية للبشرة من أجل زيادة كفاءة استهلاك الطاقة في المباني.

كلمات البحث: تقليد الطبيعة، وبناء الجلد ، وكفاءة الطاقة ، والهندسة المعمارية ، والتحقيق.

Layacha Sarah Thesis

1. Introduction

Our beautiful planet with its amazing details created by GOD is facing today a real climate change caused by the human interference in its ecosystem which was never seemed possible to believe that humans were capable of changing the basic physical and chemical properties of this entire huge planet, huge chunks of glaciers are falling off and melting in the oceans as one of the symptom of the rising temperature of Earth.

Modern building envelopes become more and more insulated and sealed to decrease the energy demand for heating. Indeed, modern buildings barely need to be heated anymore. A common problem now is the overheating of buildings in the summer (sometimes also in spring and autumn) and the increased cooling demand. Once the heat is inside the building, it is very difficult to get rid of due to the high insulating value of the façade. Simply opening a window is not an appropriate solution for every building, due to draft, too much heat loss at once and noise from the outside.

The next step in reducing the energy demand of a building is to decrease the energy needed for cooling. Increasing the ventilation rate requires bigger ducts and costs more energy. A façade that can thermo regulate could reduce the need for cooling or extra ventilation.

Since 1970, a major problem worldwide is energy shortage along with the high consumption of energy in buildings. Architects are attempting to find solutions for managing buildings energy consumption. One innovative approach is Biomimicry, Which is defined as the applied science that derives inspiration for solutions to human problems through the study of natural designs, systems, and process too.

A subcategory of biomimicry is building skin which forms the entire exterior of the building. It is the boundary through which the buildings interaction with the environment occurs.

Proper management of the building skin can significantly reduce the building's energy demand. The main objective of this thesis is to investigate the ability of reducing energy consumption by applying the biomimicry approach on buildings skin design. In order To achieve this aim, a research methodology has been designed to accomplish four objectives. First, it will carry out an in depth research on biomimicry, skin, and biomimicry in building skin through the study of existing literature. Second, international case studies will be presented and analyzed in terms of usage of biomimicry, in addition to, the impact it had on reducing the buildings energy consumption. Finally, it will conclude with guidelines for building skin biomimicry design for more efficient energy consumption in buildings.

The main motivation for choosing a biological theme is : there are characteristics of designed objects such as buildings, and characteristics of the ways designs are produced, viewed both at an individual and at a cultural level, which lend themselves peculiarly well to description and communication via biological metaphor. The ideas of wholeness‘, coherence‘, correlation‘and integration‘, used to express the organized relationship between the parts of the biological organism, can be applied to describe similar qualities in the well-designed artefact. The adaptation of the organism to its environment, its fitness, can be compared to the harmonious relation of a building to its surroundings, and, more abstractly, to the appropriateness of any designed object for the various purposes for which it is intended. Perhaps most significantly it is biology, of all sciences, which first confronted the central

Layacha Sarah Thesis

problem of teleology, of design in nature; and it is very natural that of all sciences it should for this reason attract the special interest of designers.
A second point is that as a matter of historical fact, it has been biology out of all the sciences to which architectural and design theorists have most frequently turned. Indeed it is surprising, in view of the ubiquity of biological references and ideas in the writings of the architectural theorists of the last hundred years, that no work of book length has so far been devoted to the history and theory of biological analogy. The history is certainly a fragmented one, leading into many remote corners and backwaters of the architectural literature. Nevertheless, analogy with biology is a constant and recurring theme.

2. Research questions:

In this context, the following research question is addressed:

How could the application of biomimetic principles and strategies be a solution to develop buildings skins that enhance the energy efficiency?

3. Hypothesis:

In the light of various readings, we think that answers to the questions posed previously, may be summarized in the following hypothesis:

It seems that conscious emulation of nature's genius through the biomimetic approach could be a solution to solve buildings skin's challenges aiming to optimize the energy efficiency.

4. Objective of the research:

Reaching a building envelope that is a living and breathing building envelope, has the ability to respond to outer climate conditions and accordingly control the internal temperatures in buildings in a similar way to what nature does in our "human skin" or with the "stomata guard cells", without resorting to electrical or mechanical means to control the internal temperatures, hence decreasing the energy consumption and its devastating effect on the environment. This could be achieved through using suitable smart building material and integrating it within biomimetic architectural design.

The present research looks into biology and nature to explore and define a new approach for buildings skins design in order to solve the dilemma of almost permanent overheating of buildings in an efficient way.

The main objective of this research is to link the two emerging sciences, Biomimicry and building skins, exploring their potential in energy saving of biomimetic building's skin.

5. Methodology:

The methodology of this thesis adopted the following methods to reach its objective:

Investigation – Invention – Analysis - Comparative Analysis - Simulation.

Layacha Sarah Thesis

1. Reviewing the global warming problem, its consequences and the share of building sector in this problem.

2. Studying Biomimicry in architecture and its potential in decreasing the share of building sector in global warming.

3. Reviewing case studies and projects based on biomimetic architecture.

4. Focusing on building materials as an approach from biomimetic point of view and especially smart building materials.

5. Selecting a smart building material that would allow the building envelope to perform the same as the human skin and reviewing the reasons of selection.

6. Application of the selected building material in a case study .

Layacha Sarah Thesis

Introduction:

This chapter reviews the following concepts: evolution, how natural system develop and its relevance to naturally inspired architectural design, the significant current practices of biomimicry in architecture, different approaches to biomimetic architectural design, and the last section studies the work of a selected group of architects who have addressed and integrated nature in their projects. It compares their work to show how a similar theory often leads to different outcomes in practice. The goal of this literature review is to clarify the state of biomimicry in the field of architecture and review the advantages and the disadvantages of each approach. The conclusion shows where these approaches are lacking and how they can be addressed.

1.1 On Evolution

Even though it is one of the most disputed topics in all sciences, the study of evolution helps create a better understanding of the way systems work and how they came to be what they are today, for example recall the genetic optimization. Evolution is a very broad topic, and this section only touches on a brief background about this theory and its driving forces. In general, what all theorists agree upon is that species change over time; the disagreement arises by in large in the reason behind these changes and the way they occur.

Jean-Baptiste Lamarck (1744-1829) was the first to present a coherent theory of evolution. He considered two main driving forces for evolution: first the tendency for organisms to become more complex and second, their adaptation to the environment.

This idea was later referred to as soft inheritance13and asserts that organisms pass on characteristics they have acquired over their lifetime to their offspring, these changes being subtle from one generation to the next but resulting in profound changes of the course of many generations. George Cuvier on the other hand, (1769-1832) strongly opposed this theory of soft inheritance. Through the study of fossils, he stated that changes happen abruptly and stay with the specie until the time of its extinction. He also disagreed with the idea that any part of an animal will gradually change in isolation from other parts14. More than two decades after Cuvier's death, Charles Darwin (1809-1882) proposed the idea of natural selection as the mechanism of evolution15. Natural selection suggests the idea of survival of the fittest. Natural variation exists in any group of organisms due to genetic mutations that inevitably occur. The traits arising via mutation that contribute to the survival of the organisms ensure the organism lives long enough to produce offspring with a high likelihood of possessing the very traits that ensured their parents survival. These stronger traits are passed on to the next generation and, over time; the population is almost entirely composed of these "fit" organisms increases.

The main idea of evolution is a concept shared amongst these scientists, which is the change over time. The differences are in explaining the driving force of these changes and their direction. It cannot be said, that these changes follow a linear path towards perfection. These changes are just responses to the change of needs due to internal or environmental imbalances or a combination of these two to fulfill every species' ultimate goals of survival and reproduction.

Layachia Sarah Thesis

Here is how this topic is relevant to our research; when considering an organism as model we must realize the limitations surrounding that organism to avoid blind mimicry. First of all every organism is limited to its previous state and, unlike architecture, is not created from the ground up. For example if you compare the two situations wherein an architect designs a building from the remainders of the building that previously occupied a site, or is free to use any material that he wishes, it is apparent that the second option offers far more freedom. Secondly, the pursuit of evolution is not perfection and hence creatures are not “perfect”. The ultimate goal of every creature is survival and reproduction. As long as these two are not threatened, there is no need for that creature to improve or change.

1.2 Biomimicry

1.2.1. Definitions and Historical Development

Otto Schmitt (1913-1998), an American engineer and inventor, worked on a device that replicated the nerve system in squids. He continued to work on devices that drew inspiration from nature and further developed the field of biophysics. In 1969, in one of his papers,18 he first used the term “biomimetic” as describing the transfer of ideas from biology to technology but it only entered the Webster dictionary19 in 1974. In 1958, Jack E. Steele (1924-2009) coined a similar term called “bionics”. He defined it as the science of natural systems or their analogues. However, it was not until 1997 when Jenine Benyus in her book biomimicry promoted biomimicry as an actual field of research in different design disciplines. She defines biomimicry as a systematic way of design that tries to emulate natural organisms’ principles and orders.

> “Biomimicry is not a style of building, nor is it an identifiable design product. It is, rather, a design process—a way of seeking solutions—in which the designer defines a challenge functionally (flexibility, strength under tension, wind resistance, sound protection, cooling, warming, etc.,) ,seeks out a local organism or ecosystem that is the champion of that function, and then begins a conversation” (Benyus 2008).

cha Salah Thesis

Fig 1.1The Kingfisher Bird And The Bullet Train

Fig 1.2. Mercedes Design Inspired by Nature

A biomimetic approach is an approach that takes information from nature, seeks connections and patterns therein, while observing the consequences thereof, and then mimics these, ending with a final evaluation to ensure the design is commensurate with the initial natural principles.

This field relies heavily on the iterative process, which is the key to the pursuit of perfection. Jenine Benyus claims that a biomimetic will help create products that are sustainable, perform well, save energy, cut material costs, reduce waste, and even define new products (Benyus 2002). The logic behind this claim is that since natural organisms have faced these challenges for millions of years they have gradually perfected their solutions.

Jenine Benyus has recently changed biomimicry to "Biomimicry 3.8"20. Its aim is to redistribute the "wisdom" that nature offers through creating a network of professionals. The most prominent community in biomimicry right now is an online website called "ask nature"21. The aim of this website is the creation of a place where biologists can share their studies and designers can search through the collection of natural systems, which are classified based on their design and engineering properties.

1.2.2. Different Approaches to Biomimicry in Architectur

A comparative study of the current practice of biomimicry shows distinct approaches to architectural design. Each approach inherently has its own advantages and disadvantages.

Approaches to biomimicry as a design process typically fall into two categories: Problem-Based Approach and Solution-Based Approach explained in the following paragraphs.

1.2.2.1 Problem-Based Approach

Throughout literature review, this approach was found to have different naming, such as ―Design looking to biology‖ (Pedersen Zari, M. 2007), ―Top-down Approach‖ (Jean Knippers 2009) and ―Problem-Driven Biologically Inspired Design‖ (Michael Helms, Swaroop S. Vattam

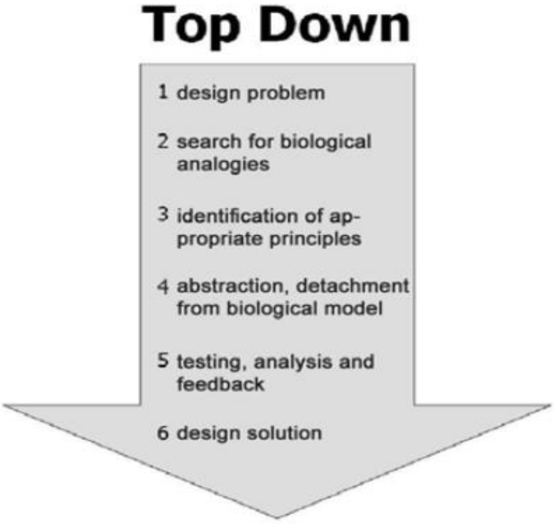

Fig 1.3 Top-Down Design Approach

The pattern of problem-driven biologically inspired design follows a progression of steps which, in practice, is non-linear and dynamic in the sense that output from later stages frequently influences previous stages, providing iterative feedback and refinement loops. (Michael Helms, Swaroop S. Vattam and Ashok K. Goel, 2009)

An example of such an approach is DaimlerChrysler‘s prototype Bionic Car (fig.1.4). In order to create a large volume, small wheel base car, the design for the car was based on the boxfish (ostracion meleagris), a surprisingly aerodynamic fish given its box like shape. The chassis and structure of the car are also biomimetic, having been designed using a computer modelling method based upon how trees are able to grow in a way that minimises stress concentrations. The resulting structure looks almost skeletal, as material is allocated only to the places where it is most needed. (Vincent et al., 2006).

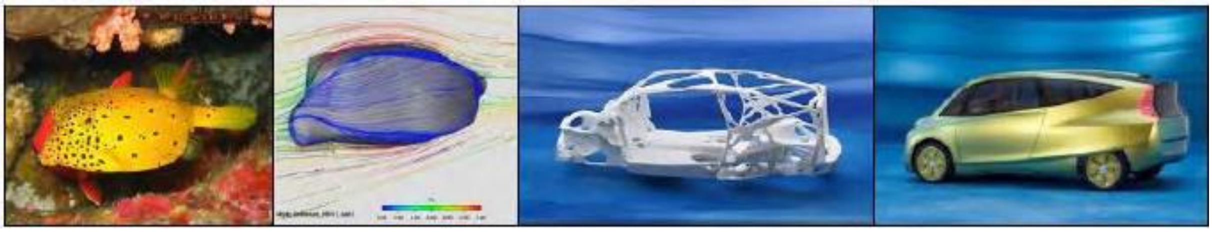

Fig 1.4: DaimlerCrysler bionic car inspired by the box fish and tree growth patterns.
(Source: Pedersen Zari, M. 2007).

Layacha Sarah Thesis

The possible implications of architectural design where biological analogues are matched with human identified design problems are that the fundamental approach to solving a problem and the issue of how buildings relate to each other and the ecosystems they are part of is not examined. The underlying causes of a non-sustainable or even degenerative built environment are not therefore necessarily addressed with such an approach.

The Bionic Car illustrates the point. It is more efficient in terms of fuel use because the body is more aerodynamic due to the mimicking of the box fish. It is also more materials efficient due to the mimicking of tree growth patterns to identify the minimum amount of material need in the structure of the car. The car itself is however not a new approach to transport. Instead, small improvements have been made to existing technology without a re-examination of the idea of the car itself as an answer to personal transport. (Pedersen Zari, M. 2007)

Designers are able to research potential biomimetic solutions without an in depth scientific understanding or even collaboration with a biologist or ecologist if they are able to observe organisms or ecosystems or are able to access available biological research. With a limited scientific understanding however, translation of such biological knowledge to a human design setting has the potential to remain at a shallow level. It is for example easy to mimic forms and certain mechanical aspects of organisms but difficult to mimic other aspects such as chemical processes without scientific collaboration. (Pedersen Zari, M. 2007)

Despite these disadvantages, such an approach might be a way to begin transitioning the built environment from an unsustainable to efficient to effective paradigm (McDonough, 2002).

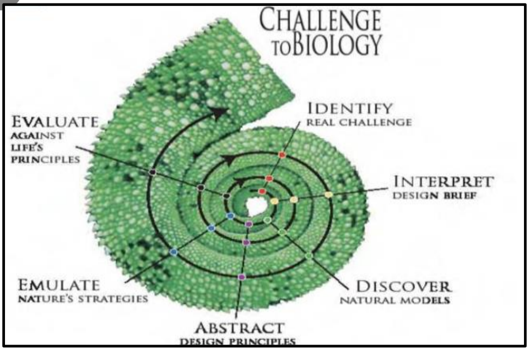

Fig 1.5 : Design Spiral by the Biomimicry Institute

The Biomimicry Institute has referred to this design approach and explained it through the Challenge to Biology Design Spiral‖ as illustrated in figure 1.14.

Research held in Georgia Institute of Technology by Michael Helms, Swaroop S.Vattam and Ashok K. Goel, at the Design Intelligence Lab in 2006, also defined this approachvthrough 6 definite steps, which are very similar to those defined by the Biomimicry Institute:

- Step 1: problem definition
- Step 2: reframe the problem
- Step 3: biological solution search
- Step 4: define the biological solution
- Step 5: principle extraction
- Step 6: principle application

(Michael Helms, Swaroop S. Vattam and Ashok K. Goel, 2009).

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1.2.2.2. Solution-Based Approach

As stated in the previous approach, this approach was also found to have different naming such as ―Biology Influencing Design‖, ―Bottom-Up Approach‖ and ―Solution-Driven Biologically Inspired Design‖. When biological knowledge influences human design, the collaborative design process is initially dependant on people having knowledge of relevant biological or ecological research rather than on determined human design problems. A popular example is the scientific analysis of the lotus flower emerging clean from swampy waters, which led to many design innovations as detailed by Baumeister (2007a), including Sto's Lotusan paint which enables buildings to be self-cleaning.

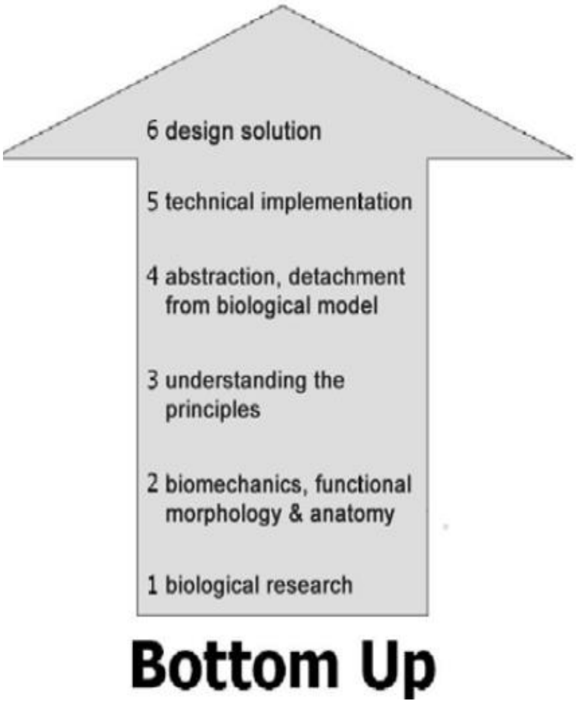


Fig 1.6 Bottom-Up Approach

Fig 1.7: Lotus inspired Lotusan Paint (Source: Pedersen Zari, M. 2007).

An advantage of this approach therefore is that biology may influence humans in ways that might be outside a predetermined design problem, resulting in previously unthought-of technologies or systems or even approaches to design solutions. The potential for true shifts in the way humans design and what is focused on as a solution to a problem, exists with such an approach to biomimetic design. (Vincent et al., 2005)

A disadvantage from a design point of view with this approach is that biological research must be conducted and then identified as relevant to a design context. Biologists and ecologists must therefore be able to recognise the potential of their research in the creation of novel applications.

Research held in Georgia Institute of Technology by Michael Helms, Swaroop S. Vattam and Ashok K. Goel, at the Design Intelligence Lab in 2006, also defined this approach through 7 definite steps:

- Step 1: biological solution identification
  Here, designers start with a particular biological solution in mind.
- Step 2: define the biological solution
- Step 3: principle extraction
- Step 4: reframe the solution
  In this case, reframing forces designers to think in terms of how humans might view the usefulness of the biological function being achieved.
- Step 5: problem search
  Whereas search in the biological domain includes search through some finite space of documented biological solutions, problem search may include defining entirely new problems. This is much different than the solution search step in the problem-driven process.
- Step 6: problem definition
- Step 7: principle application

1.2.3 Levels of Biomimicry

Within the two approaches discussed, three levels of biomimicry that may be applied to a design problem are typically given as form, process and ecosystem (Biomimicry Guild, 2007). In studying an organism or ecosystem, form and process are aspects of an organism or ecosystem that could be mimicked.

A framework for understanding the application of biomimicry is proposed that redefines these different levels and also attempts to clarify the potential of biomimicry as a tool to increase regenerative capacity of the built environment. By defining the kinds of biomimicry that have evolved, this framework may allow designers who wish to employ biomimicry as a methodology for improving the sustainability of the built environment to identify an effective approach to take. The framework that will be described here is applicable to both approaches (design looking to biology, and biology influencing design). The first part of the framework determines which aspect of _bio‘ has been _mimicked‘. This is referred to here as a level. (Pedersen Zari, M. 2007).

Layachia Sarah Thesis

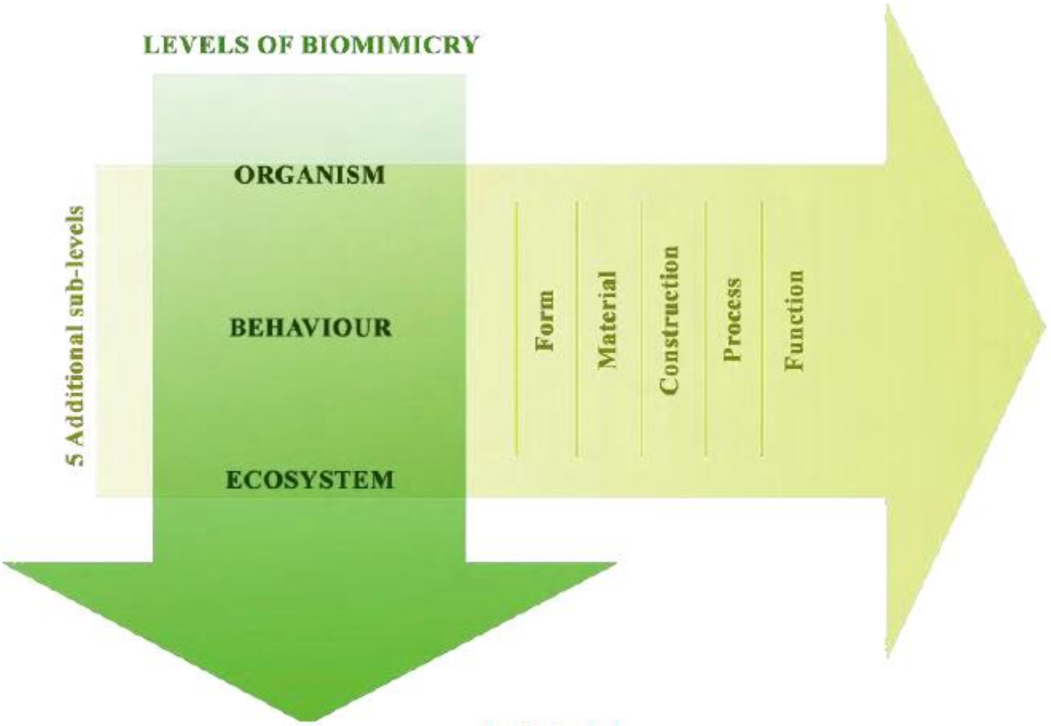


Fig 1.8 : Levels of Biomimicry

Through an examination of existing biomimetic technologies it is apparent that there are three levels of mimicry; the organism, behaviour and ecosystem. The organism level refers to a specific organism like a plant or animal and may involve mimicking part of or the whole organism. The second level refers to mimicking behaviour, and may include translating an aspect of how an organism behaves, or relates to a larger context. The third level is the mimicking of whole ecosystems and the common principles that allow them to successfully function. (Pedersen Zari, M. 2007).

Within each of these levels, a further five possible dimensions to the mimicry exist. The design may be biomimetic for example in terms of what it looks like (form), what it is made out of (material), how it is made (construction), how it works (process) or what it is able to do (function). The differences between each kind of biomimicry are described in Figure 1.17 and are exemplified by looking at how different aspects of a termite, or ecosystem a termite is part of could be mimicked. (Pedersen Zari, M. 2007)

It is expected that some overlap between different kinds of biomimicry exists and that each kind of biomimicry is not mutually exclusive. For example, a series of systems that is able to interact like an ecosystem would be functioning at the ecosystem level of biomimicry. The individual details of such a system may be based upon a single organism or behavior mimicry however; much like a biological ecosystem is made up of the complex relationships between multitudes of single organisms.

Layacha Sarah

1.2.3.1. Organism Level

Species of living organisms have typically been evolving for millions of years. Those organisms that remain on Earth now have the survival mechanisms that have withstood and adapted to constant changes over time. As Baumeister (2007a) points out „the research and development has been done‟. Humans therefore have an extensive pool of examples to draw on to solve problems experienced by society that organisms may have already addressed, usually in energy and materials effective ways. This is helpful for humans, particularly as access to resources changes, the climate changes and more is understood about the consequences of the negative environmental impact that current human activities have on many of the world‘s ecosystems. (Alberti et al., 2003)

An example is the mimicking of the Namibian desert beetle, stenocara (Garrod et al,2007). The beetle lives in a desert with negligible rainfall. It is able to capture moisture however from the swift moving fog that moves over the desert by tilting its body into the wind. Droplets form on the alternating hydrophilic – hydrophobic rough surface of the beetle‘s back and wings and roll down into its mouth (Parker and Lawrence, 2001). Matthew Parkes of KSS Architects demonstrates process biomimicry at the organism level inspired by the beetle, with his proposed fog-catcher design for the Hydrological Center for the University of Namibia (fig. 9) (Killeen, 2002). Ravilious (2007) and Knight (2001) discuss a more specific material biomimicry at the organism level, where the surface of the beetle has been studied and mimicked to be used for other potential applications such as to clear fog from airport runways and improve dehumidification equipment for example.

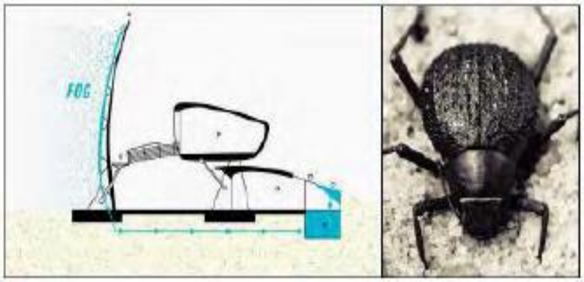


Fig 1.9: Matthew Parkes‘ Hydrological Centre University of Namibia and the stenocara beetle. (Source: Pedersen Zari, M. 2007).

Fig 1.10: Nicholas Grimshaw & Partners' Waterloo, International Terminal and the pangolin. (Source: Pedersen Zari, M. 2007).

Nicholas Grimshaw & Partners' design for the Waterloo International Terminal demonstrates an example of form and process biomimicry at the organism level (fig. 1.19). The terminal needed to be able to respond to changes in air pressure as trains enter and depart the terminal. The glass panel fixings that make up the structure mimic the flexible scale arrangement of the Pangolin so they are able to move in response to the imposed air pressure forces. (Aldersey-Williams, 2003)

Mimicking an organism alone however without also mimicking how it is able to participate in and contribute to the larger context of the ecosystem it is in, has the potential to produce designs that remain conventional or even below average in terms of environmental impact (Reap et al., 2005). Because mimicking of organisms tends to be of a specific feature, rather than a whole system, the potential also remains that biomimicry becomes technology that is added onto buildings rather than being integral to them, particularly if designers have little

Layachi Sarah Thesis

biological knowledge and no not collaborate with biologists or ecologists during the early design stages. While this method may result in new and innovative building technologies or materials, methods to increase sustainability are not necessarily explored. (Pedersen Zari, M. 2007).

