FACULTY OF ENGINEERING, ALEXANDRIA UNIVERSITY, DEPARTMENT OF ARCHITECTURE

USING SMART MATERIALS TO MIMIC NATURE IN ARCHITECTURE

Master Thesis

Yasmine Talaat Ahmed Nasr

4/19/2017

The aim of this research is studying how smart materials are used to mimic nature in architecture and showing the significance of it on contemporary and future architecture.

University of Alexandria
Faculty of Engineering
Department of Architecture

USING SMART MATERIALS TO MIMIC NATURE IN ARCHITECTURE

A THESIS

Presented to the Graduate School
Faculty of Engineering, Alexandria University
In Partial Fulfillment of the
Requirements for the Degree

Of
Master of Science

In
Architecture

By

Yasmine Talaat Ahmed Nasr

April 2017

University of Alexandria
Faculty of Engineering
Department of Architecture

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Thesis Presented by
Yasmine Talaat Ahmed Nasr

For The Degree of
M.Sc.

In
Architecture

Examiners' Committee: **Approved**

Prof. Dr. Mohamed Anwar Fikry ………………
(Professor of Architecture, Department of Architectural Engineering, Faculty of Engineering, Alexandria University, Egypt)

Prof. Dr. Walid Foad Omar ………………
(Professor of Architecture, Department of Architecture, Faculty of Fine Arts, Alexandria University, Egypt)

Prof. Dr. Hany Mohamed Ayad ………………
(Professor of Regional and Urban Planning, Department of Architectural Engineering, Faculty of Engineering, Alexandria University, Egypt)

Vice Dean of Graduate Studies and Research

Prof. Dr. Magdy Abdel Azim ………………

Supervisory Committee:

Approved

Prof. Dr. Mohamed Anwar Fikry ....
(Professor of Architecture, Department of Architectural Engineering, Faculty of Engineering, Alexandria University, Egypt)

Dr. Waled Mohamed AbdelAal ....
(Lecturer, Department of Architectural Engineering, Faculty of Engineering, Alexandria University, Egypt)

I. ABSTRACT

The purpose of this research is exploring how smart materials can be used to mimic nature in architecture, showing its impact on contemporary and future architecture, The reason for choosing this theme is the growing architectural and social concern for using evolutions in the field of bio-inspiration and smart materials to find new solutions for the increasing global environmental and social problems in terms of energy conservation and ecological design.

The availability of various types of smart materials have great prospect for utilization in the field of architecture. In this context, thinking about using smart materials as a tool to mimic nature is a controversial area for research, opening the door to exceptional approaches for concept generation and optimization in the field of architecture, building, and construction.

This thesis is an endeavor to link between innovative smart materials and bio inspiration through exploratory and analytical research, by focusing on the literature review of smart materials and bio-inspiration development, starting with exploring the taxonomy of smart materials, their types and characteristics, a set of selected properties and types is extracted, that could be used to imitate nature. Bio inspiration and methods of abstraction from biological systems are then studied, and linked with the extracted properties from smart materials, then after with comparative analysis, various crossovers from nature were explored. Case studies are then analyzed in order to evaluate the application of such an approach on current and future architecture.

Smart materials are defined to be designed reactive materials; their properties can be changed by exposure to stimuli, such as electric and magnetic fields, stress, moisture and temperature.

As the terminology suggests, the difference between bio-mimicry and bio-inspiration is that the first one is defined to be direct copying from nature, while the second is where and idea is taken from nature and improved to serve a certain purpose, bio-inspiration is the area involved in this study.

The conclusions drawn from the comparative analysis of the case studies showed that, The case studies based on inspiration from biological systems such as, adaptivity of human cells and Homeostasis function in biological systems, are all in prototype stage, thus further mean that, inspiration from plant movement such as, Bird of the paradise flower pollination mechanism and wood cones, have more tendency for technical and architectural application rather than biological systems. It can also be inferred that the most common stimuli in architectural applications are solar radiation, temperature change and relative humidity. While in terms of energy conservation qualities, solar radiation control and optimized energy harvesting comes at the first place and then maintaining moister level in equilibrium with the surrounding relative humidity.

Keywords:
Smart-materials, Bio-mimicry, Bio-inspiration, Bionics, Sustainability

II. ACKNOWLEDGEMENTS

First of all, I show my gratitude to the Almighty Allah, the most gracious and the most powerful, who bestowed me strength and knowledge to deal with this research. My sincere gratitude then goes to Prof. Dr. Mohamed Anwar Fikry and Prof. Dr. Hany Mohamed Ayad, for there endless support, extreme patience, and understanding. And finally, I am thankful to my family, specially my mother and my husband to provide me endless encouragement and consistent support throughout the process of research and writing of this thesis. Therefore, I must say that this accomplishment would have been impossible without them.

Thank you!

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VI. LIST OF ABBREVIATIONS

CAD	Computer aided design
CAM	Computer aided manufacturing
ChLCs	Cholesteric liquid crystals
CSI	Construction specification institute
ETFE	Ethylene Tetrafluoroethylene
ERs	Electrorheologicals
FE	Finite Element simulation
FRP	Fiber reinforced polymer
GFRP	Glass fiber reinforced platic
Gore-Tex ®	Waterproof, breathable fabric membrane
HVAC	Heating, ventilation and air conditioning
IAAC	Institute for advanced architecture of Catalonia
ICSF	Integrated concentrating solar façade
IR	Infrared
ITKE	Institute of Building Structures and Structural Design
KN/mm2	Kilo newton per square millimeter.
KWh	Kilowatt hour
LED	Light Emitting Diodes
Lycra ®	An elastic polyurethane fibre or fabric
MPa	Young Modulus of Elasticity
MWh	Megawatt hours
NANO	Denotes a factor of 10−9 or 0.000000001. It is frequently encountered in science and electronics for prefixing units of time and length
PDLCs	Phase dispersed liquid crystals
SPDs	Suspended particle devices
Tio2	Titanium dioxide
UV	Ultraviolet
VO2	Vanadium dioxide
€	Euro

CHAPTER 1: INTRODUCTION

1.1 Problem definition

The built environment is increasing held accountable for global environmental and social problems with the generated proportions of waste, material and energy use and greenhouse gas emitted in to the atmosphere. It is becoming increasingly clear that a change must be made in our environment. How it should be created and maintained.

By mimicking life, we can make self-sustaining ecosystems by learning from nature's processes. These processes can be developed leading to a very good eco system in our world which can be very exciting for our future generation.

Recently in the past 10 years a positive attitude started towards integrating bio-inspiration and advanced smart technologies in contemporary sustainable design, below few examples for researchers interested in this field are presented.

- **Derek Clement Croome:** *PhD. DSc Hon, MSc*
  Currently Director of Research for the School of Construction Management and Engineering; Chairman of: Natural Ventilation Group and Intelligent Buildings Group for the Chartered Institution of Building Services Engineers. Vice-President of CIBSE from May 2007 and Board Member for British Council of Offices. Research interests include Smart materials development and Architecture inspired by nature. He also have a number of publications in this area [**1**].
- **Doris Kin Sung:** *B.A. at Princeton University and M.Arch. at Columbia University.*
  Currently, she is working on developing smart thermo bimetals and other shape-memory alloys, unfamiliar materials to architecture, as new materials for the "third" skin (the first is human flesh, the second clothing and the third architecture). Its ability to curl when heated allows the building skin to respond for purposes of sun-shading, self-ventilating, shape-changing and structure-pre stressing [**2**].
- **Simon Schleicher:** *M.Arch and B.A with honors from university of Stuttgart.*
  Simon is currently working as Research Associate / Cand. Dr.-Ing. at the Institute of Building Structures and Structural Design. The institute is headed by Prof. Dr. Jan Knippers. His research aims to transfer bending and folding mechanisms found in plant movements to elastic systems in architecture [**3**].

1.2 Why choose smart materials theme?

"When nature finishes producing its own species, man begins using natural things in harmony with this very nature to create infinity of species." Leonardo da Vinci

According to the researchers, the world has experienced two ages of materials including plastic age and composite age. But, however, in the middle of these two ages an innovative covenant came in to exist, that is known as "The smart materials era". The early definitions describe the smart materials as environment responding materials in a timely manner.

Conversely, later on, that definition extended to materials that are able of receiving, transmitting, or processing a stimulus and are able to respond through creating a valuable outcome which is comprised on an indication on which the materials are acting on it. There are endless forms of stimuli, such as temperature change, stress, strain, magnetic field, electric field, chemicals, hydrostatic pressure and various kinds of radiation. The effect can be created in many forms, exemplified in, absorption of proton, chemical reaction and rotation of segments or translation that are found in the molecular structure, formation and movement of crystallographic flaws and other localized conformations. The created specific effects can be change in refraction index, change in volume and distribution of strain and stress.

Recently, architects are looking forward for using evolutions in smart materials to find novel solutions to time-honored problems in addition to exploring the prospect of smart materials in developing innovative building functions, designs, forms and responses. However, the availability of numerous types of smart materials has immense significant in the field of architecture by means of creative point of view particularly [**4**].

In this context, Thinking about using smart materials as a tool to mimic nature is a controversial area for research, opening the door to extraordinary approaches for concept generation and optimization in the field of architecture, building and construction.

1.3 Research questions

- How could smart materials be used to mimic nature in architecture?
- What is the potential of such design approach on future and current architecture?

1.4 Research aim and objectives

The objective of any scientific research is to recognize realities, limitations and restrictions, observing opportunities and making them more tangible, by providing practical methods that can be considered as a proposal or theory. The aim of this research is exploring how smart materials can be used to mimic nature in architecture, showing the significance of it on contemporary and future architecture in terms of energy conservation, and design that provide better environmental conditions in space for human occupants.

1.5 Methodology

This thesis is an endeavor to link between innovative smart materials and bio inspiration through exploratory and analytical research, by focusing on the literature review of smart materials and bio-inspiration development, starting with exploring the taxonomy of smart materials, their types and characteristics, a set of selected properties and types is extracted, that could be used to imitate nature. Bio inspiration and methods of abstraction from biological systems are then studied, and linked with the extracted properties from smart materials, then after with comparative analysis, various crossovers from nature were explored. Case studies are then analyzed in order to evaluate the application of such an approach on future architectural design.

1.6 Scope of thesis

The scope of this thesis is the study and analysis of smart materials properties as a tool for applying bio inspiration. Focusing on the link between smart material properties, building needs and there analogy with biological systems.

1.7 Definitions

Smart materials: are designed materials that have one or more properties that can be significantly changed in a controlled manner by external stimuli, such as stress, temperature, moisture, pH, electric or magnetic fields [**5**].

Intelligent environment: Intelligent environments consist of complex assemblies that often combine traditional materials with smart materials and components whose interactive characteristics are enabled via a computational domain [**6**].

The Industrial Revolution: was the transition to new manufacturing processes in the period from about 1760 to sometime between 1820 and 1840. This transition included going from hand production methods to machines, new chemical manufacturing and iron production processes, improved efficiency of water power, the increasing use of steam power, the development of machine tools and the rise of the factory system. Textiles were the dominant industry of the Industrial Revolution in terms of employment, value of output and capital invested; the textile industry was also the first to use modern production methods [**7**].

Thermo-chromics: are materials that change have the ability of changing their color due to change in temperature [**8**].

Photo-chromics: are materials that reversibly change their color upon exposure to light [**9**].

Mechano-chromics: are materials that are able of changing their colors when mechanical change in applied [**10**].

Chemo-chromics: are materials responding to the exposure of different chemicals with a change in color and/or transmission/reflection properties [**11**].

Electro-chromics: are materials able to reversibly change their color by using bursts of charge to cause electrochemical redox reactions [**12**].

Liquid crystals: are materials with properties between those of conventional liquids and those of solid crystals. For instance, a liquid crystal may flow like a liquid, but its molecules may be oriented in a crystal-like way [**13**].

Suspended particle system: the suspended particles in this system are able to align their position when change in voltage is applied [**14**].

Electro-rheologicals: are suspensions of extremely fine non-conducting but electrically active particles (up to 50 micrometres diameter) in an electrically insulating fluid. The apparent viscosity of these fluids changes reversibly by an order of up to 100,000 in response to an electric field [**15**].

Magneto-rheologicals: is a type of smart fluid in a carrier fluid, usually a type of oil. When subjected to a magnetic field, the fluid greatly increases its apparent viscosity, to the point of becoming a viscoelastic solid. Importantly, the yield stress of the fluid when in its active ("on") state can be controlled very accurately by varying the magnetic field intensity [**16**].

Electro-luminescents: are materials with optical phenomenon and electrical phenomenon in which the material emits light in response to the passage of an electric current or to a strong electric field [**17**].

Photo-luminescents: are materials able of emitting light after the absorption of electromagnetic radiation [**18**].

Chemo-luminescents: are materials able of generating light through a chemically exothermic reaction [**19**].

Thermo-luminescents: are those materials able of re-emitting previously absorbed energy from electromagnetic radiation, in the form of light upon heating the material [**20**].

Light Emitting Diodes: is a two-lead semiconductor light source. It is a p–n junction diode that emits light when activated [**21**].

Photovoltaics: is a term which covers the conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect [**22**].

Piezo-electrics: The piezoelectric effect is a reversible process in that materials exhibiting the direct piezoelectric effect (the internal generation of electrical charge resulting from an applied mechanical force) [**23**].

Pyro-electrics: in piezoelectric materials, the coupling between mechanical and electrical energy results in an electric polarization when stress is applied [**24**].

Thermo-electrics: the thermoelectric effect is the direct conversion of temperature differences to electric voltage and vice versa [**25**].

Electro-restrictives: electrostriction is a property of all electrical non-conductors, or dielectrics that causes them to change their shape under the application of an electric field [**6**].

Magneto-restrictives: magneto-striction is a property of ferromagnetic materials that causes them to change their shape or dimensions during the process of magnetization [**6**].

Biomimicry: is the imitation of the models, systems, and elements of nature for the purpose of solving complex human problems [**26**].

Bio-inspiration: is where you take an idea from nature and find a way to improve on it for your own purposes [**27**].

Sustainability: is the property of biological systems to remain diverse and productive indefinitely. Long-lived and healthy wetlands and forests are examples of sustainable biological systems. In more general terms, sustainability is the endurance of systems and processes [**28**].

Ecological design: is defined by Sim Van der Ryn and Stuart Cowan as "any form of design that minimizes environmentally destructive impacts by integrating itself with living processes." [**29**].

Energy conservation: refers to the reducing of energy consumption through using less of an energy service [**30**].

Greenhouse gas: is a gas in an atmosphere that absorbs and emits radiation within the thermal infrared range. This process is the fundamental cause of the greenhouse effect [**31**].

Interactive Architecture: refers to the branch of architecture which deals with buildings featuring the trio of sensors, processors and effectors, embedded as a core part of its nature and functioning. Interactive architecture encompasses building automation but goes beyond it by including forms of interaction engagements and responses that may lay in pure communication purposes as well as in the emotive and artistic realm, thus entering the field of Interactive art [**32**].

1.8 Structure

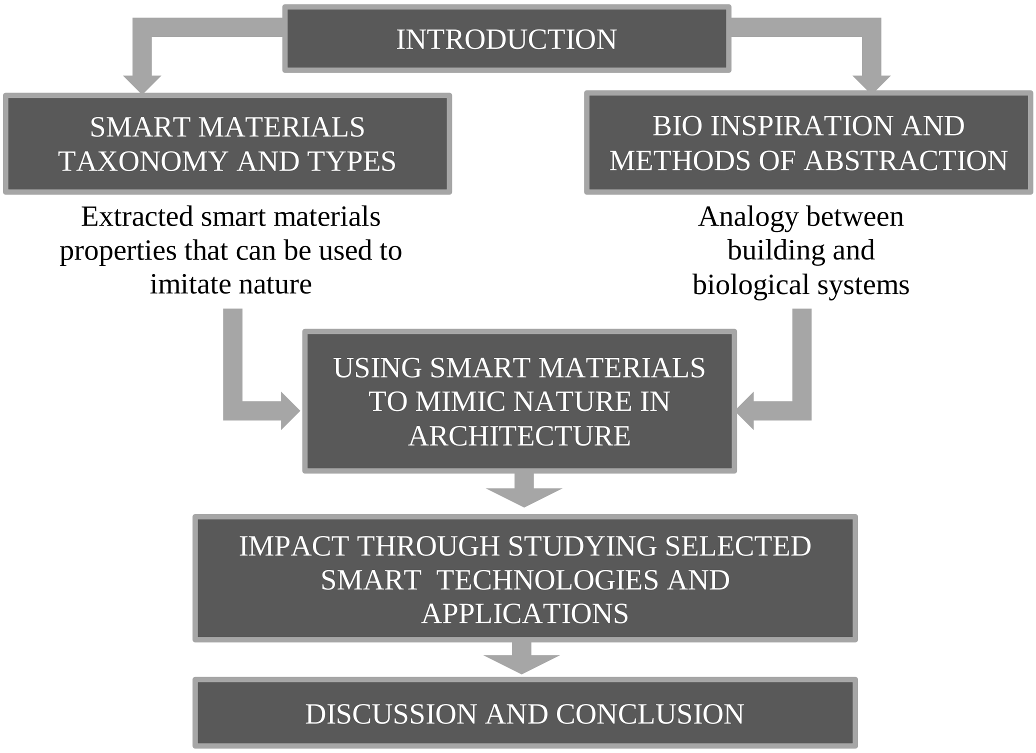


Figure 1. Thesis Structure Diagram **[The researcher].**

CHAPTER 2: MATERIAL CONSIDERATION IN ARCHITECTURE

2.1 Introduction

According to the researchers, it has been investigated that the usage of smart materials for the architectural purpose has immense significant in order to fulfill the demands and needs of twentieth first century. Moreover, using smart materials in architectural field opens a wide door for energy conservation and enables architects to provide better environmental conditions for human occupants.

Smart materials are identified as the objects that can process sensory information, sense environmental event and then react with the surrounding environment [**4**]. The most five significant characteristics that distinguish the smart materials from the traditional ones in the field of architecture are:

1. Transient
2. Selectivity
3. Instancy
4. Self-actuation
5. Directness

Smart materials have the ability to create useful effects such as; change in distribution of stresses and strains, color change, volume change and alteration in the index of refraction identify smart materials significant to architectural design as buildings are always faced with variable conditions.

The aim of this chapter is to understand the characteristics and behavior of smart materials. So, firstly, smart materials characteristics will be presented and compared with traditional material classification system to further recognize smart material behavior, secondly, taxonomy of smart materials will be elaborated.

2.2 Taxonomy of smart materials

Smart materials are differentiated by four main characteristics from traditional materials: (1) Ability of property change, (2) Ability for energy exchange, (3) discrete size/location, and (4) reversibility. Architects can take advantage of these characteristics by optimization of material properties or behavior to better match the surrounding conditions in the environment [**33**].

2.2.1 Property change

Ability of property change enables these materials of reacting to change in environmental conditions [**4**].

Change in a property or properties (Chemical, thermal, mechanical, magnetic, optical or electrical) are created in response to change in the surrounding environmental conditions. This might be ambient or simulated by direct energy input [**6**].

Table 1. Characteristics for property changing materials **[**34**]**.

Type of Smart Material	Input	Output
Property-changing		
Thermo-chromics	Temperature difference	Color change
Photo-chromics	Radiation (Light)	Color change
Mechano-chromics	Deformation	Color change
Chemo-chromics	Chemical concentration	Color change
Electro-chromics	Electric potential difference	Color change
Liquid crystals	Electric potential difference	Color change
Suspended particle	Electric potential difference	Color change
Electro-rheological	Electric potential difference	Stiffness/viscosity change
Magneto-rheological	Electric potential difference	Stiffness/viscosity change

2.2.2 Energy exchange

Many applications in architecture can take advantage of materials with the energy exchange ability, through receiving an input energy, based on thermo dynamic law, it chage to another form of energy, based on the surrounding conditions [**4**].

In spite of the fact that energy effectiveness of smart materials like thermoelectric and photovoltaic is lower than traditional energy transformation technologies, however, the effectiveness of the energy used is much higher. For instance, the connection between input and output energy releases most of energy replacing smart materials including pyro electrics, piezoelectric and photovoltaic serving as a perfect eco-friendly sensor. The resulted productive energy can be utilized in actuation features including those expressed via electro restrictive, chemo luminescent and conducting polymers [**6**].

