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Advanced building's skin design towards the optimization of the energy consumption in hot and arid regions.

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DEDICATION

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I dedicate this work to all my family members who always encouraged me to do my best. Their assistance, along with their continuous motivation kept me going. I am forever thankful to my parents Naceur KHELIL and Leila DJEROU for being such understanding and supportive figures in my life. Many thanks to my sister Asma and my brothers Alla Eddine, Hatem and Sofiane, I can never thank them enough for their endless support and encouragement especially in difficult times.

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Chapter 1

INTRODUCTION

" Architecture is the triumph of human imagination over materials, methods, and men, to put man into possession of his own earth. It is at least the geometric pattern of things, of life, of the human and social world. It is at best that magic framework of reality that we sometimes touch upon when we use the world order."

- Frank Lloyd Wright

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The International Panel on Climate Change (IPCC) classified buildings as a sector that has the potential to minimize the global warming problem [Loonen 2010]. This dilemma has changed our vision and priority given to the energy efficiency, in both new and existing buildings low energy implementation should become a part of the practice of designing a building, rather than the novelty of the project.

Today improvement of building services application such as in lighting, heating, ventilation and air-conditioning (HVAC) (Heating, Ventilating and Air-conditioning), have been assigned to enhance the performance of indoor environment and thermal comfort. Therefore, external building envelopes are starting to lose their role as a moderator of energy and comfort and as a consequence, a building place a significant energy load on maintaining optimal condition in building indoor environment and this problem contributes to one third of total greenhouse gas emissions.

In hot and arid regions, the major challenge now is the overheating of buildings in the summer (sometimes also in spring and autumn) and the increased cooling demand, which leads to use active strategies to address the challenge like the HVAC systems. However we believe that the important point is the building design rather than external treatment like the HVAC system, because these systems cause a noticeable global warming affect by burning fossil fuels, and we keep adding CO2 in the atmosphere, increasing this affect. Besides the greenhouse effect, we face depletion of our natural resources.

To solve this dilemma of almost permanent overheating of buildings in an energy efficient way and to assure the thermal comfort; which is the pursuit of indoor environment design; where its zone is different and changeable depending on the individual difference and preference [Culp 2008]; there is a demand for a new architectural trend. Architecture is currently experiencing a demand for smart, responsive-based designs, where the occupants comfort level is achieved through means of perception, processing, and response. Buildings are becoming more like high performance working robots/machines.

Adaptive systems combine the best of existing strategies: low energy use and control over building environments and they have the ability to adapt and interact with the surrounding environment and its variants, which include light, sound, wind, heat or with people [Elkhayat 2014b]. For instance, a building's energy requirements can be considerably lowered if its design can adapt to temperature fluctuations. An adaptive system that is modulated to control the volume and direction of heat flow in response to external and internal conditions can enhance comfort and energy performance [AlThobaiti 2014].

Architecture evolved in the belief that the static, permanent forms of traditional architecture are no longer suitable for use in times of major change. So we are obliged to develop a stronger design science approach and open the lines of communication between design and science disciplines, which is critical, science can find creative solutions and design can develop more innovative creations. Faced with endless influencing parameters such as time, weather, functions, information, human needs, etc. architecture should be designed with multiple dimensions to face this infinity of forces. The design process should consider the adaptation to the changing conditions, which can be in terms of the building usage, environmental factors or even in the changes of sociological demands.

Adaptive architecture has potential for using our natural resources in efficient way and also for responding to the era's needs. Many design techniques and technologies, which aim to respond to the constantly changing needs, have appeared. The most prominent of these is kinetic architecture [Elkhayat 2014b].

The new paradigm shift in architecture coincides with advancements in computer science, cybernetics, and building technology that have altered the architecture from a static form to a more kinetic and dynamic form ([Kolarevic 2009];[Kensek 2011]). Kinetic architecture is supposed to be dynamic, adaptable and capable of being added to, reduced, or even being disposable [Maria 2008], aiming to link past practices related to kinetic form with motion-based emerging technologies in a meaningful way and project into the inherent architectural possibilities [Elrazaz 2010]. The integration of motion into the built environment, results the aesthetics, design and performance of buildings that is of great importance to the field of architecture. Although the aesthetic value of virtual motion may always be a source of inspiration, its physical implementation in buildings and structures may challenge the very nature of what architecture really is [Elrazaz 2010].