1.2.3.2 Behaviour Level

A great number of organisms encounter the same environmental conditions that humans do and need to solve similar issues that humans face. As discussed, these organisms tend to operate within environmental carrying capacity of a specific place and within limits of energy and material availability. These limits as well as pressures that create ecological niche adaptations in ecosystems mean not only well-adapted organisms continue to evolve, but also well-adapted organism behaviours and relationship patterns between organisms or species. (Reap et al., 2005).

Organisms that are able to directly or indirectly control the flow of resources to other species and who may cause changes in biotic or abiotic (non living) materials or systems and therefore habitats are called ecosystem engineers (Jones and Lawton, 1995, Rosemond and Anderson, 2003). Ecosystem engineers alter habitat either through their own structure (such as coral) or by mechanical or other means (such as beavers and woodpeckers)

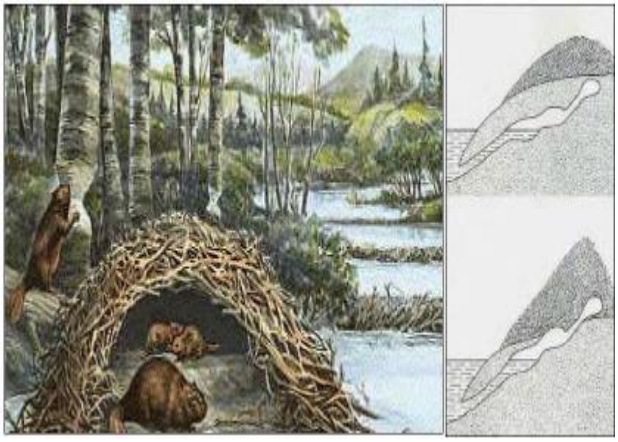


Fig 1.11: The North American beaver.
(Source: Pedersen Zari, M. 2007).

Humans are undoubtedly effective ecosystem engineers, but may gain valuable insights by looking at how other species are able to change their environments while creating more capacity for life in that system. Several authors provide examples and details of organisms altering their own habitats while facilitating the presence of other species, increasing nutrient cycling and creating mutually beneficial relationships between species. The building behaviour of other species is often termed „animal architecture" (von Frisch and von Frisch, 1974, Hansell, 2005) and may provide further examples of such ecosystem engineers.

The famous example of the North American beaver (castor canadensis) (fig. 1.20) demonstrates how through its altering of the landscape, wetlands are created and nutrient retention and plant and animal diversity is increased, helping in part to make the ecosystem more resilient to disturbance. (Rosemond and Anderson, 2003)
In behaviour level biomimicry, it is not the organism itself that is mimicked, but its behaviour. It may be possible to mimic the relationships between organisms or species in a similar way. An architectural example of process and function biomimicry at the behavior level is demonstrated by Mick Pearce‘s Eastgate Building in Harare, Zimbabwe and the CH2

Building in Melbourne, Australia (figure 12). Both buildings are based in part on techniques of passive ventilation and temperature regulation observed in termite mounds, in order to create a thermally stable interior environment. Water which is mined (and cleaned) from the sewers beneath the CH2 Building is used in a similar manner to how certain termite species will use the proximity of aquifer water as an evaporative cooling mechanism. (Pedersen Zari, M. 2007).

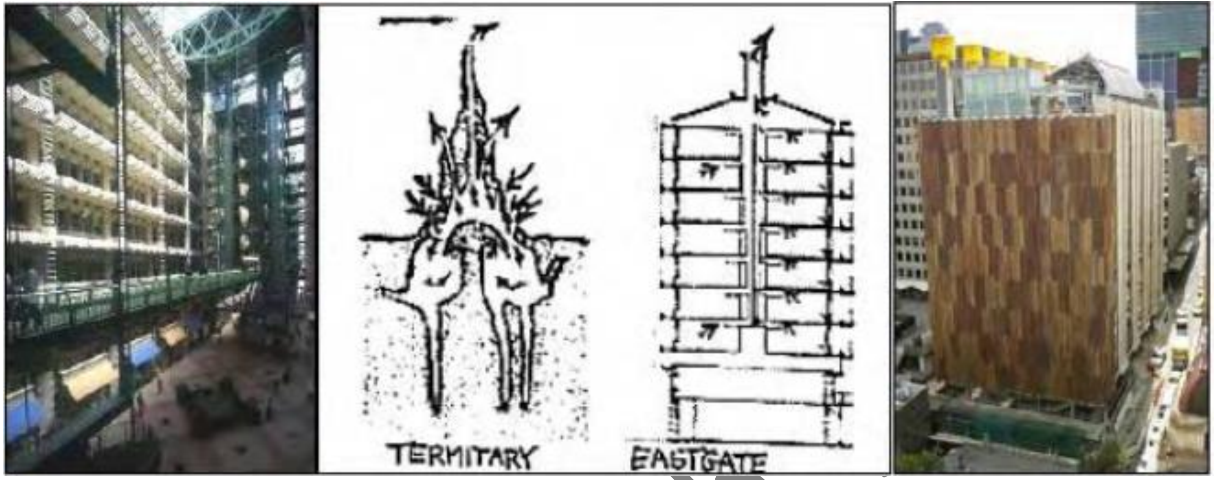


Fig 1.12: Eastgate Building in Harare, Zimbabwe and CH2 Building in Melbourne, Australia.
(Source: Pedersen Zari, M. 2007).

Behaviour level mimicry requires ethical decisions to be made about the suitability of what is being mimicked for the human context. Not all organisms exhibit behaviours that are suitable for humans to mimic and the danger exists that models of consumption or exploitation could be justified on the basis of how another species behaves. For example, mimicking the building behaviour (and outcome of that) of termites might be appropriate for the creation of passively regulated thermally comfortable buildings. Mimicking the social structure of termite colonies would not be suitable however if universal human rights are valued. It may be more appropriate to mimic specific building and survival behaviours that will increase the sustainability and regenerative capacity of human built environments rather than mimicking that could be applied to social or economic spheres without careful consideration. It may be more appropriate to mimic whole systems rather than single organisms in this regard. An example is Benyus‘ (1997) assertion that we should „do business like a redwood forest‟. (Pedersen Zari, M. 2007).

1.2.3.3 Ecosystem Level

The mimicking of ecosystems is an integral part of biomimicry as described by Benyus (1997) and Vincent (2007). The term ecomimicry has also been used to describe the mimicking of ecosystems in design (Lourenci et al., 2004, Russell, 2004), while Marshall (2007) uses the term to mean a sustainable form of biomimicry where the objective is the wellbeing of ecosystems and people, rather than ‘power, prestige or profit‟. Proponents of industrial, construction and building ecology advocate mimicking of ecosystems (Graham, 2003, Kibert et al., 2002, Korhonen, 2001) and the importance of architectural design based on an understanding of ecology is also discussed by researchers advocating a shift to regenerative design. (Reed, 2006)

Lavacha Sarah

An advantage of designing at this level of biomimicry is that it can be used in conjunction with other levels of biomimicry (organism and behaviour). It is also possible to incorporate existing established sustainable building methods that are not specifically biomimetic such as interfaced or bio-assisted systems, where human and non-human systems are merged to the mutual benefit of both. An example is John and Nancy Todd‘s Living or Eco Machines where the process of waste water treatment in ecosystems is mimicked and also integrated with plants (Todd, 2004, Todd and Josephson, 1996). The Australian developed Biolytix® system mimics soil based decomposition to treat grey and black water and again integrates actual worms and soil microbes into the process. (Allen, 2005, Baumeister, 2007a)

A further advantage of an ecosystem based biomimetic design approach is that it is applicable to a range of temporal and spatial scales (Reap et al., 2005) and can serve as an initial benchmark or goal for what constitutes truly sustainable or even regenerative design for a specific place.

The most important advantage of such an approach to biomimetic design however may be the potential positive effects on overall environmental performance. Ecosystem based biomimicry can operate at both a metaphoric level and at a practical functional level. At a metaphoric level, general ecosystem principles (based on how most ecosystems work) are able to be applied by designers with little specific ecological knowledge. Several authors have offered such general principles (Benyus, 1997, McDonough and Braungart, 2002, de Groot et al., 2002). A set of ecosystem principles derived from comparing these cross disciplinary understandings of how ecosystems function is detailed by Pedersen Zari and Storey (2007). If the built environment was designed to be a system and was expected to behave like an ecosystem even if only at the level of metaphor, the environmental performance of the built environment may increase. (Korhonen, 2001)

On a functional level, ecosystem mimicry could mean that an in-depth understanding of ecology drives the design of a built environment that is able to participate in the major biogeochemical material cycles of the planet (hydrological, carbon, nitrogen etc) in a reinforcing rather than damaging way (Charest, 2007). That a greater understanding of ecology and systems design is required on the part of the design team is implicit. Also required would be increased collaboration between disciplines that traditionally seldom work together such as architecture, biology and ecology. Such an approach challenges conventional architectural design thinking, particularly the typical boundaries of a building site and time scales a design may operate in. (Pedersen Zari, M. 2007)

While Kibert (2006) cites a number of authors advocating similar ideas, he criticises this kind of approach to design, because of the difficulty in understanding and modelling ecosystems and asserts that „…the mimicking of nature in human designs is one dimensional [and] non-complex…‟ This is true in terms of realised built form, but does not suggest that mimicking what is known about ecosystems is not a worthy goal in terms of increasing sustainability or indeed that it is impossible, particularly when one takes into account that biological knowledge may be doubling every 5 years. (Benyus, 1997)

As discussed, most examples of biomimicry are organism biomimetic. While biomimicry at the organism level may be inspirational for its potential to produce novel architectural designs (Aldersey-Williams, 2003, Feuerstein, 2002), the possibility exists that a building as part of a larger system, that is able to mimic natural processes and can function like an ecosystem in its

Lavacha Sarah Thesis

creation, use and eventual end of life, has the potential to contribute to a built environment that goes beyond sustainability and starts to become regenerative (Van der Ryn, 2005; Reed, 2006). This does not prevent organism biomimicry at a detail or material level.

The examples provided in table 1 demonstrate the deepening of the levels of biomimicry in terms of regenerative potential from form biomimicry at the organism level to functional biomimicry at the ecosystem level. A building that is exhibiting form biomimicry, which is stylistically or aesthetically based on an organism, but is made and functions in an otherwise conventional way, is unlikely to be more sustainable than a non-biomimetic building. (Pedersen Zari, M. 2007)

A building that is able to mimic natural processes and can function like an ecosystem in its creation, use and eventual end of life has greater potential to be part of a regenerative built environment. It is suggested that if biomimicry is to be conceived as a way to increase sustainability of an architectural project, mimicking of general ecosystem principles should be incorporated into the design at the earliest stage and used as an evaluative tool throughout the design process as described by the Biomimicry Guild (2007), Pedersen Zari and Storey (2007) and Hastrich (2006)

1.3 Nature and Architects

This section selects examples of work from four architects and studies them comparatively. The common ground between them is that these architects all try to address nature in their design. Although some seemingly have the same outlook towards nature, its manifestation in their work is drastically different. Louis Sullivan was one of the founders of the modern archtiecture movement and, unlike his following modern architects, his buildings did not end up as boxes of glass and steel26. He was the first to coin the phrase “form ever follows function”27. In his book, Autobiography of an Idea, 28 he explained that it is not so much that the form should be expressive of the function but that the function must create or organize its form. The form of a building should be predetermined and organized by its functions. In this book he also talked about his childhood fascination with nature, humans, and engineering.

acha Sarah Thesis

Fig 1.13: National farmers banks by louis Sullivan
Combination of the multiple color tiling and the contrast and forms is clearly a metaphor of natural.

Fig 1.14 Guaranty/ prudential building by louis sullivan
In this design, the building seems to be an add-on to the vegetal ornaments.

Sullivan and Wright strived for bringing nature into architecture. In this approach, nature and architecture remain two different realms, and architects create relations and dialogues between the two. They respect nature and try to integrate it with the architecture. They are not after copying any component but looking to unify with nature and in that sense, this approach can be considered a poetic one.

Another manifestation of nature in architecture is the approach of taking an isolated natural phenomenon or organism and creating an architecture that simulates that specific organism. The success of this approach depends on the goal that the architecture is trying to fulfill. In Jorn Utzon's Sydney opera house (Figure 1.24), seashells allegedly inspire the form. Although iconic and memorable, the form deviates from the complete dome shape and fails from an engineer's point of view. This creates a non-optimal load distribution necessitating secondary supporting beams in the middle. Extra support adds cost and longer construction time, all concepts that contradict our aim of turning to natural inspiration in the first place.

Fig 1.15 Sydney's opera house by jorn utzon

Fig 1.16 Sea shells

This is an example of using natural forms in a way that is partial, out of context, and on a vastly divergent scale. As a result, it does not acquire original structural attributes of a seashell form. All that being said, no one can deny the uniqueness and elegance of this building, characteristics expected from an opera house. So is the opera house successful in emulating nature? If its goal was to take benefit from the inherent qualities of the seashell form, the answer is no. However, if Utzon aimed to create a memorable icon by taking a beautiful form out of its context and presenting it in a different light, he has definitely succeeded.

The last example is the National Aquatic Center in Beijing (Figure 1.26), which lies on the opposite spectrum of the formal mimicry in the opera house. It uses the sciences of physics and chemistry to study the structure of foam and water molecules. This building has brought the designers to look into the same concept not only in uncovering the inner structure of this natural phenomenon but as in taking a direct formal inspiration from it. This approach blends the formal and the structural aspects of the building making them as one. The skin is made from lightweight ETFE fabric, which resembles the actual membranes of soap bubbles.

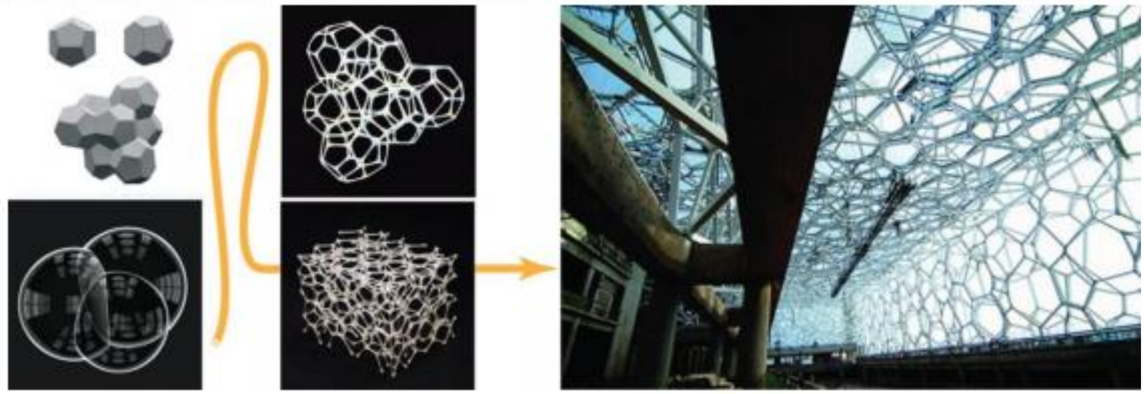


Fig.1.17 National aquatic center beijing

A full emulation engages at least three levels of mimicry: form, process, and ecosystem (Benyus 2008). This center also called the "WaterCube" is the closest example in architecture that incorporates natural emulation at the level of form and process simultaneously.

The design blows the micro scale structure of a soap bubble into a much larger scale of a building. Whereas a traditional sports center structure would have consisted of large columns and beams, in this project the structure combines architectural space, structure, and façade all into one unified element. Unlike the opera house, the Aquatic Center in Beijing is designed in a way that the copied form carries all the inherent properties of the original organism. The idea is carried out in a holistic and non-linear way with all the technical and aesthetical aspects integrated into one concept. On this note, the prefix of "bio" is interchangeable with other natural sciences. For example, John Harrison is an Australian scientist and part of Gaia engineering group. He introduces the term geomimicry to describe processes and technologies that mimic long-term geological processes. Concluding from this study, the group proposes a process of building material production that follows the aim of sequestering atmospheric CO2, converting waste to valuable resources, and production of fresh water.

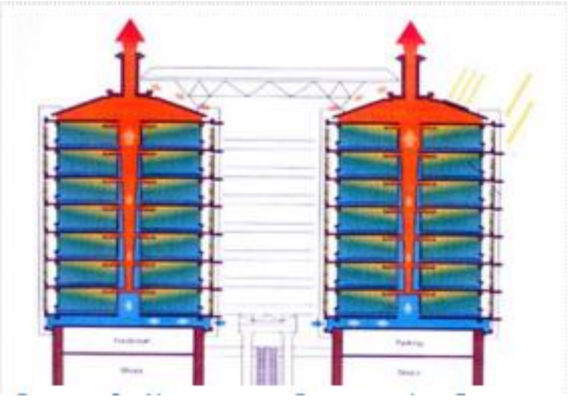
1.4 Examples of biomimetic architecture

1.4.1 Eastgate Center Building

This building, located in Zimbabwe Harare, solves one of the prominent building

issues of the region, air conditioning. It was found that termite mounds keep a constant inside temperature of 87°F in the outside range of 35°F-104 °F. The mound consists of numerous shafts that narrow all the way to the top. During the night the warm air rises up, the negative pressure created sucks the cooler outside air from the openings at the bottom of the shaft. During the day, the thermal mass of the mound prevents heat gain (Gould and Gould 2007).

Layacha Sarah Thesis



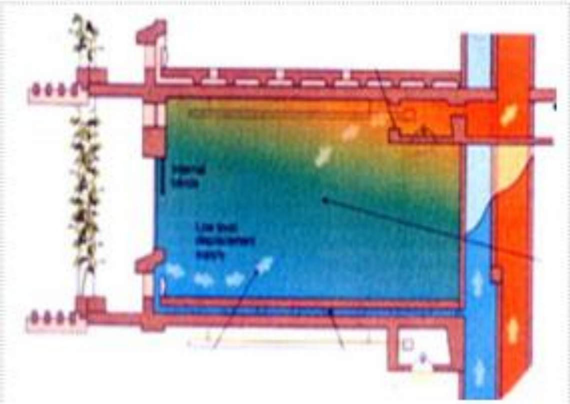


Fig 1.18 Ventilation diagram in eastgate shopping center
Image Source: www.archnet.org

Fig 1.19 Circulation of air in each floor
Image Source: www.archnet.org

This process inspired the design of the ventilation system in Eastgate Center, Zimbabwe’s larges office building and shopping center. The temperature swings of 10-40 °C during the day makes passive or mechanical cooling system a practical alternative to closed loop air-conditioning. The building is largely made of concrete, which acts as a thermal mass. During the night, cool air penetrates the building and passes through openings in the floor slabs (Figure 1.19). During the day the heat rises but the thermal mass prevents it from rising greatly. Towards the end of the day, warm air is vented through the central chimneys both naturally and with the assistance of fans. This motion draws in the outside cool air and this cycle continues (Figure 1.18). This building uses 10% energy compared to similar building of this size.

1.4.2. Exploration Architecture LTD

Michael Pawlyn is an architect who has established the company called “Exploration” in 2007 with the aim to focus on environmentally sustainable projects thatbtake their inspiration from nature. In his latest book Biomimicry in Architecture (Pawlyn 2011), he explores six key environmental concerns: efficiency in structures, manufacturing materials, zero-waste energy, water management, thermal control, and building energy production. Amongst the examples, he is dismissive of structures that simply emulate the natural form.

Amongst the few sustainable ideas Pawlyn has proposed, two projects specifically pertain to biomimicry, the Eco-Rainforest and the Las Palmas Water Theatre (Figure 1.20).

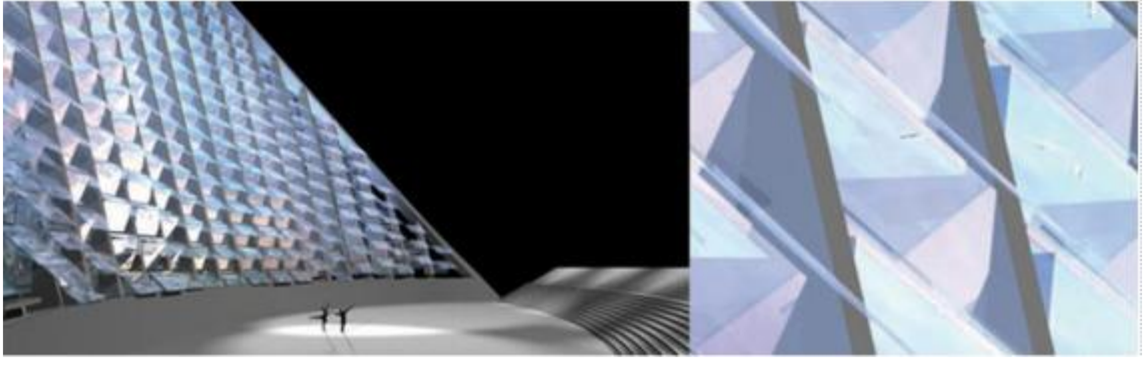


Fig 1.20 Las Palmas Water Theatre. Different wind flaps adjusting to the wind direction.

Jayacha Sarah Thesis

Water management is addressed in the Las Palmas Water theatre. This project is a sculptural outdoor theatre that doubles as a desalination plant, inspired by the Namibian desert beetle. This beetle radiates heat at night and as a result becomes cooler than the surrounding environment creating a perfect surface for condensation. In addition, this creature raises its wings to take advantage of the wind and increase its chances of capturing the fog and turning it into water. In collaboration with Charlie Paton, the inventor of Seawater Greenhouse, Pawlyn designed an array of condensers and evaporators that are stacked on top of each other. Wind flaps are designed mimicking the open wing of a beetle that guide the sprayed seawater into condensation panels, optimizing this process according to the wind direction. The consistent winds all year around, proximity to seawater and plentiful sun made Las Palmas the ideal location to incorporate this strategy. Although this project is not realized, three commercial greenhouses are currently creating freshwater through this strategy

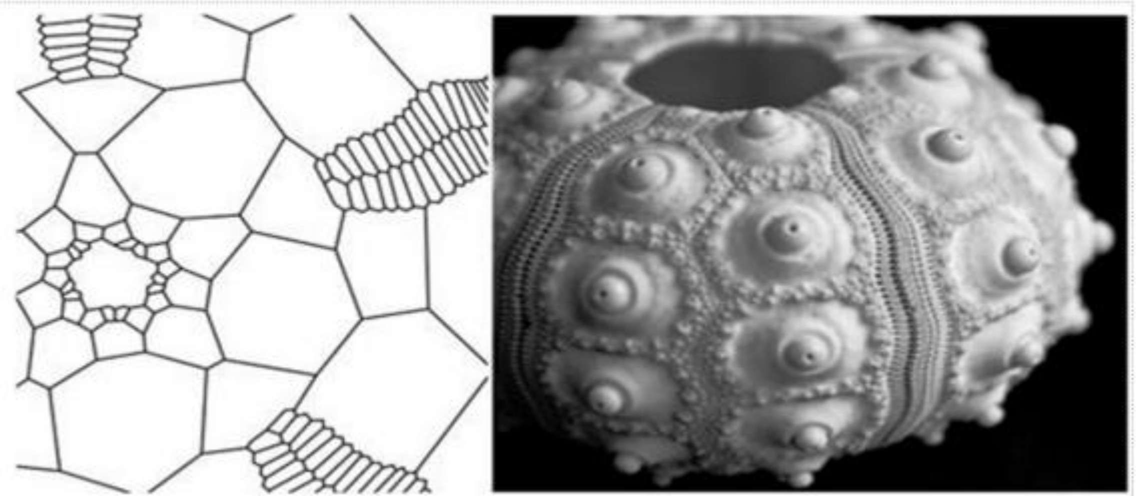


Fig 1.21 Sand dollar structure
Analysis of sand dollar geometry
Images: ICD/ITKE University of Stuttgart

1.4.3 ICD/ITKE Research Pavilion

The institute of computational design (ICD) and the Institute of Building Structures and Structural Design (ITKE) from the University of Stuttgart have joined forces and formed a successful interdisciplinary collaboration between architecture, computational design, engineering, and biology. The pavilion 2011 is the result of a design studio as an embodiment of this collaboration. The project explores the architectural interpretation of biological principles of a sand dollar (Figure 1.9) by means of computer-based design, simulation,

Layacha Thesis

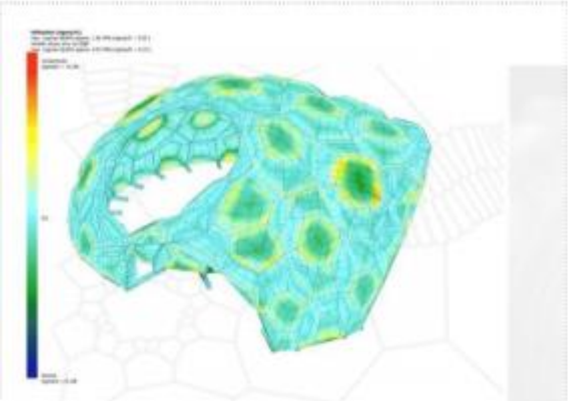


Fig 1.22 Structural analysis
Image source: ICD/ITKE University of Stuttgart

Fig 1.23 ICD/ITKE 2011 Pavillion interior
Image source: ICD/ITKE University of Stuttgart

and manufacturing. The sand dollar has a modular structure and consists of polygonal sheets that interlock in the edges through finger-like projections. The sand dollar has two openings on top and bottom and towards these opening the modules become smaller. Three fundamental properties of this biological structure were applied to the wood structure: heterogeneity (varying cell size adapts to dome's curve), anisotropy (loads directed through planar surfaces), and hierarchy (two types of connections for the respective shells) (Kaltenbach 2012). The pavilion is made of 6.5mm thick plywood and is extremely lightweight and its design can be applied to any geometrical form. The success of this project lies in its closed loop computational design and fabrication system, fundamentally identical the genetic algorithm.

All the critical points in the project were modeled and optimized repeatedly through the constant exchange of data between design and simulation software. In addition, the joint systems were fabricated by robots and tested experimentally. The results of these tests were then fed back into the structural calculations. This project created the opportunity to explore the transference of a biological principle to an architectural design and construction and test it in full scale

Layacha Sarah Thesis

Conclusion

This section showed that most architects have taken the biophilic approach rather than a biomimetic one. A biophilic design is one that "appreciates" nature instead of emulating its concepts and processes. This approach involves using environmental features such as water, light, plants, natural shapes, forms, pattern, and processes. These approaches have been mainly the result of a movement or the trends of a certain time period. Nature and architects shows that nature and all its elements have always been "appreciated" in architecture and the architects have tried to address it one way or another. However, this interest has mostly stemmed from the architect’s personal views or the general trend. In this research, we are merely interested in biomimicry and wish to dismiss the superficial formal mimicry of nature.

Biomimicry has become more popular amongst architects in the past few years with the promise of creating a more sustainable environment by way of mimicking nature in every imaginable manner. Although this promise is greatly appealing to all architects, to this day, there is no evidence of an actual biomimetic building that fulfills this promise on all levels. The studies show that, there are two distinct approaches to the biomimetic design process. First involves mimicry at either levels of organism, behavior, and ecosystem. Second is a holistic biomimetic approach that mimics the evolutionary development of a system and because of the complexity of its process, relies heavily on creation of algorithms and computational processes. As Menges mentions, for a building to be completely biomimetic its design process must be biomimetic as well, following the complete developmental sequence of a biological system. It is quite possible that once software is developed, or properly implemented, to simulate the building performance in all levels a genetic algorithm (holistic approach) will be capable of designing a biomimetic building that fulfills this promise on all levels. In fact the more variable available, the better the performance of genetic algorithms in some cases (Parks 2012).