Table 2. Characteristics for energy exchanging materials **[**34**]**.

Type of Smart Material	Input	Output
Energy-exchanging		
Electro-luminescents	Electric potential difference	Light
Photo-luminescents	Radiation	Light
Chemo-luminescents	Chemical concentration	Light
Thermo-luminescents	Temperature difference	Light
Light-emitting diodes	Electric potential difference	Light
Photovoltaics	Radiation (Light)	Electric potential difference

2.2.3 Reversibility/Directionality

Energy exchanging materials can show reversibility properties at the same time, and can return to their initial condition [**4**].

The one of the most important features of phase change materials that is energy absorption, has been utilized in order to settle an atmosphere and to produce energy for the atmosphere, according to the direction of phase change. The shape memory alloys that have bidirectional nature can be used to release various outputs, enabling the material to substitute components possessed of many parts [**6**].

Table 3. Characteristics for energy exchanging materials-reversible **[**34**]**.

Type of Smart Material	Input	Output
Energy-exchanging (reversible)		
Piezo-electric	Deformation	Electric potential difference
Pyro-electric	Temperature difference	Electric potential difference
Thermo-electric	Temperature difference	Electric potential difference
Electro-restrictive	Electric potential difference	Deformation
Magneto-restrictive	Magnetic field	Deformation

2.2.4 Size / Location

Internal regulations of position and discrete size of smart materials, allows them to perform in the most efficient position [**4**].

The one of the most important features of phase change materials that is energy absorption, has been utilized in order to settle an atmosphere and to produce energy for the atmosphere, according to the direction of phase change. The shape memory alloys that have bidirectional nature can be used to release various outputs, enabling the material to substitute components possessed of many parts [**6**].

2.2.5 Relevant properties and behaviors

Architectural advanced materials are used in massive quantities. Moreover, the integration of building systems is increasing to provide cohesive interior environment. Materials and systems have to endure various inconstant exterior conditions. Thus renders buildings of increased thermal and mechanical endurance. Subsequently, although buildings consume various types of materials for a lot of functions, there are minimal areas in which smart materials are utilized efficiently [**6**].

2.2.5.1 Building façade

Oversized complicated systems are essential to accommodate the wide range of the inconstant exterior environmental changes. Including those changes that influence heat transfer and daylight transmission through building facade. However, due to the significant feature of smart materials that is property changing have the most effective used in the field of architecture.

2.2.5.2 Structural system

The environmental swings may produce dynamic loading such as earthquake and wind on the building structural system. Since, the energy exchanging materials endures effective solutions for application in building structural systems.

2.2.5.3 HVAC and Lighting systems

According to the researchers, it has been found that around two thirds of the electrical energy has been generated in the United States which is consumed by buildings. Besides, most of the electrical energy is used to accommodate the building environmental systems like, HVAC systems. The primary purpose of mentioned systems is to create an intended influence for the interior environment. Through defining a specified lighting level, or optimizing of temperature and relative humidity. Energy exchanging materials class has effective application for energy supply sources and lighting delivery systems. The most significant uses of smart materials in building systems are using them as sensors and actuators for controlling ambient environmental systems [**6**].

2.3 Link between building characteristics and different materials

According to D. Michelle Addington, in anticipation of industrial revolution, the relation between architecture discipline and materials had been directed completely. However, either materials were selected due to their usefulness and approachability, or for visual aspects and ornamental qualities. Foundations and walls were made from locally available stone; marbles were usually used for construction covering. Material selection was defined according to decisions about building and architecture, for example, the use of materials in the pre 19th century were subject to form and function issues.

Emergence of industrial revolution extremely changed the role of materials. Instead of relying on conjectural consideration of material characteristics and durability, most of the architects are in progress with advanced engineered materials. However, in the early of 19th century by means of steel invention that resulted in the evolution of long span and high rise buildings, materials changed from being inferior to architectural needs into a way to extend functional performance.

Developments introduced in environmental systems, in addition to glass industry evolution, allowed spreading of the transparent architecture international style, were glass facades can be located at any type of weather as well as in any condition. In addition, facade material has been separated from the building infrastructure due to wide propagation of curtain wall systems. However, in order to make the facade material as a separate element, the material selection decision has been released from pragmatic functions accordingly.

Developments in Computer Aided design which is commonly known as CAD and computer Aided Manufacturing which is commonly known as CAM, enabled engineered materials like aluminum and titanium to be effectively appointed as building skins, introducing wide range of building façade forms. Materials have developed to provide visibility coupled with the best visual aspect a building could experience, for both the interior and exterior visual experience, Based on that, architects have started to use the materials as a crucial part of the design palette, that leads to select and utilize as a visual surface.

In this context many started to emulate the usage of smart materials. Conversely, smart materials are enhancing the appropriate expansion of material development by means of selective performance. For ages, architects were forced to follow standard material properties as for wood and stone, there designs were confined to material limitations, while in the 20th century, and engineering special characteristics of high performance materials had become possible in order to meet definite needs and demands. Smart materials enable more uniqueness, transformable properties [**33**].

2.3.1 Traditional material classifications in architecture

In 1948, a classification system was devised by the Construction Specification Institute (CSI), which was widely used in the field of architecture and construction industry. The classification system was divided into two parts; the first part is dedicated to expansive material classes generally utilized in buildings, comprising paints, laminate, and concrete, and the second part classifies standard building components, for example, doors, windows, and insulation. Both categories focus on application, not on material behavior or properties. For instance, in Division 6, wood characteristics are explored in relationship to their adequacy to the desired application: the class of wood convenient for load bearing roof structures or the kind of wood convenient for floor finish [**6**].

In architecture, application of new materials is enforced to suit in the previous approach, which has manifestly proved debatable in this context. CSI material classification is not meant to encourage development in the field of materials. But, they are intended to be practical templates for communication between construction multi-disciplines (Architects, contractors, fabricators and suppliers). Thereafter the completion of the preliminary design and approvals, construction documents are prepared by architects providing instructions for the building construction. Every element presented on the design drawings, is defined by a textual document, identifying materials or components. This document acts as binding contract for construction professionals and contractors. In order to simplify the specification process for architects, material and product specifications are written in the previous format by most of trade manufacturers of building products. An internal set of construction specifications are maintained by most architectural firms to serve as baseline for their projects. Although contractual applications are substantial, especially in the field of architecture that is responsible for public safety and welfare, using such specification driven system causes exclusion of innovative materials and technologies [**33**].

2.3.2 Traditional technology classification in architecture

Technologies used in architectural design and construction are categorized by the CSI index. Technologies utilized in engineering and construction field are categorized on process and product basis, the technologies are classified into two groups: the first one is usually issued by manufacturers and is committed to operational systems including HVAC, lighting, and plumbing systems, and the second one is committed to construction systems including structural, drainage, and vertical circulation systems [**6**].

2.3.3 Proposed classification system for smart materials

The unveiling of smart materials into architectural field introduced a contest to standard classification system. Although smart materials can replace a traditional material in various components and applications, smart materials characterized by their active behavior, thus, they can be applied as technologies. For instance, Electro chromic glass can be utilized as a glazing material, a window, a curtain wall system, a lighting control system, or an automated shading system. In that context the product can go under various categories, which was hard for architects to take into count the multimodal character of smart materials. However, novel technologies in the field of architectural design are unveiled by using smart materials such as sensors, whose application was limited for extremely specialized functions. Table 1 present a proposed framework in which smart materials set a relationship between materials and technologies. The proposed framework focus on the application of the traditional classification system.

Table 4. Proposed Classification System for Smart Materials and Systems [6].

Category	Fundamental material characteristics	Fundamental system behavior
Traditional materials		
Natural materials (stone, wood) Fabricated materials (steel, aluminum, concrete)	Materials have given properties and are "acted upon"	Materials have no or limited intrinsic active response capability but can have good performance properties
High performance materials:		
Polymers, composites	Material properties are designed for specific purposes	Materials have no or limited intrinsic active response capability but can have good performance properties
Smart materials:		
Property-changing and energy-exchanging materials	Properties are designed to respond intelligently to varying external conditions or stimuli	Smart materials have active responses to external stimuli and can serve as sensors and actuators
Intelligent components:		
Smart assemblies, polyvalent walls	Behaviors are designed to Behaviors are designed to respond intelligently to varying external conditions or stimuli in discrete locations	Complex behaviors can be designed to respond intelligently and directly to multimodal demands
Intelligent environments		
	Environments have designed interactive behaviors and intelligent response materials and systems "act upon" the environment	Intelligent environments consist of complex assemblies that often combine traditional materials with smart materials and components whose interactive characteristics are enabled via a computational domain

2.4 Chapter Summary

This chapter has presented the material classification in architecture and discussed a framework for the relationship between architecture and material; their different types, evolution, impact and applications.

Then with studying the characteristics of smart materials and concentrating on their actuation capabilities, and ability of reacting to environmental conditions, Smart materials can be grouped into 4 categories;

Smart materials main characteristics:

- Materials with property change capability
- Materials with energy exchange capability
- Materials with discrete size/location
- Materials with reversibility properties

CHAPTER 3: ANALOGY BETWEEN BUILDING AND BIOLOGICAL SYSTEMS

3.1 Introduction

“Architecture should strive to imitate the principles of nature without imitating its forms.” Frank Lloyd Wright

The field of architecture is an outcome that has learned from Nature. According to the researchers, it has been found that learning from Nature means capturing ideas from natural creativity and creating novel functional materials that are based on such concepts including bio-inorganic materials which is commonly known as bio mineralization, bio inspired, bio Nano-materials (bio-nanoparticles), smart biomaterials, multi scale structured materials (chiral morphologies), smart biomaterials and hybrid organic or inorganic implant materials that are known as bonelike composites. However, bio inspired smart materials have unique and attractive properties. Therefore, they are attracting more and more interest that has been paved the way of different real-world applications. Such as neural memory devices, biomimetic fins, dual or multi-responsive materials, smart micro or Nano containers for drug delivery, actively moving polymers and various sensors. In addition, majority of smart materials possess dynamic surfaces due to which they transform their physicochemical properties because of environmental swifts. There are significant creations of Nature such as the anisotropic de-wetting property of rice leaves, self-cleaning effect of lotus leaves, the attachment mechanism of geckos, the hydrophobic forces exerted by a water strider’s leg and there are many other natural phenomenon that are related to the micro-and nanostructures on natural surfaces. However, the production of such complex functional features in bio inspired materials depends on well-organized multi-scale structures.

In this chapter, strategy for analogy between building needs and biological systems will be presented, through studying a selection of different types of smart materials, followed by methods of abstraction from biological systems. Thus, examples for conceptual inspiration from nature will be further discussed and evaluated.

3.2 Smart materials and building systems

The smart materials and advanced technology that are integrated for the building construction, whether they are used for the foundation or the electric system are quite immune to change then the ornaments and products that decorate the building systems. However, except of some glazing technologies, majority of current applications that are used in the building structures, tend to become pragmatic and confined with the standard building structural systems including mechanical and electrical respectively.

According to the researchers it has been investigated that most of the systems are often founded within the infrastructure of building and many of the smart materials are placed hidden. However, as the structure of building is quite significant in order to determine its public occurrence rather than the exterior facade. On the other hand, the lighting systems have enormous impact on the perception of the users for the building. Conversely, it has been analyzed that huge developments have put forwarded in this area, while, they have not permeated into the consciousness of architect with high extent. As soon the global environment have mounted, energy systems have become more significant progressively. On the other hand, there is still enormous confusion about the role of the building as it can or it should play significant role in the complex web of energy production and application. In addition, one of the most motivating and least visible of smart material uses in a building structure comprises on the control and monitoring of building structural systems [**35**].

3.2.1 Selection of smart material types and their characteristics

When the researchers carried out research on smart materials, it has been found that smart materials are dynamic in nature as compare to traditional materials. In addition, smart materials interact and respond to their immediate environment that is one of their unique features. Due to adaptive characteristics, they are fulfilling those functions that were impossible previously. Moreover, Smart materials make products and services for the private and public spaces able to fulfill the possibility of tomorrow's global age.

In the global age, it is quite feasible to create the materials for a specific purpose according to the needs of the building owner. As the researchers stated, smart materials are playing vital role in the ordinary daily life. Most of the time, it is probable that you already put on smart materials while doing sports. Such as Lycra is light and stretchy but it is comfortable and smooth clothing. Similarly, in order to pursue outdoor clothing such as Gore-Tex is waterproof, but it is breathable and all-weather clothing.

According to the scientific studies, it has been found that smart materials are capable to do work at very fundamental functional levels. Such as plates and temperature responsive cups for little children. In addition, smart materials have been used in order to simplify and fragment complex technical systems by enhancing advanced functionality and new properties, such as independent energy supply systems for microelectronic components [**34**].

3.2.1.1 Piezoelectric materials

In 1880, Jaques and Pierre Curie discovered the piezoelectric effect by conducting a wide range of experiments by means of quartz crystals. Therefore, due to this reason the piezoelectric materials are considered one of the oldest types of smart materials. However, these materials which are primarily ceramics in nature have been found with a wide range of applications [**36**].The researchers found that the word piezoelectric has been derived from the Greek word 'piezein' that refers to press or squeeze, and the word 'piezo' refers to push in Greek. However, piezoelectric effect is the ability of some materials to produce an electric charge in reaction to applied mechanical pressure.

According to the researchers it has been analyzed that one of the most significant features of piezoelectric effect is that it is reversible effect that means, if a certain material possesses the direct piezoelectric effect which is generation of electricity while applying stress. Ultimately, exhibits the converse piezoelectric effect means production of stress while application of an electric field [**37**]**.**

However, the fundamental principle behind the phenomenon of piezoelectricity is quite simple. It has been found that certain electromagnetic materials produce electric field by means of application of mechanical stress. Take for example a staircase or floor that has been fitted with this advanced technology in order to harness the pressure that has been produced by footsteps and transform that pressure in to electricity.

In addition, the staircase or floor would possess certain sensors that would utilized the pressure that has been exerted on them caused by footsteps and convert the pressure into electricity including piezoelectric materials such as crystals or ceramics. However, piezoelectric materials convert the mechanical stress into electric charges and store it, while the amount of stored energy is utilized for a renewable power source respectively.

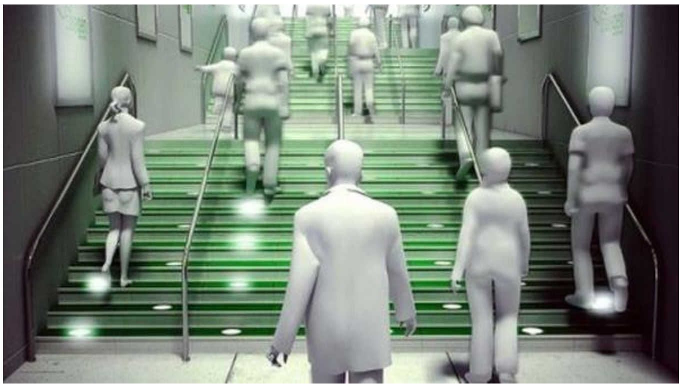


Figure 3. Imaginary model for a staircase fitted with piezoelectric technology, Photo adapted from ecofriend.com

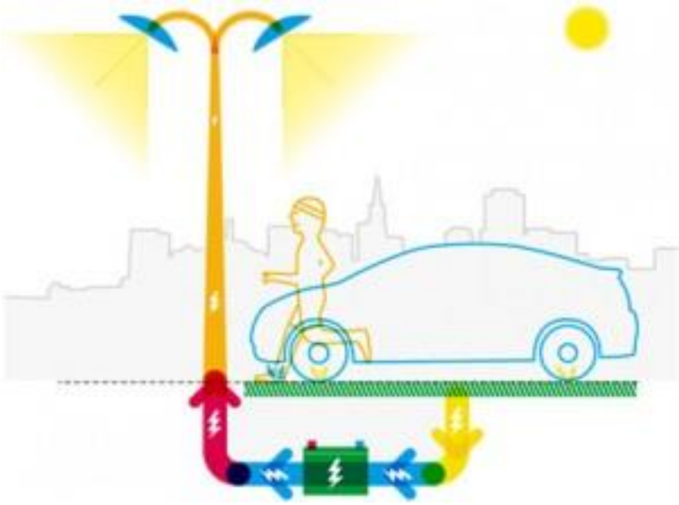


Figure 2. Diagram for harvesting mechanical energy from roadways, figure adapted from ecochunk.com

In addition, the fruitful utilization of piezoelectric technology for transportations yields power outputs of around 200 kilowatt-hour (KWH) for each kilometer by means of single line road. Moreover, 1 megawatt-hour (MWH) is utilized for each kilometer for a highway or four lane road. Furthermore, the piezoelectric technology has been utilized in other sectors as well such as pedestrian walkways, airport runways and even discotheques. For instance, most of the piezoelectric sensors are embedded under the dance floor that absorb mechanical energy which is produced by the locomotion of bodies and transform the mechanical energy into enough electricity in order to power almost sixty percent of the total energy that is required for the discotheque [**38**].

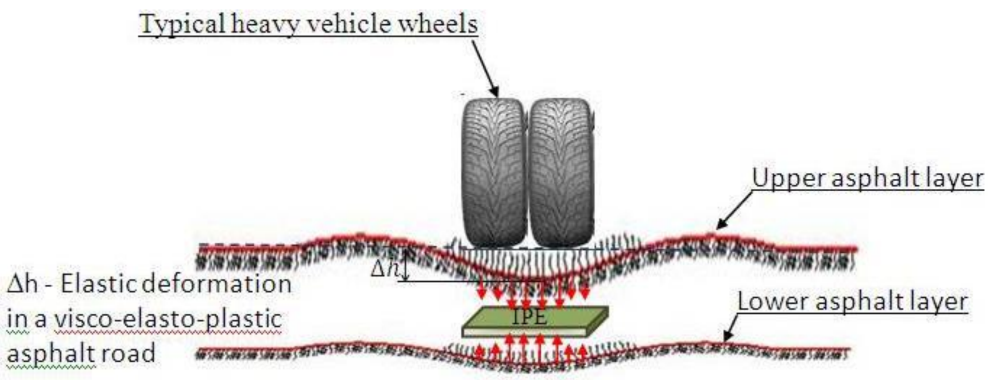


Figure 4. Embedded piezoelectric generator under upper asphalt layer, figure adapted from cheburek.net

Since piezoelectric technologies are commonly used as sensors and actuators; they can be effectively devised with other technologies creating systems to mimic natural functions.

As an inspiration from body fat biological function, piezoelectric technologies can be used as actuators along with thermo tropics as sensors for closing mechanism system to control heat loss. Some species of spiders and scorpions are able to locate and capture prey, through their ability to monitor the wave characteristics of substrate vibrations, As an inspiration from this natural function piezoelectric technologies are used to monitor stress deformation, crack and vibration monitoring in structural systems [**39**].