Today's life is dynamic, therefore the space we are living in should be dynamic as well, adjustable to our needs that change continuously to our concept of design and our mood. Kinetic buildings can follow the rhythms of nature and can change direction and shape from spring to summer, from sunrise to sunset and adjust themselves to the weather so; buildings will be alive [Elrazaz 2010].

The challenge of developing sustainable, adaptive kinetic architecture requires unconventional approaches to innovative knowledge about composition and dynamic interaction between the building and environmental conditions. Nature has always inspired humanity by solving the basic needs with minimum material and sustainable solutions. Observation of nature enables architects and engineers familiar with highly developed structures and lead to the creation of new forms. The designs that are produced by learning from nature lead to practical engineering solutions in terms of sustainability. This biomimetic approach is developed via an evaluation of preceding research in various fields, focusing on the applications of their biomimetic principles, and an investigation of potential biological strategies relevant to the predefined performance criteria.

In this research, we are treating building's skin as the intersection of energy and human comfort, as well as aesthetics. The building's skin is a multifunctional component; it provides stability, regulates air pressure (fenestration) and protects the interiors from direct environmental factors (sunlight, rain and wind). The building's skin plays a crucial role in saving or consuming energy, depending on its type and design, that is why architects are obliged to consider many issues when designing envelopes like environmental issues, appearance, the quality of view and the occupant comfort, embracing a belief that the building's skin is increasingly the key component for improving the sustainability. Therefore, it is a vital component to resolve the issues of responsive architecture, as they are a medium through which intelligence can be imparted to the building system to respond to an environmental stimulus. Thus, key characteristic of an effective intelligent building skin is its ability to modify energy flows through the building envelope by regulation, enhancement, attenuation, rejection or entrapment. Designers are investigating the potential of making building's skin elements move in response to other stimuli, whether human or natural.

Over the past twenty-five years, computers have become extremely prevalent in the architecture and design fields. Originally used as a way to draft more quickly, technology advancements have allowed computers to be an integral design tool to architects. The emergence of parametric design tools, allowing designers to quickly explore many ideas within a given set of parameters, has gained much popularity in recent years. These tools have even spawned a theory called parametricism, which has been described as the first epochal shift in design since modernism.

Through this research, we are aiming to evaluate the introduction the parameterization of buildings skins as a valuable strategy for reducing energy consumption in hot and arid regions through the integration of kinetic shading systems, and how could these kinetic modes of envelopes be derived from certain biological models. The major contribution of this research is a dual methodology for designing and evaluating bio-kinetic skins, using parametric design as an alternative platform for designers to improve, validate and make informed decisions during the early design development while offering unprecedented ways of exploring design options and strategies in realizing the kinetic facades towards environmental performance.

This thesis is an investigation of parametric design and the benefits it offers to the field of kinetic architecture. The introduction of these new digital design tools has given architects a new way to approach design, utilizing quantifiable data to reinforce design decisions regarding form and sizing of their designs. Parametric design can significantly improve the field of kinetic architecture by providing new tools of design investigation, form generation, and environmental design efforts.

1.1 THE SCOPE OF THE STUDY

The scope of this thesis can be concisely determined with three terms as specified in the thesis title: Adaptive skins, bio-kinetic Architecture and parametric design in architecture.

1. The adaptive / responsive skin
   The term 'adaptation' is commonly used in architecture in relation to the changing morphologies of the architectural artifact. These changing morphologies have been a result of timely changes and evolution of architecture as a social entity, technological product and as a practice. Through years of architectural evolution, changes have occurred in notions of how buildings are conceived and built. The architectural morphologies adapt to the time, in which they are conceived and realized. These adaptive morphologies are a resultant of changing times, social form, economic support, user needs and environmental effects. The environmental changes that occur in a given time, such as a day, can be a constant force of changes that need to occur in an architectural object, leading to local adaptations. The global climatic change, occurring over a course of time, creates forces for architectural object to change over the years, in order to survive and sustain itself. Adaptation in architecture is a long-term process that occurs with time and generations, where improvements in the technology, economic support as well as human thought-process, contribute to the adaptive response.The responsive skin, as the boundary between architectural interior and exterior, demonstrates the ability to adapt itself to specific functional requirements [Moloney 2011].