This does not discredit other approaches but rather points out their limitations. Furthermore, although the first approach might not fulfill the ultimate promise of biomimicry, it could be a viable transition for the industry. Since the resources of a large company like HOK are not available to everyone, experimenting at the level of organisms may be something that is far more practical for most architects. This process could even be part of the educational curriculum, which can raise awareness and generate models and ideas that further advance this field.

We asserted that in this process the most challenging part is the availability of biological information researched from the point of view of architects. Whenever a designer stumbles across an interesting phenomenon, the available information is either too generic or from the point of view of a specific discipline (Gruber and Jeronimidis 2012). Realizing the importance of a targeted study, points out the deficiencies of a website like Asknature31. Although the idea of gathering all the information from nature in one place can potentially be helpful, the classifications appear too broad for the purpose of biomimicry in architecture. This is due to two factors, first the infinite pool of data and inspiration in nature and secondly the unidentified audience. This will create an irrelevant or intractably large search results. Although these results might be “interesting”, they are often too general to be applicable to real problems. We also stated that the iterative process is crucial to the efficacy of biomimicry. Therefore, this thesis pertains to the development of an efficient means of iterating the process of biomimicry by utilizing input from architects, engineers, and biologists by way of the development of a shared database.

Layacha Sarah Thesis

Introduction

Buildings still represent a great challenge which is globally responsible for approximately 23% of the global primary energy usage and 30% of the global electricity consumption. In addition, where 60% of the total consumed energy in buildings is accounted for space heating and cooling. Building envelope plays the main role in controls energy consumption in buildings and maintains internal comfort. Conventionally, a building envelope has been considered a thermal barrier to prevent heat loss or shade to control solar gain. In fact, most of the building envelopes are constructed to provide static design solutions. Conventional solutions for building envelopes also lack the ability to adapt to contextual issues and needs.

Armstrong stated that learning from nature is the answer. Biology presents a new paradigm in various fields, such as engineering or medicine, as a novel basis for technological thinking. Biology has been integrated with architecture through biomimicry that involves nature as a massive database of mechanisms and strategies to be implemented in designs. Biological solutions can be multi- functional, complex and highly responsive and thus can replace the concept of conventional building envelopes as static to improve energy performance in a new adaptive form. This approach can help future building skins to be more responsive and adaptive to both external and internal conditions and satisfies comfort levels. Biomimicry provides many possibilities of adopting designs from nature into sustainable building systems. However, the transfer of knowledge from biology to architecture or technology is difficult. The transfer of superficial research without information from life sciences, unimaginative approach or non-scalable phenomenon can cause failure. Thus, it was found that designing building skins is impeded by uncertainty and hence can barely result in any further technical advancement in architectural designs and energy efficiency. Therefore, this review aims to establish a clear design process based on technical aspects to design adaptive building skins. This paper presents a critical review on applying adaptive building skins that optimize nature within the development of biomimicry knowledge in architecture.(Armstrong R. Living architecture: how synthetic biology can remake our cities andreshape our lives. TED books; 2012.)

2.1. Definition of Skin in Nature

The definition of skin typically refers to the softer outer membrane of animals, mainly vertebrates. In this research, the definition of skin is expanded to any living species or its component that portrays characteristics of a membrane or a surface that takes characteristics such as protection, filtration, heat regulation, boundary definition, and connection. In this sense, this definition will include non-vertebrate animal coverings and organisms such as shells and leaves. Skin in multiple definitions is as follows:
A: the external limiting tissue layer of an animal body, especially the 2-layered covering of a vertebrate body consisting of an outer epidermis and an inner dermis
B: an outer covering (as a rind or husk) of a fruit or seed
C: a membranous film or scum (as on boiling milk or drying paint)

Layachia Sarah Thesis

2.2. The Parallels

To draw analogies between natural skin and a building envelope, we must first study the similarities and the parallels that exist between these two entities. This involves the study and interpretation of the common forces and criteria affecting both natural and architectural design processes.

2.2.1. Function

The volatile nature of an architectural façade's function calls for flexibility of the design solution in various aspects like spatial arrangement, connectivity with the exterior, extensive and versatile noise, light and ventilation controls, conformity to different occupancy and circulation scenarios, and the need for a monumental and expressive identity. Building skin or envelope is the boundary through which the building's interaction with the environment occurs. It can consist of layers and filters that respond to light, air, moisture, sound, and heat. The most common feature amongst most living forms is the ability to maintain the optimal internal conditions responsive to the functions they carry. Building envelope like the natural skin is the boundary between the controlled environment and the uncontrolled. Its formation is the result of internal and external forces. Building envelope or skin determines how exterior and interior interact, what is kept out, and what is let in.

The concept of inside outside, protection and filtration are recurrent in both nature and building envelope. Skin in nature deals with a similar kind of complexity and seems often to handle both functionality and aesthetics perfectly.

2.2.2. The Evolutionary Process of Design

Nature has perfected the form and the solutions that natural systems provide to address different problems over years and years of evolution. The so-called "natural selection" ensures that the only survivors are the "successful" specimens. Evolution refers to the incremental change through millions of years of experience. Species evolve due to destabilization of the environment and internal needs to better adapt to conditions.

As an integral part of the natural domain, architectural design has somewhat followed a similar evolutionary process. Natural selection in architectural design occurs in many different levels. Multiple factors cause instability in the environment and necessitate the need for the architecture to change. Some examples of these factors are technological advances, the speed of information transmission through current media, the emergence of rapid transit systems, and population growth. These factors directly reflect on human needs, culture, way of life and, consequently, the design that embodies them all.

2.2.3. Complexity

In the battle for resources, natural systems learn to be efficient. Nature responds to this problem through developing multifunctional components. Obviously, efficiency is relative and context dependent both in nature and in architecture. For example, using wood as a primary source of material for a building may be an efficient solution in countries with abundant forests, whereas in arid climates brick or stone make more sense.

Layacha Sarah Thesis

Further, architectural façade is a component that must address a diverse array of needs and therefore, has the potential for becoming a multi-functional element. Nature's ability to find an excellent solution in the context of many, often seemingly conflicting requirements is highly applicable to architectural façade design.

2.2.4. Soft Transition

Redefining the concepts and deviating from the rigid ideas of boundaries has enabled architects to create architectural spaces that offer unique experiences. The example of the blur building (Figure 2.1 and Figure 2.2) built for the Swiss Expo 2002 on Lake Neuchatel offers a unique experience. “Upon entering the fog mass, visual and acoustic references are erased, leaving only an optical "white-out" and the "white-noise" of pulsing nozzles.” These types of architecture play with the concepts of outside and inside and the level of separation and filtration. Nature is a master of soft transition and this quality is especially evident in skin.

Fig 2.1 The blur building
A lightweight metal structure sprays water and creates a unique atmosphere.
Image source: http://www.dillerscofidio.com/blur.html

Fig 2.2 The blur building inside
Image Source: http://www.dillerscofidio.com/blur.html

It has no beginning and no end and every component transforms seamlessly into another. This quality in natural skin can be inspirational specifically in the building envelope design.

2.3. Evolution of the Role of Architectural Façade

This section is a brief preview that shows the evolution of the formal qualities and design requirements of building envelope. These changes have brought the building envelope to acquire a more “skin” like quality. Animal skins were one of the earliest types of shelters that man used to protect himself from the unwanted changes in climate (Figure 2.3). As building technology developed and societies and human needs evolved, this element, the building envelope, retained its fundamental role although it had acquired many forms.

Fig 2.3 Caribou tent construction
Photo Courtesy of Helge Ingstad

2.4. Innovations in Form, Function, Material, and the Concept

Le Corbusier claims: “The history of architecture was the same as the history of window” (Leatherbarrow and Mostafavi 2002). In 1930, he introduced the concept of free façade and liberated the windows, which then were the only defined openings, from the load-bearing wall. For the first time, the window is not a mere opening dictated by structural constraints. It has now become an element capable of acquiring a new poetic quality and creating an independent identity for the building (Figure 2.4).

Fig 2.4.Villa savoy by le corbusier
Because the façade is free from structure, the windows can be continuous to create a panoramic view to the exterior landscape. It creates a visual continuity between the interior and exterior.

Buckminster Fuller in his geodesic dome transforms the scale and the range a facade can bear by spanning over a long range without any support from columns or bearing walls. Interestingly enough, the icosahedral form of a virus protein at a microscopic level inspired this dome (Figure 2.5) with a diameter of 250 feet and height of 200 feet. In this design, the envelope acquires the responsibility of the wall, the roof, and the structure all at once. The boundaries are dissolved, and the whole envelope transforms into one element. This type of seamless transition is a typical characteristic of a natural skin.

Renzo Piano with his partner Richard Rogers in the Pompidou Center (Figure 2.6) uses the envelope as a system-bearing component. They challenge the concepts of inside

Thesis

Fig 2.5 Montreal's geodesic dome
The skin acts as a piece of clothing for the different functions it serves. Originally built in US for an expo, this dome was later transferred to Montreal and served as a birds and plants exhibition.

Fig 2.6 George pompidou center
Renzo Piano, Richard Rogers
In 2007 when reporting about the Roger's Pritzker prize the New York Times stated the design "turned the architecture world upside down".

and outside and transform the meaning of envelope by bringing all the systems to the outside level. This design changes the whole concept of skin as a mere aesthetic element to a fully functional one. Frank Gehry has been one of the most influential architects of our time. He breaks the boundaries of formal and technological standards by practicing a very sculptural quality in his buildings. In Frank Gehry's Guggenheim museum in Bilbao (Figure 2.7) and in his later works, the facade and specifically its material accommodates for the sculptural quality that the building is trying to convey. Titanium sheets as thin as a third of a millimeter wrap around the building and with their reflective quality are responsive to the changes in the surrounding lighting.

Fig 2.7 Guggenheim museum in bilbao

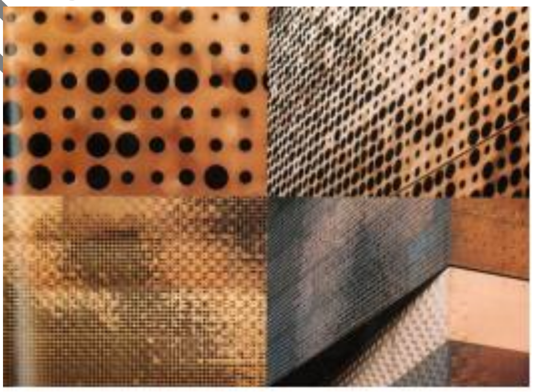


Fig 2.8 De young musem san francisco

Herzog and de Meuron in a number of their projects, through designing with light, material porosity, and different textures, bring about a poetic approach to building skin design. In the Museum of San Francisco (Figure 2.8), the semi-transparent skin of this museum uses a repeating pattern varying in scale, and the copper material well blends in with the natural surroundings.

2.5. From Façade to "Skin"

The shared concepts and technical requirements between natural skin and building envelope create a solid ground for their association. Moreover, the separation of façade and structure after the modern period has transformed the role of the building façade from a load bearing

Lay Sarah Thesis

mass to that of a conceptual one. The thickness, materials, form, levels of transparency, porosity, and many other characteristics of this element were not determined by structural constraints anymore. It has been liberated from all its prerequisite functions and enabled to carry new ones. It has become an independent element, a mere curtain, a “skin”.

Fig 2.9.The yas hotel by asymptote in Abu dhabi
The skin of this hotel-Formula one racetrack is the element that conveys the aesthetics associated with speed and movement the geometry is reminiscent of Islamic patterns. The façade is like a blanket thrown over the whole building, a concept far from the traditional heavy and constricted definition of a façade

After the building façade became a skin, the possibilities became endless, ranging from a fully functional identity to that of a poetic and metaphoric one (Figure 2.9). The building skin became the buffer, redefining the concepts of “outside” and the “inside”.
This new skin is responsible for controlling the nature and level of interaction between these two realms, creating transitory spaces that served purposes relating to new needs.

2.6Concept of mimicking nature

Several architectural projects utilised biomimicry; for instance, in terms of adaptive envelopes, the first project was inspired by the valvular pollination mechanism in Strelitzia reginae flower called Flectofins. This envelope adopts the mechanism of reversible material deformation when an external mechanical force is applied. The adaptive approach is clearly applied in adaptive exterior shading system. The second project is inspired by the research on kinematic mechanisms and plant movements, such as Flectofins called the One Ocean Thematic Pavilion, in Korea. A shading system adapts and responds to changing sunlight conditions during daytime. The third project is based on the movements observed in spruce cones as a passive response to humidity changes called ‘HygroSkin’. This pavilion uses relative humidity; the responsive capacity of its material interacts with the surroundings. Generally, Lurie-Luke conducted a study to identify biomimetic applications in cientific discipline based on innovations, as shown in Fig.2.10 Results showed that the most advanced area under research are materials followed by idea and prototype of movement and materials

Layacha Sarah The

2.7. Issues in implementing biomimicry in the built environment

Biomimicry is a new paradigm and emerging field in architecture and faces several issues that limit its development. For instance, the development of biomimicry in engineering and technology is limited only on certain scales to transfer technological aspects from biology to design. These limitations have narrowed the scope of inquiry that reduces biomimicry application to sustainable design. Nature has various mechanisms and strategies that can be adopted in biomimetic approach. Even though there are several types of biomimetic designs available, obtaining a successful design is very challenging in architecture.

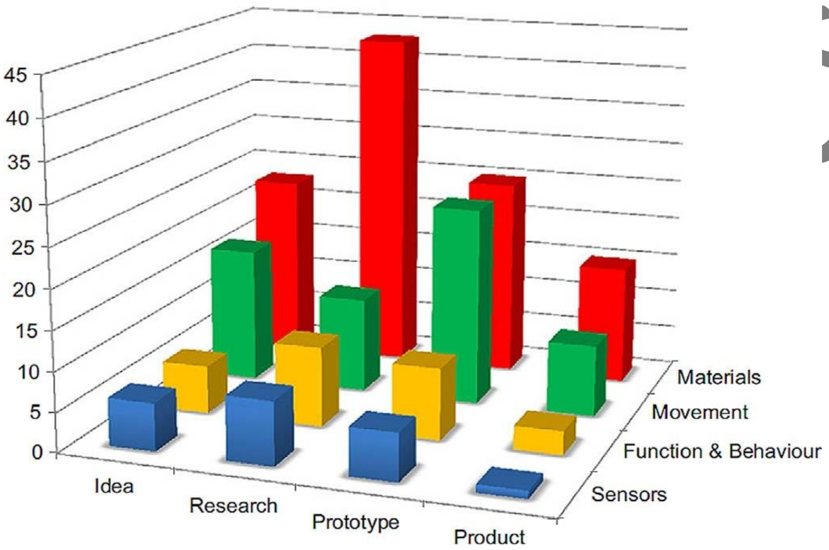


Fig. 2.10. Biomimicry applications in different areas and their development stage.

Badarnah and Kadri and Lepora et al. stated that the major drawback in biomimetic design is the lack of a clear systematic methodology; the absence of design methods from the ecosystem's perspective restricts delivery of clear strategies and mechanisms from the adopted systems. Currently, form and morphology are trends to mimic nature into architecture. However, such advantage rarely possesses any function to imitate natural systems; thus, it hardly presents a successful biomimetic design. Badarnah and Kadri stated that in architecture, three obstacles limit the implementation of biomimicry:

1. exploration and selection of strategies from nature,
2. scaling difficulties as some functions work on specific scales (e.g. nano to micro) and
3. conflict of integrated parts of the design concept.

Royall stated several issues in implementing biomimicry, such as the difficulty to segregate the approach from basic problem solving and biomimicry is frequently simplified into a linear process. Vogel indicated that mimicking technology found in nature without any adjustments creates many unsuccessful projects. El Ahmar stated several issues with biomimicry. First, biomimicry relies heavily on very specific knowledge, skills and tools. Second, design approach heavily depends on computer software. The problem relies on the gap of recognition between computers and human beings. Third, identification of the optimum material for a system requires a large number of physical tests and geometric description. Fourth is the issue

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of finding the relation between components. Fifthis selection of suitable algorithmic growth processes. Sixth is the recurrent interfacing with appropriate analysis applications. Seventh is the control of continuous evaluation and feedback. Therefore, Zari and Storey and Badarnah and Kadri addressed that the practical application of biomimetic methods remains elusive in architecture.

2.8. Mechanisms of adaptation in nature and engineering

Natural systems have developed the optimum means of protection against changing environmental conditions; thus, nature is the best source to learn adaptation. Natural systems are iterative feedback loops of continuous processes, such as thermodynamics, acoustics, and optics, which can be described as self-organisation. Self-organisation is one of the main dynamic and adaptive processes for complex adaptive systems. It is a process where the internal organisation of a system adapts to the environment to develop a particular function without being managed or directed externally.

Many studies in biology have described the adaptation process in internal organisation of natural systems by understanding the function of organisms in ecosystems. (Benyus JM. Biomimicry. New York: William Morrow; 1997. p. 1) Hensel and Menges (Hensel M, Menges A. Designing Morpho-Ecologies. AD-Versatility & Vicissitude:Performance in Morpho-Ecological Design, p. 102-111, 2008) and El Ahmar (El Ahmar SAS. Biomimicry as a tool for sustainable architectural design. Faculty ofEngineering, Alexandria University; 2011, (Doctoral dissertation) indicated that organisms use energy and materials for more than one function to maximise efficiency. Odum (Odum EP. The strategy of ecosystem development. Science 1969;164:262–70) stated that wastes produced by one organism become the nourishment for the next in a cycle of large closed-loop systems. In addition, form in the natural systems can function given the limited resources, which means that function generates form and form directs organisms behaviour in the ecosystem within different environments. Moreover, natural systems have always utilised energy and materials to optimise the whole system rather than the individual components. McDonough and Braungart (McDonough W, Braungart M. Cradle to cradle: remaking the way we make things.MacMillan; 2010.) indicated that efficiency is different between individuals compared to the entire system, as inefficiency in an individual could be often equated to effectiveness for the whole system. As a result, the performance of natural systems does not depend on a single parameter; however, it is based on the effectiveness of multi- parameters for optimisation and efficiency.

Some researches stated that for a system to adapt to change, nature uses an insurance effect that creates a level of redundancy to allow adaptation to changing conditions at various rates. Weinstock et al. stated that biological systems are complex and respond and adapt to stresses and dynamic loadings. The form of responsivity is nonlinear, arising from the interactions of multiple hierarchies. This response is developed and adapted based on redundancy over time, which is similar to the stochastic approach. The adaptation and being responsive in the nature is different in that the former needs to have a dynamic balance in production and reprocessing of materials to generate energy, whereas the latter needs to respond to local conditions through extensive feedback loops shaped by the relationships among these organisms. The relationship between nature and climate is stressed and indicated that climate is the main

Layacha Sarah Thesis

factor that influences the principles of adaptations. Designing an adaptive system in the built environment requires incorporating some levels of redundancy to allow complexity evolution over time. This redundancy creates a more responsive system to the environment which possibly will be more self-maintained.

In the engineering field, adaptive or self-adaptive concept represents systems that can acclimatise their actions to dynamic working conditions and react to environmental changes. These systems can independently alter their performance in response to alterations in their operating conditions to meet certain requirements with less energy consumption. These systems based their corrective actions on sensors that function specifically to deliver information for dynamic environments. Cámara et al. (Cámara J, Lopes A, Garlan D, Schmerl B. Adaptation impact and environmentmodels for architecture-based self-adaptive systems. Sci Comput Program 2016) stated that designing adaptive systems to be responsive to the change requires embodying knowledge about themselves. In fact, implementing knowledge on these systems is essential when decision making involves comparing alternative adapta- tions in real time.

The limitation of applying adaptation depends mainly on the accuracy of analytical models that are used for decision making. Cámara et al. stated that current adaptive models in engineering fields cannot capture the underlying uncertainty and variability of such dynamic execution environments due to the low level of abstraction. Therefore, enhancing the selection of the best corrective action is crucial in adopting these systems. In addition, Cámara et al. stated that to characterise an adaptation in a genuine manner, three dimen- sions should be considered: (1) uncertainty in the outcome of adaptation actions, (2) context variability and (3) assumptions about the evolution of the environment during the execution of adaptations. Self-adaptation is divided into two forms: (1) a systematic method of demonstrating the influence of individual adaptation actions and (2) the behaviour of the system and its medium with a lower level of abstraction to differentiate component and connector types.

Layacha Sarah Thesis

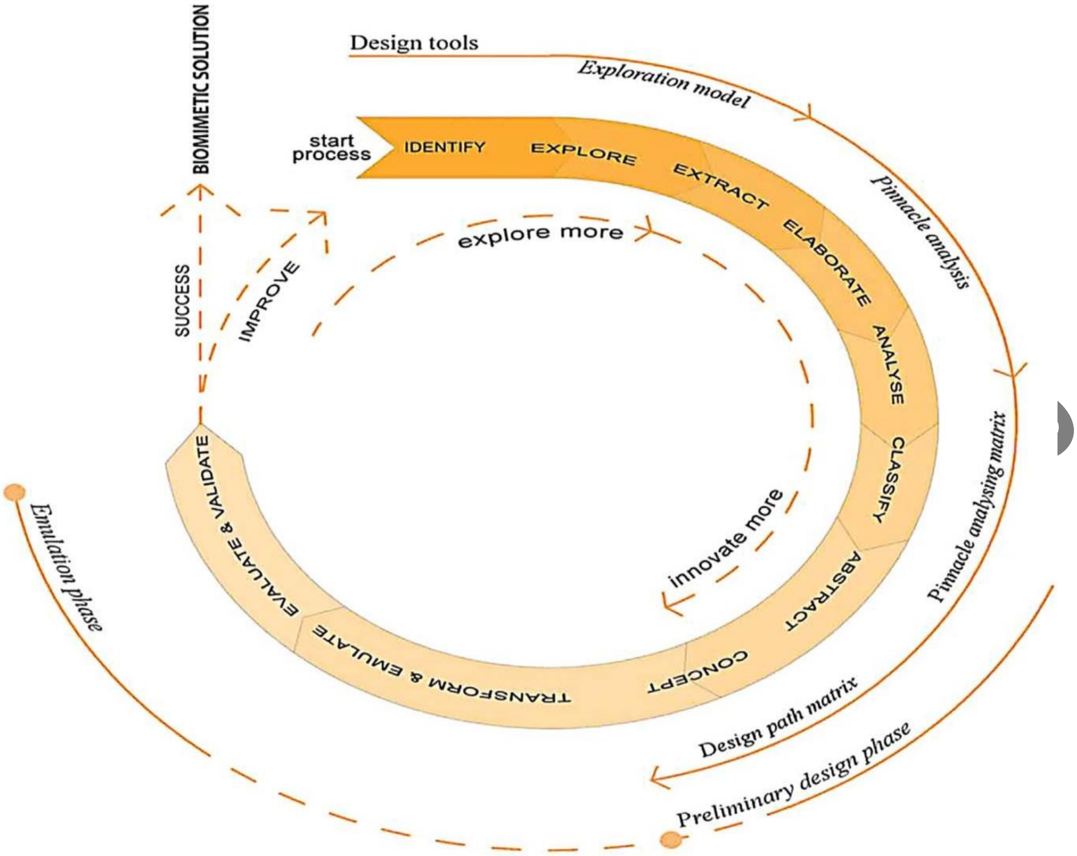

Fig. 2.11. Exploration model and design path matrix for BioGen method to design an adaptive wall system.

2.9. Inspired materials from nature

This section presents an overview of the most common natural materials that adapt with nature and possess adaptive features such as functional surfaces for animals and dynamic movements in plants through some typical characteristics of morphologies, structures and movements.

2.9.1. Adaptive functional surfaces

Han et al. (Han Z, Mu Z, Yin W, Li W, Niu S, Zhang J, Ren L. Biomimetic multifunctional surfaces inspired from animals. Adv Colloid Interface Sci 2016) stated that the application views of the biomimetic functional surfaces are wide. Recently, various forms of animals' functional surfaces have been examined by professionals from several disciplines. These investigations helped to propose several functional surfaces which resulted due to a complex interplay between surface morphologies with physical and chemical properties. Han et al. stated that animals have adapted to produce the most efficient surfaces based on multi-functional performance. Therefore, optimizing their biological solution is an inspiration for constructing adaptive synthetic surfaces. Different types of surface function and structure could be found in nature surfaces.

Layacha Sa

Surfaces for anti-wear could be found in animals with special body surface that survived in the desert to withstand wear and tear caused by the sandy wind. Understanding their properties would help to over- come material erosion and causes of damage and failure of equipment as caused by ground beetle (Carabidae), dung beetle (Copris ochus Motschulsky), earthworm (Lumbricidae), dung seashells and whelks, desert lizards and scorpions. Surfaces for superhydropho- bicity are special surfaces that hardly get wet and distinguished by static contact angles with water (θw) above 150°, such as those of water strider and Parnassius butterfly wing. Surfaces acting as smart adhesives could also be found in animals that produce high (dry) adhesion to support its weight with a high factor of safety, which can be found in soil-burrowing animals such as gecko. Surfaces for drag reduction are commonly found in underwater animals that can swim freely because of their special surface structures that have a low drag surface function, superoleophilicity in air, and superoleophobicity in water, such as those of the carp and shark skin. Surfaces for anti-fogging can provide an effective protective mechanism for main- taining clear vision in a humid habitat, such as those found in the compound eyes of the Culex pipiens mosquito. Surfaces for noise reduction that generate lower sound intensity and lower frequency noise have great sound absorption property, such as the feather of the eagle owl. Surfaces for water capture or superhydrophobic patterns help to collect drinking water from fog-laden wind. One of the most famous examples is the Stenocara beetle in the Namib Desert. Optically functional surfaces are found in many tunable optical structures, such as helicoidal structure, irregular network, photonic crystal, double-facet microlens, moth eye ridge, multilayer structures, nonreflective surfaces, highly reflective surfaces that lead to advanced optical effects including dynamic structural colour, light focusing, iridescence, antireflection, ultra-whiteness and ultra-blackness, colour mixing, polarisation and broad-angle structural colour. Different types of insects and animals contribute to optical novelty in design, such as the Trogonoptera brookiana butterfly, moth eye, sea mouse, peacock feather, male beetles Chlorophila obscuripennis (Coleoptera), Papilio ulysses butterfly and paradise whiptail.

2.9.2. Adaptive dynamic movements

Plants represent one of the main players of learned biomimicry in architectural design. Plants have special features that can respond to changing environments, such as darkness, light, humidity, rainwater, fire, temperature, freezing, air movement or air quality, which make plants an inspiration of adaptive movements. For example, motion and surface structure can be learned in three ways: morpho- logical, physiological and behavioural. Studies have shown that plants blur mechanism, material and structural borders. Meanwhile, other works have presented how plants transfer force, torque and motion to structural elements, and how these subsequently become associated with biologically compliant mechanisms and forms. Some plants also possess response features like tropisms or nasties, which allow them to move depending on the direction or position of external stimuli.