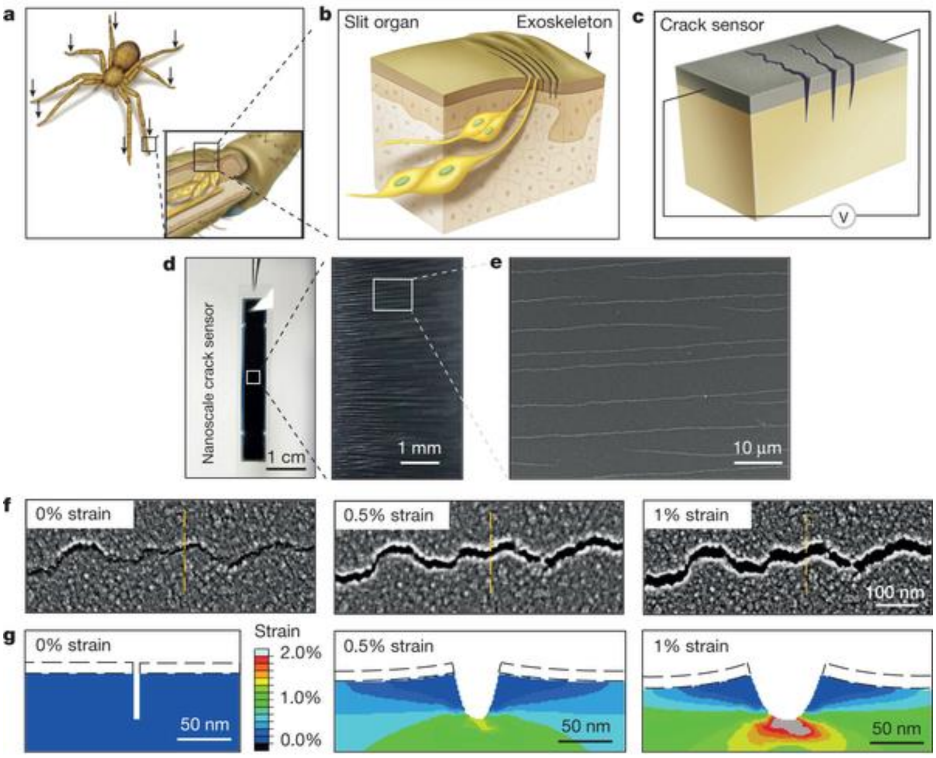


Figure 5. Ultrasensitive mechanical crack-based sensor inspired by the spider sensory system, figure adapted from nature.com

3.2.1.2 Thermoelectric

The thermoelectric effect is the conversion of a thermal differential into a current (Seebeck effect) and vice versa (Peltier effect) [**33**]. Imitation of sweating biological function can be applied through walls with capillary mechanism by using thermoelectric technologies with phase change materials, where the thermoelectric material is used as actuators and the phase change materials acts as energy reservoirs, preventing overheating during the day and helps reduction of heating costs during the evening hours.

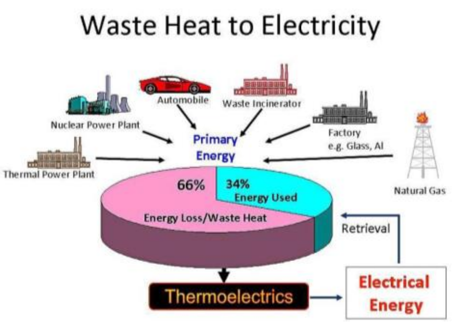


Figure 6. Diagram for conversion of waste heat to electric energy, figure adapted from albanianjournalism.com

3.2.1.3 Shape memory alloys

A shape memory alloy (SMA) which is commonly known as memory alloy or smart alloy is a type of alloy that remembers it's cold-forged and original shape that means it returns into the pre-deformed shape while on heating. The shape memory alloys have significant characteristics such as light weight, solid-state substitute to conservative actuators including pneumatic, hydraulic as well as motor-based systems. Shape memory alloys are significantly used in industries, medical purpose and aerospace. The crucially interesting property of these alloys is that they depend on the phenomenon "Shape Memory Effect" that identifies the capability of a specific type of alloy material to remember or recall or revert to its earlier remembered or recent shape. The unique feature has derived from phase transformation features of the certain material. Moreover, a molecular rearrangement or a solid state phase transformation has been occurred in the shape memory alloy that is reversible and temperature-dependent as well. For instance, the material can be molded into an arrangement at a very high temperature and dramatically deformed at a low temperature and then regain its original shape while on the application of any kind of heating, even by means of electric current. In addition, the phenomenon of super elasticity that means the material has the ability to experience reversible deformation or enormous elasticity is also correlated to the shape memory effect [**33**].

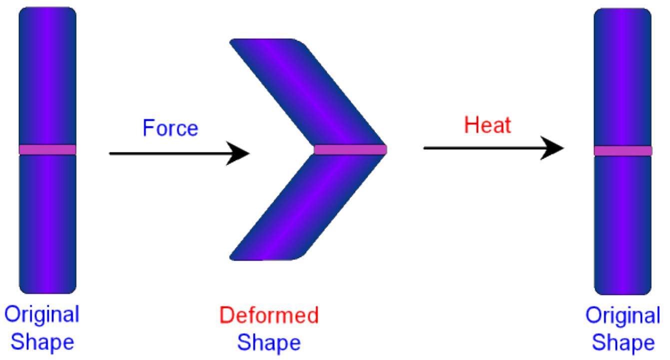


Figure 7. Diagram for shape memory alloy effect, figure adapted from gcsescience.com

Imitation from biological self-healing / repair can be applied by using systems devised from the engineering of shape memory alloys for structural and surface integration check and healing.

3.2.1.4 Photochromic materials

Figure 8. Photochromic effect, figure adapted from vivimedspecchem.com

According to the researchers, the photochromic materials have the property to absorb radiant energy that brings a reversible change of single chemical specie into two different energy states. However, they have diverse absorption spectra. In addition, photochromic materials have a unique character to absorb electromagnetic energy from ultraviolet region in order to yield an intrinsic behavior change. Due to dependency on incident energy, the material has been shifted between the absorptivity and reflectively by means of specific parts of the visible spectrum. In addition, the molecule in its deactivated form that is used for the purpose of photochromic dyes seems without color. When it is exposed to photons with a specific wavelength as well as the molecular structure is transformed into an excited state and then it activates to reflect in the visible spectrum with longer wavelengths. However, the molecule will regain its original state when the ultraviolet

(UV) source has been removed. Similarly, a typical photochromic film is essentially colorless and transparent before it is exposed to sunlight, when the film starts to transit certain wavelength particularly such as a transparent blue. In addition, it transforms into its original colorless state when there is absence of sunlight. However, its intensity highly depends on the directness of exposure [**33**].

The photochromic materials are quite useful; they are used in a wide range of applications due to its significant nature. In the field of architecture, photochromic materials are used in different facade or windows manufacturing. Inspiration of moth eye biological function is on the top of effective applications in terms of designing better solar panel coatings and anti-reflective surfaces.

3.2.2 Typical building systems and smart materials

Most of the times glowing curtains and thermo chromic paint have been seen on the walls but they tend to place in the architectural environment and therefore replace easily. However, some serious actions and commitment are necessary to go further.

The smart materials and advanced technologies that are integrated into the building construction, whether it is the electric system or the foundation beneath the earth, are enough immune to transform rather than the ornaments and products that decorate and fill the building structures. Due to this reason, such systems and components must be efficient in such a way that they meet fairly rigorous performance needs. And it is therefore that experiential data does nearly not exist and there are very little facts and figures about their endurance. However, In spite of this mentioned negation. Smart materials have already developed inroads in most of the prosaic for the building technologies.

According to the researchers, it has been found that with the exception of some glazing technologies, majority of recent applications try to be pragmatic and are confined by means of standard building systems such as mechanical, electrical and structural. In addition, as these systems are embedded in the infrastructure of building therefore the smart materials are often hidden.

Most of the smart materials are utilized as sensors. However, sensing plays a crucially important and often overshadowed role for the performance of the building structural systems. Although the most important routine operation of Heating Ventilation Air Conditioning (HVAC) system needs very precise identification of environmental factors specifically relative humidity and air pressure. Furthermore, the most perceptible kind of smart material usage is occupied in the façade and window systems area. It has been found that these materials are utilized for their cache as they as utilized for their performance. Due to this reason, architects have become quite involved in this area [**33**].

3.3 Methods of abstraction from biological systems

According to the researchers, it has been found that in the last decade the usage of nature as an inspirational source in order to resolve the technical complexities has become recognized increasingly. By means of the evolutionary pressure of natural assortment on organisms in order to stay alive under specific boundary conditions, the most optimized systems have generated. In addition, the top down approach has been utilized in order to solve the technical problems by means of communicating a summarized question for which nature has already developed an answer significantly [**40**].

3.3.1 Question

The first step in finding nature inspired solution is having a question, The most developed and complex answers are often found in organisms that developed structures under high selective pressure, e.g. pollination mechanisms.

3.3.2 Screening criteria

The next step in finding nature inspired solutions is a screening, biological concept generators with a high potential for a translation into technical applications are collected.

For example the evolutionary optimized actuation systems in plants are excellent concept generators for a transfer into elastic structures in architecture. As the plant kingdom holds ready a multitude of kinetic systems that come into consideration, the screening must be confined to plants whose moving organs show clear structure-function-principles as opposed to growth movement. This is the case when movements follow predetermined directions due to the organ’s anatomy.

3.3.3 Selection criteria

The selection criteria are aimed at finding examples with potentially efficient cost, energy and material solutions.

3.3.4 Phenomenon

Presentation of the natural system.

3.3.5 Analysis of the functional morphology

Dissection of the biological example to expose the decisive members.

3.3.6 Levels of abstraction

The verification of the first level abstraction can be done with a physical model; this is a very quick method to gain an understanding of the system and to prove the functionality of the extracted system.

The second level abstraction is analysis of the structural system, stiffness distribution, actuation system.

The third significant level of simplification is the simulation of the kinetics by means of finite elements. Therefore, in order to advance a thoughtful knowledge of the structural characteristic of the system a determinate element model has been developed.

Function and technical application: The completion of the Third abstraction level allows a detailed investigation of the system.

Reverse Bionics: In order to optimize the abstracted model and demonstrators at lab scale, a focused analysis of the functional morphology and biomechanics becomes necessary. This process is referred to as reverse bionics.

3.4 Inspiration from natural biological systems

As the terminology suggests, the difference between bio-mimicry and bio-inspiration is that the first one is defined to be direct copying from nature, while the second is where and idea is taken from nature and improved to serve a certain purpose, bio-inspiration is the area involved in this study.

According to recent scientific studies the first step to learn from nature is the selection of unique features from biological systems and utilizes them as a bio inspiration efficiently. However, lots of scientific questions have been deduced because nature has given smart responses to the external factors. In addition, it has been found that biological systems are one of the most organic-inorganic hybrid composite materials that cause the response to the external stimuli. For example; vision, smell, hearing, sound, response to scent, and light. On the other hand, the mentioned biological response systems are quite complex and complicated to emulate directly. Moreover, in recent times, some specific features have been grasping attention in biology that is less complicate to imitate. According to the researchers, it has been stated that, four types of biological inspirational characteristics have been found in nature. Such as self-cleaning features (duck feather, lotus leaf and movement of mosquitoes eyes from left to right), mechanical properties (water strider, octopus suckers and gecko feet), color by means of structure (butterfly wings, beetle shells and peacock feather), and optical characteristics (moth compound eyes, cicada wings and sponge spur). All these four important characteristics are shown in figure 9 that is comprised on image of the biological feature and scanning electron microscopy photographs of corresponding structures. All mentioned characteristics are examples that are suitable to overlook the bio-inspiration.

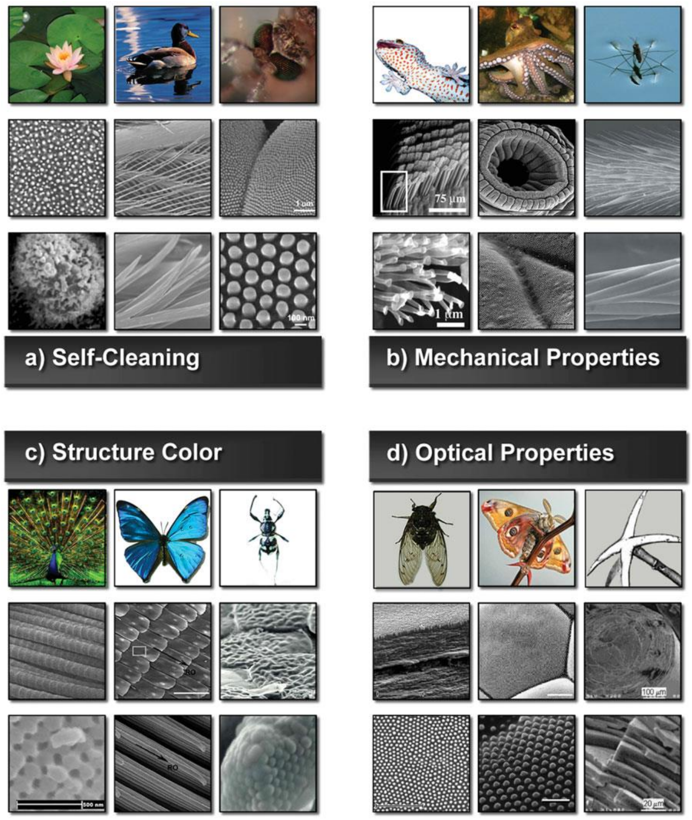


Figure 9. Multiscale structure in biology [40].

3.4.1 Inspiration from skin

Skin tissues are characterized by special absorption properties. That makes it capable of adaption in order to protect the mankind from detrimental environmental disorders. For example; strong sun light radiation that are ultra violet rays, physical and chemical wounds and invasions due to micro-organisms.

The color of human skin has been identified by means of various factors including blood concentration, amount of melanin pigment and its chemical structure, carotene, oxygenated and de-oxygenated hemoglobin and many other chemical [**41**].

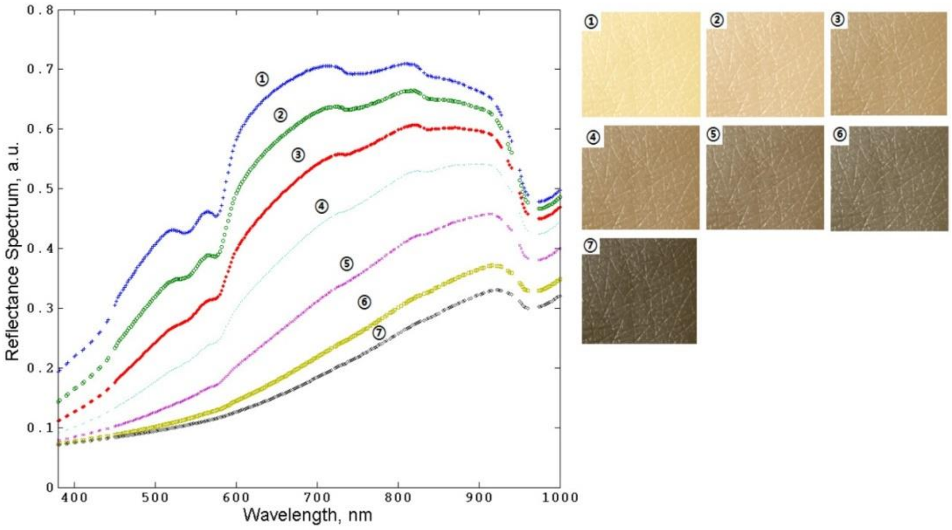


Figure 10. The results of simulation of human skin spectra (left) and corresponding colors (right) while varying the melanin content in living epidermis **[**42**].**

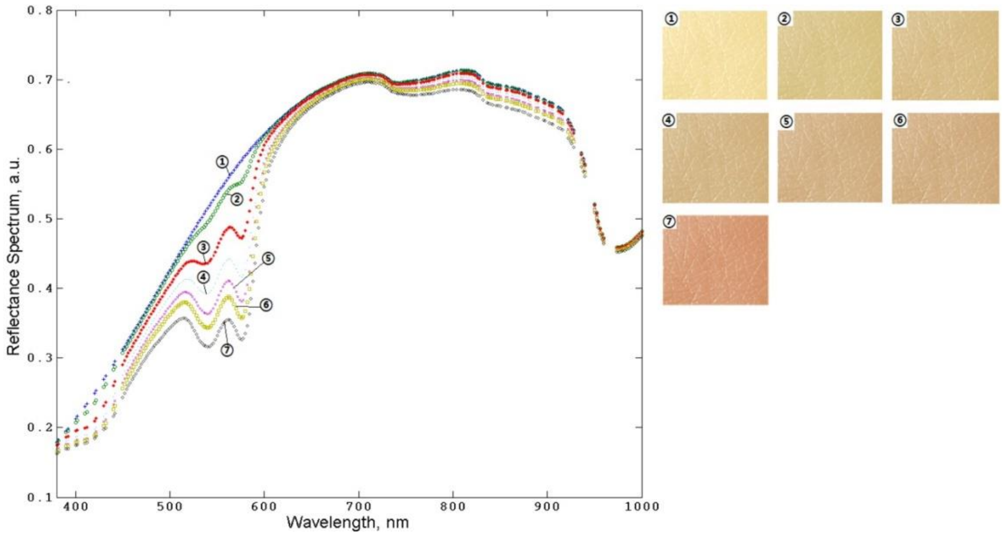


Figure 11. The results of MC simulation of human skin spectra (left) and corresponding colors (right) while varying the blood concentration in the layers from papillary dermis to subcutaneous tissue. **[**42**].**

An inspiration derived from human skin (Spectral absorptivity of skin) can be applied to control the solar radiation through enveloping material.

Inherent smart materials to this system include Photo chromic materials, Electro chromic materials, Liquid crystal panels and suspended particle panels. However, by applying these technologies, the glass is converted in to a protective envelop that helps to protect the occupants of a building structure from fire, noise, heat and also from dirt and dust by means of controlling solar radiation, self-cleaning features, behaves as a thermal insulator and much more. All protective envelops made by glass that are used for facade glazing also used for curtain walls, balustrade, doors, windows and skylight as well. Figure 12, shows glazing envelope in Lucas-film's New Singapore Headquarters, Designed by Andrew Bromberg, the building is clad in a state-of-the-art multi-layered glass façade which allows natural light to penetrate the interior while limiting solar heat gain.

Figure 12. Example of human skin inspiration, figure adapted from archdaily.com

3.4.2 Inspiration from human vellus hair

As the researchers found in their researches that a vellus hair that is very fine, light-colored hair found on most of the parts of the human body. In spite of their light colored pigment, vellus hairs are easily detectable due to their small size. Their size is about 2mm (0.08 inches) in length and their shafts are smaller or same size in diameter than the inner sheaths. However, on the upper dermis region of the skin, the bulb of vellus hair follicle is easily found. Researchers found that the vellus hair follicle is not interlinked with sebaceous gland. Subsequently, some researches appeared to identify the relationship between vellus hair growth and sebaceous gland activity. The major functions of vellus hair are; they help to normalize the body temperature, they provide protection to the human body and they are utilized as conduits in order to remove the perspiration [**43**].

Figure 13. Vellus hair, photo adapted from wikipedia.org

An inspiration derived from vellus hair can be applied to control the interior heat generation through enveloping material or membrane. For instance, using green foliage on exterior facades and roofs integrated with façade material is one of the proposed solutions. Also louvers and paneling systems with embedded sensors and actuator mechanisms can be considered for more efficiency. Figure 14. shows an example of human vellus inspiration.

Figure 14. vertical Living Gallery by Sansiri and Shma, photo adapted from jebiga.com

3.4.3 Inspiration from sweating

Researchers made an investigation to know the regulation of human body temperature. However, they found that thermoregulation is one of the significant processes that permit the human body to regulate its internal core temperature. By means of temperature receptors, human body detects the temperature changes that occurred in the external environment. In addition, the temperature receptors convey these informative signals to the processing center that is present in the brain, known as hypothalamus. Interestingly, the hypothalamus triggers changes automatically to the effectors including muscles and sweat glands in order to regulate the temperature of human body up to 37°C.

In case, if human body is too cold or too hot, nerve impulses are sent to the skin by the processing center that leads to either maximize or minimize the amount of heat loss from the surface of human body [**44**].

According to various researches, it has been observed that the hairs that are standing up on the human skin trap maximum warmth while on the other hand, if the hairs that are lying flat on skin, trap less warmth. Moreover, very tiny muscles that are present in the skin pull the hairs rapidly in order to lower the heat loss and flat them in order to maximize the heat loss. However, if the human body is too warm then the sweat glands that are present in the skin secrete sweat on the body surface in order to maximize the heat loss by means of evaporation so that the body gets cooling effect.

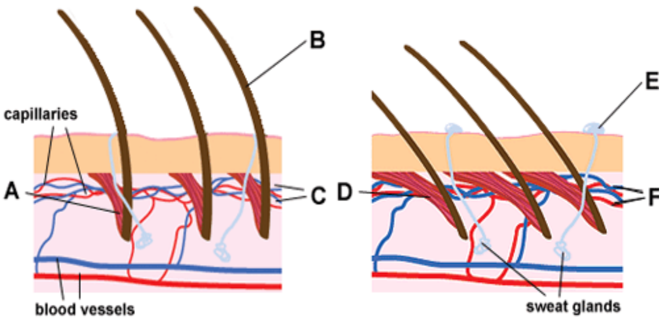


Figure 15. Body temperature control, Left when body is cold, right when body is hot. Figure adapted from bbc.co.uk

Imitation of sweating can be applied through walls with capillary mechanism by using phase changing materials and thermo electrics. Phase change materials are capable of storing sun warmth during the day and releasing it at night; this helps preventing overheating during the day and helps reduction of heating costs during the evening hours. In addition, the tracking mechanism in which the concentrated solar glass receptors are used to respond the location of sun in order to maximize the exposure of light by means of integrated concentrating solar facade (ICSF). Moreover, for the cooling and heating systems of building, the ICSF is also used to absorb thermal energy that is confined by glass receptors. However, the kinetic receptors also maximize and focus on the incoming light based on photovoltaic cell [**45**].

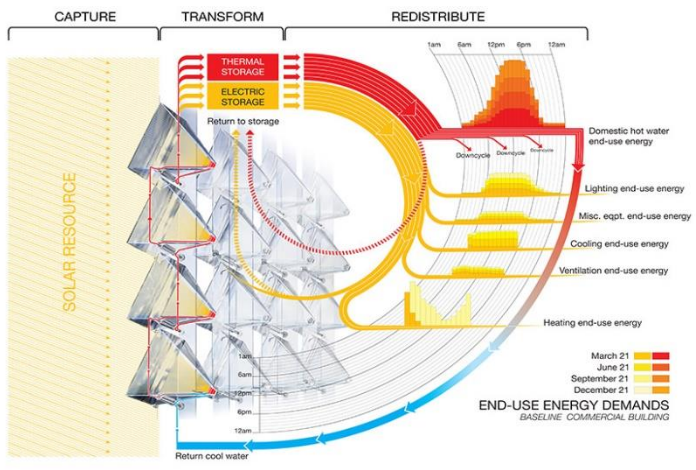
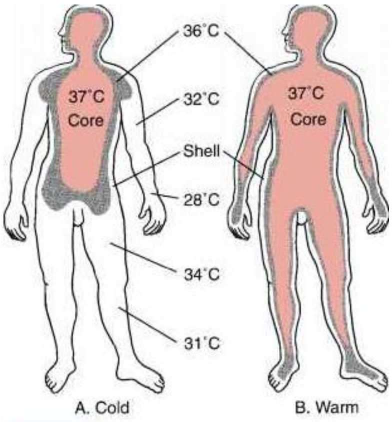


Figure 16. Example of body sweating inspiration is Integrated Concentrating Solar Façade (ICSF) by SOM. Figure adapted from som.com

3.4.4 Inspiration from body fat



Nature has created the human body in such a way that is divided into a cooler outer shell and a warm internal core as shown in figure 17. However, the temperature of the outer shell is highly influenced by the environmental factors and it is not controlled within thin boundaries as compare to the internal core temperature of the human body.

The vital organs of the human body inside the trunk and head are comprised with the internal core temperature. However, it is interlinked with numerous quantity of other fats and tissues and undergoes the warm internal core of a body [**46**].

Figure 16. Distribution of temperatures in the body's core and shell. A, During exposure to cold. B, In a warm environment. Since the temperatures of the surface and the thickness of the shell depend on environmental temperature, the shell is thicker in the cold **[**46**].**

Inspiration of body fat role in controlling heat loss from core areas (human operational areas) can be applied by using enveloping materials with special thermal conductivity. In addition, an active electrically measured switching and passive stimuli such as light intensity and temperature cause variation in optical properties of the facade or glazing elements.

Moreover, the phase change materials are significantly utilized for energy reservoirs. Piezoelectric materials are utilized for closing mechanism by means of sensors. Furthermore, the thermo tropic systems are also used such as casting resins, hydrogels, thermoplastic films and polymer blends.

Luisa Roth from the institute of advanced architecture of Catalonia has developed a humidity sensitive composite system titled ‘hydro-membrane. The membrane is composed of three materials organized in six different layers which results in distinct chemical and physical properties. the resulting material, when exposed to moisture, responds with aperture deformations that increases water absorption and evaporation rates, creating a passive cooling system.

Figure 17. Example of body fat inspiration, HYDROMEMBRANES a hydro-active textile for passive cooling **[**47**]**.

3.4.5 Inspiration from plants growth mechanism

Nature has created the living organisms in such a beautiful way that they interact and relate themselves with their environment. However, it is absolutely true for plants as well. The growth and life span of plants are strongly influenced by the abiotic factors such as; wind, water, amount of carbon dioxide and light. Researchers have been observed that plants sense all these mentioned factors and utilize them for growth, physiological and functional response [**48**].

Interestingly, researchers found that when the enlarged section of bean leaves is affected during day time they become horizontal. While, they appear less or more vertical during night time because of movement of enlarged section of leaves as shown in figure 19.

The sleeping movement of bean leaves increases the photosynthetic surface area during day time, while it lowers the loss of water by means of transpiration during night time. However, in such cases, the movement of bean leaves is like an internal rhythm.

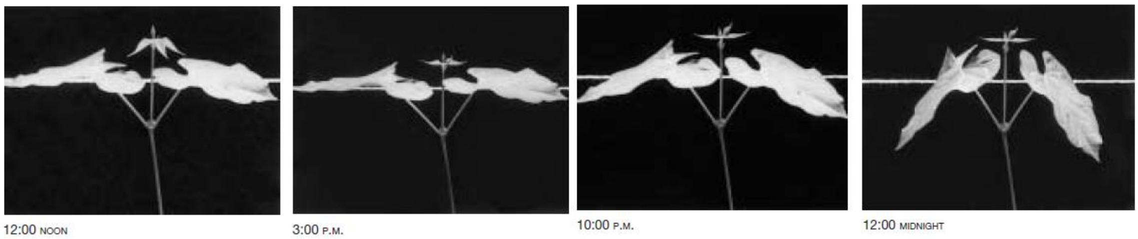


Figure 18. Sleep movements in bean leaves. In the bean plant, leaf blades are oriented horizontally during the day and vertically at night **[**48**]**.

An inspiration derived from plants mechanism can be applied for optimization of temperature and air quality of buildings. By using temperature, humidity, and air quality sensing, also occupancy sensing and Systems devised from the engineering of Thermo electrics, Pyro electrics, Biosensor, Chemical sensors, Optical MEMS.

3.4.6 Inspiration from termitaries

Termites probably have been written about more than any other insect with regard to their dwellings. In this age when sustainability is so important natural ventilation of buildings is seen as an energy saving and durable system. Termitaries demonstrate this perfectly.

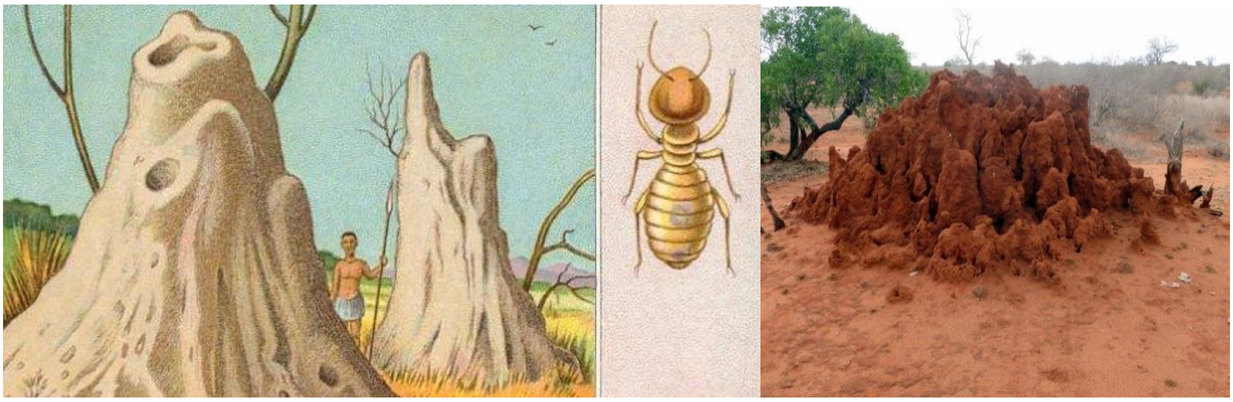


Figure 19. Nest of termitries, figure adapted from dianabuja.wordpress.com.

Nature created each and, every specie in a wonderful way. However, researchers wondered when they came to know about the nest of termites and they got inspiration from their nests. It has been found that termites like to build their nests in those places that fulfill their preferences for temperature and moisture. There are various kinds of termites that are found in nature like termites species Apicotermes gurgulifex build their nests under the soil as per their preferences for living while the dry wood termites build their nests under wood [**49**].

Interestingly, the nests of termites are well insulated and have ventilation slits. Moreover, according to Clements-Croome, (2013) these slits interlink the internal and external spaces.

Termite dwelling is another example of automatic ventilation as shown in Figure.21. The termitary of the species Macrotermes bellicosus have a height of around 3 or 4 meters and more than 2 million termites live in it. The oxygen in the fungus chamber is warmed due to the fermentation process and heat is utilized from termites spontaneously. Moreover, the warm air evolves and consumes in duct system by means of ridges wall that are spongy in nature and allow the carbon dioxide gas to evolve and oxygen gas to move in the dwelling. Based on that, the cool air replaces the warm air by means of flowing down to the cellar. That is how termites show variety in style in building their nests in different regions.

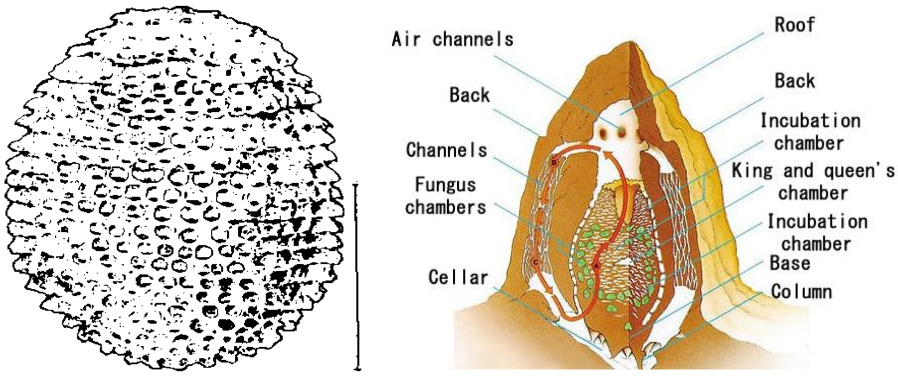


Figure 20. On the left side, nest of a termite species Apicotermes gurgulifex. The nest, about 20 cm. high, lies below ground and is surrounded by an air space. The surface is pierced by ventilation slits each surrounded by a raised ring, On the right side, cros s section through the nest of Macrotermes bellicosus (formerly, natalensis) from the Ivory Coast, Africa.
Figures adapted from harunyahya.com | es.wikipedia.org

Termites is an example from many in nature for natural ventilation system, Evaporative cooling through porous membranes is an architectural solution inspired from termitary dwellings, by using earthen vernacular architecture material like moist clay and dung.

Also, limitation of sweating mechanism through walls with capillary mechanism by the use of: Phase change materials, Thermo electrics, Nano tubes with closing mechanism.

3.4.7 Inspiration from Moths eye

Researchers investigated about the remarkable function of moth eye as they found nature has created the moth having significant feature of eye. The eye of moth rather reflects the light but it absorbs almost completely. This feature helps the moth to maximize the capturing light in order to see in the dark. However, by getting inspiration from such remarkable feature of moth eye, engineers have imitated the tiny structure of moth's eye in order to design efficient antireflective surfaces that show high performance with low fabrication cost, solar panel coatings and many other products with potential applications. Furthermore, according to Clements-Croome, (2013) it has been found that scientists are utilizing the very same principle in order to design a thin film that captivates energy efficiently from X-ray machines [**49**].

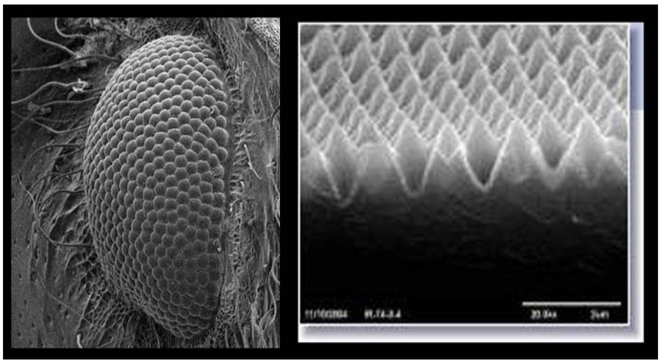


Figure 21. Microscopic view of a schematic membrane **[**49**]**.

A schematic diagram attached in the figure displays how it is working. The photovoltaic cells are used by means of membrane to absorb all incident rays coming from sunlight regardless of any direction and time as well as without any need for automatic or manual override. The figure shows the pattern of incoming rays that pass into the moth eye and how it is reflected within the cell. The remarkable feature of moth eye is incorporated to design the photovoltaic cell. The absorption of light goes on throughout the year in different conditions and causes potential difference in order to generate electricity. Moreover, the pattern created between the transparent membrane and photovoltaic cell develops a visual glass effect.

The vast usage of the electroluminescent membrane that derives the electrical energy produced by means of stored energy of the photovoltaic cells permits the glowing of whole membrane during night time. Similarly, the inner member contains an electro-chromic film. However, the electrical energy that is produced during day time by means of photovoltaic cells, charge the electro-chromic film by shading the interior structure with incident ultraviolet sunlight. Therefore, it becomes a zero energy facade and the exterior of building contains illumination system.

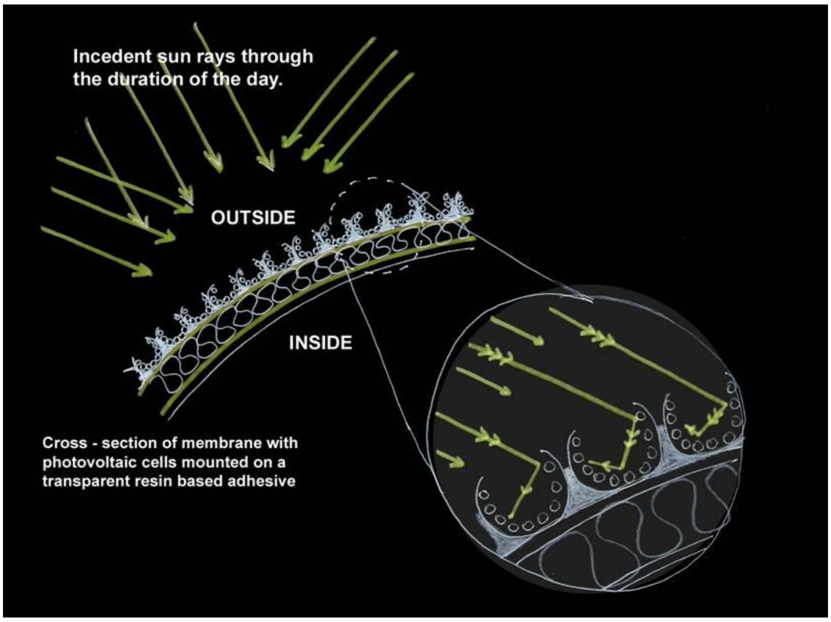


Figure 22. Example of Moths eye inspiration, cross sectional sketch of the proposed photovoltaic cell over the membrane absorbing sunrays from all directions **[**49**].**

3.5 Selected smart technologies and applications

The discipline of architecture is quite creative that always seeks better and innovative ways to build the building systems by selecting smart technologies and utilizing their applications. It is the thirst of an architect to bring new technologies and express innovative ideas to utilize the space. Moreover, architectural history is based on development of new and bold building structure and advanced construction. However, the Nano and new smart materials have immense significant in the discipline of architecture to open the new vistas in constructing the building systems and architectural design. The smart materials enable the architects to broaden the horizon from smaller scale of building structure to the larger scale of building systems.

Reason being, the designers and architects are very curious to know the advanced solutions of the technical complexities that are usually occurred on the site during construction. They are willing to identify the new ways and technologies to apply design concepts that are emerging from the inspiration of natural resources [**50**]. Therefore, the new concepts to utilize the Smart and Nano materials encourage the architects to engage and respond with fast paced by means of media-centric, responsive, and tech-centric.

In this section a selection of relevant applications and technologies to smart materials will be presented. That could be used as a tool to mimic nature and study there impact on architecture.

3.5.1 Chromogenics (Intelligent glazing)

Intelligent glazing is an application of smart materials that could be applied to simulate human skin natural function by adaption to the surrounding conditions.

The intelligent glazing is expanding due to new types of materials. It is one the significant features of the chromogenic family that it is easily switchable technology which is reasonably useful for transparent displays, mirrors, glazing and many other productive applications. Suspended particle devices (SPDs) also called electrophoretic media, electro chromic, cholesteric liquid crystals (ChLCs) and phase dispersed liquid crystals (PDLCs) are the most common examples of electrically powered technologies. In addition, the most common chromogenic effects are thermo-chromism and photo-chromism. The thermo-chromics are those materials that change their color due to change in temperature, they are mostly transitional metal oxides such as; VO_2. As they are sensitive to temperature therefore they are mainly used in aerospace industry in order to alter the emissivity of surfaces on exposure of heating. Furthermore, thermo chromic inks are utilized for temperature indication. Similarly, the photochromic materials are those materials that change their color on the exposure of ultra violet sunlight. They have been used in ophthalmic products for a very long time.

Figure 23. Electrochromic dynamic glass façade, Century Link Technology Center, Monroe, LA. Photo adapted from constructionreviewonline.com

Thermo tropic polymers are another class of chromogenic materials. These materials switch optically to the scattering state while temperature increases. However, external power is not required for it. Most of the materials are polymer blends or hydrogels, show a wide range of physical change on heating. In addition, there are hybrid materials as well including photoelectrochromic which is based on dye-sensitized nanomaterial [**51**].

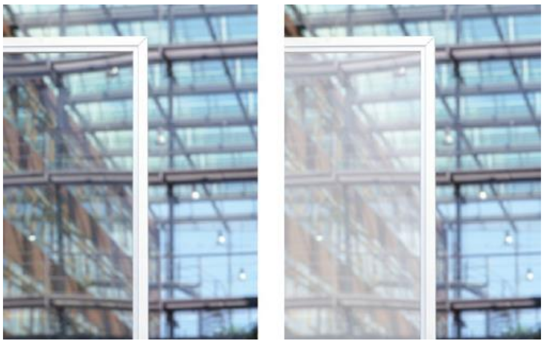


Figure 24. Thermo tropic glazing (off and on state) [52].

Architectural applications are playing vital role in building structures. In addition, the development and research for smart materials have been dominated due to architectural applications. Moreover, the flat glass for glazing in building structure is one of the most eye-catching markets since sufficient possible applications are present for architectural purpose with respect to location and type of building.

Thermo tropic materials contribute to more energy efficiency in buildings. Modern architecture is characterized by large area of glass facades creating a light and airy atmosphere inside a building. From an energy-saving point of view, a high amount of glass has pros and cons: In winter, solar light reduces the energy consumption for heating and artificial lighting. However, in summer, sun-drenched buildings heat quickly and require an immense effort for air conditioning and air circulation. In such cases, intelligent glass facades with thermo tropic properties open up new perspectives.

Thermo tropic glass systems consist of a layer containing either a thermo-sensitive resin or polymer film. By an increase of temperature induced by solar radiation, this thermo tropic layer changes from transparent to opaque and a large part of the solar radiation is reflected by back scattering. Thus, the energy requirements for cooling can be reduced significantly.

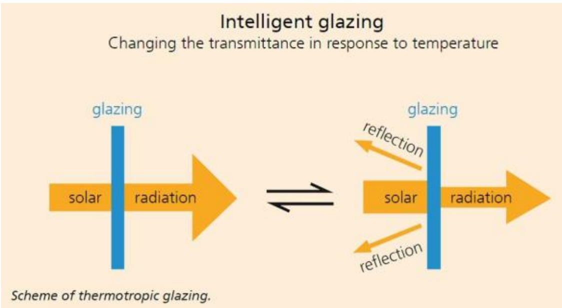


Figure 25. Intelligent glazing diagram [52].