Schleicher et al. have introduced three types on the basis of plant structure and properties, namely, Strelitzia reginae, Aldrovanda vesiculosa and Lilium Casa Blanca. Strelitzia reginae (bird of paradise flower) moves elastically, which inspired the development of a hinge- less flapping mechanism particularly suited for buildings with curved glass facades that are

Layacha Sarah Thesis

difficult to shade. Aldrovanda Vesiculosa (waterwheel plant) has a fast reversible snapping motion, a type of movement that is hydraulically determined by a central surface common to plants with bidirectional mechanisms. Lilium Casa Blanca from the lily family is an example of a firmly packed plant with unidirectional movement; its flowers, each consisting of three outer and three inner petals, are prominently curved. López et al. introduced five plant types with motion and surface properties: (i) the hairy leaves of Gynandriris setifolia, which can reflect sunlight from their surface; (ii) Echeveria glauca, an example of a plant with crassulacean acid metabolism, which can efficiently use water; (iii) Salvia officinalis (Sage) and Kalanchoe pumila (Dwarf Purple Kalanchoe), both with passive responsive and adaptive systems, which are advantageous to changing temperatures, and reflective structures for protection against excessive sunlight; (iv) the leaves of Mimosa pudica (Sensitive plant) with motion-sensing mechanisms linked to a signal-and-response feedback system, such that leaves fold inward upon contact to a stimuli; and (v) the seeds of many Mesembryanthemums and the leaves of Rhododendron, both with valve-like mechanisms that can use rainwater to trigger capsule launch and dispersal as shown in Table 3 and listed below:

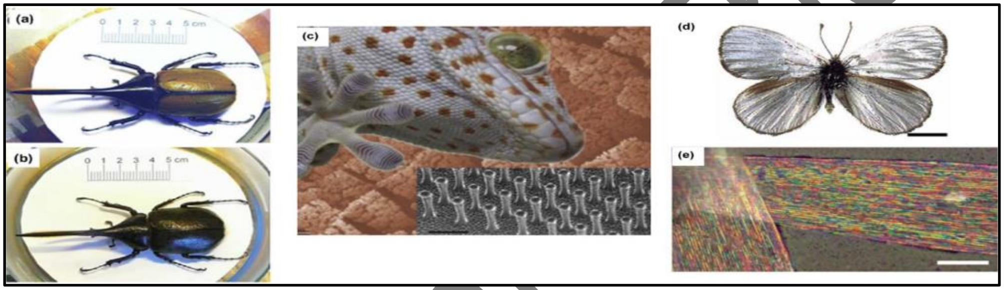

Fig. 2.12. Different types of adaptive functional surfaces from animals.

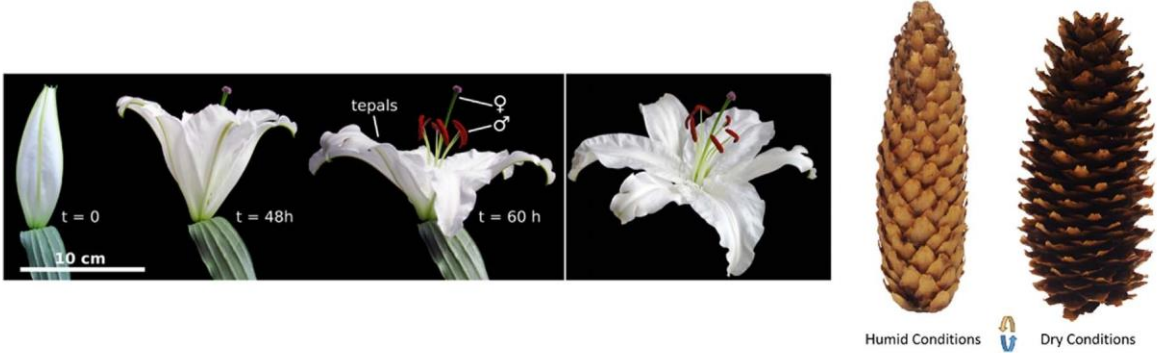

Fig. 2.13. Two types of plants with adaptive dynamic movements; the opening movement of a lily bud is driven by differential edge growth in the petals and reversible moisture- driven opening (dry conditions) and closing (wet conditions) of spruce cones.

2.10. Material development based on biomimetic design

Biomimetic-based materials represent majority of current research initiatives due to their wide application in many disciplines, including medicine, engineering and architecture. In the study of Lurie-Luke, biomimicry-based materials are classified into four clusters:

(1) smart materials that change and react in response to external stimuli; (2) surface modifications with innovative surface structures and improved functions; (3) nature-inspired material architectures that are focused on innovative forms and structural arrangements; and (4) technologies that improve current systems by deploying specific adaptive parameters.

The first cluster is for organism-like smart materials that can change specific characteristics and parameters in response to a series of mechanical, chemical, spatial and temporal information in different environmental conditions. The group is divided into two sections: chemical stimuli and physical stimuli. For chemical stimuli, the specific receptor of a material detects and promotes highly specific internal response. Common biomimetic applications are for pH changes and metal ion components of smart materials. Meanwhile, physical stimuli can range anywhere from heat to light and water content. The second cluster are for materials with surface modifications (e.g., drag-reductive, repellent and anti-reflective proper- ties) typical of novel designs. On the basis of repellent surfaces, specifically water-repellent properties, majority of plants possess highly hydrophobic surfaces that allow water to easily run off over the leave epidermis through a waxy cuticle. Moreover, the ability of geckos to stick to different surfaces and break free easily also gives insights into well-built joints in architectural design. A gecko footpad has nanoscale, microscale and filamentous structures that can interact with any given substrate.

The third cluster is for material architectures with natural endos- keletons and exoskeletons; at the initial stages of architectural design, these materials represent the production of new materials with many potential applications. There are many good examples of natural structural adaptations that enable the construction of lightweight structures, including the two-layer Beetle elytra that maintain their integrity through a series of interconnecting attachments. Imitating natural photonic structures and developing new nanoscale structures can enhance the development of new structures and material properties in the field of architecture. Finally, materials with technologies for targeted applications (e.g., locomotion) represent one of the largest areas of biomimicry implementation, and they are known to increase robotics and vehicle movement efficiency, and even help in the development of new types of transport. Mimicking provides insights into the movement principles inspired by muscular and skeletal systems [60]. Lurie-Luke has classified biomimicry applications into three types: (1) improvements based on movement kinetics; (2) improvement-based release mechanisms; and (3) im- provements based on structural configuration (e.g., energy-efficient shapes). Generally,these classifications can help improve design ap- proaches and innovate building skins.

Layacha Sarah Thesis

2.11 Adaptive building skins

2.11.1. Systems and materials for adaptive building skins

Generally, building skins are a complex system that requires the control of many aspects, such as heat, light, humidity and ventilation, among others. Applying adaptivity in building skins requires various elements of the building system, such as sensors, actuators and command wires to be efficiently correlated with the approach of nature such as metabolism and morphology. Nonetheless, Addington and Schodek, (Addington M, Schodek D. Smart materials and technologies for the architectureand design professions. Oxford: Elsevier Architectural Press; 2005. p. 12) Dewidar et al. (Dewidar KM, Mohamed NM, Ashour YS. Living Skins: A New Concept of SelfActive Building Envelope Regulating Systems. SB13 Dubai., 2013) and Barozzi et al. (Barozzi M, Lienhard J, Zanelli A, Monticelli C. The sustainability of Adaptiveenvelopes: developments of KineticArchitecture. Procedia Eng 2016;155:275–84) have reported that uncertainties still abound in terms of roles, responsibilities and professional accountability in contemporary architecture.

The terms smart, responsive and adaptive concepts have been used loosely and interchangeably, which confuse many professionals. First, smart building skins refer to automated or largely automated self-monitoring systems similar to building management systems, which deploy integrated instruments within a building. Kiliccote et al. have suggested that smart building skins be regarded as a self-aware and grid-aware mechanism utilizing smart sensors that operate in four areas: (i) perception of individuals of comfort at different times of the day and year; (ii) changes in occupancy or building use; (iii) variations in occupancy characteristics; and (iv) variations in yearly average external weather conditions.

Second, responsive building skin is a term frequently interchanged with ‘adaptive’ building skin. Beesley et al. have defined the term as a simple form of adaptation wherein functional and performance characteristics are similar to those of a ‘smart’ building skin, which require physical manipulation of elements. The term responsive suggests control of environmental conditions with the use of computa- tional algorithms, thus allowing a building system to learn new concepts while educating the occupants. Kretzer developed a responsive system using elastomeric films, which could be deformed upon electric charging. In general, the functionality of a responsive system is larger than that of smart systems. Compared with smart systems that focus only on a specific range of climatic conditions and predictable reactions, responsive systems accommodate conditions and performance criteria that are much broader.

Third, adaptive building skin refers to a morphogenetic evolution and real-time physical adaptation of a design in relation to its surrounding environment. The term is more complex compared with previous types, as adaptivity unite multi-scalar factors in order to reach a symbiotic energy-efficient design solution. The term adaptivity suggests solving problems with multiple parameters rather than merely responding to individual concerns. Adaptive is also a much broader concept than responsive, as the adaptive approach seeks to optimise functionality and waste reduction (i.e., energy consumption and availability of material resources). In fact, Hoberman and Happold have introduced a model called Adaptive Buildings Initiative, which helped develop several types of kinetic shading and cladding systems.

Layacha Sarah Thesis

The abovementioned systems can also use smart materials to enhance their performance. In fact, smart materials play an important role in smart, responsive and adaptive building skins due to their intrinsic properties, which include the ability to change physical properties or shape without any energy source. Addington and Schodek have classified smart features in terms of ‘immediacy’ (real-time response), ‘selectivity’ (discrete and predictable response), ‘transiency’ (responsive to more than one environmental state), ‘self- actuation’ (internal intelligence) and ‘directness’ (a response is local to activating events). Many types of smart materials can function in different forms and sense environmental stimuli, where responses can be thermal, radiant, chemical, electrical, magnetic and others. Elattar divided (Elattar SMS. Smart structures and material technologies in architecture applica-tions. Sci Res Essays 2013;8(31):1512–21) smart materials into three groups:

(i) Passive smart materials work as a sensor for their inner system and the surrounding environment. All shape memory alloys and fibre optic materials fall into this category. Shape memory alloys respond to temperature by changing shape without analysing signals, while fibre optics act as sensors but not as actuators or transducers.
(ii) Active smart materials have similar properties as passive materials; however, active smart materials can also react to stimuli. For instance, piezoelectric materials use a feedback loop for its actuator circuit to recognise both change and initiation of appropriate response.
(iii) intelligent materials adapt their behaviour to circumstance. Addington and Schodek further classified this material into two groups: (1) materials that undergo change in one or more of their properties to respond directly to external stimuli, such as thermochromic, magnetorheological, thermotropic and shape memory, as well as photochromic materials that change colour in response to ultraviolet radiation, and (2) smart materials that transform energy from one form to another (e.g., thermoelectric, electrostrictive, photoluminescent, piezoelectric and photovoltaic materials).

2.11.2. Adaptive materials for adaptive building skins

Recently, many studies have been conducted to improve the sensing abilities and active properties of robotics. However, there have only been a few precedent literature on building skins. Moving from mechanism concepts to technical implementation requires the understanding of material functions and properties. Designing adaptive building skins require low-technology and low-energy adaptive materi- al systems. Subsequently, the selected materials should have physical properties and structures that can generate movement and adapt to real-time environmental changes. Several factors are considered in the design of adaptive systems, such as workability, responsiveness to stimulus, durability, resistance to corrosion, and achievable move- ments to impress force . In addition, materials must possess performative and self-actuating abilities, innate to the system and can react to changing environmental conditions. Generally, materials that can fold, shrink or expand can respond to change, but they must be stable enough in terms of configuration to utilise their implementation in adaptive models.

Layacha Sarah Thesis

Many examples of adaptive materials can be deduced from nature, including conifer cones with repetitive opening–closing cycles and other structural abilities in response to humidity. Lopez et al. introduced a model for adaptive walls using adaptive materials based on dynamic mechanisms and static strategies, and classified the materials in to four areas: temperature reactive materials, light reactive materials, humidity reactive materials and carbon dioxide reactive materials (Fig. 11). The study reviewed and updated the literature based on the classifications below.

2.11.2.1. Temperature reactive materials

Several types of materials have been applied in the architectural field, such as the following: (1) Thermo-bimetal materials represent a self-actuating material that deforms and curves when heated or cooled based on a specific range of air temperatures. Such materials laminate two metals together with different thermal expansion coefficients, as shown in Fig. 2.20 (2) Heat sensitive plastics are similar to thermo-bimetal materials with two-layer plastics and different thermal expansion coefficients that generate movement through heat-sensitive actuation. (3) Shape memory alloy is divided into thermo- responsive and magneto-responsive approach, where both mechanisms involve reversible martensitic transformation below transition temperature (Ts), and in effect, conserving shape memory. However, after reheating the material above transition temperatures, the original shape is recovered. (4) Thermochromic polymers are materials that change their original colour in reaction to tempera- ture changes, and they are commonly used as building envelopes to improve energy efficiency. (5) A phase-change material is divided into four types: organic, inorganic, eutectics and hygroscopic materials, all of which have the ability to control thermal–mass behaviour and allow light reflection with absorption.

2.11.2.2. Light reactive materials

Several types of materials have been applied in the architectural field:

1. Phosphorescence pigments, such as conductive paints that fabricate passive and active luminous skin, which allow materials to glow in dark environments. Such materials are applied on surfaces to form conductive surfaces and create capacitance that can detect moving
2. Light responsive polymers or light-induced shape- memory polymers are polymers that undergo light-induced shape changes, which can be deformed and temporarily fixed as a new shape.
3. Photochromic dyes allows a reversible change of colour upon exposure to ultraviolet light in the range of 300–360 nanometres. A full change of colour can be obtained within 20–60 s in sunlight. The material can change to colourless when removed from the ultraviolet light source. In other words, the materials have the potential to be mixed with others or to produce a wide range of colours, as they can also be dissolved in inks or extruded/injected into moulds and casts.

Layacha Sarah Thesis

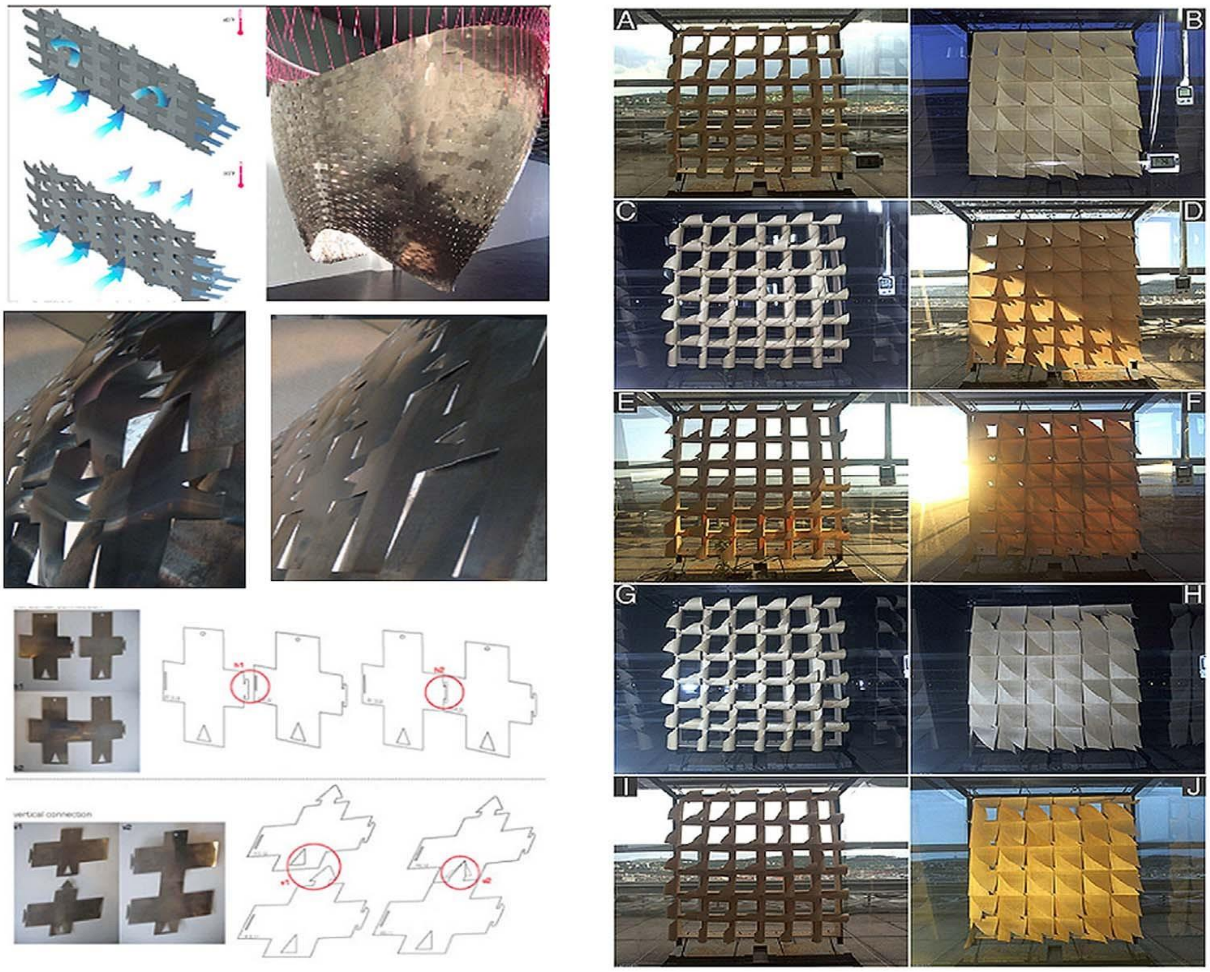

Fig. 2.14 Two types of adaptive materials based on temperature and humidity. Left figure, breathable façade using thermobimetal that operates with weather temperature. Right figure, meteorosensitive architectural systems based on the biomimetic transfer of the hygroscopic actuation of plant cones of wooden veneer.

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2.11.2.3. Humidity reactive materials

Several types of materials exist in the architectural field based on hygroscopicity and anisotropy properties of wood materials. Understanding wood properties can help shape a new type of design that can convert wood into a humidity reactive material. In principle:

- ✓ The cellular structure of wood always seeks to reach equilibrium moisture, which result in constant dimensional movement. The movement in wood is similar to Pinophyta (conifers) where motion is triggered by external stimuli that are not related to the molecular structure of the material. Reichert et al. specified a few types of wood, such as beech (Fagus sylvatica), European maple (Acer pseudoplatanus) and cut veneer (German: Schnittfurnier), as shown in Fig. 12.
- ✓ Hydrogel is a smart gel that consists of an insoluble network of polymer chains that swell up when water is added; it can store large amounts of water, which is similar to the functions of natural tissue. Currently, hydrogels are utilised for bio-inspired cooling.

2.11.2.4. Carbon dioxide reactive materials

This type of reactive material has been applied only very recently in architectural design. Some examples include:

- CO_2 responsive polymers, which are divided into two types, namely, carbon dioxide responsive polymers and carbon dioxide polymers for CO_2 capture (i.e., carbon dioxide is used as a green eco-trigger, and to absorb CO_2 directly from air), and
- Titanium dioxide, a pigment that can convert mono-nitrogen oxides into less harmful substance, such as calcium nitrate and water, and which acts as a catalyst for chemical reactions when activated by sunlight. Titanium dioxide in tiles do not change and persists indefinitely.

Smart materials differ from adaptive materials. Smart materials have the ability to be smart, but in order to function, it requires external stimuli based on conventional energy sources. In contrast, adaptive materials can function naturally in existing environmental conditions (e.g., plants).

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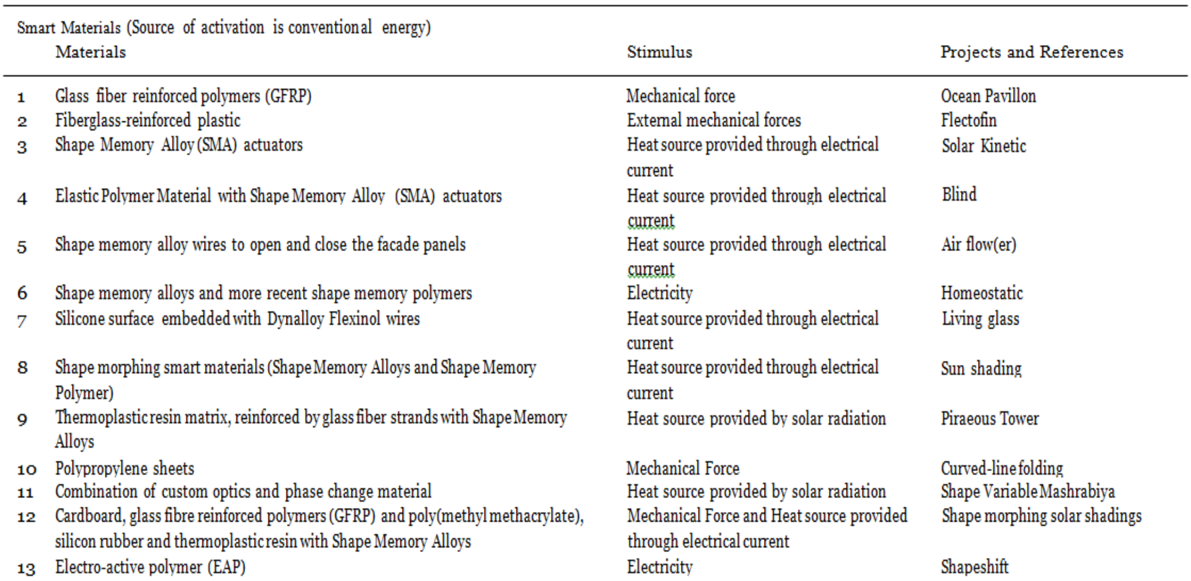
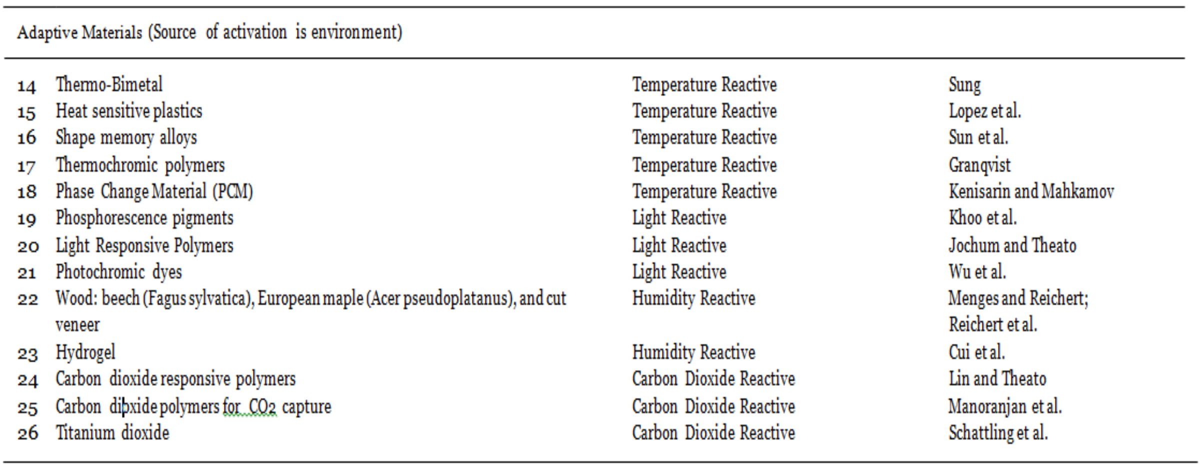
2.1 Table :

Classification of materials based on smart and adaptive approach for implantation in adaptive building skins.



Smart Materials (Source of activation is conventional energy)

	Materials	Stimulus	Projects and References
1	Glass fiber reinforced polymers (GFRP)	Mechanical force	Ocean Pavillon
2	Fiberglass-reinforced plastic	External mechanical forces	Flectofin
3	Shape Memory Alloy (SMA) actuators	Heat source provided through electrical current	Solar Kinetic
4	Elastic Polymer Material with Shape Memory Alloy (SMA) actuators	Heat source provided through electrical current	Blind
5	Shape memory alloy wires to open and close the facade panels	Heat source provided through electrical current	Air flow(er)
6	Shape memory alloys and more recent shape memory polymers	Electricity	Homeostatic
7	Silicone surface embedded with Dynalloy Flexinol wires	Heat source provided through electrical current	Living glass
8	Shape morphing smart materials (Shape Memory Alloys and Shape Memory Polymer)	Heat source provided through electrical current	Sun shading
9	Thermoplastic resin matrix, reinforced by glass fiber strands with Shape Memory Alloys	Heat source provided by solar radiation	Piraeous Tower
10	Polypropylene sheets	Mechanical Force	Curved-line folding
11	Combination of custom optics and phase change material	Heat source provided by solar radiation	Shape Variable Mashrabiya
12	Cardboard, glass fibre reinforced polymers (GFRP) and poly(methyl methacrylate), silicon rubber and thermoplastic resin with Shape Memory Alloys	Mechanical Force and Heat source provided through electrical current	Shape morphing solar shadings
13	Electro-active polymer (EAP)	Electricity	Shapeshift



Adaptive Materials (Source of activation is environment)			
14	Thermo-Bimetal	Temperature Reactive	Sung
15	Heat sensitive plastics	Temperature Reactive	Lopez et al.
16	Shape memory alloys	Temperature Reactive	Sun et al.
17	Thermochromic polymers	Temperature Reactive	Granqvist
18	Phase Change Material (PCM)	Temperature Reactive	Kenisarin and Mahkamov
19	Phosphorescence pigments	Light Reactive	Khoo et al.
20	Light Responsive Polymers	Light Reactive	Jochum and Theato
21	Photochromic dyes	Light Reactive	Wu et al.
22	Wood: beech (Fagus sylvatica), European maple (Acer pseudoplatanus), and cut veneer	Humidity Reactive	Menges and Reichert; Reichert et al.
23	Hydrogel	Humidity Reactive	Cui et al.
24	Carbon dioxide responsive polymers	Carbon Dioxide Reactive	Lin and Theato
25	Carbon dioxide polymers for CO_2 capture	Carbon Dioxide Reactive	Manoranjan et al.
26	Titanium dioxide	Carbon Dioxide Reactive	Schattling et al.

Smart materials operate in different scales, such as sensors and actuators with separate systems. Sensors analyze variations of external stimuli and transfer information to actuators. Meanwhile, actuators provide the structure with a change in properties based on a range of external conditions (Table 2.1).

Studies on adaptive walls have been expanding by way of the adaptive shading systems, which can track changes in sun radiation. Adaptive walls can also provide a breathing envelope to building skins, thus influencing air pressure on the surface to perform an inhaling–exhaling process; a thermo- regulating envelope by maintaining adequate balance between heat gain and heat loss without seeking air-tightness and water-tightness; and light regulating envelope to improve visual comfort of occupied space. Two examples of adaptive wall systems are presented: plant-mimicking functions (basic approach) and animal-mimicking functions using deep pro- blem-based (top-down) approach, which represent an easy architectural approach to biomimicry.