Chromogenic materials allows a new level of design freedom for a revolutionary experience, with wide area of benefits ranging from visual experience, natural light optimization, occupant comfort, intelligent control, freedom of design and energy efficiency.

Lighting, heating and cooling effects are considered as extensive costs in a building structure. Chromogenic materials are the most energy efficient product that makes the building structure energy efficient by reducing the lighting and HVAC costs. Therefore, energy consumption and cooling peak load are lowered significantly as well as cost saving and economizing of HVAC systems occur on the basis of annual operating costs. Since, designers, architects and owners of construction projects know the main contribution of LEED certification by using chromogenic materials.

3.5.2 kinetic facades

The main aim of the building envelope is to safeguard the occupants from the environmental factors. By using smart materials, the facades become dynamic so they are adaptive to the surrounding conditions, promote comfort zone to the inhabitants and gain sustainable and flexible design by lowering the compromised necessities to acquire balance. Furthermore, facades adapt themselves according to the given environment and make their own adjustments to gain required objectives.

Researchers found that kinetic facade could come in many shapes and expressions. Their design is based on the benefits that smart materials and technologies may offer. They also can be used as a tool for various conceptual inspirations from nature, as plant movement with respect to the solar radiation.

“One Ocean” pavilion for EXPO 2012 in south Korea is one of the contemporary examples of kinetic facade. It’s design majorly based on the theme of Living Ocean and Coast that transform it into a wide range of architectural experiences. Kinetic facade that is utilized for this project based on 108 fiberglass lamellas that cause the movement. Since, a biomimetic solution was suggested to incorporate hinge-less animated façade elements [**52**]. In addition, the biomimetic approach meets the wishes of the clients and it is adopted due to inspiration of nature. The design of this project has been done according to the climatic conditions. The performance of building has been analyzed in comprehensive simulations to increase efficiency and to reduce the consumption of energy.

The design proposal was selected as the first prize winner in an open international architecture competition.

Figure 26. One ocean pavilion kinetic façade, South Korea, by Soma Architects.
Figure adapted from soma.us

3.5.3 ETFE foil membrane

Ethylene Tetrafluoroethylene which is commonly known as ETFE, is highly transparent foil, durable and very lightweight as compare to glass structures. In addition, this material is used to incorporate the long span structures for traditional skylight as well as for building facades.

The ETFE foil is coditioned with a wide range of radiation treatments in order to reduce the level of infrared (IR) rays and ultraviolet (UV) rays that are transmitted by means of membrane skin. When extra layers of ETFE foil are added to a cushion it controls the solar gain and light transmission. Moreover, multi-layer cushions can be designed in order to deal with offset intelligent printing and movable layers. However, in order to achieve reduced shading or maximized shading as per requirement, individual chambers are pressurized alternatively within the cushion. Furthermore, it has become possible to design or construct the building skin which is adaptable to the environmental factors using change of climate [**53**].

Subsequently, most of the architects are still in research phase and some have reached on development phase to utilize these systems. However, there is a remarkable example of installation of smart skin in building structure that is Media-TIC building. It was constructed in 2011 in Barcelona and it was designed by envelope specialists Vector Foil Tec Ltd and cloud9 Architect [**54**]. The pillow cladding system has been made by polymer ETFE having encased lamella fins. The pneumatic mechanisms of lamella fins activate automatically by means of light sensors that put forward an active response to the occurrence of solar energy.

Figure 27. Smart envelope comprised of ETFE encased solar-activated lamella shades developed for the Media-TIC building in Barcelona, Cloud 9 Architects, 2011, figure adapted from dezeen.com

3.5.4 Evaporative cooling

Evaporative façade systems are made of materials able to accumulate great quantities of water and release it as vapor, subtracting heat from the envelope and thus cooling the interiors (Hydro ceramic systems, Cool bricks, Tio2 evaporative cooling).

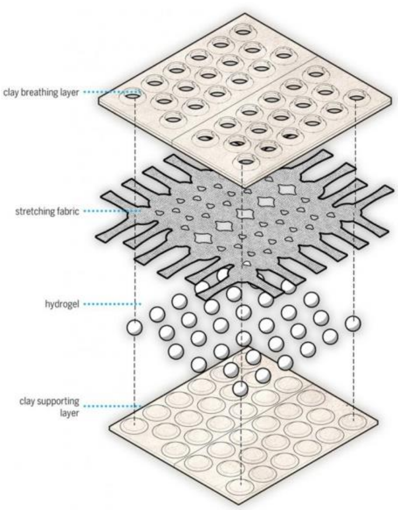


Figure 28. Hydro ceramics exploded 3D, figure adapted from iaac.net

Some students from studio of Digital Matter Intelligent Constructions (DMIC) at Barcelona's IAAC have designed Hydro ceramic, an architectural element that employs globes of hydrogel, a material absorbs more than five hundred times it's weight in water, usually made of insoluble polymers of hydroxyl ethyl acrylate, acrylamide, or polyethylene oxide (Fig. 30). By sandwiching hydrogel pellets between two breathable ceramic layers and a water supply fabric, a large evaporating surface is achieved, in contact with both interior and exterior, which can be applied on walls and roofs.

Testing has shown a reduction of internal temperature of more than 6 °C after 20 min, with an increase in air humidity of 15.5%. This solution is already weather responsive, since the evaporation and thus the cooling effect are greatest for higher temperatures and decrease when the surrounding air is already cool. This system claims to be inexpensive in manufacture (estimated cost €28/m^2) and operation (requires 1 L/m^2 water to function, which can be supplied directly by rainwater or from a harvesting tank), saving up to 28% of power consumption.

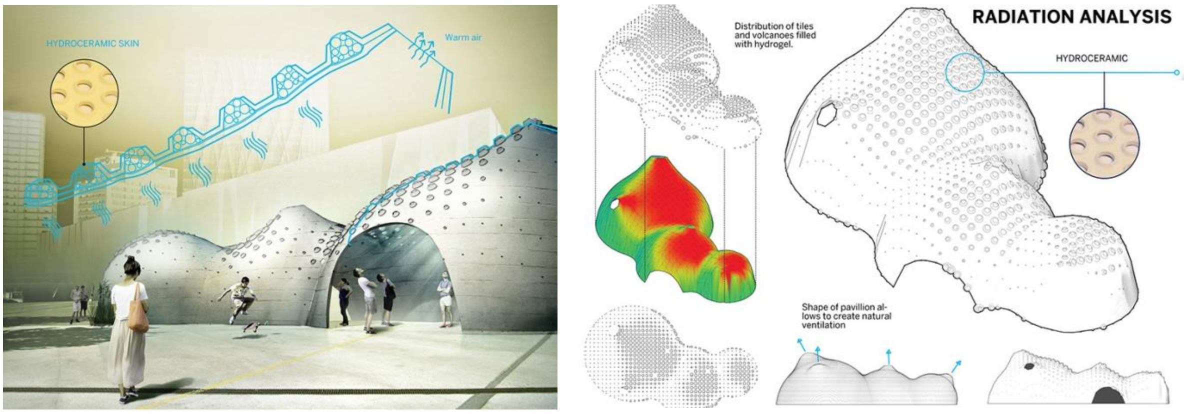


Figure 29. Hydro ceramic project of IAAC, Institute for Advanced Architecture of Catalonia developed in the Masters in Advanced Architecture in 2013-14 **[**75**]**

Cool bricks are interlocking modular blocks designed by studio Emerging Objects (Fig. 31). Their 3D-printed, porous ceramic structure is able to accumulate rainwater like sponge while remaining air permeable and then to cool interiors by evaporating water into incoming airflow, following a principle proven millennia ago by evaporative windows in Muscat, Oman.

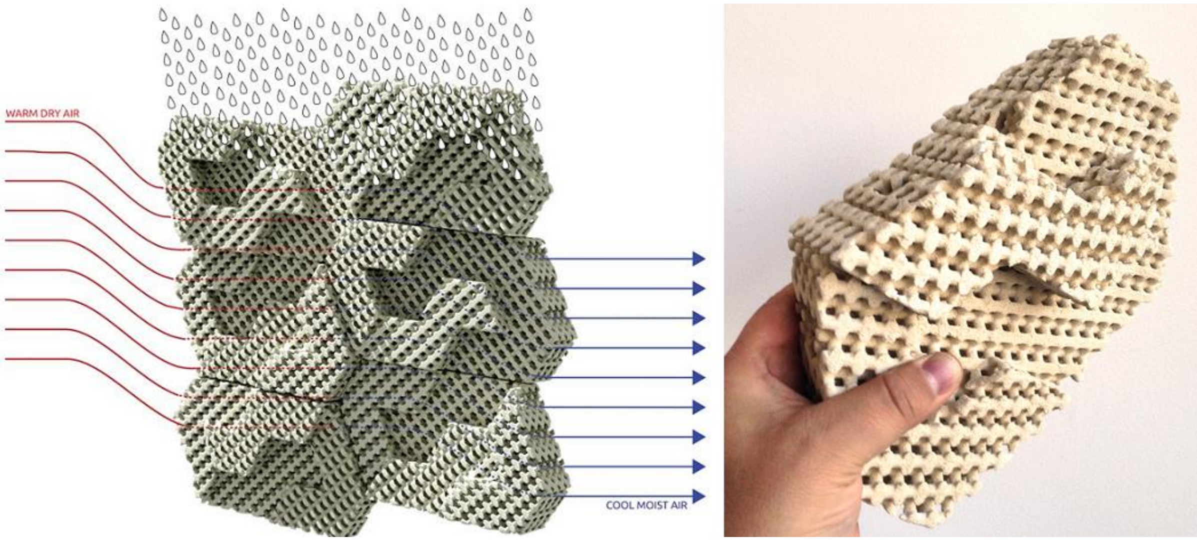


Figure 30. Interlocking modular cool bricks, figure adapted from emergingobjects.com

Evaporative cooling may also be exploited by spraying a continuous water layer on building surfaces to cool them by subtracting heat via its evaporation. A recent innovative method takes advantage of a Tio2 photo catalyst, which when irradiated by the sun causes the surface to become highly hydrophilic to minimize the consumption of water to create the water film. This way it is possible to shield the entire building with small amount of water supply, as the water layer is just 0.1 mm thick. However, testing showed lowering of temperature about

15°C on window glass while 40-50°C on black roof tile surfaces on a clear day of summer, a promising result that could significantly reduce electricity consumed for air conditioning or avoid its need altogether [**55**].

3.5.5 Thermo bimetal Skin

Thermo bimetals consists of two metals with different thermal expansion coefficients laminated on top of each other. The smart thermo bimetal Self-Ventilating skin prototype devised by DO|SU Studio Architecture is able to open its pores to allow ventilation when exposed to heat and UV rays; thermo bimetals panes react by expanding and contracting unevenly at different rates, creating tensions capable of bending the surface and eventually varying the configuration of the building envelope [**55**].

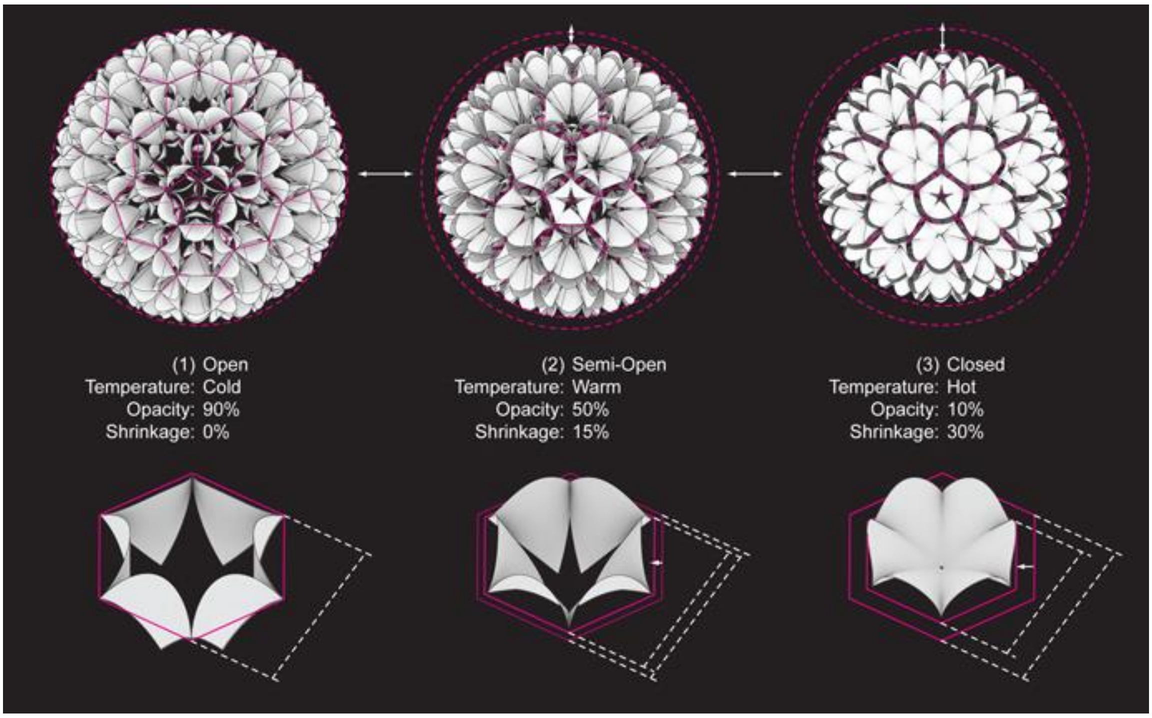


Figure 32. Hex sphere bimetal, figure adapted from DO|SU Studio Architecture.

Figure 31. Hex sphere prototype mock up, figure adapted from DO|SU Studio Architecture

The current step, more ambitious than the last, is to stitch the many aspects of thermo bimetal together into a more comprehensive prototype. The direct application to architecture is unknown at this time, but the implications for high-performance buildings are tremendous. It is part of what is called a "bottoms-up" approach, a new way of thinking about the world. Designing and building an expandable surface that opens and closes in the shape of a sphere as temperatures change is not an easy task. It will take a year of designing and redesigning. But when it is done, the product will mesh art with technology, architecture with science, aesthetics with engineering, raising new questions and spawning new ideas [**56**].

3.6 Link between natural functions and relevant smart technologies

Biomimetic science brings opportunities to think about architectural strategies as well as sustainable advancements. Since, there is need of private and public involvement of every individual in order to utilize it by open minds. Table 5 summarizes some of the features in Nature which are relevant in the man -made world and link applications by way of processes and functions that occur in Nature.

Humans possess a biological inclination to affiliate with natural systems and processes instrumental with their health and productivity. Wilson (1984).

Table 5. Various useful crossovers from Nature **[**49**].**

BIOLOGICAL INSPRIATION	BUILDING SYSTEM	REQUIRED CHARACTERISTICS	INHERENT SMART MATERIALS	ACTIVE ENGINEERING SYSTEMS
HUMAN SKIN				
	Control of Solar radiation through enveloping material	Spectral absorptivity of the skin	Photochromics	Amalgamation of two or more of these technologies for a multilateral energy exchange system. Eg photovoltaic cells mounted over Photocromic film
HAIR ON THE HEAD				
	Control of heat transfer	The relative position of the screens with respect to the skin	Use on green foliage exterior facades and roofs integrated with facade material E.g. creepers grow on membranes	Louvers and paneling systems with embedded sensors and actuator mechanisms
SWEATING				
	Control of Interior heat generation	Evaporative cooling	Earthen and vernacular architecture materials like moist clay and dung	Invitation of sweating mechanism through walls with capillary mechanism by the use of: Phase change materials Thermoelectrics
BODY FAT				
	Control of heat loss from core areas (human operational area)	Thermal Conductivity of enveloping material	Phase-change materials used as energy reservoirs.	Thermo tropics, Piezoelectrics as sensors for closing mechanism

BIOLOGICAL INSPRIATION	BUILDING NEEDS	REQUIRED CHARACTERISTICS	INHERENT SMART MATERIALS	ACTIVE ENGINEERING SYSTEMS
MOTHS EYE				
	Absorption of Solar radiation through enveloping material	Highly absorptive material in order to maximum incident radiation from the sun to generate electricity	Photovoltaics Photochromics Electrochromics	Amalagramation of two or more of these technologies for a multilateral energy exchange system. E.g. Photovoltaic cells mounted over a Photochromic film
SPIDERS WEB				
	The ability to absorb/drain/direct, moisture from the air (indoor/outdoor) and harvest water	Silky tail-shaped protein fibres which change structure in response to water	Nano-fibres provide a roughly knobby texture	Replicate the architecture of the web to channelize water
TERMITES				
	Natural ventilation	Evaporative cooling though porous membranes	Earthen vernacular architecture material like most clay and dung	Limitation of sweating mechanism through walls with capillary mechanism by the use of: Phase-change materials Thermoelectrics Nano tubes with closing mechanism
SHARK SKIN				
	Low resistance to Winds thus increasing the life of the building and reducing structural stresses	Low Friction Drag	Nano technology paints with “dermal denticals” similar to that found on the skin of a shark	
INSECTS				
	Optimization of lighting	Size, location, color and efficacy	Light-emitting diodes (LEDs) Electroluminescent Chemo luminescent paints	Product engineering with Photovoltaic materials generating electric energy for electroluminescent materials would theoretically make zero energy street lighting and ambient lighting possible.

Analogy between building and biological systems

BIOLOGICAL INSPRIATION	BUILDING NEEDS	REQUIRED CHARACTERISTICS	INHERENT SMART MATERIALS	ACTIVE ENGINEERING SYSTEMS
GROWTH MECHANISMS WITHIN PLANTS				
	Optimization of Temperature and Air Quality	Temperature, Humidity and Air Quality sensing. Also occupancy sensing		Systems devised from the engineering of Thermoelectrics Pyroelectrics Biosensor Chemical sensors Optical MEMS.
SPIDER AND SCORPIONS				
	Monitoring of Structural Systems	Stress and deformation monitoring Crack monitoring Vibration monitoring and control	Fiber-optics Piezoelectrics	Systems devised from the applications of: Electrorheologicals (ERs) Magneto rheologicals Shape memory alloys
SELF HEALING /REPAIR				
	Health monitoring of facades	Structural and surface integration check and healing	Fiber-optics Piezoelectrics Self-healing materials (Self-healing in polymers and fiber-rein forced polymer composites)	Systems devised from the engineering of Shape memory alloys
LOTUS LEAF				
	Surface finishes	Self-cleaning Heat and Radiation reflection Durability	The lotus leaf inspired Nanotechnology in: Self-cleaning paints & finishes Self-cleaning films & membranes Conductive paints Luminescent paints	
BLOOD VESSELS				
	Energy Delivery: HVAC Electrical Plumbing etc	Minimum waste of energy in conversation and also in delivery	Embedded branching analogies delivered from nature such as the branching of a tree and other such tubular systems embedded within the structural framework E.g. Fiber optics	Engineering piping and ducting within the structural framework of a building by deriving the principles of branching in nature

3.7 Chapter summary

This chapter started with individual enumeration for a selection of different types of smart materials, discussing their characteristics and their potential to conceptually mimic natural functions, followed by presenting a strategy for methods of abstraction from biological systems.

Furthermore, a group of examples for conceptual inspiration from nature was discussed and evaluated, illustrating their potential on architectural design. In that context, the previous studies was linked in table 5, summarizing some of the features in Nature which are relevant in the man -made world, representing the relationship between the way of processes and functions that occur in nature.

CHAPTER 4: CASE STUDIES

4.1 Introduction

Inspiration is the fundamental factor responsible for motivating scientists to understand and describe the complex mechanisms and processes of nature. Among the vast complexities of nature, the feats of biology present few of the greatest examples of a highly functional and efficient design, attained through centuries of biological evolution. As an idea, bio-inspiration has existed for many years. However, real-life applications of bio-inspiration cannot be seen in earlier times.

Bio-inspiration, as an idea, has only recently begun leading scientists and engineers to devise innovative solutions to real-life problems. In the present chapter, a number of studies based on the use of smart materials in architecture as an application of bio-inspiration will be reviewed. Furthermore, a comparative analysis will be evaluated, focusing on its limitations about applicability and efficiency in energy conversation**.**

4.2 Case studies for Inspiration from nature

4.2.1 Flectofin

Flectofin was designed by an interdisciplinary team consisting of biologists, architects, and engineers. It is meant to be a unique kind of louver system, as it has the special characteristic that there are no hinges to support and move the mechanical parts in the entire system. Flectofin is entirely hinge-less and it can easily rotate through an angle of 90 degrees. The system accomplishes this flexible rotation through simulation by change of temperature or displacement of the material supporting the lamina which causes the spine to bend by the stresses thus produced. Flectofin flaps can move through 90 degrees in either direction, and it has a high resolution of degrees for precise adjustment at any angle in the range 0 to 90.

The researchers were inspired by studying the kinematics of plants, which possess remarkable flexibility and elasticity, and have no need for hinges. In order to make a pliable louver system, it was first necessary to get rid of all rigid parts. In particular, the authors investigated the mechanism by which the plant strelitzia reginae pollinates. Strelitzia reginae therefore serves as the natural model on which the design of Flectofin is based. During pollination, the movement of the plant occurs by a modification of anatomical and morphological characteristics, which gives it the flexibility and elasticity it is noted for [**57**].

Figure 33. Phenomenon: The bending of Strelitzia's petals due to the bird's weight creating a simultaneous rotation of the lamina by 90 degrees in a sideways direction.
Left: Closed position, lamina at 0. Right: Open position, lamina at 90 [39].

The close examination of the plant's kinematic mechanisms led the authors to devise methods to imitate the movement of these plants in the movement of the louver system. In modern times, interactive façade systems with smart louver and blind systems are getting popular. However, these façade systems require maintenance on a continual basis as they are not free of mechanical hinges. On the other hand, the louver system of Flectofin is made of soft materials which can be readily designed for 3D printers, having no need of hinges for support [**58**].

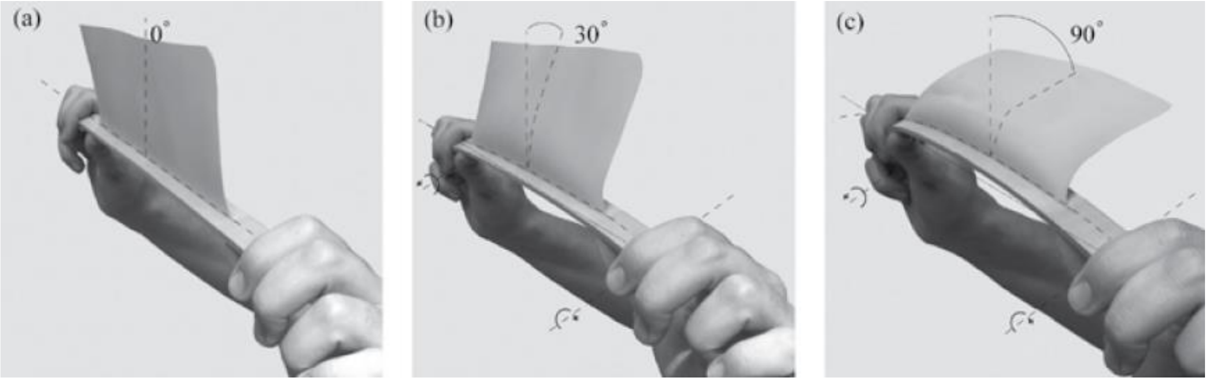


Figure 34. Physical model of the deformation principle of strelizia Reginae.
Bending the back bone causes the attached lamina to deflect up to 90 degrees sideways, which is initiated by lateral torsional buckling.
Left: Closed, lamina d at 0°
Right: Open, lamina d at 90° [55].

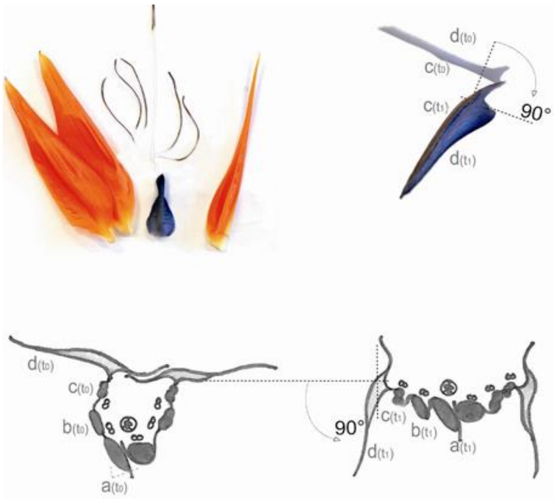


Figure 35. Analysis of the functional morphology

Top left: off cut of non decisive members

Top right: exposed kinetic system

Bottom left: section through perch closed (t0), showing the lamina d, the top strands c, the middle strands b and the double strand at the bottom a.

Bottom right: section through perch open (t1) [39].

Bio-inspiration story: All plants found in nature move, shift, and bend without support from hinges of any kind. Different plants have a different elastic range depending on their material, but the movement of every plant in reversible. Sunbirds feed on nectar and pollinate the plant Strelitzia reginae. The flower is positioned approximately at 90 degrees to the stalk, acting as a prominent spot for the bird to alight on. The shape and structure of Strelitzia reginae flower are such that the weight of the bird, as it lands on the projected section of the flower, causes the petals situated at its bottom to be pulled down, exposing the anthers of the flower. The pollen contained in the exposed anther sticks to the bird's feet as it feeds on nectar, so that when the bird lands on another flower, its pistils are deposited with the pollen covering the bird's feet. By investigating this whole process, the researchers learned the mechanism of the plant which they replicated in the design of the hinge-less structure of Flectofin louver system [**40**].

Architectural Application:

Thematic Pavilion at the EXPO 2012 in Yeosu: The Thematic Pavilion is a kinetic façade system composed of 108 lamellas of glass fiber reinforced polymers (GRFP) that move to generate a variety of animated patterns. The lamellas are driven by a screw spindle, which is in turn attached to a high-precision servomotor. The opening and closing of the fiberglass, apart from creating spectacular visual effects, also controls the lighting in the interior of the structure, functioning as an interactive window. Each lamella has a dedicated actuator, allowing individual control of these lamellas. Synchronization in the movement of actuators is accomplished by a central computer that controls each actuator through a bus system. The actuators produce compression forces on the edges of the lamellas, causing them to bend in an elastic fashion similar to Flectofin. During this process, elastic energy of the system increases due to the deformation of louvers as some of the activation energy is transformed to elastic energy and some to electrical energy. The electrical energy is produced during the closing procedure by using the servomotors acting as electrical generators [**59**]. The opening angle of louvers is related to their length: the longer is the lamella the larger is the illuminated area and the resulting spectacular effect [**60**].

Figure 36. Kinematic façade of the Thematic Pavilion EXPO 2012 in Yeosu, South-Korea. Lef: closed Lamellas, Right: Open Lamellas, Architects: soma-architecture, Vienna; Engineer for Kinetic Façade: Knippers Helbig, Stuttgart, New York, Photo adapted from e-architect.co.uk.

Figure 37. FRP lamellas blow-up, Photo adapted from e-architect.co.uk.

The climate of the project location is cool in winter, hot and humid in summer and moderate in both spring and autumn. Natural ventilation is enhanced using the adaptable skin façade through capturing and orienting the wind during non-humid intermediate seasons. Sea water heat exchangers are used for cooling radiant floor systems. High efficient turbo compression chillers, connected to seawater heat exchanger are responsible for dehumidification of air supply and radiant floor cooling during hot summer periods. Through the winter period, the chillers are operated in reverse on heating mode using seawater as an energy source for generating heat to radiant floors and mechanical ventilation system. Solar electricity is generated through integration of photovoltaic panels into the roof landscape, granting approximately 66% of the energy consumption of the building system per year [**61**].

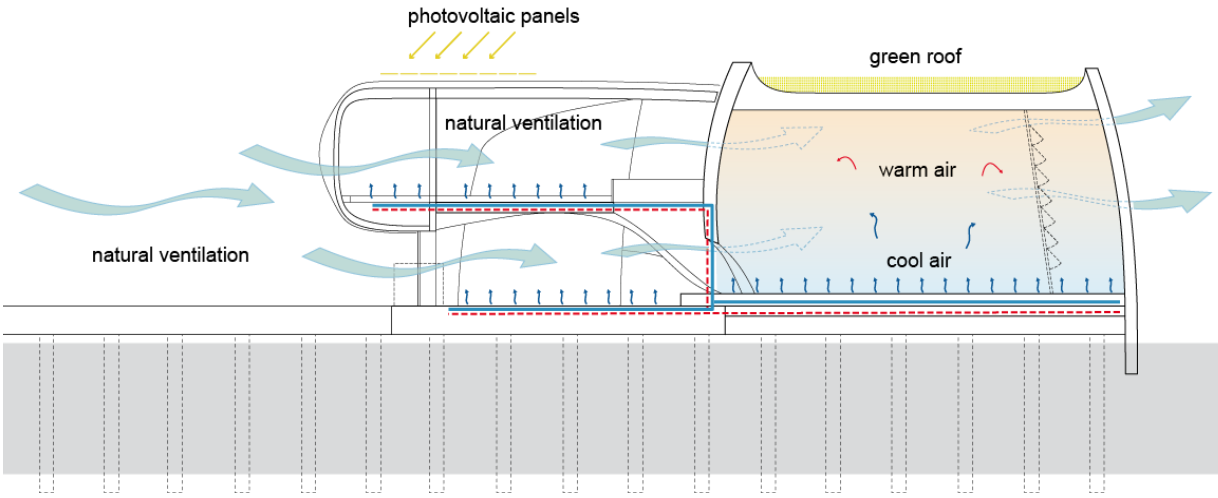


Figure 38. Section showing the existing climate design concept for the pavilion, figure adapted from Transsolar, Stuttgart München, New York.

IBA-Softhouse in Hamburg: The IBA Softhouse revealed for the first time in the international exhibition 'Bauausstellung' in Hamburg in 2013 consisted of soft textile shadings as well as elastic kinetics embedded into the textile façade. The system operates by two mechanisms of shape adaptation that the textile façade of the Softhouse can utilize.
In the Softhouse, boards made of glass fiber reinforced polymers (GFRP) are placed on the rooftop, which can change their alignment based on the sun location. Through this process, the PV cells can be positioned at various angles and make adjustments in this way. Where the GFRP boards enable vertical adjustment, membrane strips attached to the front of the façade allow the PV cells to rotate by twisting, following the East to West movement of the Sun for daylight harvesting. The Cantilevering GFRP effectively perform the function of compound springs: as it twists, the variation in the length of the membrane strip attached to GFRP is compensated [**62**].

Figure 39. IBA-Softhouse in Hamburg, Photo adapted from Kennedy & Violich Architecture.

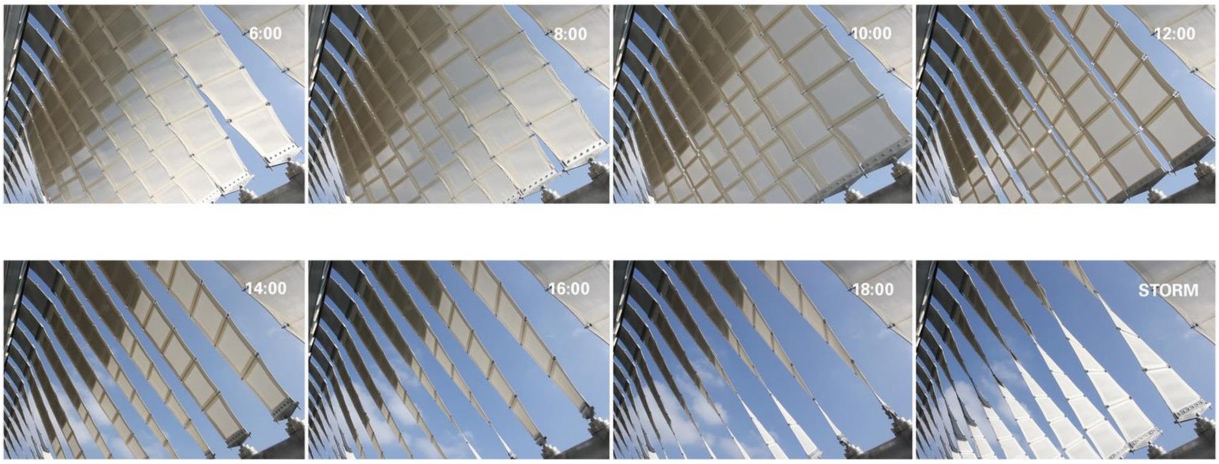


Figure 40. Responsive energy harvesting, Figure adapted from architizer.com

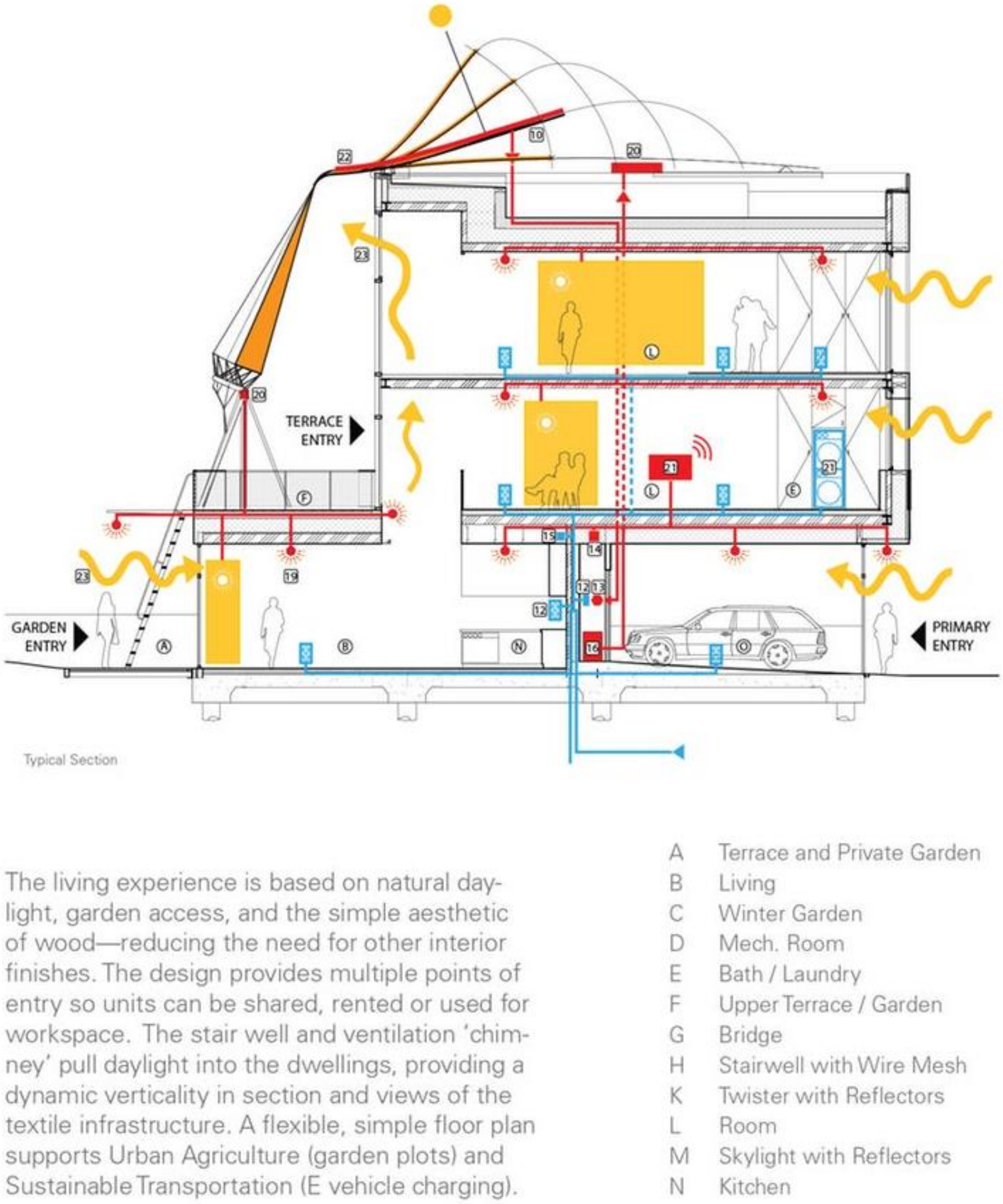


Figure 41. Typical section showing IBA-soft house components, Figure adapted from architizer.com

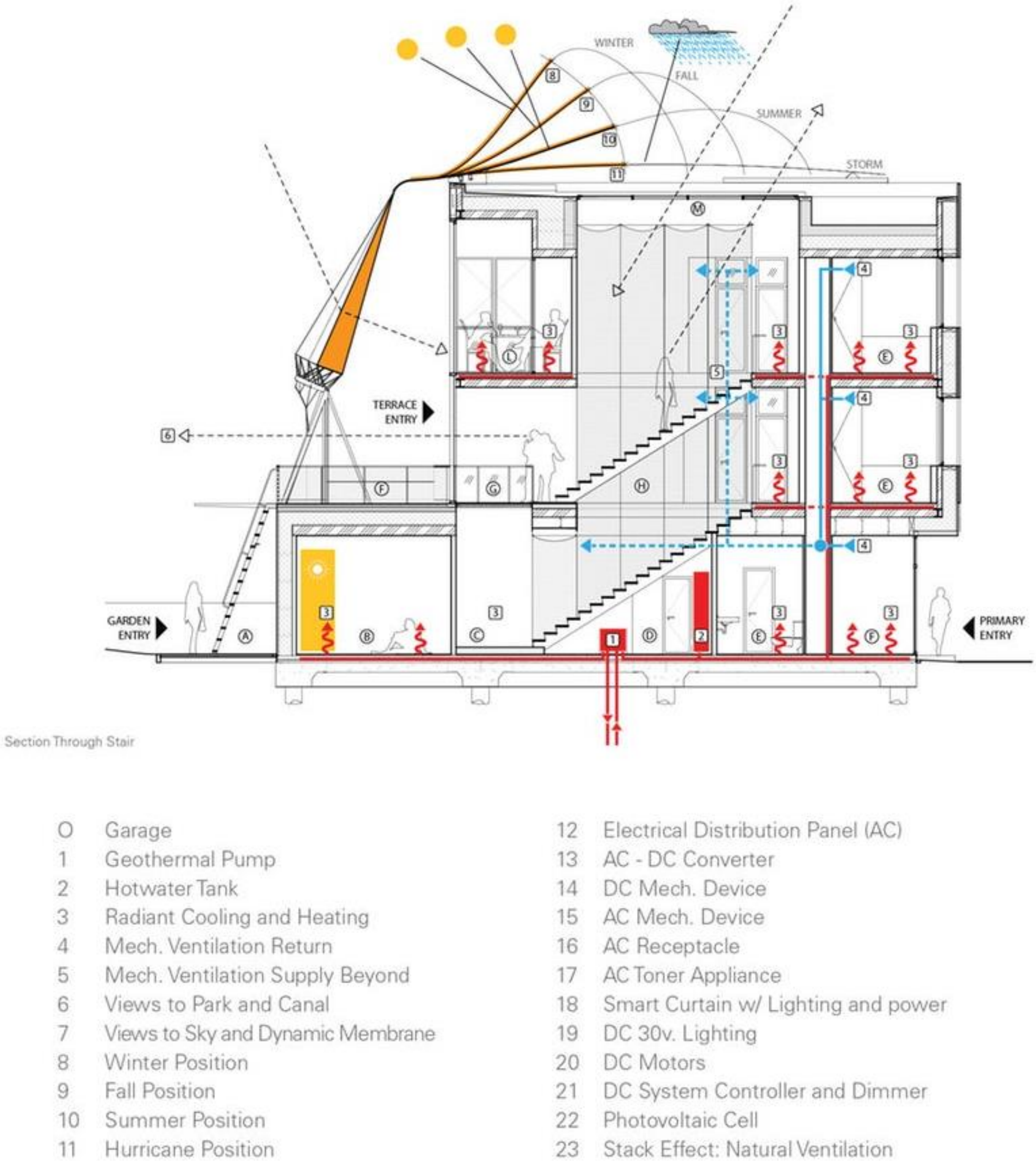


Figure 42. Section through the stair, Figure adapted from architizer.com

4.2.2 Curved-Line folding elastic kinematics

This study intends to gain a better understanding of the curved-line folding elastic kinematics of Aldrovanda vesiculosa, also known as waterwheel plant. The abstraction of the elastic kinematics of Aldrovanda vesiculosa is highly complex. A very small linear displacement actuates the complex deformation of multiple surfaces. To analyze how the patterns deform, a software called Rigid Origami Simulator software is used. The biological lobe is converted in a quad-dominant mesh with planar faces so as to study the pattern [**58**].