Dewidar et al. presented a theoretical model for an adaptive wall system that can mimic nature called the Self-Active Bioclimatic Strategy (SABS), as shown in Fig. 13. SABS uses algae bio-reactor panels with a kinetic responsive façade system to develop self-sensing abilities, and it adapts to environmental demands to achieve energy efficiencies. The walls of the system generate two types of energies, namely, microalgae-cultivated energy from bioreactor panels by (i.e., utilises waste carbon) and solar thermal energy. SABS can operate as opaque panels (shading devices), transparent panels, controlled open- ing systems (ventilation) and other responsive materials that provide kinetic features for the building skin. The system is controlled by integrated sensors, and its actuators operate without any use of mechanical power by adopting the ‘thermo-bimetal’ application of shape memory alloys. In fact, [8] has introduced the world´s first bio-reactive façade that generates renewable energy from algal biomass and solar thermal heat, however, SABS is limited, and it represents only a theoretical model without any validation of application.

Badarnah and Kadri also proposed a wall system based on a biomimetic design, which is a theoretical model for fog-to-water collection and a water-harvesting system for building skins (Fig. 2.21). The system was developed based on an innovative design method through several processes, including challenges, process, flow, adaption, scale, environmental context, morphological features, structural features, material features and others. The system utilises an external surface with several layers. For the water collection, the system adapts the

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morphological features of the bumpy elytra with hydrophilic and hydrophobic alternating properties for the bumps and grooves. Subsequently, water is retained on hydrophilic peaks, builds up until they reach a specific volume, and finally roll down through hydrophobic grooves. The second layer applies the thorny devil the concept on semi- tubular capillary system, which allows water transport over the surface through a hexagonal network and capillary action to the storing chambers. The closing and opening of chambers are controlled by smart materials, which swell when saturated and shrink when dry. The system collects water at night time and releases it internally during the daytime. Similar to the previous model, this system is limited and represents only a theoretical model without any validation of its application.

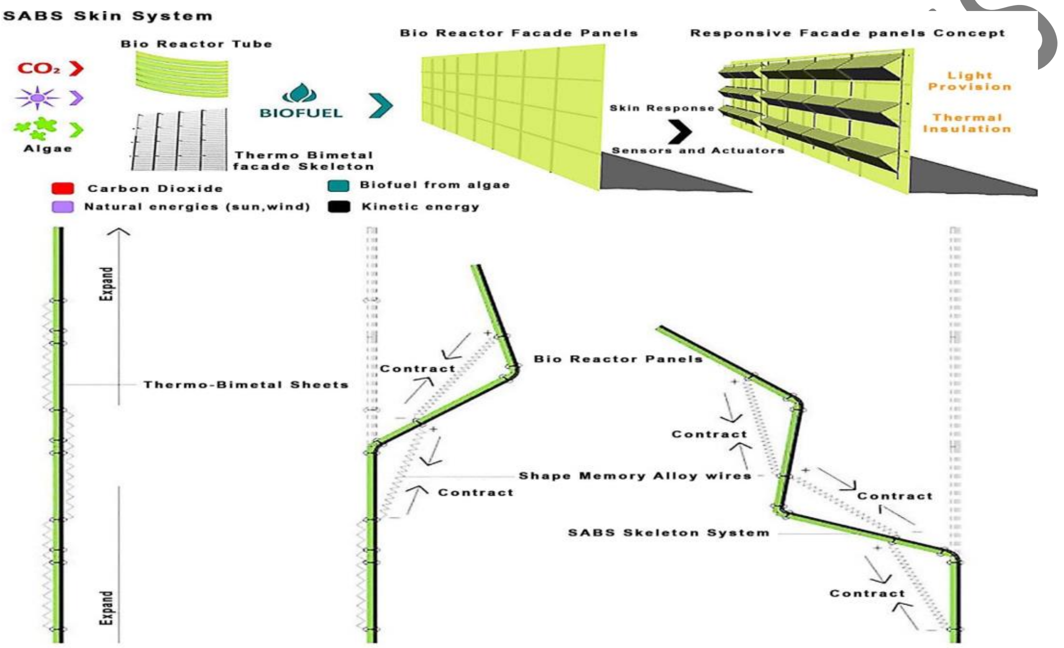

Fig. 2.15. Integrated approach of Self-Active Bioclimatic Strategy.

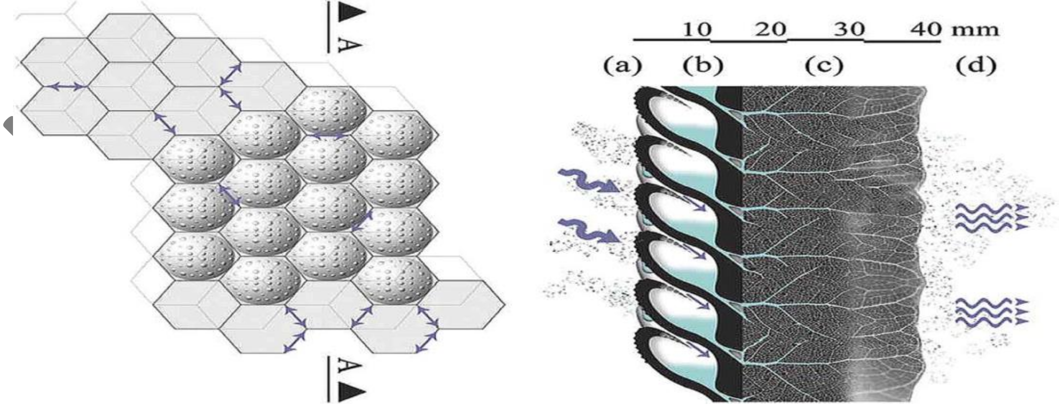

Fig. 2.16. Biomimetic wall to collect water from fog.

Steps	Phases	Description
1	Biomimetic levels	(1) Form (organism), (2) Process (behavior), (3) Ecosystem.
2	Biomimetic Approaches	Bottom-up and Top-down.
3	Biomimetic Classification	Concept, Process or Behavior, Morphology, Form, Structure, Skin, Material, Expression, and Symbolism.
4	Methods and Tools	(1) BioTRIZ, (2) Helix Model (Design spiral), (3) Computational Architectural Design Based on Biological Principles, (4) Bio- inspired Environmental Architectural Design, (5) BioGen, (6) Biomimicry Theoretical Model (BTM), (7) BioMAPS, (8) Biomimicry 3.8, (9) Typological Analysis, (10) Analogical Translation, (11) Nature Studies Analysis, (12) Ecosystem for Biomimetic Design, (13) Ecomimetic, (14) New Product Development (NPD) Process, (15) The Law of System Completeness, (16) Idea-Inspire, (17) Engineering-to Biology Thesaurus and (18) Biomimetic principles for the development of adaptive architectural envelopes.
5	Mechanisms of Adaptation	Nature: (1) dependent on contemporary sunlight, (2) optimize the system rather than its components, (3) dependent on local conditions and situations, (4) diverse in components, relationships, and information, (5) create conditions favorable to sustained life, (6) evolve at different levels and at different rates, (7) self-organization, (8) creates a level of redundancy. Engineering: (1) embedding knowledge of systems within themselves, (2) accurate analytical models for decision making, (3) selecting of the best corrective actions, (4) uncertainty in the outcome of adaptation actions, (5) context variability and (6) evolution of the environment during the execution of adaptations.
6	Adaptive materials in nature	Adaptive Functional Surfaces: (1) surfaces for anti-wear, (2) surfaces for super hydrophobicity, (3) surfaces acting as smart adhesives, (4) surfaces for drag reduction, (5) surfaces for anti-fogging, (6) surfaces for noise reduction, (7) surfaces for water capture and (8) surfaces for optical function. Adaptive Dynamic Movements: (1) reversible snapping motion, (2) unidirectional changes at the periphery, (3) smart opening-closing system, (4) touch and vibration sensitivity, folds inward as a reaction to contact, (5) oriented and folded based on temperature sensitivity, (6) change temperature levels passively, (7) water-use efficiency and (8) reflect sunlight from hairy leaves.
7	Biomaterials devlopment	(1) smart materials, (2) surface modifications, (3) material architectures and (4) technologies that based on improving

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		existing systems.
8	Adaptive behavior in building skin.	To regulate temperature, light, humidity and carbon dioxide Dynamic mechanism: sliding, folding, creasing, expanding, rolling, hinging, fanning, inflating, rotating or curling. Static strategies: morphological features as density, pattern or geometrical strategies and change in materials properties as reflection, absorption or change energy from form to another.
9	Adaptive materials in architecture.	(1) Temperature Reactive, (2) Light Reactive, (3) Humidity Reactive and (4) Carbon Dioxide Reactive.
10	Adaptive Systems.	(1) shading system to track the change in sun radiation, (2) breathing envelope as a skin to influences the air pressure on the surface to perform a process of inhaling and exhaling, (3) thermo regulating envelope through maintaining an adequate balance between heat gain and heat loss without seeking air-tightness and water-tightness, (4) light regulating envelope to improve visual comfort of the occupied spaces and (5) water-harvesting system.

Table 2.2 : Summary of phases to obtain knowledge on how to design an adaptive building skins.

2.12. Discussion

The study uncovered many aspects of biomimetic design and adaptive building skins that remedy many limitations in architectural design. Most architectural systems are limited in terms of their adaptation to user needs and weather conditions only, an approach that uses automatic control concepts with smart materials. The study found that biomimicry offers many possibilities for adaptive sustain- able building designs. However, biomimetic studies face several obstacles, particularly when translating natural concepts into technical systems. Most mimicking approaches only focus on individual parts rather than the whole system. Moreover, the present study has established that applying biomimicry concepts in architecture is still in its infancy stage, as evidenced by the several levels and scales of ideas, especially those systems that deal with function and process. In understanding adaptation, the optimum connection between external factors (ecosystem and process) and internal factors (form and behaviour of organism) should be established to successfully approach and achieve functional systems.

Designing adaptive systems are complex and should be similar to natural systems, which deal with different factors and conditions. Beyond the typical comparison, adaptive systems should be understood at different levels (organism, behaviour and ecosystem). The present study found that past literature mainly focused on materials and ideas—not on implementation—due to lack of clear ecosystem-based systematic designs and shortage in corresponding design methods. In addition, there are also limitations in terms of searching and selecting strategies from nature, resulting in scaling difficulties and conflict of integrated parts within design concepts. Most research attempts to understand the structural, procedural and informational aspects of biomimetics. However, there are still some difficulties in terms of classifying

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biomimicry concepts due to the inevitable overlap of many categories and the complexity of having to describe biological systems. Other factors have also limited the outcomes of adaptive design (i.e., bottom-up and top-down approach), which deter biologists, ecologists and designers to work effectively.

The study reviewed 18 methods and found that the most common methods in the architectural field follows the problem-based approach, which still in the development stage. Most methods are still on their theoretical concepts and models, except for few that have been applied, such as the mimicry of termites to holistic view architecture of Eastgate Centre. In addition, the study explored and explained the mechanism of adaptation in nature and engineering; addressed the mechanism and the behaviour of organisms and how they react to external and internal conditions; and explored the concept of adaptation in engineering by defining its current limitations. These explorations helped elaborate the functionality of natural materials, which served as inspiration in understanding adaptation in nature. The review found two approaches to adaptation, namely, by functional surfaces and by dynamic move- ments. Animals and plants represent a good source of understanding adaptation, as they give many examples and techniques to explore architectural design. Such understanding helps connect biomaterial development and the built environment. Impact evaluation can help enhance the aforementioned adaptive design models.

Understanding adaptation in a holistic view helped review the current development of architectural designs and explain the most contemporary directions of designs inspired by nature. The review delineated many issues and confusions, especially those on smart, responsive and adaptive methods in architecture. Several materials and systems following certain architectural movements were also identified; however, no clear distinctions were established in terms of their directions. Based on research, most adaptive materials are controlled by an external stimulus, which can change physical structures on the basis of direct signals or conventional energy sources to stimulate the function of a specific system. As a result, recent studies have started to redefine the design, application and functions of smart materials. Several studies have been proposed on the stomata and their natural behaviour, a key design on dynamic and static changes, and these have opened a new paradigm to design adaptive systems.

Finally, the study identified materials that meet the adaptation concept, and which use adaptive materials without utilizing conven- tional energy sources, to improve the development of the adaptive models. However, most dynamic architectural systems are designed as a responsive system, and only a few models were classified as adaptive. Findings indicate a lack of understanding of adaptation, which requires an adaption of features, behaviour or configurations with external conditions, as well as controlling internal process to recycle materials and generate energy. On this note, the most important phases to design adaptive building skins are summarised (Table 2.2).

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Conclusion

A review of biomimetic building skins to achieve adaptation was presented. Various theories, concepts, issues, approaches, methodolo- gies, materials from nature, developed materials and systems in architectural applications based on developed models and investigative studies are discussed. The study elaborated the technical and func- tional aspects linking several levels of biomimicry. Such elaboration helped in the discussion and identification of adaptive building skins. In addition, the study evaluated the limitations and potentials of adaptation, which offers many application possibilities in the architec- tural field. The study classified and compared adaptive approaches in biological, engineering and architectural fields to create a connection between biological systems and building skins. The study achieved its aim of providing a clear design process that summarizes the develop- ment of biomimetic building skins based on the adaptive approach. In addition, the research achieved its aim of providing a clear under- standing of developing adaptive building skins based on functional aspects and to overcome technical challenges and promote innovative and sustainable architectural systems.

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3.1 Museum

(Museum) architecture is defined as the art of designing and installing or building a space that will be used to house specific museum functions, more particularly the functions of exhibition and display, preventive and remedial active conservation, study, management, and receiving visitors.

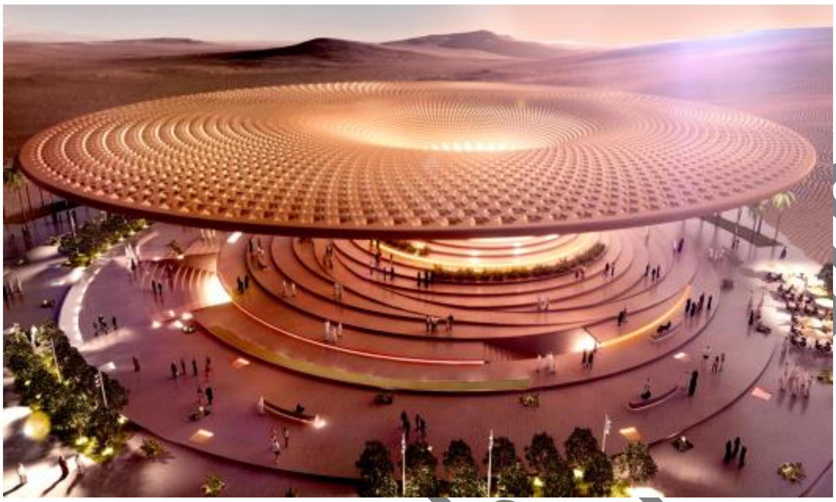

Fig 3.1 Museum Image: Fernando Romero Architects

Since the invention of the modern museum, from the end of the 18th century and the beginning of the 19th, while old heritage buildings were also being reconverted for museum use, a specific architecture evolved that was linked to the requirements of preserving, researching and communicating collections through perma- nent or temporary exhibitions. This architecture is evident in the earliest museum buildings as much as in the most contemporary ones. The architectural vocabulary has itself influen- ced the development of the idea of the museum. Thus the form of the temple with a cupola and columned portico became established along with the gallery, conceived as one of the main models for fine arts museums, and by extension gave rise to the names gallery, galerie, galleria, and Galerie in France, Italy and Germany and in Anglo-American countries.

3.1.1 Definition of Botanic Museum

A botanical museum is a territory developed by a public institution, private, or associative (sometimes mixed management) which aims to the presentation of species and plant varieties.

The many species and varieties of wild and / or horticultural plants present are strictly identified and gathered in collections. They are cultivated and studied to satisfy four main objectives: conservation, scientific research, education and teaching, while remaining compatible with tourism. Globally, the most important botanical gardens, in terms of area and size of the collection, are the Royal Botanical Gardens of Kew followed by the Montreal Botanical Garden.

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3.1.2 History

The Botanical Garden of Padua (Italy), founded in 1545, the oldest botanical garden still in existence (16th century engraving)

Montpellier Botanical Garden, the oldest botanical garden in France, founded in 1593

The botanical garden was invented during the Renaissance, a period of great encyclopedic curiosity, taking precedence over the simple garden of the Middle Ages. The latter is then oriented essentially to the diet and medicinal use of plants, but is characterized by the appearance of a classification and a more scientific nomenclature.

The first botanical garden was created under the name of Orto botanico in Pisa in 1543. In 1545, Padua and Florence opened theirs. Padua, the oldest one still in existence, quickly acquired a great reputation, probably because of the university chair to which he is attached. A botanical garden open to the public is created at the University of Bologna in 1568.

In France, it is in Montpellier, in 1593, that appears the first botanical garden, the Garden of Plants of Montpellier founded by Pierre Richer de Belleval, currently managed by the University Montpellier 1. The second botanical garden of France, the Botanical Garden of the University of Strasbourg, is created in 1619.

In the French capital, Jardin des Plantes, also called Garden of the King, was created by order of Louis XIII by Guy de La Brosse in 1635.

The Leiden Botanic Garden (Hortus Botanicus Leiden) was founded in 1590 and is the oldest botanical garden in the Netherlands. The Amsterdam Botanical Garden was founded in 1638 under the name of Hortus Medicus, where medicinal herbs for doctors and apothecaries are grown. In spite of its modest surface area (1.2 ha), its plant collection is the source of research by Carl von Linné who is developing the species classification system.

Fig 3.2 Montpellier Botanical Garden, the oldest botanical garden in France, founded in 1593 (Source:Wikipedia)

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The oldest surviving North American botanical garden, Bartram's Garden (Philadelphia, Pennsylvania), was created in 1728.

In 1735, the first tropical botanical garden was born in Pamplemousses, in Mauritius.

The oldest private botanical park in France is the Arboretum Balaine created in 1804.

In France, the number of universities with a botanical garden is in decline partly for financial reasons or policies favoring the whole molecular and genetic research to the detriment of the garden. This orientation generates an inestimable loss of scientific and historical knowledge.

3.2 Analysis of Exemple of Botanic Center Irland

The efflorescence of Botanic Museum :

- Metamorphosis and energy solidarity

Metamorphosing is turning the caterpillar into a butterfly. Advance technological, innovative and constructive principles (biomimicry) and sustainable.

Implement the concept of "Energy Solidarity" between a heritage - modern in this case - combined with a contemporary project.

- Preliminary sketches

Its facade, consisting of 274 identical modules, does not reflect war its baptismal name related to that of Botanical Garden not far located.

The concept proposes the efflorescence of the existing building in the botanical sense of the term: "Beginning of flowering". Plantation beds and a network of cables serve as a substrate for dressing the mineral facade of a plant dress listing the entire panel of the endemic flora of Brussels.

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Fig 3.3 The Botanic Center Bloom Brussels, Belgium – 2016 (source: vincentcallebaut.com)

- Urban Integration

Completely mineralized, it seemed obvious to propose an ecological landmark, a plant architecture. It thus absorbs the carbon particles contained in urban smog by photosynthesis while integrating advanced renewable energies to better meet its own needs.

The chrysalis gently placed on the roof.

On the ground floor, a contemporary facade and its structural glass awning reinforce the attractiveness of the public space by increasing indoor / outdoor.

Fig 3.4 The efflorescence of the botanic center (source : vincentcallebaut.com)

- Energy design

The hull with high thermal inertia follows the curves imposed by the urban withdrawals.

The annual total production of renewable energies (solar + wind) represents a production of 128,340 KWh / year, either to cover part of the building's needs or to ensure the self-sufficiency of new spaces dedicated to the core of the chrysalis.

- Design of « carbo-absorbent » facades

Imagine a vegetal envelope on the three facades of the Botanic Center.

Repatriate biodiversity in the heart of the city.

Colorize the building according to the seasons.

This plant facade also reinforces the thermal inertia of the frame as well as curved double glazing with tilt and turn chassis performance, especially vis-à-vis the airtightness.

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3.3 Site analysis

3.3.1. Presentation of the city of Guelma

3.3.1.1. General presentation

The Wilaya de Guelma, created in 1974, covers an area of 3,686.84 km2 and has a population (estimated at the end of 2015) of 530,736 inhabitants, 25% of which is concentrated in the capital of Wilaya. The average density of this population is 144 Hab. / L <rn2.

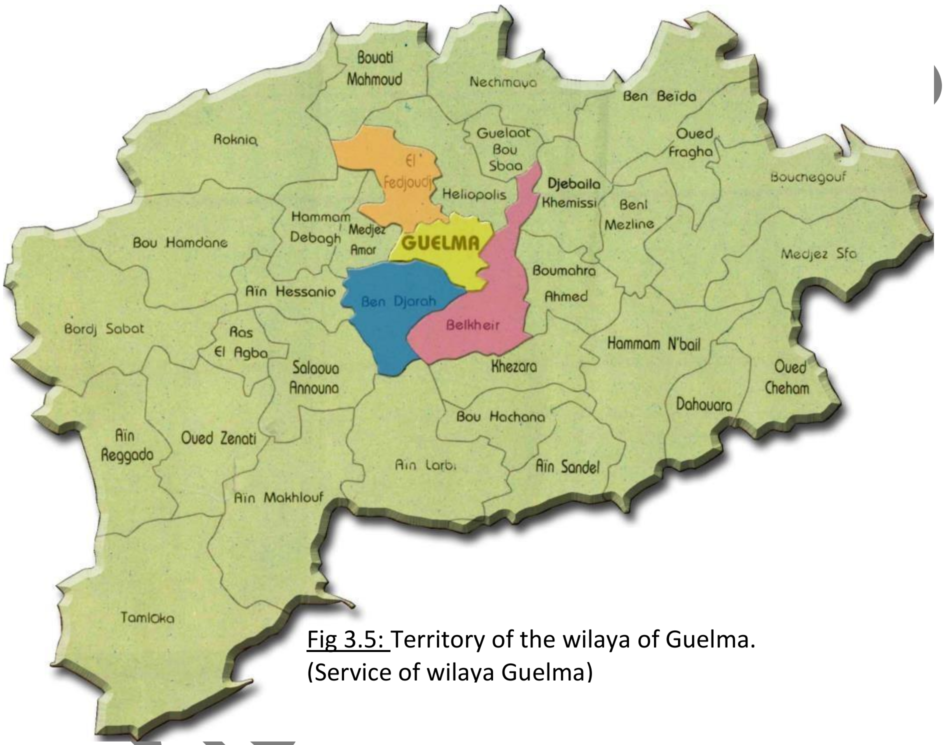

Fig 3.5: Territory of the wilaya of Guelma. (Service of wilaya Guelma)

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Bordered by six (06) Wilayas (Annaba, Skikda, Souk Ahras, Taref, Constantine and Oum ELBouaghi), it constitutes from a geographical point of view a meeting point, to see a crossroads between the industrial centers of the North (Annaba and Skikda) and the Wilayas of the highlands namely Oum El Bouaghi, Tebessa, Batna ... etc. It occupies a median position between the North of the country, the highlands and the Southeast.

a) The relief: The geography of the Wilaya is characterized by a diversified relief of which one mainly retains a significant forest cover (28,59%) and the passage of the Seybouse which constitutes the principal stream of water.

b) Potentialities:

- Natural potentialities:

If the wilaya of Guelma is distinguished by the importance of the agricultural sector, it also contains very interesting potential for its development in the field of forests, water resources and tourism.

1) Agricultural potentialities:

With a predominantly agricultural vocation, the Wilaya of Guelma has great potential, namely:

- Total agricultural area (SAT): 264,618 ha, or 72.15% of the total area.

- Usable agricultural area (UAA): 187,338 ha or 50.80% of the total area of the Wilaya and 70.42% of the S.A_T.

- Irrigable area: Nearly 17,000 ha, or 9.20% of the UAA likely to reach 26,000 ha, or 14.02% in the long term. From the UAA with the full commissioning of the irrigated perimeter and the optimization of surface water mobilizations.

2) Forest potentialities:

- Total forest cover: 116,864 ha, representing a rate of 31.70% of the total area of the wilaya with a discontinuous and heterogeneous forest landscape confined in massifs distributed from west to east.

- Large areas of land: forest-oriented in the Southeast.

- Important potential "I drink": (Zen oak and cork: forests of Beni Satan to Bouchegouf, from Houara to Ain Ben Beida and Djeballah, Mahouna to Ben Djerrah and ... Medjeled to Bouhamdane) totaling nearly 19,771 ha of forests and a production of about 510.10 Steres of Zen Oak and Cork Oak and 345 m3 of wood.

- On the physical level of the Wilaya de Guelma is divided into 04 zones namely:

1. Guelma area: This is the most extensive area of the Wilaya territory. It encompasses the entire middle part from North to South. It is characterized by significant forest cover in the North and East.

2. Bouchegouf Zone: It is characterized by a strongly mountainous relief (nearly 75%). This area is also crossed by the Seybouse. Its authors are covered with forests such as Beni Salah and Ain Ben Beidha.

3. Oued Zénati Zone: It is characterized by calcareous brown soils, hence its cereal vocation. Some areas are reserved for market gardening and arboriculture.

4. Tamlouka area: The Tamlouka area is more expressed in the semi-arid bioclimatic floor area. It is part of the region of the high plains whose average altitude is higher than 800 M. It is crossed by Oued M'guisba.

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3) hydric potential:

The hydraulic sector has significant infrastructure (dams, reservoirs, P ... etc.) for a capacity of 283.46 million m3.

- Groundwater: 04 under watersheds. 1620 operational water points totaling a total mobilisable potential of 94.1 Million m3 / year.

- Surface Water: 189,355 million m3 are distributed as follows:

* Bouhamdane dam: 186 million m3.

* Small Dam of Medjez Beggar (Ain Makhlouf): 2,86 million m3

* A large number of hillside reservoirs that require a special cleaning effort: 0.495 million m3.

4) Mining potentialities:

The soil of the Wilaya de Guelma has significant mineral wealth and little exploited.

These riches essentially concern:

- The Kaolin Jebel Debagh (Hammam Debagh)
- The jebel Mahouna marble (Ben Djerrah)
- The Gypsum
- Limestone for aggregates
- Clay
- Aggregates

5) Tourist potentialities:

The Wilaya of Guelma holds important tourist potential to know: Sauces and sites:

- Thermal springs: The most important are those of;

- ✓ Hammam Debagh.
- ✓ Hammam Ouled Ali.
- ✓ Hammam N'Bails.
- ✓ Hammam Belhachani in Ain Larbi.

- Tourist sites and monuments:

- Roman Theater (4,500 places) in Guelma
- Roman pool in Hammam Bradaâ Heliopolis
- Ancient ruins of Thibilis (Actuel Sellaoua)
- Dolmens and funerary caves of Roknîa
- Great Waterfall Hammam Debagh
- Jebel Taya cave in Bouhamdane.

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- Climatic mountain resort, natural sites, oak forests, mineral springs in Mahoura.
- Forest reserves of blessed Salah in Bouchegouf.

Common	name	Period	Ranking	Observation
Guelma	Roman Theater	Romaine	Classified in 1900 as a heritage site National.	Average state
	Wall of the barracks	Romaine	Classified as 03-11-1999 as a historical site belonging to the National heritage	Good condition
	Moorish baths Roman baths	Romaine	Classified in 1900 as a heritage site National	bad condition
	El Atik Mosque	Turkish	Unclassified	/
	Website of Jebel Halouf	Prehistory	Unclassified	/
	Border Cemetery Hmeme	Romaine	Unclassified	/
	Rampart of the city	Period of the French occupation	Unclassified	/

Table 3.1: Location of historical sites in the Guelma group. (Service of wilaya Guelma)

- Existing infrastructures: These are mainly

- ✓ A 03 star hotel (Mermoura) in Guelma
- ✓ El Chellala complex in Hammam Debagh.
- ✓ El-Baraka Thermal Complex
- ✓ Bouchahrine thermal complex

- Strengths of the wilaya:

- Geographical position constituting a crossroads connecting the northern region of the country and the highland regions.
- Soil rich in deposits or materials used in the manufacture of building materials that may constitute investment niches for developers.
- High proportion of the young population.