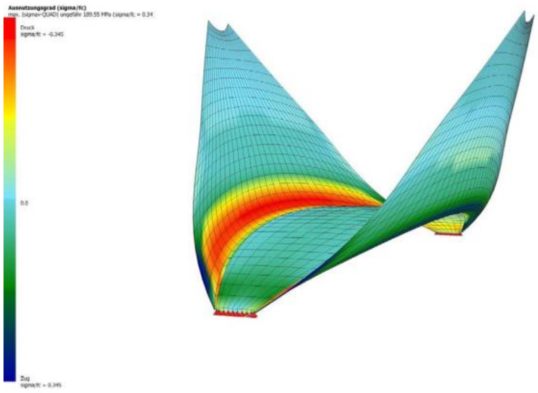


Figure 43. Simulation with bending zone **[**57**]**.

Bio-inspiration story: The plant Aldrovanda is a genus of aquatic plants. This means that its plant movement has to function underwater. The aquatic Aldrovanda is native to Asia, Africa, Australia, and Europe and can be typically found in acid bog pools with warm and standing water. Aside from its natural occurrence, Aldrovanda is also popular among hobby gardeners and is cultivated worldwide. Within the Aldrovanda genus there are only one extant species known, which is called Aldrovanda vesiculosa. This free floating and rootless aquatic plant is rather small and has a length of about 2 to 30 cm. The plant is colloquially called the waterwheel plant because it produces numerous whorls of leaves that grow on the main stem like the spokes of a wheel. These whorls are supported with air bladders, which allow them to float in the water. There are 5-10 mm long clam-like traps at the end of each Aldrovanda leaf. With these traps the plant captures and devours little aquatic organisms [**59**].

Figure 44. Aldrovanda vesiculosa. Figure adapted from **[**57**]**.

Architectural application: This novel bio-inspired pliable shading system is ideal for architectural applications with double curved, free-form geometries. The analyzed curved line folding kinematics is suitable for non-planar and non-rectangular facades, as it retains its functionality even when distorted. This geometrical flexibility in the form of double curved free form facades provides outstanding possibility for spreading the shading. Although, the cladding divisions are highly rationalized, they seem smooth in appearance. The shape of this shading system is divided into collections of planar curved panels or single ones due to economic and constructability reasons, leading to the creation of triangular or quadratic meshes. As an illustrative example of this, the folding component of a curved-line was used and applied on both curved and planar surfaces. For this process, any curved shape can act as the base, provided that the curvature is convex. However, in the present scenario, a four-sided polygon, was used for mapping the kinematical abstraction. This implies that the boundary of the polygon encompasses all segments running between two vertices. Consequently, any arrangement that is non-orthogonal is also possible [**58**].

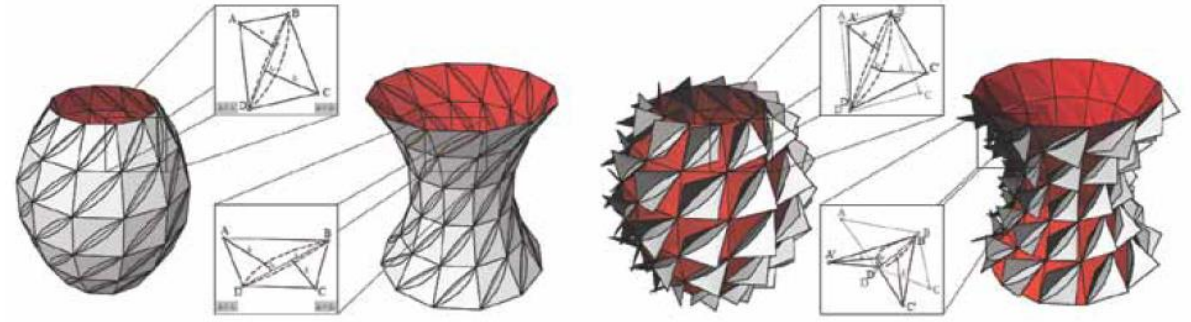


Figure 45. Parametric simulation showing synclastic and anticlastic surfaces mapped with a curved-line folding components **[**56**]**.

4.2.3 E-Skin

Buildings are non-sentient, non-living structures, which renders them static in nature like all non-living objects. They cannot adapt to changes in their immediate surroundings and have no way of sensing changes in their environmental surroundings. In the following passages, research focused on eliminating this limitation of buildings as static structures are presented.

A research team consisting of experts from various disciplines including biology, architecture, and engineering aims to herald the next breakthrough in construction and architecture through the introduction of building skins. The question of how modern issues pertaining to sustainability and ecology may be addressed by organically designed buildings lies at the heart of the e-Skin project. These researchers began the e-Skin project by contemplating how architecture may benefit from the construction of buildings having some of the behavioral characteristics of real living organisms. The basic idea behind the e-Skin project is the design and development of responsive sensors, transducers, and materials. E-Skin is a newly emerging field of research and the work discussed here is only one of the research studies being conducted by experts from diverse scientific disciplines.

The E-Skin project is concerned with examining materials from the macro to micro scales, using the behavior of human cells as the starting point for the whole project. E-skin consists of an array of low-cost responsive transducers and sensors, that is intended to be generically homogenous, yet capable of adapting to variations in the local spatiotemporal conditions. The functioning and energy demands are thus reduced for a building designed in this way. The e-skin effectively transforms the whole building to an adaptable system capable of adjusting to changes in its immediate spatiotemporal vicinity. As such a building equipped with e-skin sensors would have no need for conducting time-consuming and costly surveys, site analysis, and planning, rendering the building itself capable of adjusting its behavior by sensing the environment. Thus, e-skin buildings can significantly boost not only the immediate per formative efficiency, but also allow for ongoing contextual adaptation [**63**].

Figure 46. e-skin façade speculation, Figure adapted from jennysabin.com

Bio-inspiration story: The idea for a flexible and adaptive building has clear origins in the biological characteristics found in all forms of life. The human cells and their adaptive and flexible characteristics will serve as a real-life model for researchers in order to develop materials and sensors necessary to produce adaptive building skins. Biological experts studying cytoskeleton and motility in cancer cells, will identify the adaptive characteristics of epithelial cells. Computer scientists will then be able to model in real-time these adaptive changes by developing sophisticated algorithms. Finally, the algorithms thus developed will allow the crafting of 3-D materials equipped with feedback mechanisms and efficient transducers. The ultimate goal is improved and superior performance and optimization of energy.

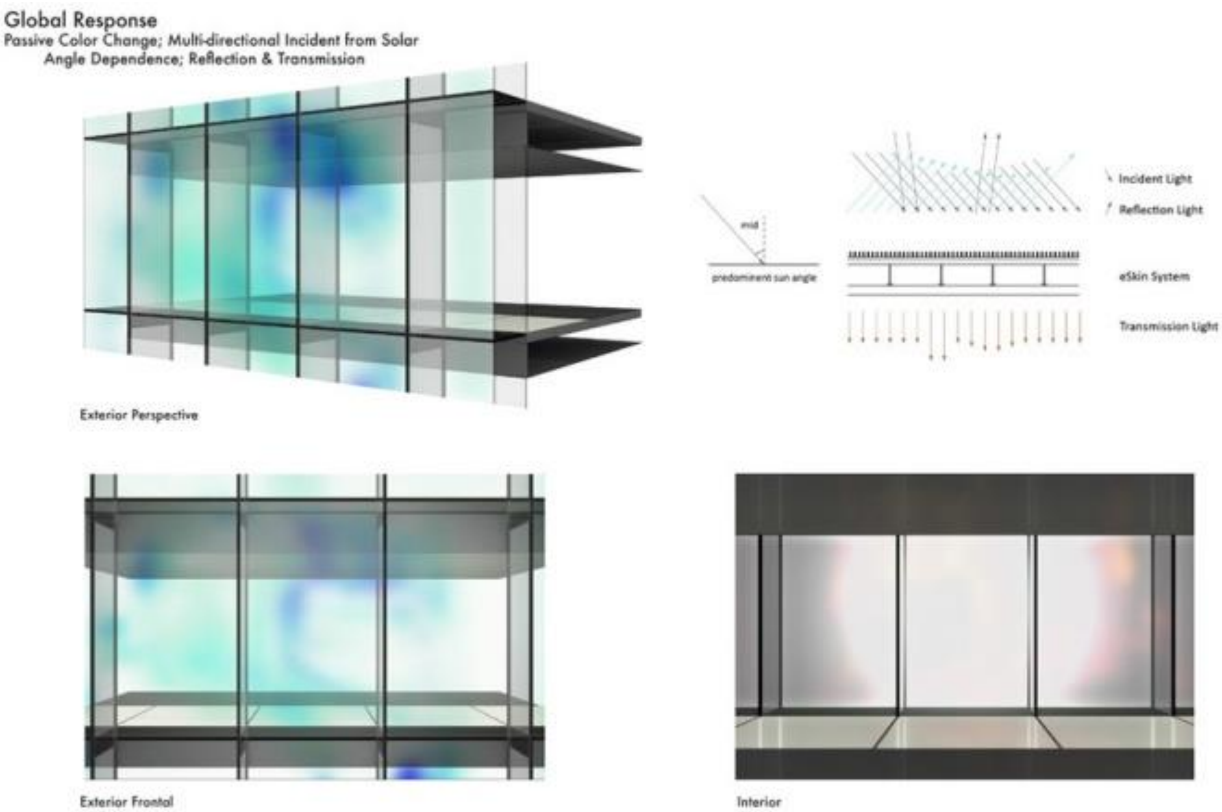


Figure 48. e-skin passive color change, Figure adapted from jennysabin.com

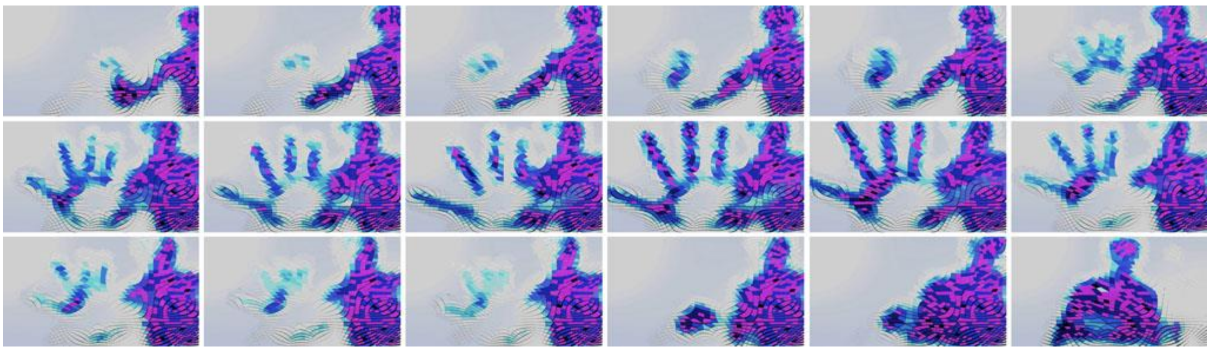


Figure 47. A sequence of still images shows a real-time simulation of e-Skin as a person comes into contact with it. Figure adapted from Jenny E. Sabin article on azuremagazine.com

Architectural Application: Future application of e-Skin is likely to solve many architectural challenges such as the existing inability of modifying building characteristics automatically in response to changes in surroundings. The subsequent phase is the testing of the responsive surface at a building scale. Realistically speaking, according to Jenny E. Sabin, we are about six to ten years away from having industry-ready e-skin products [**63**].

Figure 49. An exploded view shows eSkin's cell matrix interface and adaptive wall assembly. Figure adapted from sabinlab.aap.cornell.edu

4.2.4 Hygro-skin

The Hygro-Skin project deals with the possibility of developing architecture capable of responding to the climate. The means by which this project aims to accomplish climate-sensitive architecture include the combination of robotic manufacturing, material-inherent behavior, and computer morphogenesis. A particular example of climate-responsive architecture is in the utilization of dimensional instability of wood related to the level of moisture in the atmosphere. The architectural skin developed through this process can close or open depending on the climatic changes without any need for a power supply or other sensors. The ambient relative humidity is taken as the feedback to vary accordingly. The envelope's mechanism is controlled by the wood-composite aperture which is embedded within robotically fabricated, lightweight structural components made of elastically bent plywood panels [**64**].

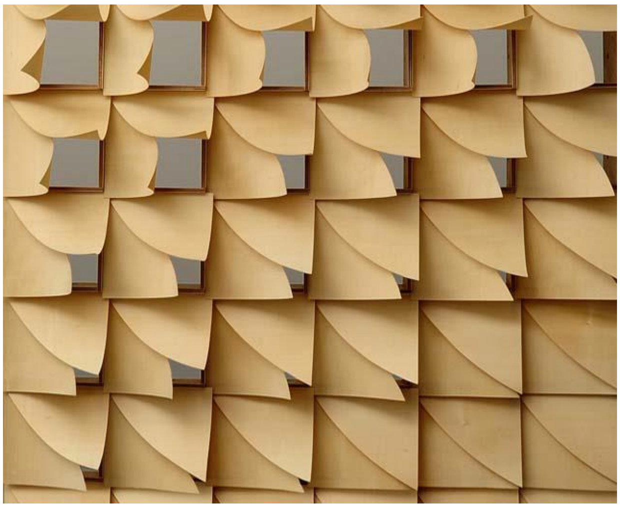


Figure 50. Responsive surface mockup structure, Photo adapted from icd.uni-stuttgart.de

Hygroscopicity is the property of some materials to absorb moisture from the atmosphere when the material is dry, and release moisture back into the atmosphere when the material is wet. This process effectively maintains the equilibrium of moisture content in the material with the relative humidity of its immediate surroundings.

Bio-inspiration story: Hygro-skin is the result of a research process that aims to deepen the intrinsic capacity of wood to reach changes of relative humidity. The most remarkable feature of this project is that it utilizes ordinary wood as a climate-sensitive component. In this adaptable system, wood cones are capable of closing and opening in order to maintain equilibrium in moisture with the surrounding atmosphere. These projects have the capability to mould the natural characteristics of the used materials to create energetically self-sufficient adaptable systems [**62**].

Figure 51. Hygro-skin inspiration from wood cones, Figure adapted from achimmenges.net

Smart materials offer a great advantage due to their energy-conservation and automation properties. Nonetheless, the narrow limits that are placed on manual operation have been a considerable disadvantage. These systems are so rigid that manual intervention is practically unfeasible. This is one of the major reasons that most smart materials are only developed as prototypes. Most infrastructures are not suitable for the application of smart materials, especially buildings that are in private use.

In public buildings such as museums and airports, smart materials are more feasible as direct intervention of the user is usually not required there. The results of several studies suggest that personal comfort is related to the degree of control a person feels in modifying his living/working environment. This means that user control should not be neglected by paying all attention to smart automation of building environments [**62**].

Architectural application: The Meteorosensitive Pavillion in Stuttgart is the most notable application of climate-sensitive architecture. The Meterosensitive Pavillion project is based on the exploitation of the adaptive ability of the materials used in the structure itself. This application is in contrast to most of the other applications of climate-responsive architecture which consist of sophisticated sensors and equipment integrated with materials that are otherwise inert and static. The Meterosensitive Pavilion, as explained above, uses the dimensional instability of the wood material to open or close the apertures on the skin depending on changes in climate. The meter sensitive architectural skin requires no power supplies or any other form of energy input to function. The only parameter that affects its behavior is the climate itself [**65**]. Therefore, apart from being effective in adjusting in response to climate changes, it is energy-efficient as well, with zero carbon foot print.

Figure 55. Meteorosensitive Pavilion in Stadtgarten, Stuttgart, Figure adapted from achimmenges.net

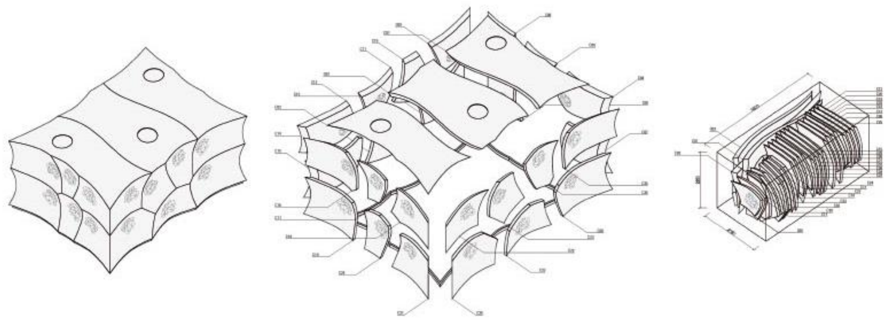


Figure 54. . The modular construction of the Pavilion, displayed in an axonometric view, Figure adapted from achimmenges.net

Figure 52. Interior view of the HygroSkin Pavilion [62].

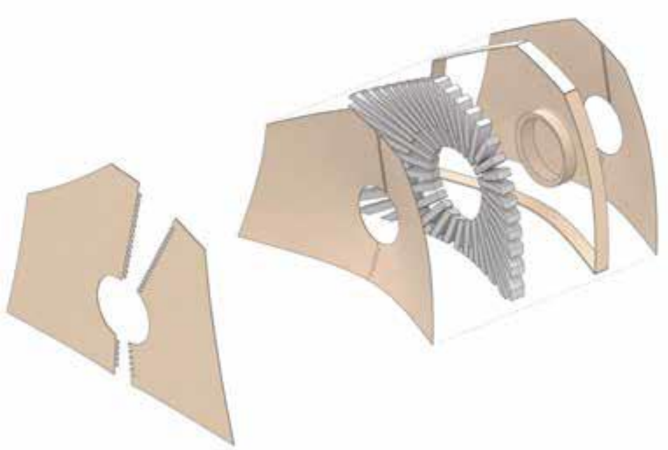


Figure 53. Exploded axonometric view of the module layers [62].

The design of the structure was modeled after the plate shell geometry as explained by Anne Bagger. The modules are arranged such that connection lines never appear along the same axis, increasing structural strength as well as flexibility of the structure.

The finite element analysis (FEA) corroborates the supposition that most of the loads are present axially, and bending loads are small in strength. For the HygroSkin Pavilion, an integration of the performance of wood and properties of materials were integrated into the fabrication process and the computer model. The adoption of a parametric production process ensured precision and dimensional accuracy in the development of the material, geometric and structural data, the computational detailing of all joints, the elastic bending process, and connections and the milling and trimming of each building component with a 7-axis industrial robot.

This interrelationship of material computation, computational design, digital development, and robotic fabrication resulted in a highly precise, lightweight, geometrically complex morphology with a climate responsive architectural skin [**64**].

Figure 56. Finite Element Analysis of the HygroSkin Pavilion.
Left: Von Mises stress results of the overall structure.
Right: Von Mises stress results of the structural frame [**62**].

Homeostatic system

The technologist Decker Yeadon developed a façade system operating on similar principles as the HygroSkin. It consists of a double-skin glass façade that is capable of closing or opening by sensing the temperature within the building and adjusting the skin apertures accordingly. The homeostatic façade system utilizes smart materials to maintain the temperature of the building at comfortable levels. The system operates like living organisms that regulate their temperatures in a process known as homeostasis. In appearance, the façade mimics the look of a window curving lines imposed on it. These lines are composed of ribbons of an elastomer coated with a flexible polymer core. The surface of the “window” is deformed by an electrical charge deposited by the silver coating on the elastomer [**66**].