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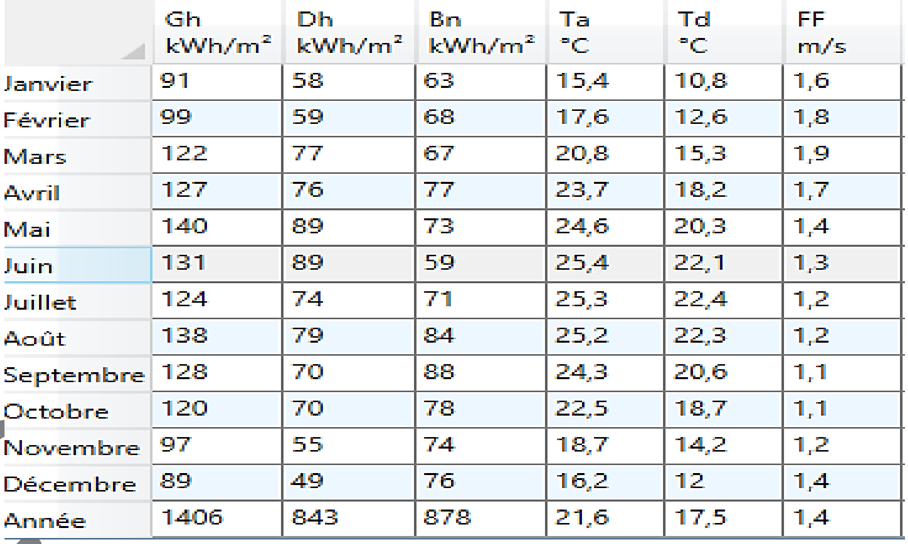
- The territory of the Wilaya of Guelma, being well served by a road network more particularly (national roads), constitutes a hub in the north-east region of the country and must play the role of crossroads (inter-regional link).
- Territory rich in tourist and archaeological sites that can contribute to the economic development of the Wilaya.
- Soil rich in deposits and materials used in the manufacture of building materials.

3.3.1.2. Climatology:

Climatic factors have a permanent impact on the social and economic life of a region, the inter-communal group of (Guelma, Belkheir, El Fedjoudj, Ben Djerrah) is dominated by a sub-humid climate.

The climate in Guelma is warm and temperate. In winter, there is much more rainfall in Guelma than in summer. The average temperature is 17 ° C during the year, the average precipitation is 557 mm.

Climatic studies according to the METEONORM7 software report:



	Gh kWh/m²	Dh kWh/m²	Bn kWh/m²	Ta °C	Td °C	FF m/s
Janvier	91	58	63	15,4	10,8	1,6
Février	99	59	68	17,6	12,6	1,8
Mars	122	77	67	20,8	15,3	1,9
Avril	127	76	77	23,7	18,2	1,7
Mai	140	89	73	24,6	20,3	1,4
Juin	131	89	59	25,4	22,1	1,3
Juillet	124	74	71	25,3	22,4	1,2
Août	138	79	84	25,2	22,3	1,2
Septembre	128	70	88	24,3	20,6	1,1
Octobre	120	70	78	22,5	18,7	1,1
Novembre	97	55	74	18,7	14,2	1,2
Décembre	89	49	76	16,2	12	1,4
Année	1406	843	878	21,6	17,5	1,4

Fig 3.6: Data table. Meteonorm7. (Author)

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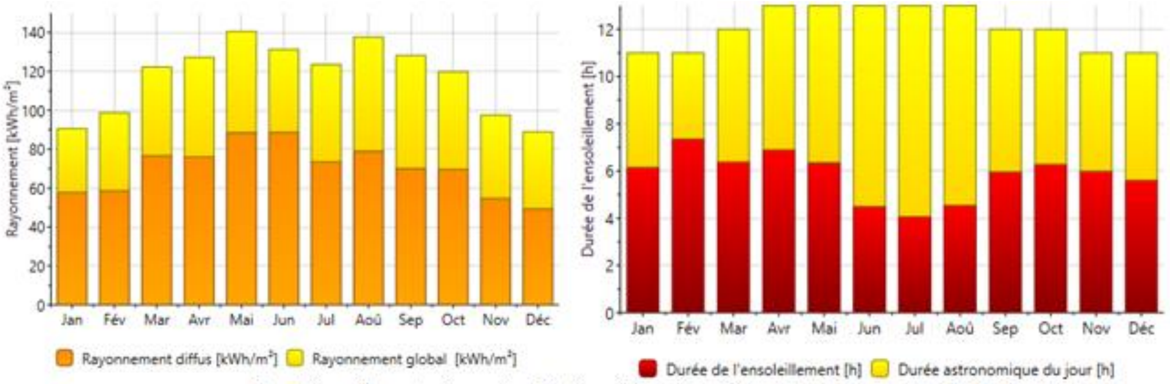

Fig 3.7 Duration of sunstroke and radiation of the city of Guelma. Meteonorm7. (Author)

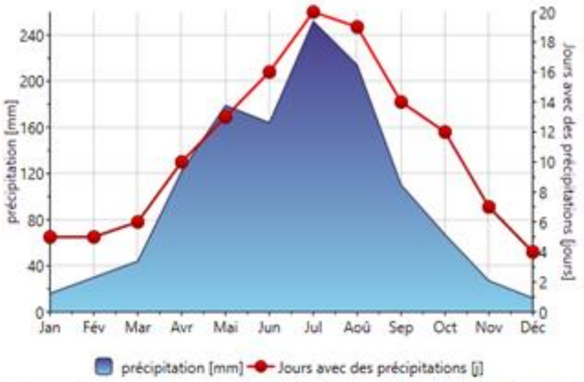

Fig 3.8 Extreme temperatures in 2016-Guelma. (INFOCLIMAT.COM)

3.3.2 The site analysis

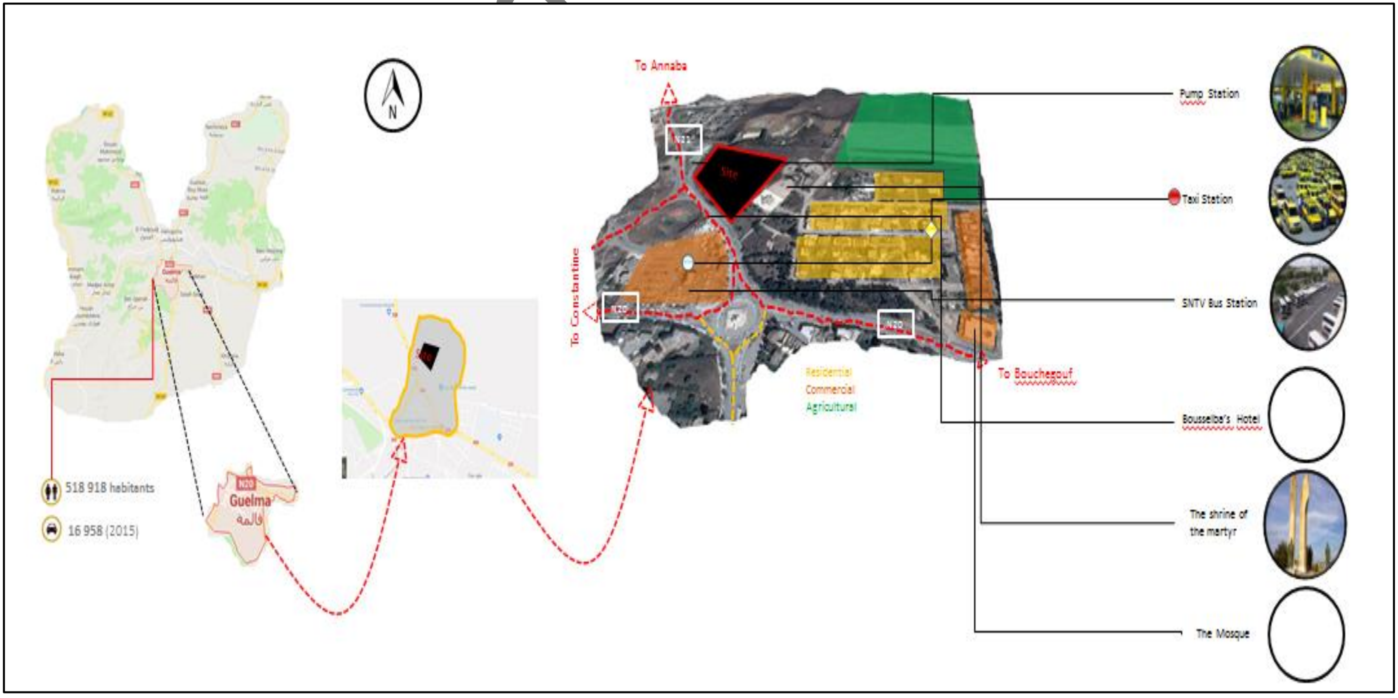

Fig 3.9 Site Analysis (Author)

The site has the cultural aspect as well as natural, it is a form of urban intervention of continuation in downtown Guelma.

It can make the city attractive and alive as soon as he enters.

Enhance the knowledge of nature.

Its geographical position in the center of the city is remarkable in all points of view:

- Urban core.
- Its architectural and urban quality and its monuments testify to different times lived by the city of Guelma.

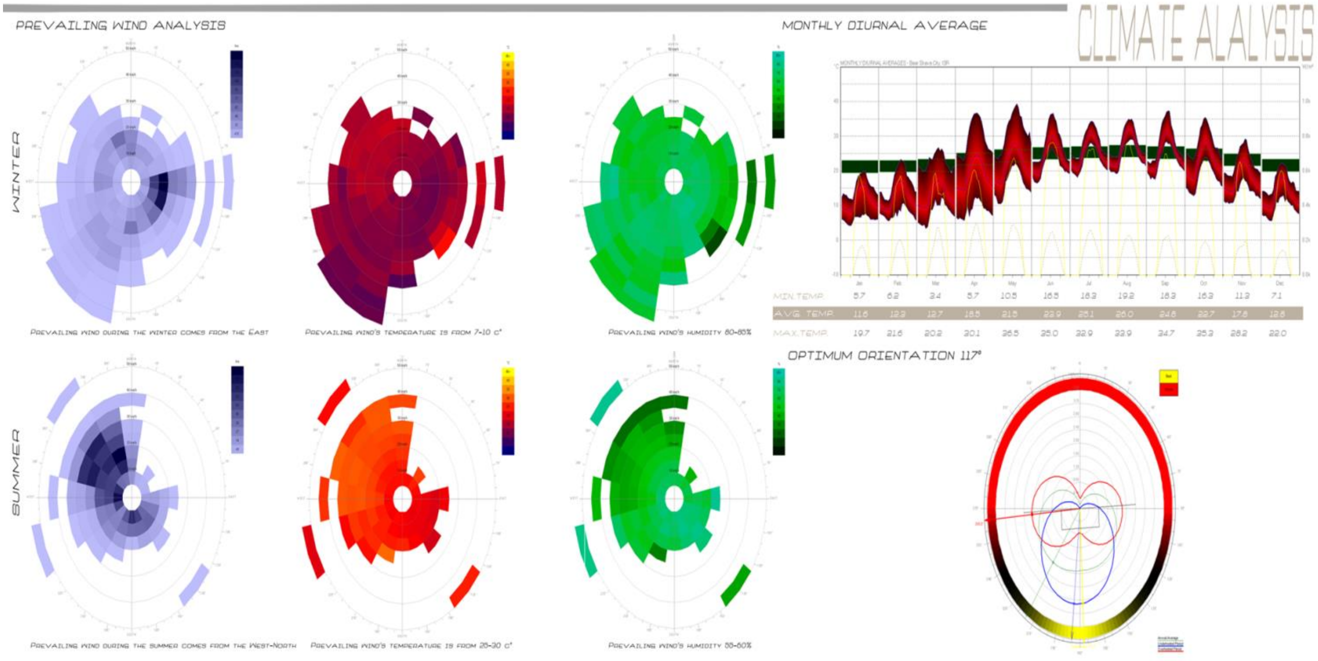

Fig 3.10 : Ecotect Analysis (Author)

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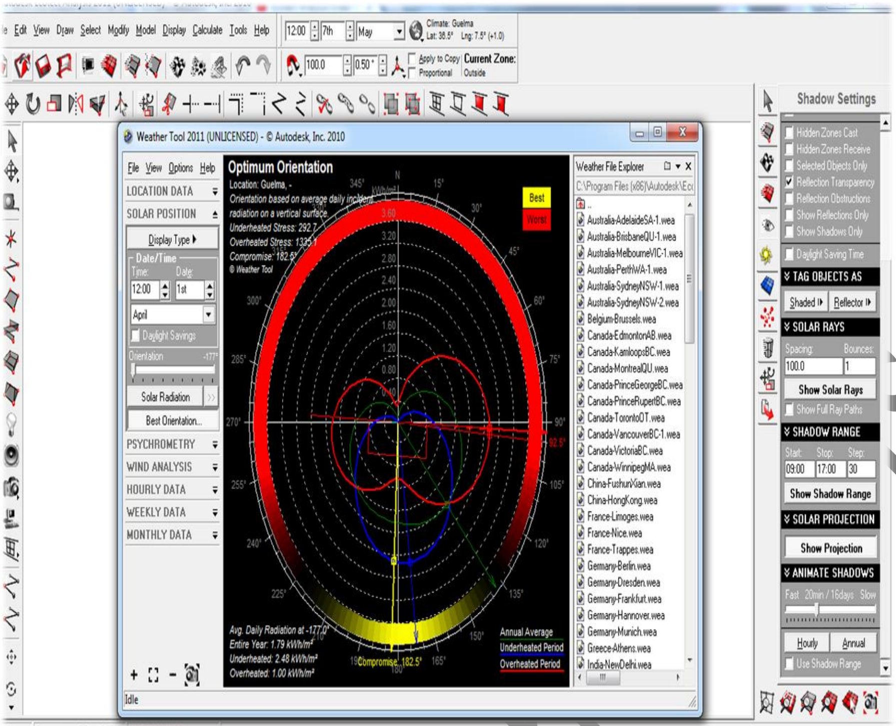

Fig 3.11. : Best orientation with Ecotect (Author)

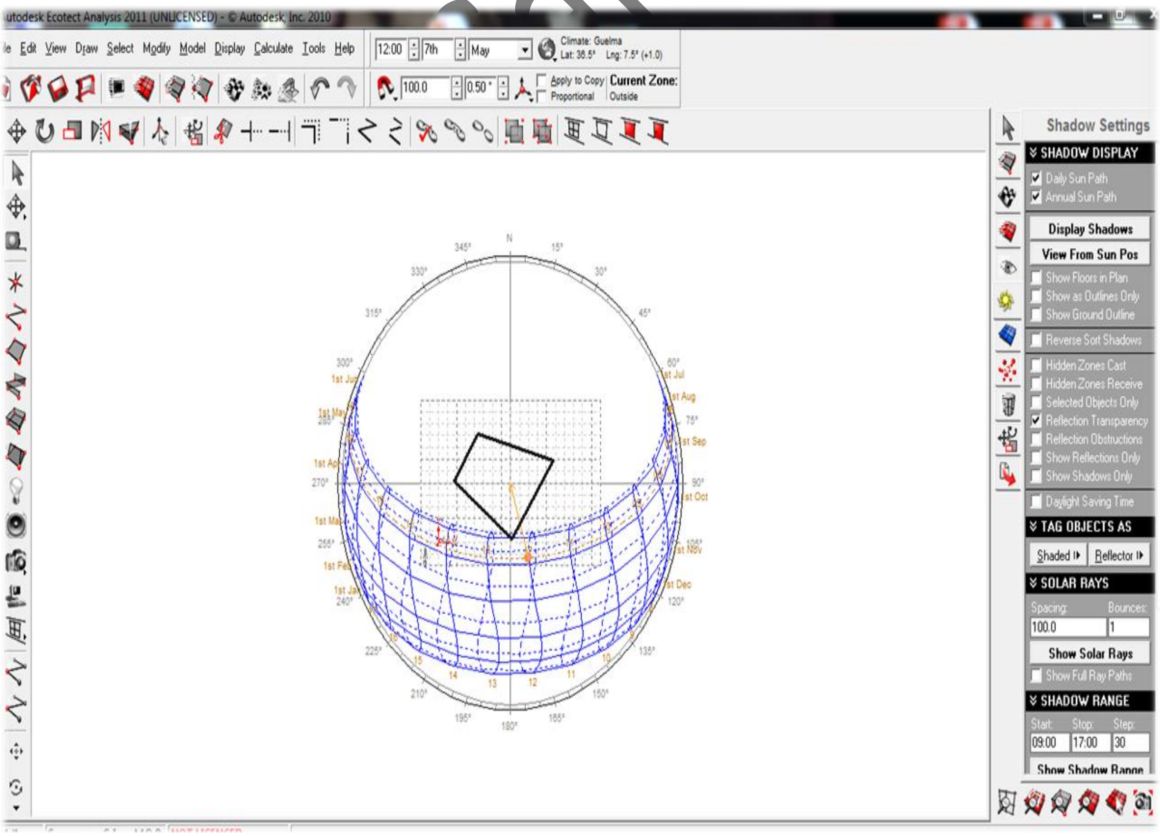

Fig 3.12 : Solar analysis / Ecotect (Author).

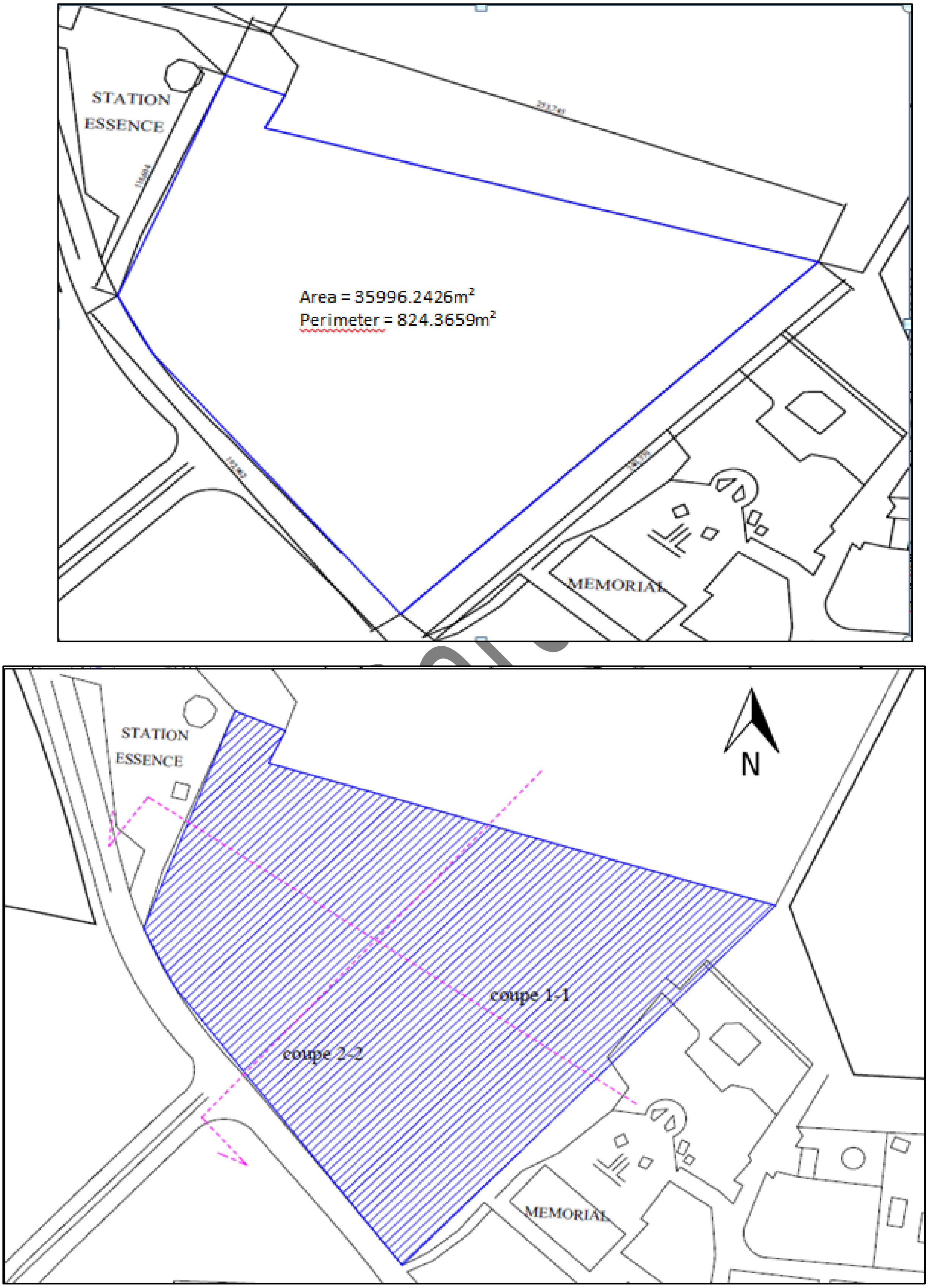

Fig 3.13 : The Site autocad (Author)

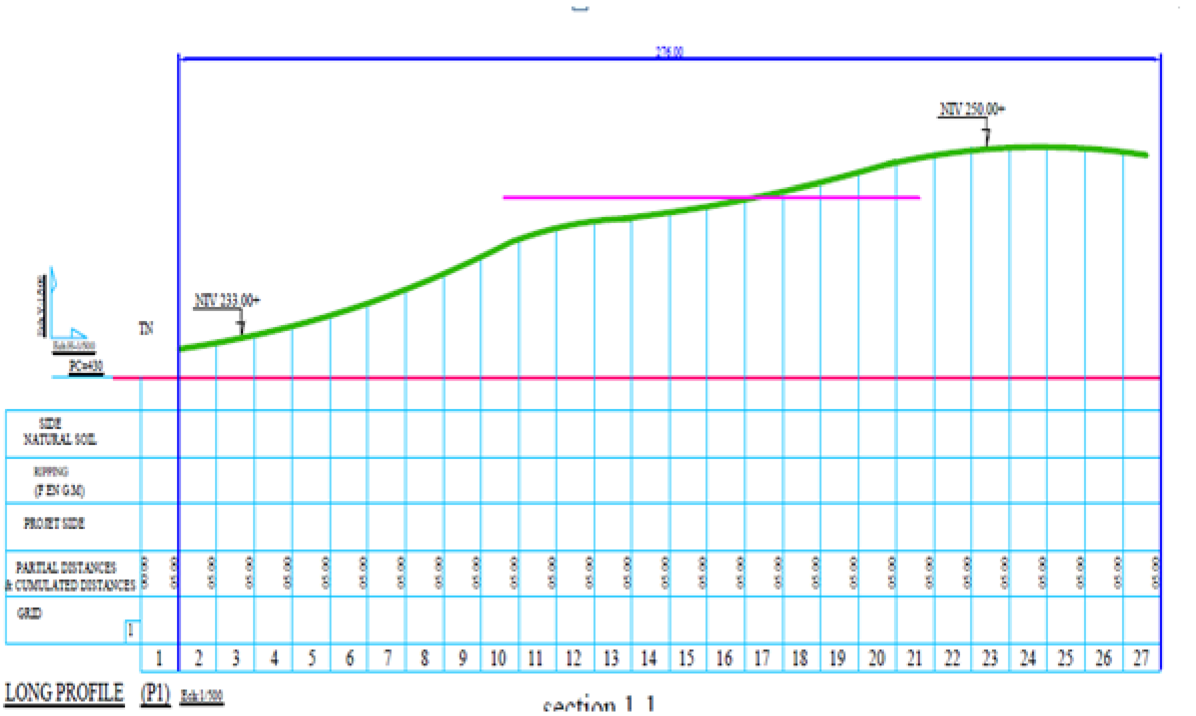

Fig 3.14 : Section 1-1 of the site (Author)

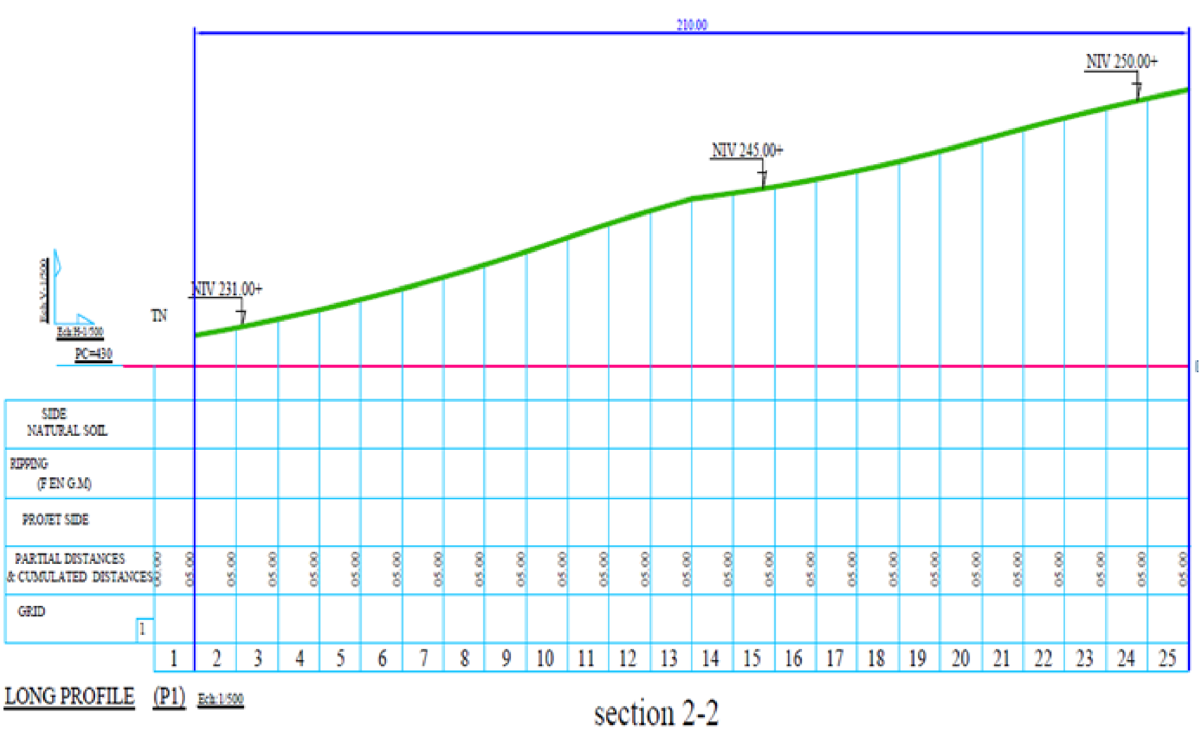

Fig 3.15 : Section 2-2 of the site (Author).

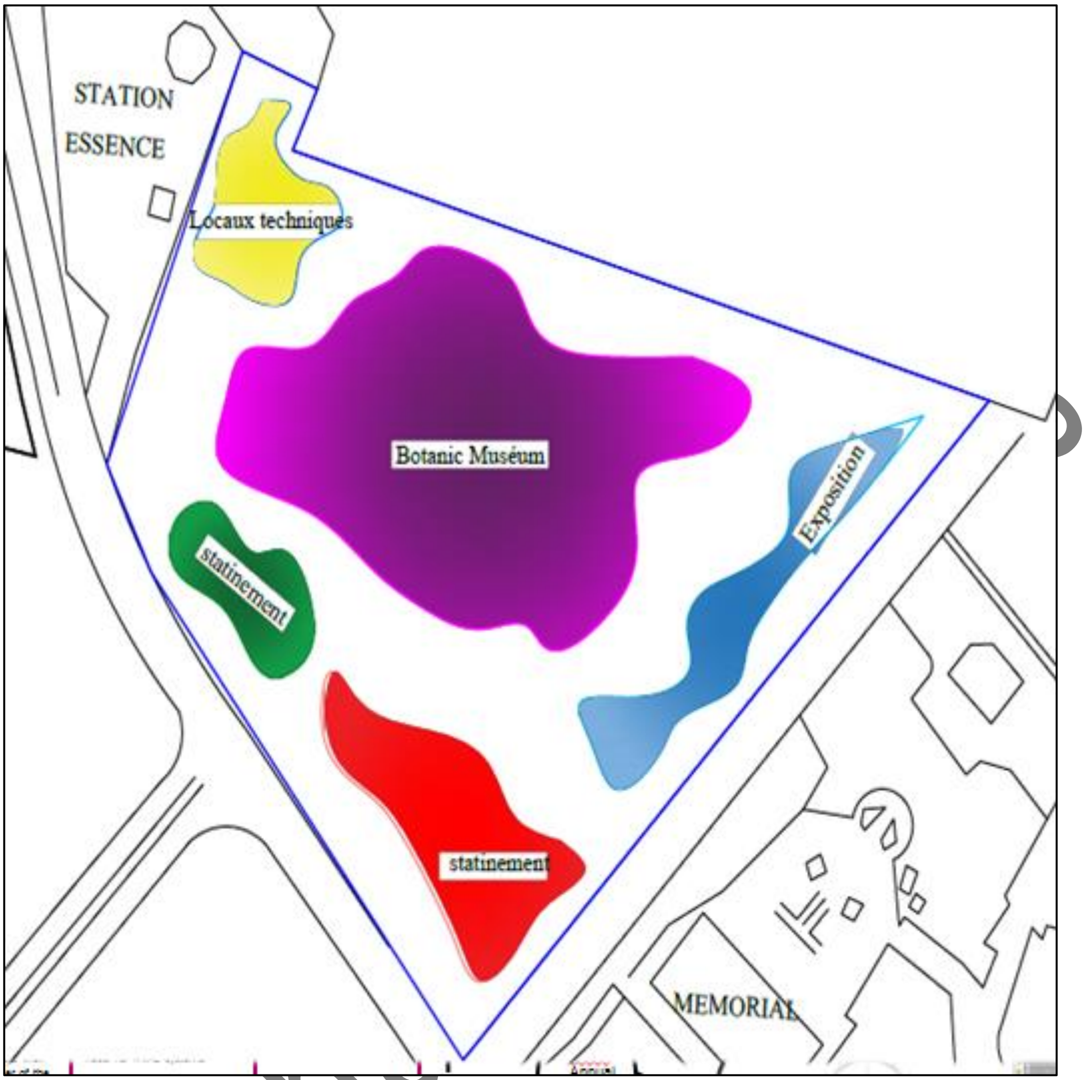

Fig 3.16 : Zoning (Author).

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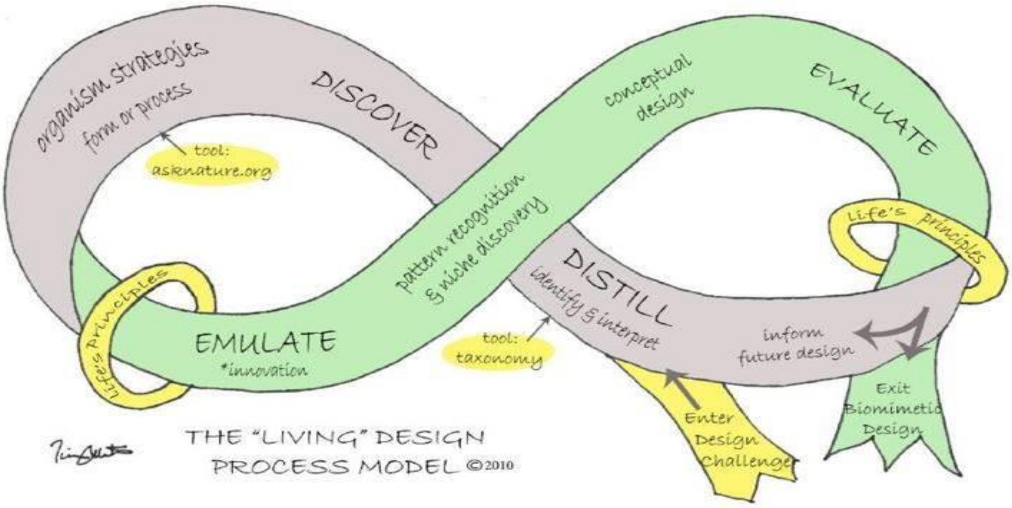
3.4The program

Designation	Area m²	*Number*	*Total area m²*
Welcome and orientation			
Lobby	240	1	240
Reception	20	1	20
Waiting room	60	1	60
Ticketing	20	1	20
Permanent exhibition			
Fossil Room	200	1	200
Plant room	400	1	400
Farm Tool Room	200	1	200
Wooden Sculpture Room	200	1	200
Greenhouse Mediterranean	400	1	400
Tropical greenhouse	400	1	400
Temporary exhibition			
temporary showroom	400	1	400
Culture			
library	100	1	100
Internet room	100	1	100
Conference room	400	1	400
Administration			
Manager's office	45	1	45
Secretary's Office	30	1	30
Meeting Room	50	1	50
Archive room	30	1	30
Accounting Office	20	1	20
Office	20	4	80
Leisure			
Cafeteria	250	1	250
Playground	400	1	400
sanitary	100	2	100
Technical premises and services			
Deposit	800	1	800
Maintenance workshops	200	1	200
Workers' Services	100	1	100
Laboratory			
Laboratory of Soil Analysis	50	1	50
Hybridization laboratory	80	1	80
Chemistry laboratory	80	1	80

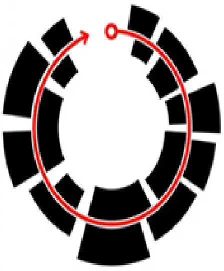
Table 3.2 Program of botanic musuem

Layacha Sarah Thesis

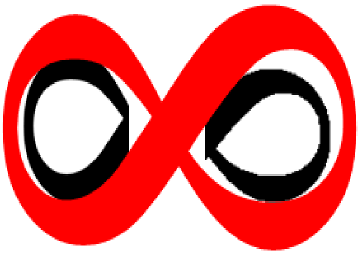
4.1 Design Inspiration :



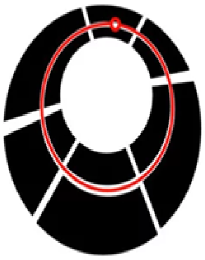
Living Design Process Model



Looping the program : the loop allows an experience of the entire program to the visitor in a easy readable way.

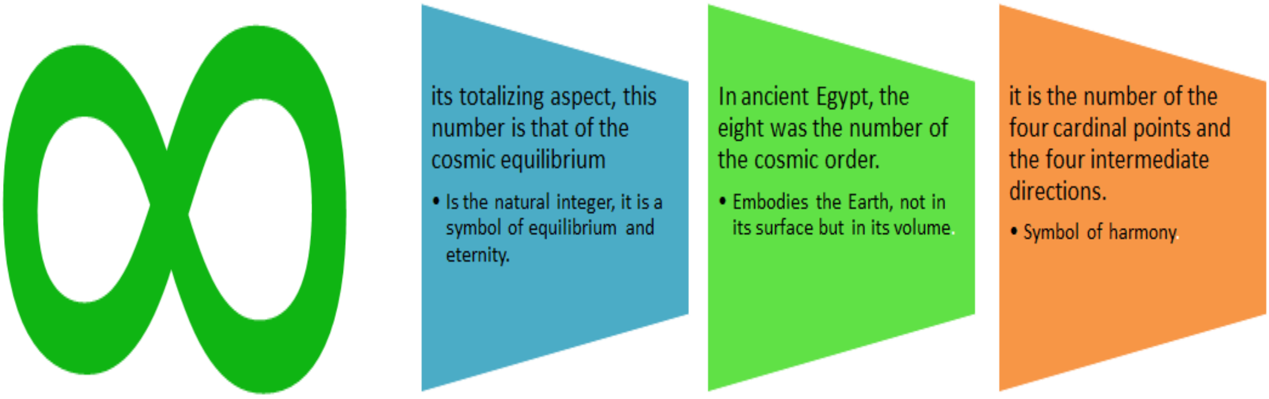


Infinity : Expand the principles of sustainability, energetic efficiency
Low carbon impact based on circular economy "cradle to cradle"
To draw up the energetic balance of the life of the building, from its delivery to its complete "recyclability" is a duty.
Spatial flexibility over time and in the implementation of biobased materials.
Technical, structural and fluid innervation, design an "out of the box" architecture that has an ecological footprint



Optimized program: the program loop is adjusted according to recyclable cycle and infinite.

- **The infinity :**



its totalizing aspect, this number is that of the cosmic equilibrium

- Is the natural integer, it is a symbol of equilibrium and eternity.

In ancient Egypt, the eight was the number of the cosmic order.

- Embodies the Earth, not in its surface but in its volume.

it is the number of the four cardinal points and the four intermediate directions.

- Symbol of harmony.

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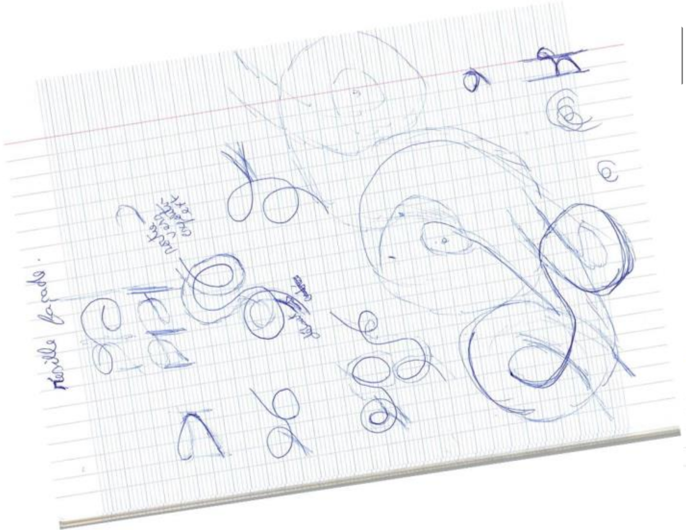
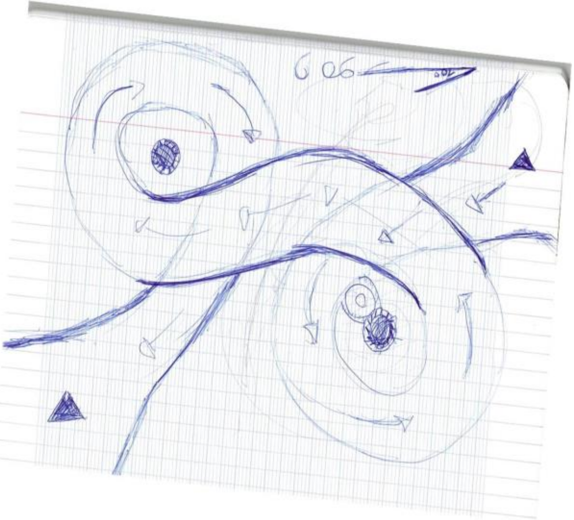
4.2 Ideas Sketch :





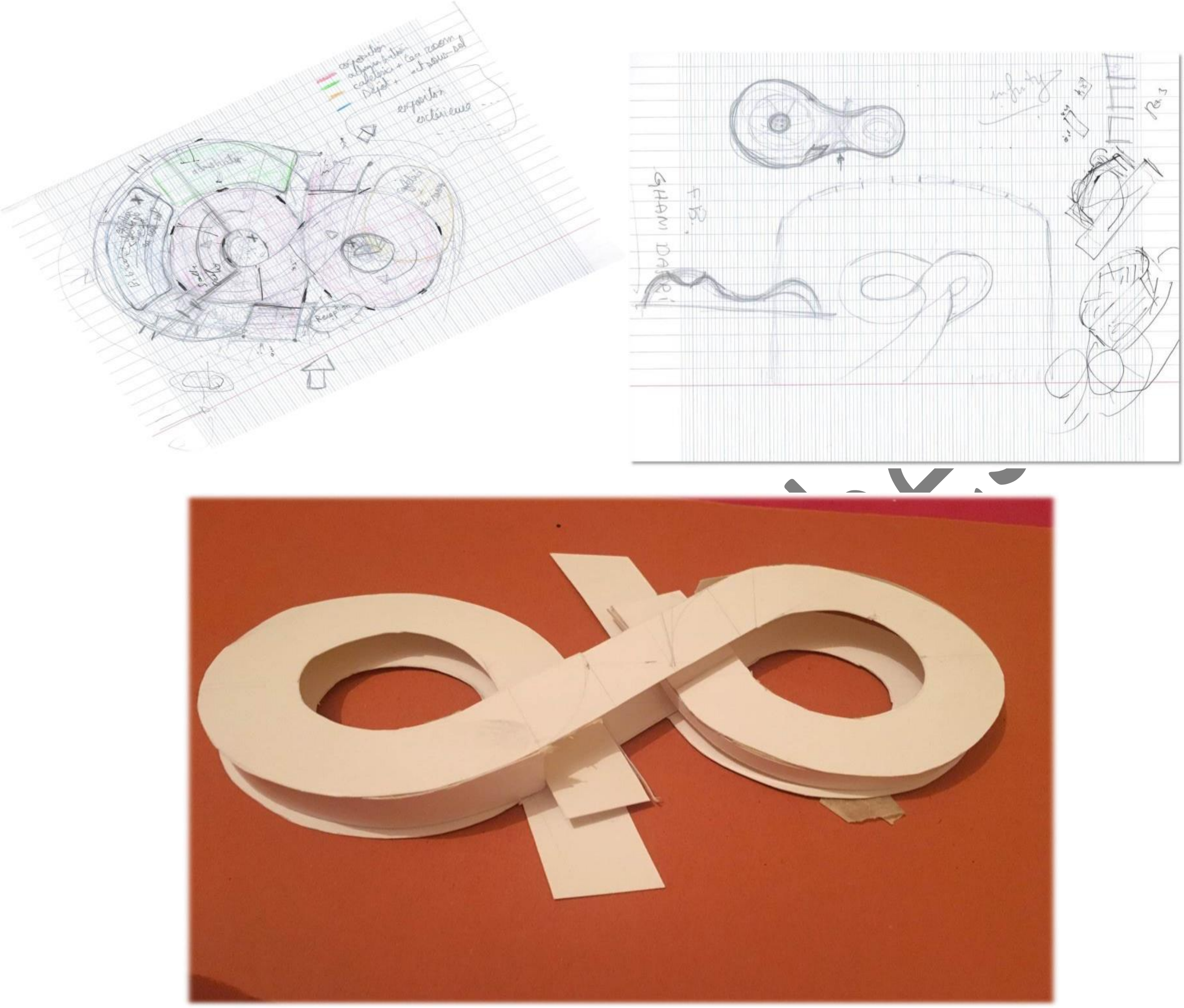


Fig 4.1 : first modelisation of the project / sketches (Author)

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4.3 Constructive System :

Fig 4.2 The constructive system of the ramp (Source: vincentcallebaut.com)

As the name suggests, the Infinity Museum forms an endless ribbon articulated around two patios planted. with its primary steel structure and secondary timber frame, the unit is built from the repetition of one trapezoidal module. a sloping pedestrian path contains the exhibit, while the panoramic ground floor comprises the fonctinal spaces. the insulating green roof provides an external area of recreation, which also incorporates a photovoltaic glazed roof.

4.4 Second Skin : Biomimetic skin

Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness.

4.4.1 Natural responsiveness :

In nature there are various examples of climate responsive, dynamic movements. Of special interest is the hygroscopic shape changing adaptation that can be observed in a variety of plants as it provides particularly interesting potential for architectural applications.

Moisture driven plant motion can be categorized in two major groups: (a) active cell turgor pressure movement as seen in e.g. Dionaea muscipula (Venus fly trap) or (b) passive movement triggered through differentiated elongation of material e.g. the hygroscopic movements of fruit awns or the opening of the seed capsules of ice plants. While active cell pressure movement is connected to the metabolism of plants, the passive alternative is a result of the material's hygroscopic behaviour and its anisotropic composition, in response to environmental changes.

For instance, the Pinophyta (conifers) possess cones to protect internal seeds (Fig.4.3 —the plants reproductive structures. Once the cone becomes mature, the scales dry out and open up to release the seeds. At that point, the materiality of the cone is already dead and has no direct connection to the tree. However, since the motion is triggered by external stimuli and does not

Layachia Sarah

plastically alter the molecular structure of the material, it is fully reversible for a large number of opening and closing cycles. The geometric deformation of the scale is achieved through two different fibre layers; the outer layer consists of parallel, long and densely packed thickwalled cells while the inner layer of the seed scale possesses differentiated sclerenchyma fibres with cellulose fibrils at a higher angle (upper part) and lower angle (lower part) in relation to the longitudinal axis. Through swelling and shrinking, the material performs the passive autonomous deformation. The instrumentalization of the hygroscopic material behaviour is particularly promising for architecture, since it does not require any type of external actuation, electrical or otherwise.

Fig.4.3. Cone of conifers (Pinophyta) in (A) high moisture content (MC) and (B) low moisture content (dry condition). Even after the cone has fallen off the tree, the material'sintrinsic performance within the cones' scales remains. The moisture content in the scales changes as it finds equilibrium with the surrounding humidity level ((C)–(J)).

Source: Images courtesy of Iva Kremsa, Kenzo Nakakoji and Etien Santiago.

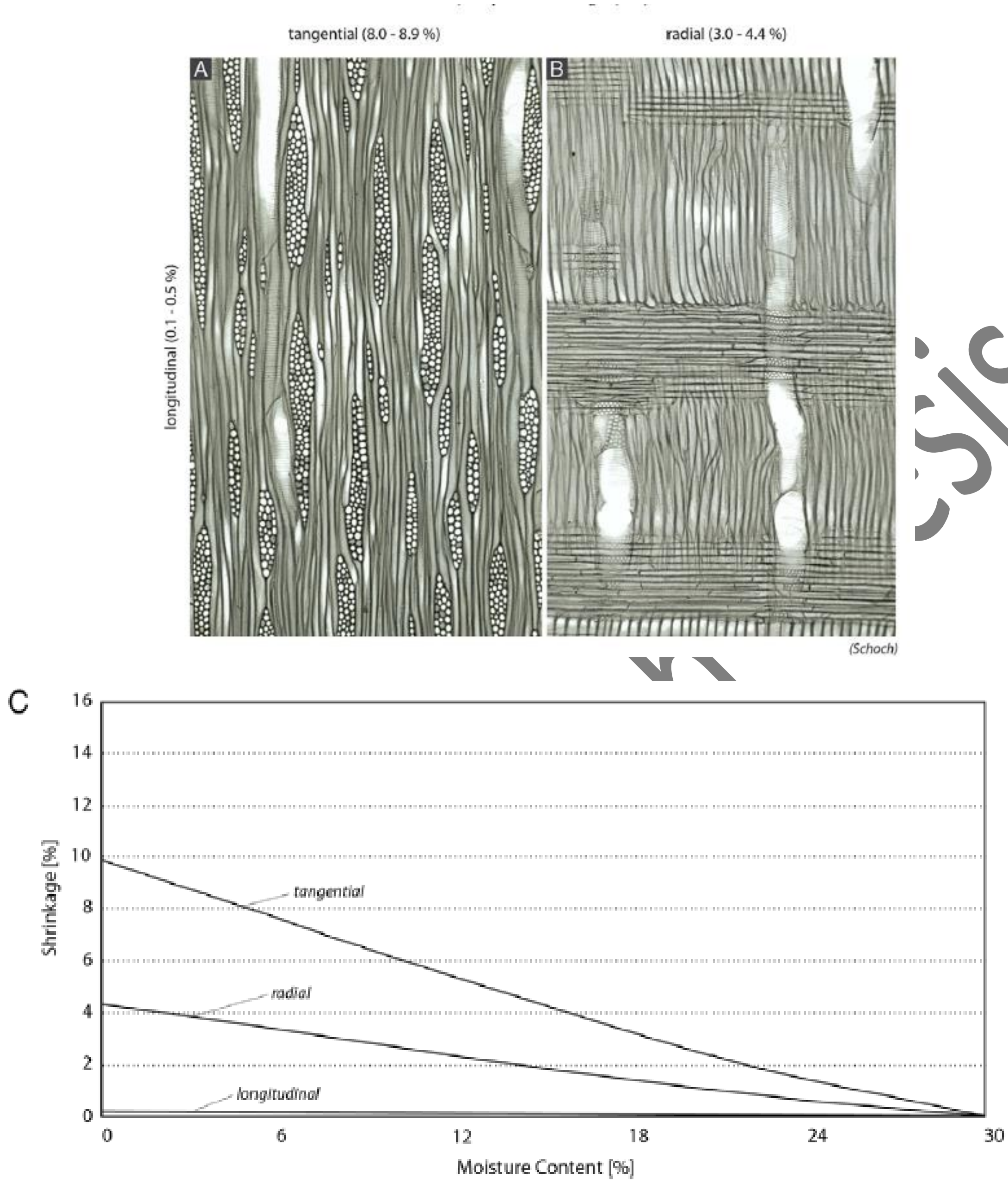

Fig. 4.4. The fibrous, anisotropic material composition leads to differentiated swelling and shrinkage behaviour (A + B). The graph (C) shows the relation between the shrinkage and moisture content of maple.
Source: Images courtesy of Werner H. Schoch.

4.4.2 Materials and experiments :

Through the understanding of the microstructural principles that facilitate hygroscopic actuation in the pine cone, suitable analogues can be developed to produce a similar responsive motion to that of the presented cone. The research also presents an opportunity to utilize the actuation principle of the pine cone at larger scales. In this way, the cone’s principle of transferring an anisotropic dimensional change into a shape change can be utilized in developing a humidity responsive, integrated technical system. A suitable starting point for doing so is employing the anisotropic dimensional change of wood as the actual responsive layer within a technical composite element. Wood (from the stem) can be considered to be the most effective and closely related material to the specialized woody scales of the cone as it has similar material make up and hygroscopic behaviour. Although the vascular tissue of the stem does not present the specialized microstructural arrangement required to achieve the same motion, it does possess hygroscopic properties that create dimensional changes in the material, namely, shrinking and swelling. These are important functional properties, as they are dependent upon the relative humidity level of its surrounding environment; a specific increase in moisture content will consistently induce the same amount of swelling. In the simplest case, a control experiment exposing one layer of the material to a different humidity level than the other can easily induce differential expansion between the two layers. If the sample is thin enough, the material responds by dissipating the stress through an elastic deformation of the overall shape—that is, a curling of the material. This behaviour is not only predictable and reproducible but also highly reversible. The authors have conducted an extensive series of experiments to explore, analyse, manipulate and calibrate the various parameters affecting the behaviour of wood.

Thesis

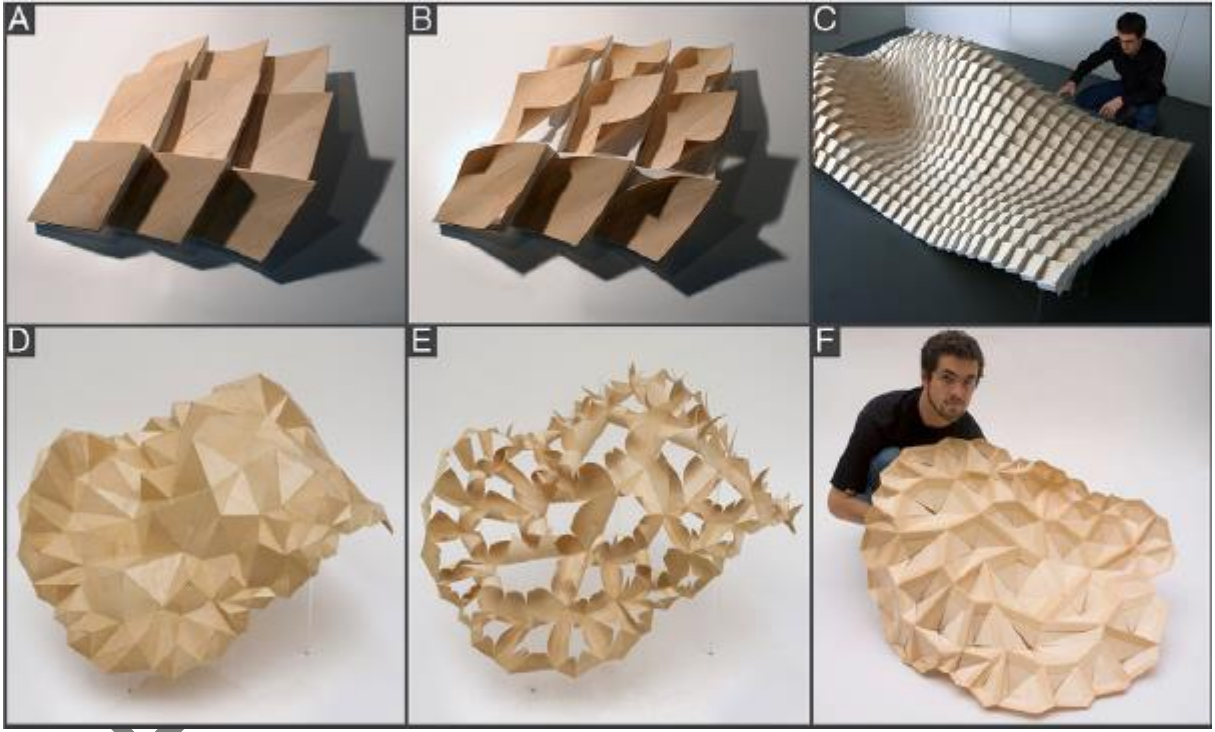

Fig. 4.5 Responsive Surface Structure 1 (RSS1); Array of nine cell components with hygroscopic veneer top layer in (A) closed state, (B) open state and (C) overall display configuration. Responsive Surface Structure 2 (RSS2); (D) closed and (E) open condition; (F) rear view.