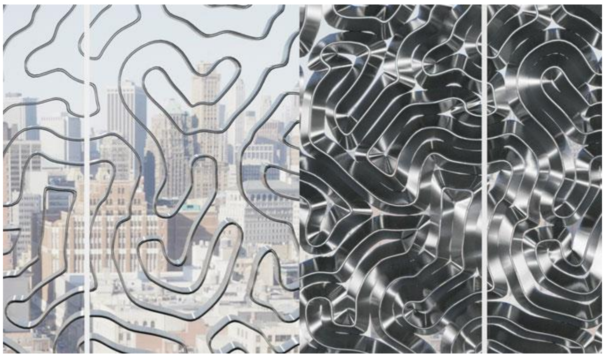


Figure 57. Homeostatic façade system, Photo adapted from http://www.conservationmagazine.org

As the warmth of sunlight increases the temperature of the building during the day, the elastomer increases in size, obstructing a greater amount of sunlight to cast shade within the building. When the building becomes cooler during the latter part of the day, the elastomer shrinks so that more light can enter the building and produce a heating effect inside.

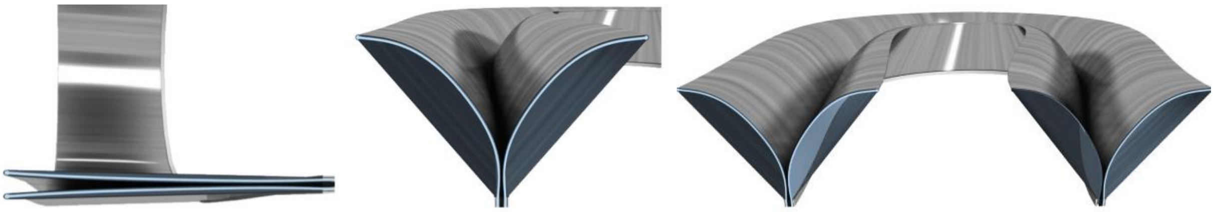


Figure 59. Homeostatic ribbons in different states [78].

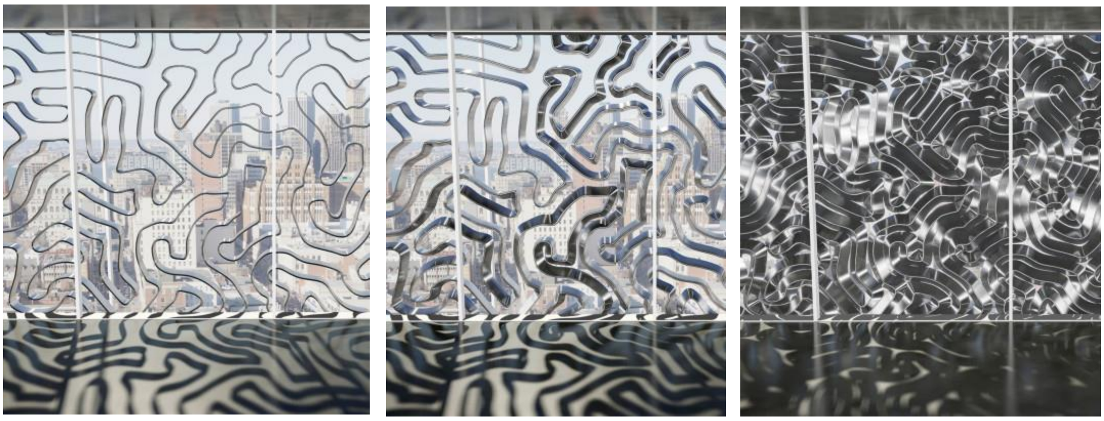


Figure 58. Homeostatic interior experience, Left Fully open, Middle Partially open, Right Fully closed, Photos adapted from [78]

Bio-inspiration story: For the homeostatic façade system, Decker Yeadon took inspiration from the homeostasis system inherent in living organisms, and the shape of brain corals. The design of the swirling lines on the "window" of the façade is inspired by the patterns of brain corals. Living organisms can regulate and maintain the functioning of their internal systems at the optimum level in the process known as homeostasis. Decker Yeadon replicated this biological mechanism in the façade system, enabling it to regulate its internal conditions by sensing the external environment. Using locally available energy and substances, the façade system adjusts itself to local conditions effectively [**66**].

Figure 60. Brain coral, Photo adapted from intlfieldstudies.org

Architectural Application: The homeostatic system is still in prototype stages. However, the results of the system are already showing great promises. Studies show that the homeostatic system is highly sensitive to environmental conditions. It is extremely effective in detecting minor changes in the surrounding enviroment and adjusting its internal conditions in response. Natural variations such as partial and momentary obstruction of sunlight and shadows cast by surrounding structures are sensed very well by the system. Moreover, the greatest advantage of this façade system is that it has no need for a power supply or devices, providing remarkable energy efficiency. Nonetheless, the disadvantage of the system is that it is rigid and does not offer the user the controls to manually change the conditions within the building [**67**].

Figure 61. Homeostatic system Architectural façade speculation [78].

4.3 Case studies analysis

4.3.1 Comparative analysis

The technologies utilized for transforming most buildings into adaptable systems are based on sensing of conditions by the building skin, as shown by the case studies considered above. This is accomplished through the simulation of various bio-inspiration models and application of relevant smart materials. The table below is an attempt to analyze the efficiency and applicability of the studied systems.

Table 6. Case studies analysis **[The researcher].**

Flectofin "Expo thematic pavilion"	**Flecofin** "IBA-Softhouse"	Curved line folding elastic kinematics	E-Skin	Hygro-Skin	Homoeostatic system
Adaptive System					
Elastic kinetic shading system	Solar tracking system	Elastic kinetic shading system	Adaptable real-time building envelope	Climate responsive envelope	Climate responsive envelope
Bio-inspiration model					
Bird of the paradise flower pollination mechanism		The elastic kinematics of Aldrovanda vesiculosa	The flexibility and sensory adaptivity of human cells	Wood cones changes with relative humidity	Homeostasis function in biological systems
Relevant smart materials / technologies					
Shape memory behavior of "GFRP"	Flexible photovoltaics attached to "GFRP"	N/A Digital simulation stage	Patterned 3-D materials with integrated sensors and feedback controls	Responsive wood composite with Hygroscopicity + shape memory behavior	Elastomer ribbons wrapped over a flexible polymer core
Actuation stimuli / Input					
Programmed user input	Solar radiation and sun angle	N/A Digital simulation stage	Solar radiation, Occupancy, Heat transfer	Change in relative humidity	Building interior temprature
Actuation mechnism					
User input	Intrinsic control "Passive system"	N/A Digital simulation stage	Intrinsic control "Passive system"	Intrinsic control "Passive system"	Intrinsic control "Passive system"
Energy conservation qualities					
Solar radiation control	Solar radiation control and Optimized energy harvesting 24,000 KWh/year	Solar radiation control	Optimization of building skin, Building adaption to changing external environments	Maintain moisture content in equilibrium with the surrounding RH	Regulation of building climate

Flectofin "Expo thematic pavilion"	**Flecofin** "IBA-Softhouse"	**Curved line folding elastic kinematics**	**E-Skin**	**Hygro-Skin**	**Homoeostatic system**
Architectural application					
Kinetic façade integrated system in South Korea	Solar tracking façade integrated system in Hamburg	N/A Digital simulation Stage	N/A Prototype stage	Climate responsive envelope of Meteorosensitive Pavilion in Stuttgart	N/A Prototype stage
Research year and place "Research development"					
2011 University of Stuttgart, Germany.		2011 University of Stuttgart, Germany.	2013 University of Pennsylvania, USA.	2007 University of Stuttgart, Germany.	2011 Decker Yeadon Architects New York, USA.
Architectural application year					
2012	2013	N/A Digital simulation Stage	N/A Prototype stage	2013	N/A Prototype stage

4.3.2 Analysis conclusions

The aim of composing the above table was to compare different aspects of the case studies presented earlier, and that comparison revealed various promising conclusions, Discussed and presented below.

Inspiration model prospect for technical application: The case studies based on inspiration from biological systems such as, adaptivity of human cells and Homeostasis function in biological systems, are all in prototype stage, thus further mean that, inspiration from plant movement such as, Bird of the paradise flower pollination mechanism and wood cones, have more tendency for technical and architectural application rather than biological systems.

Smart material stimuli: The previous analysis revealed that the most common stimuli in architectural applications are solar radiation, temperature change and relative humidity.

Passive and Active smart systems: Intrinsic control plays a key role in this case, as 80% of the presented case studies are based on passive systems that automatically responds and adapts to the surrounding climatic changes without energy input.

Energy conservation qualities: The solar radiation control and optimized energy harvesting comes at the first place and then maintaining moister level in equilibrium with the surrounding relative humidity.

4.4 Chapter Summary

This chapter has presented 5 case studies for bio-inspiration along with their architectural applications, concluding with a comparative analysis of the case studied used.

Selected case studies for analysis

- Flectofin
- Curved line folding elastic kinematics
- E-Skin
- Hygro-Skin
- Homeostatic system

Comparative analysis critiria

- Adaptive system
- Bio-inspiration model
- Relevant smart materials and technologies
- Actuation stimuli
- Actuation mechanism
- Energy conservation qualities
- Architectural application
- Research development "Year and place"
- Date of Architectural application

Consequently, the comparative analysis was used as a basis to draw a set of conclusions.

CHAPTER 5: SUMMARY AND CONCLUSIONS

5.1 Summary

This thesis is the outcome of integration between smart materials investigation and studying of bio-inspiration approach. Linking the two parts reveals a promising conceptual approach for architectural design.

Although nature and architecture seems distinct, both are commonly based on material and system issues. Moreover, with the rapid development of smart and Nano-scale materials, more approaches are exposed, connecting nature with architecture. Accordingly, massive changes will occur in the field of architecture and construction. That shall dramatically change our perception of buildings.

This thesis started with exploring the taxonomy of smart materials; their properties, attributes and relevant applications, then understanding the link between building characteristics and different materials. Analogy between building behavior and biological systems are then discussed in chapter 3, introducing conceptual study for a selection of smart materials focusing on their characteristics and discussing theoretically how these materials can be used as a tool for conceptual inspiration from nature, following these with a strategy for abstraction from biological systems and sample instances for inspiration from nature. A comprehensive table is consequently presented linking conceptual inspiration from natural functions and relevant smart materials.

The case studies was elaborated in chapter 4, presenting 5 selected cases for bio-inspiration and their architectural applications. By doing a comparative analysis between different aspects of the presented case studies, a set of promising conclusions was extracted showing the potential of the thesis scope within the context of architectural design and building performance.

5.2 Impact on current and future architecture

The following points can be concluded from the previous studies;

- As we have seen in the case studies presented in chapter 4, most of the adaptive systems are dynamic facades. Many of the modern buildings achieve their adaptivity through interpretation of the building skin. The most common form is shading systems which can be blinds, openable louvers or dynamic shading. For this thesis, bio-inspired shading systems based on smart materials are analyzed, and evaluated in terms of energy conservation qualities and applicability prospect.
- The case studies based on inspiration from biological systems such as, adaptivity of human cells and Homeostasis function in biological systems, are all in prototype stage, thus further mean that, inspiration from plant movement such as, Bird of the paradise flower pollination mechanism and wood cones, have more tendency for technical and architectural application rather than biological systems.
- It can be inferred that the behavior of adaptive systems carries more importance than the mechanism of adaptation itself. The mechanism is only the potential that triggers the system behavior.

- A new generation of buildings is on the way; buildings with extremely high technological aspects, that are excessively sustainable and ecological in their behavior using the intelligent properties of adaptive materials and technologies that have the ability to respond and react to changes of their surroundings, and adjust themselves to perfectly adapt.
- Materials have recently developed to provide visibility coupled with the best visual aspect a building could experience, for both the interior and exterior visual experience. Based on that, architects starts to think of materials as a part of the design palette. That could be selected and utilized as visual surface.
- The presented approach of using smart materials as a tool to mimic nature enables architects to develop new forms and express new ideas of space, by opening a new era in architectural design and construction.
- New concepts of materiality emerging from Nano and smart materials can allow architects to further respond and engage our present connected.
- Architects are enabled to develop more advanced architecture in terms of sustainability.

5.3 Limitations

There are three great limitations facing the scope of this research.

- Firstly, most of the smart material applications require huge funding, as they are too expensive in terms of manufacturing, incorporation and installation.
- Secondly, bio-inspiration is an emerging discipline and therefore still in developmental stage. Though the field of architecture has consistently been the most intrigued by bio-inspiration, and there are numerous commercial products and several individual buildings that have demonstrated lessons from nature. Yet, within the built environment, bio-inspiration is still in its infancy. But from another side, there is a positive attitude towards moving contemporary sustainable design towards smart materials and bio-inspiration development.
- Thirdly, the intrinsic systems based on smart materials behavior, such as homeostatic façade system, are highly responsive even to small changes as it responds in real-time, such as to the sun going behind clouds or to the shadows of the neighboring building. As the system does not need any sensors or electrical power to work, it offers exceptional levels of energy efficiency. Nonetheless, the disadvantage of the system is that it is rigid and does not offer the user the controls to manually change the conditions within the building

5.4 Recommendations

- To advance the implementation of the presented Approach, It is necessary to encourage and carry out the tasks of research and technological development in a wide spectrum of disciplines, such as materialization design and its industrialization, biomimetic design, Structural and mechanical design, and computational design as well.
- Governments should encourage carrying out programs that provide financial support of scientists with funding for project costs and coordination between researchers from different disciplines (e.g. consumables, student assistants, equipment etc.)

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ملخص البحث

تعتبر المواد الذكية من أهم الحلول الفعالة لمواكبة متطلبات القرن الحادى و العشرون, فاستخدام المواد الذكية له تأثيركبير على طرق و ادوات التصميم المعمارى, الهدف من هذا البحث هو دراسة كيفية استخدام المواد الذكية لمحاكاة الطبيعة فى التصميم المعمارى و توضيح أهميتها و تأثيرها على شكل العمارة المعاصرة و العمارة فى المستقبل. يتبين هذا التأثير فى شكل خفض معدلات الطاقة المستخدمة لتشغيل انظمة المبانى و توفير ظروف بيئية افضل لمستخدمى الفراغات.

المواد الذكية هي مواد معالجة هندسيا تتأثر بالظروف المناخية المحيطة, و لها خواص يمكن ان تتغير وتتعدل بشكل تبعا للمحفزات الخارجية مثل الضوء, الحرارة , الرطوبة, القوة ميكانيكية وأيضًا المجالات الكهربية والمغناطيسية.

يرجع اختيار موضوع خاص بالمواد الذكية الى تزايد الاهتمام المجتمعى و المعمارى للاستفادة من التطور المستمر و السريع فى هذا المجال, بحثا عن حلول مختلفة للعديد من المشاكل. فتوفر انواع متعددة, ذات خصائص متعددة, من المواد الذكية يجعلها ملائمة للتطبيق فى مجال الهندسة المعمارية. فى هذا السياق, التفكير فى استخدام تطبيقات المواد الذكية يمثل منطقة مثيرة للاهتمام و البحث, و يفتح الباب لطرق تفكير مختلفة و بعيدة عن المألوف فى مجال الهندسة المعمارية و مجالات التشييد و البناء.

تتكون هذه الرسالة من خمسة فصول, يتناول كل منهم جانب من العناصر المكونة للبحث.

يتناول الفصل الاول مقدمة تعريفية للمصطلحات الاساسية المستخدمة فى هذا البحث. و ينقسم الى قسمين, القسم الاول يسلط الضوء على اهداف هذه الدراسة البحثية (كيفية استخدام المواد الذكية لمحاكاة الطبيعة و تأثير ذلك على مجال التصميم المعمارى و مجالات التشييد و البناء), ثم يتم توضيح المنهجية المتبعة للوصول لتلك الاهداف (المنهج الاستطلاعى التحليلى). القسم الثانى يتناول نبذة عن الخلفية التاريخية لتقنيات البناء و تطور مجال مواد البناء, يليه عرض للوضع البحثى الحالى لموضوع الدراسة.

يمثل الفصل الثانى محاولة لفهم طبيعة و خصائص المواد الذكية, و ينقسم الى قسمين, القسم الاول يدرس العلاقة بين خصائص المبانى و المواد المختلفة. و الجزء الثانى يتناول طبيعة المواد الذكية و ما يميزها من خصائص,عن المواد التقليدية.

يمثل الفصل الثالث جوهر البحث و الجزء الاهم, حيث يتم فيه الربط بين العناصر المكونة لهيكل البحث (دراسة المواد الذكية و دراسة محاكاة الطبيعة). و ينقسم الى خمسة اقسام, القسم الاول يتناول امثلة مختلفة للمواد الذكية, لتوضيح استخدامهم و امثلة لتطبيقاتهم. يلى ذلك عرض منهجية تجريبية لكيفية الاستخلاص من الانظمة الحيوية فى القسم الثانى, و يركز القسم الثالث على تقديم امثلة موجزة لمفهوم محاكاة الخصائص الطبيعية و الانظمة الحيوية. يليها عرض لمجموعة من التطبيقات للانظمة و المواد الذكية. يتبع ما سبق دراسة تحليلية تربط بين العناصر المكونة لهيكل البحث موضحة كيفية استخدام المواد و التطبيقات الذكية الحديثة لمحاكاة الطبيعة و الانظمة الحيوية فى القسم الخامس.

يتناول الفصل الرابع الجانب التطبيقى للبحث, و هو منقسم الى جزئين, الجزء الاول يتناول دراسات لأمثلة تطبيقية لمحاكاة البيئة بأستخدام المواد الذكية. يلى ذلك فى القسم الثانى, تقديم دراسة تحليلية عن طريق عمل مقارنة للامثلة السابق ذكرها.

يشتمل الفصل الخامس و الاخير على ثلاثة اقسام , القسم الاول يقدم عرض لنتائج البحث, وصولا للهدف الرئيسى للبحث من وضع استيراتيجية لكيفية استخدام المواد الذكية لمحاكاة الطبيعة فى العمارة و توضيح ما لها من اثار لتحسين اداء المبانى المعاصرة و توفير بيئة افضل لمستخدمى الفراغات ودعم لمفاهيم الاستدامة, بالاضافة الى التأثير على شكل العمارة المعاصرة و تكنولوجيا البناء و التشييد. يلى ذلك عرض للتحديات و العوائق المواجهة لموضوع البحث, و اخيرا توصيات على ضرورة الاهتمام و دعم البحوث متعددة التخصصات , مما يساهم فى توفير بيانات تجريبية اكثر من شأنها التشجيع على تطبيق الاستيراتيجية المقدمة فى هذا البحث بشكل اوسع فى مجالات التصميم المعمارى و تكنولوجيا البناء و التشييد.

لجنة الاشراف **التوقيع**

الاستاذ الدكتور / محمد انور فكرى ....
(أستاذ العمارة, قسم الهندسة المعمارية
كلية الهندسة, جامعة الاسكندرية)

الدكتور / وليد محمد عبد العال ....
(محاضر, قسم الهندسة المعمارية
كلية الهندسة, جامعة الاسكندرية)

محاكاة الطبيعة فى العمارة باستخدام المواد الذكية

رسالة مقدمة من

ياسمين طلعت احمد نصر

للحصول على درجة

ماجيستير العلوم فى الهندسة المعمارية

لجنة المناقشة والحكم على الرسالة	التوقيع
الاستاذ الدكتور / محمد انور فكرى (أستاذ العمارة, قسم الهندسة المعمارية كلية الهندسة, جامعة الاسكندرية)	....
الاستاذ الدكتور / وليد فؤاد عمر (أستاذ العمارة, قسم العمارة كلية الفنون الجميلة, جامعة الاسكندرية)	....
الاستاذ الدكتور / هانى محمد عياد (أستاذ التخطيط و التصميم العمرانى , قسم الهندسة المعمارية كلية الهندسة, جامعة الاسكندرية)	....

وكيل الكلية للدراسات العليا والبحوث
كلية الهندسة – جامعة الاسكندرية

أ.د. مجدى عبد العظيم

محاكاة الطبيعة فى العمارة باستخدام المواد الذكية

رسالة علمية

مقدمة الى قسم الهندسة المعمارية – جامعه الاسكندرية

استيفاء للدراسات المقررة للحصول على درجة

ماجستير العلوم الهندسية

فى

الهندسة المعمارية

مقدمة من
ياسمين طلعت احمد نصر

ابريل 2017