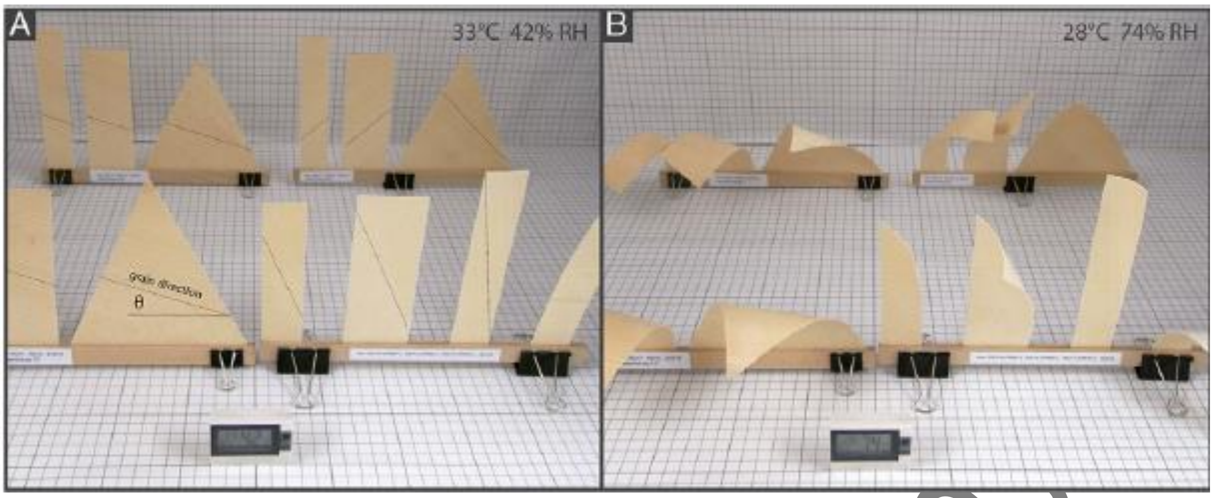

Fig 4.6. Demonstrating dependencies between direction of grain (A) and direction of deformation (B). The greater θ, the smaller the deformation.

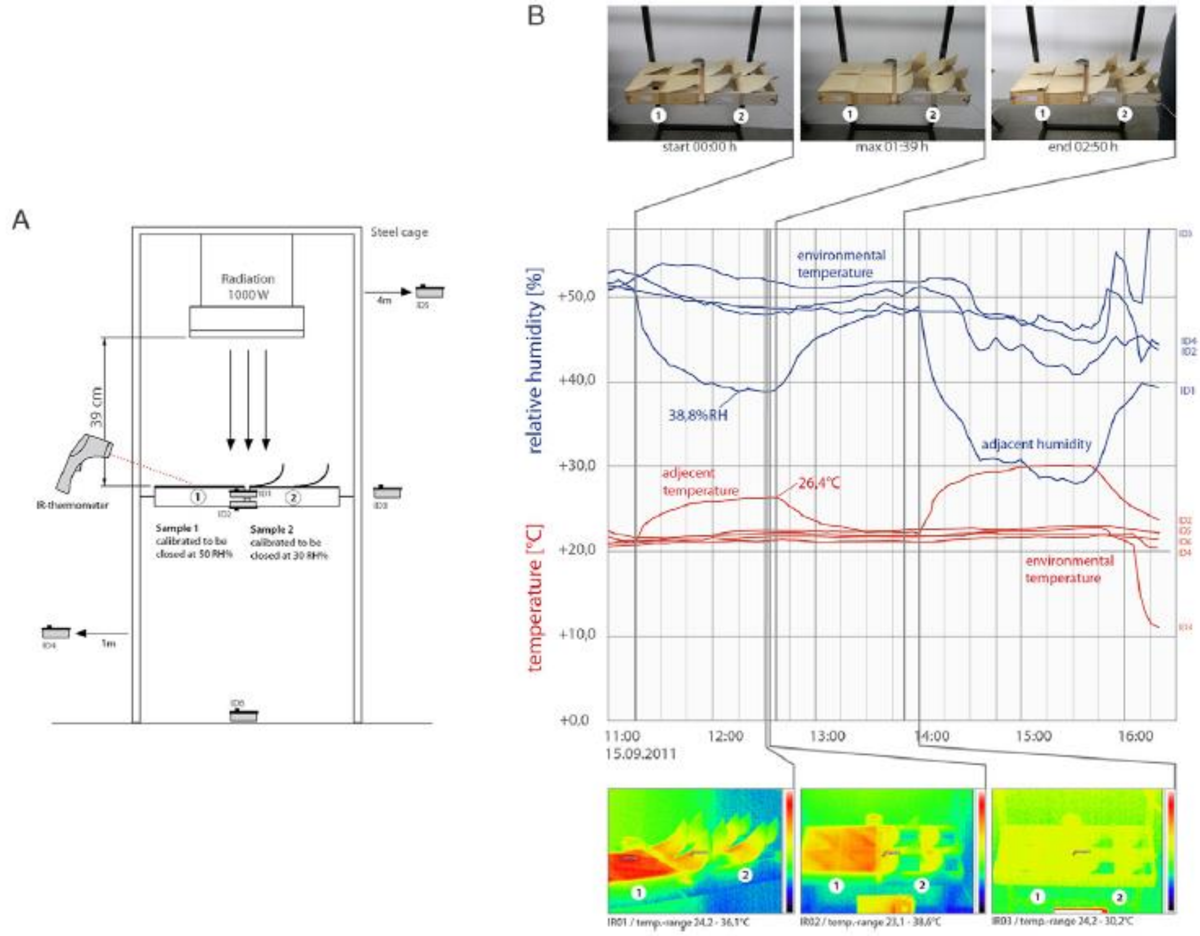

Fig. 4.7. (A) Experimental setup for thermal radiation test. A radiation source was positioned at 39 cm from the specimens. Specimen 1 (left) was calibrated to be flat at 40 RH% and specimen 2 at 70 RH%. (B) The experiment was monitored by an array of wireless humidity and temperature.

sensors, while an infrared camera was used to capture the heat distribution triggered through the radiation source.

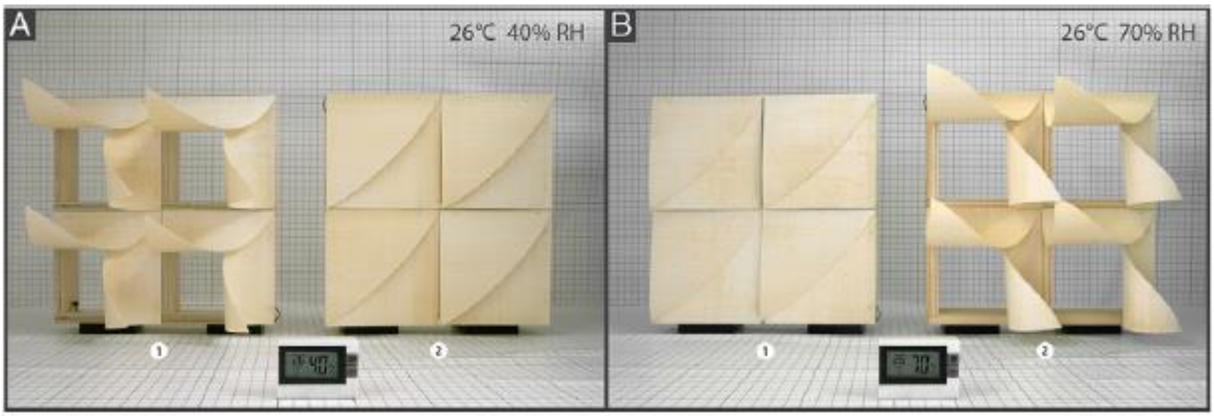

Fig 4.8. Through the manipulation of the fabrication parameters for the reactive veneer–composite, it is possible to calibrate the material to react within a specific humidity range. Here, with an increasing relative humidity level, specimen 1 (left) closes while specimen 2 (right) opens.

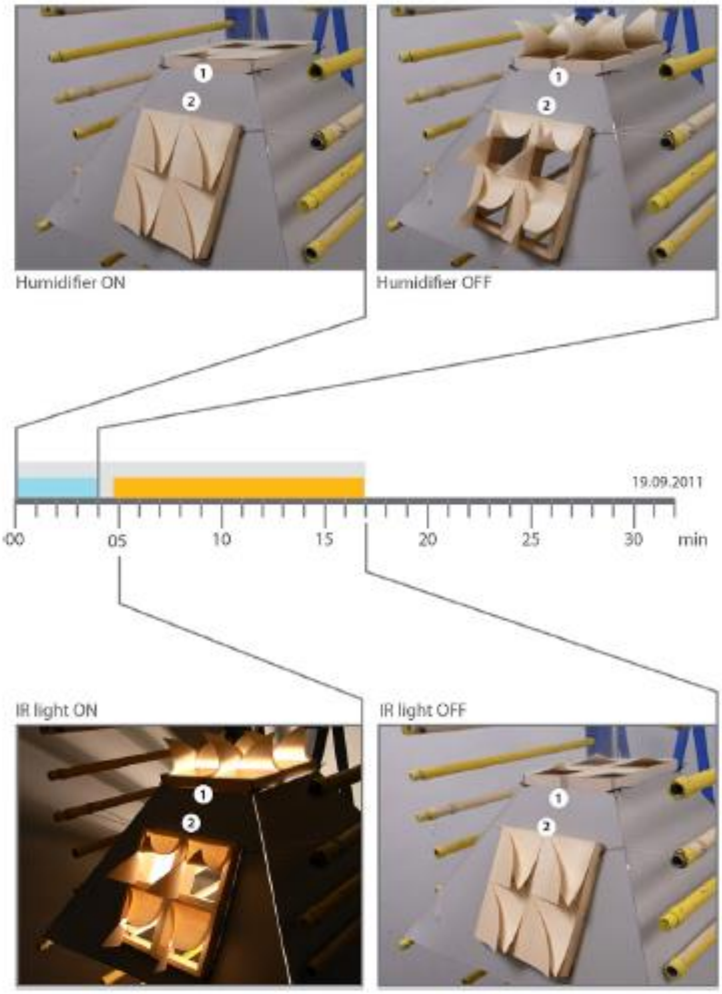

Fig.4.9. Using a steam-based humidifier and a radiation source, the responsive reaction time can be accelerated. With this configuration it was possible to achieve full opening of the mechanism in under 3 min while the closing process time was reduced to only 12 min.

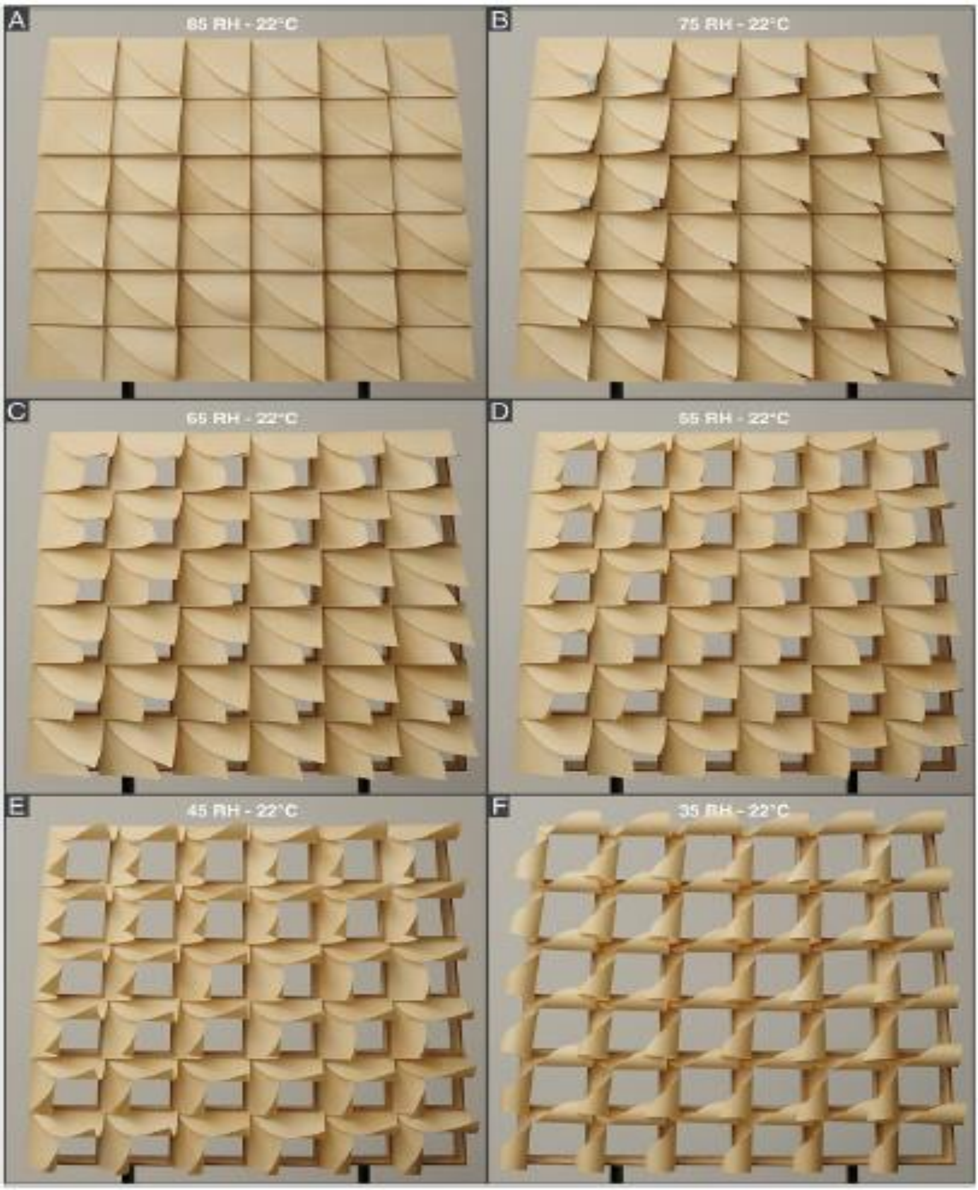

Fig. 4.10. Laboratory test of a 6 × 6 array of elements under controlled climatic conditions. Global changes in humidity levels coupled with appropriate material qualitycontrols during fabrication enable a homogeneous opening and closing motion across the array. From fully closed (A) to fully open (F), the veneer performs various formal states as moisture is removed from the air.

4.4.3 Simulation methods:

Real-time simulation of the curling motion greatly supports the design process by allowing pre-visualization of morphological changes at various stages and the troubleshooting of problematic stages that may cause interlocking between elements. Additionally, a secondary collision detection indication routine has been implemented to visualize, identify and resolve the intersections of pieces in complex multi-component assemblies. The digital curling simulation has been addressed using two different approaches: (a) a linear geometric representation model (GRM) and (b) a nonlinear simulation model using a non-linear spring-based method (SSM).

4.4.4 Results :

1. Architectural prototypes

The two physical prototypes discussed in this paper present an autonomous responsive architectural system that has been achieved through a biomimetic rather than an electromechanical paradigm. The projects build upon the previous research on material embedded programming with passive, autonomous hygroscopic actuation, while suggesting an architectural approach based on inherent material behavioural capacities that can respond to exterior climate changes. The following prototypes demonstrate the range of performance capacities enabled by the previously developed responsive system. While the ‘‘HygroScope’’ prototype is configured to open as relative humidity levels increase, the ‘‘HygroSkin’’ prototype follows the converse response, closing under high relative humidity levels. Both demonstrators offer a tangible direction towards an integrative design process where design thinking involves the development of responsive and systems (Fig. 4.11).

2. Meteorosensitive morphology: HygroScope installation, Centre Pompidou Paris

The installation ‘Hygroscope—Meteorosensitive Morphology’ was designed and realized for the permanent collection of the Centre Pompidou in Paris and was first shown in the context of the special exhibition ‘‘Multiversité créatives’’ (2012) (Fig. 4.12).

The project, being exhibited in the interior space of the museum, has to operate in one of the most stable climate zones in the world—the highly controlled indoor climate of the Pompidou that would not trigger any responsiveness. Therefore, the meteorosensitive morphology has been suspended in a fully transparent glass case with a custom, programmable climate-controlled system; the case serves as a container for the climatic patterns based on local Parisian weather data within the stable conditions of the museum. The sculpture’s material assembly is programmed to acutely respond to changes in the environment’s relative humidity and allows one to visually experience the otherwise invisible humidity changes of Paris. When moisture levels rise, the system changes its surface porosity to breathe and ventilate the moisture-saturated air. The climatic changes within the case directly influence the system’s behaviour; therefore, the micro-climate inside the case is based on Parisian atmospheric patterns. This is achieved through the use of custom humidity control mechanisms enclosed within the case’s base.

Layacha Sarah Thesis

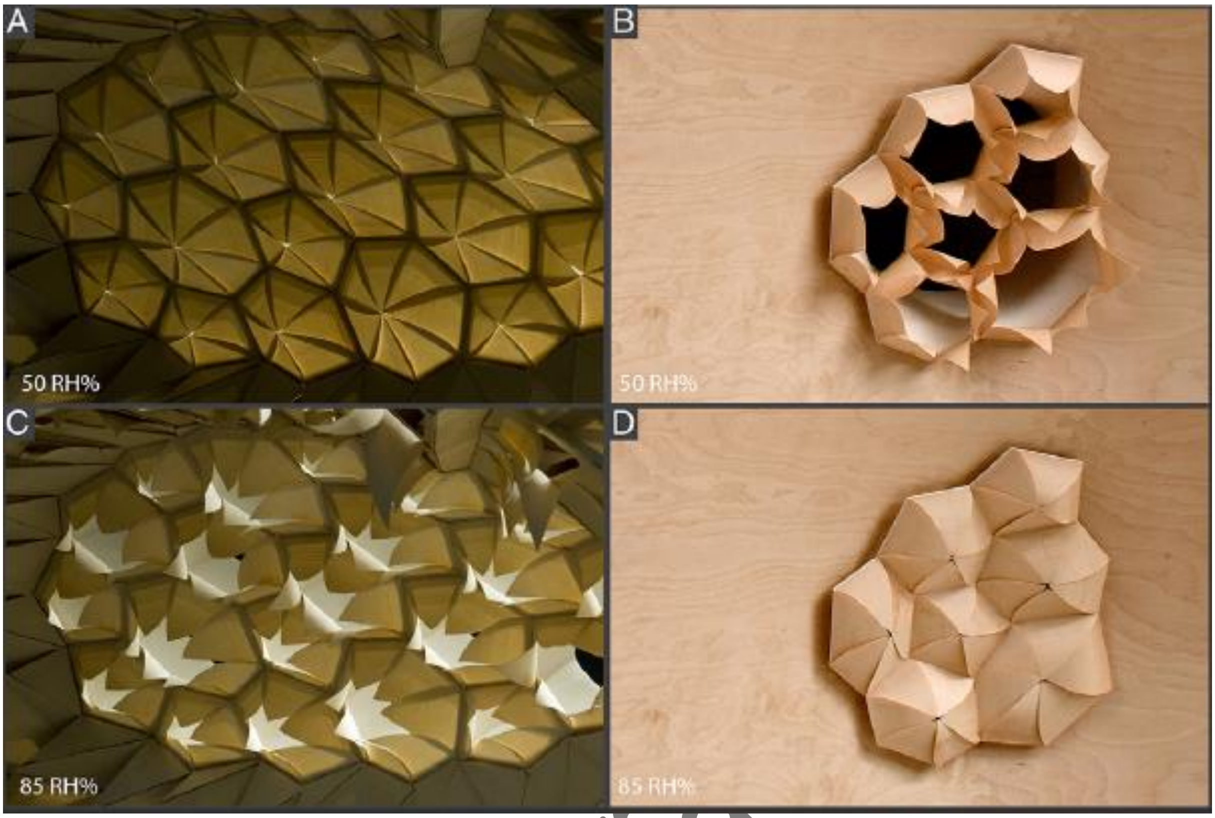

Fig. 4.11. HygroScope installation calibrated to (A) 50 RH% (closed) and (B) 85 RH% (open). Exterior HygroSkin installation designed to perform inverted behaviour: (A) 50 RH% to (open) and (B) 85 RH% (closed).

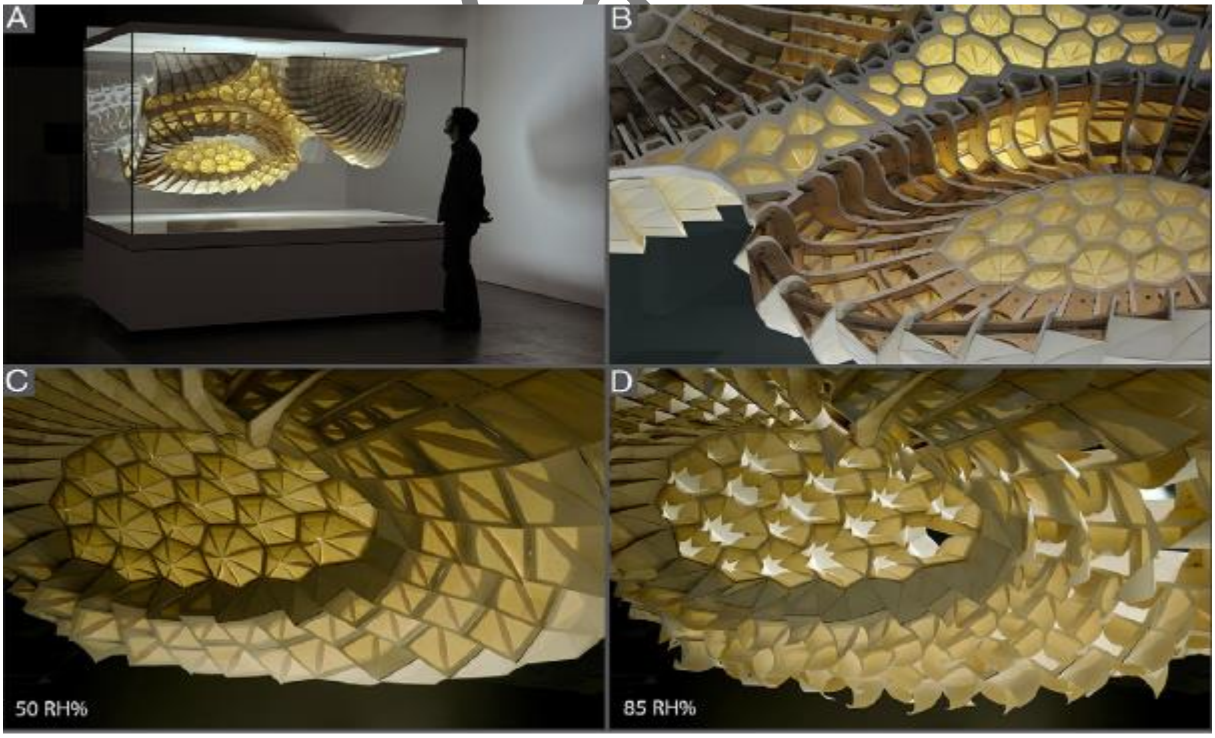

Fig 4.12. HygroScope installation at the Centre Pompidou, Paris.

Conclusions :

Complex electromechanical mechanisms require high maintenance and constant oversight, while their computational capacity can easily extend beyond the required task—a great asset in many applications. However, extended use in simple applications where instructions and signals follow predictable cycles may be best addressed by reverting to systems where embedded instructions and controls can be implemented. Not only are complex systems more prone to failure over an extended period of time—due to more points of failure in controllers, connections, energy supply, etc.—but they also tend to be more unreliable when performing repetitive tasks. In contrast, material systems based on biomimetic principles distribute the embedded knowledge at a molecular level; this framework reduces the number of failure points and allows the system to operate even when substantial sections of the system fail. The presented work illustrates how this interdependence between the system and its environment can be best harnessed when it serves an analogue's purpose, as is the case with the relation of wood and atmospheric conditions. Here, the material system has been instrumentalized to compute morphological operations in response to the environment, which conversely actively affects such environment.

Layacha Sarah Thesis

Introduction

In this thesis, we explored the application of Nature-Inspired Design Strategies (NIDS), Biomimicry, within the field of architecture. The design strategies are currently used in design practice and are taught in institutions of higher education. However, little empirical knowledge is available on how these strategies are applied and how they actually support product designers in the development of sustainable construction. Accordingly, we started this investigation with the main research question: In this thesis, we explored the application of Nature-Inspired Design Strategies (NIDS), Biomimicry, within the field of architecture. The design strategies are currently used in design practice and are taught in institutions of higher education. However, little empirical knowledge is available on how these strategies are applied and how they actually support product designers in the development of sustainable construction. Accordingly, we started this investigation with the main research question:

"How could the application of biomimetic principles and strategies be a solution to develop buildings skins that enhance the energy efficiency?"

5.1. Recommendations for design practice:

In this study, we explore how Biomimicry have helped designers in sustainable product development, and provide theoretical propositions for the way in which NIDS (Nature-Inspired Design Strategies) contribute to the results. The findings give rise to several recommendations for designers who aim to develop energy saving potential. In addition, these recommendations may be valuable for lecturers, as they highlight the qualities and limitations of biomimetic's skin. This section presents six recommendations which represent what the author considers the most valuable insights for those practicing and teaching nature-inspired design.

5.2. Define sustainability

We hold the perspective that designs can contribute to sustainability. To be able to verify a product's contribution, it will be necessary to make explicit what is meant by 'sustainable': when do these designs benefit people, planet, and profit? We recommend designers to define or adopt a consistent set of criteria that describe when a product can be considered truly sustainable (see Chapter 1). These were used in this thesis to define four conditions of environmental sustainability.

In this study, Biomimicry design principles were used to define the conditions of environmental sustainability for and minimize energy consumption naturally. The goal is quite different; not analytical but generative, to provide inspiration to designers to achieve beneficial designs. In the cases included in this study, design principles, or even the generic

Layacha Sarah Thesis

principle of "learning from the principles of nature", have clearly guided the designers in their decision-making process. For example, the principle of "waste equal to food" invented by McDonough and Braungart (2002), formulated by Benyus as "nature recycles everything" (1997), clearly expresses how designers can implement ecosystem knowledge to manage natural resources.

5.3. Make a roadmap

This study has provided an understanding of the difficulties designers face when aiming to realise a beneficial design. Developing a product that benefits people, planet, and profit, requires designers to change both the product design as well as the processes in the product-system, which will inevitably take time, very probably more time than available in most product-design projects. To create a fully beneficial outcome, both the Biomimicry call for the integration of all of their design principles, although they do acknowledge that not all of them can be achieved at once. However, the cases included in this study highlighted that designers tend to focus on biomimetic building's skin based on materially embedded and hygroscopically enabled responsiveness.From our analysis, we identified one material aimed at developing a systems based on the biomimetic transfer of the hygroscopic actuation of plant cones. This strategic tool seems to have more potential than the cases included in this study have shown. The application of this material can help designers to produce

The cone principle of transferring anisotropic dimensional change into a shape change can be used in the development of an integrated technical system, sensitive to moisture, light and temperature.

5.4. Wrapping Up

In this thesis, I have explored the value of Nature-Inspired Design Strategies specifically Biomimicry for sustainable construction development by analyzing the state of the art and the experience of the material captured in the laboratory (Steffen Reichert, Achim Menges, David Correa, Institute for Computational Design (ICD), University of Stuttgart, Germany). The results demonstrate how learning from nature can provide inspiration, valuable insights, and key ecosystem knowledge. This applying helped designers to tackle barriers in the cycling of resources, by designing both the product and the material cycle. In addition, the study revealed how design may play a role in generating beneficial environmental impacts, with products that contribute to the ecosystems of which they are part. On the other hand, this project also highlights the disadvantages and limitations of the current strategies. Designing products as intelligent as the Blowball still seems an aspirational goal rather than an easily attainable objective.

Layacha Sarah Thesis

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