2. Bio-kinetic architecture is the core of this research.
   Between building and environment or between building and its occupants, a certain level of interaction can be achieved by advanced building technologies, such as simple folding and sliding shutters that responds to the sunlight, or non-conventional kinetic elements with deployable and morphing structures. This smart structure, referred to as a concept of kinetic systems, creates an adaptive spatial configuration on various scales.
   In this research, we are aiming to present a systematic knowledge about kinetic architecture, also propose a combination between natural organisms and buildings. Biomimetic approach is used as the tool that externalizes the responsive connectedness between nature and built environment. In addition, it establishes the design framework to implement this responsive connectedness in the adaptive skin system.

3. The last term,parametric design in architecture
   A powerful tool currently being used by architects and planners. Through research and design, this thesis seeks to answer two questions: what is parametric design and how can it benefit the field of bio-kinetic architecture in hot and arid regions? Looking at historical and present-day sources, the evolution of computer-aided design has been drawn out leading to the emergence of parametric design.

1.2 RESEARCH AIM

This research aims to assess the impact of buildings skins parameterization on the energy efficiency and the thermal comfort in hot and arid regions. To this end, we introduce a novel design concept based on parametric design strategies; creating a responsive bio-kinetic skin system that adapt to dynamic environmental fluctuations to regulate the internal conditions in an office space over time and exhibit a state of motion and dynamism via adaptation strategies inspired by nature. This new strategy leads to the optimization of the energy performance of the building in hot and arid regions.

1.3 RESEARCH QUESTION

This research sought to address the gaps in the design spectrum of building's skins, in relation to adaptativity and sustainability. The following research question is taken as the core of the research: How could the parameterization of buildings skins and bio-kinetic shading systems enhance indoor thermal comfort and be a valuable strategy to optimize the energy performance of buildings in hot and arid regions?

1.4 HYPOTHESIS

The hypothesis tested in this thesis is: parameterization of buildings skins and combining evolutionary design process with adaptive mechanism inspired by nature, can generate a responsive skin system for buildings located in hot and arid regions. Further, it can reduce the overall energy consumption of the building and enhance the indoor thermal comfort.

1.5 RESEARCH APPROACH AND METHODOLOGY

This research is undertaken in a clearly defined research scope that addressed gaps in the design spectrum of buildings skins design, in relation to sustainability. The research approach is based on a successive workflow of theoretical reviews and methodical simulation studies, which eventually establish an original framework for an integrated building skins design methodology. This research adopts both quantitative approach and a framework for qualitative analysis based on different factors that includes theoretical design elements. The research is based on three phases and each phase has its tools and techniques:

- Exploratory phase

  In this phase, a framework for state of the art about the scope of the research is proceeded (Adaptive architecture, Kinetic architecture, Biomimicry, Parametric/ computational design) and on case studies and used tools (Figure 1.1).

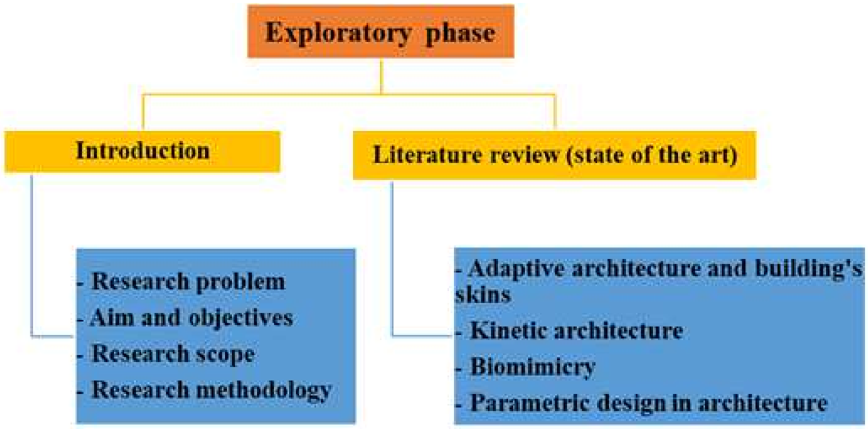

Figure 1.1: Exploratory phase diagram (Author)

- Qualitative/ design phase

  Since we attempt to evaluate the effect of the parameterization of the buildings skins, we propose and apply a biomimetic-computational design approach, a number of steps are adopted in this phase: Biomimetic inspirations and analysis, translation of ideas to architecture, digital and physical modelling. To conduct this research, we have engaged directly with a range of computational design tools and become familiar with number of digital and analogue fabrication processes. These tools are explored in an organic way to ensure the kinetic design work effectively in order to achieve specific design objectives. Throughout the investigations, different types of tools and techniques are used (Figure 1.2).

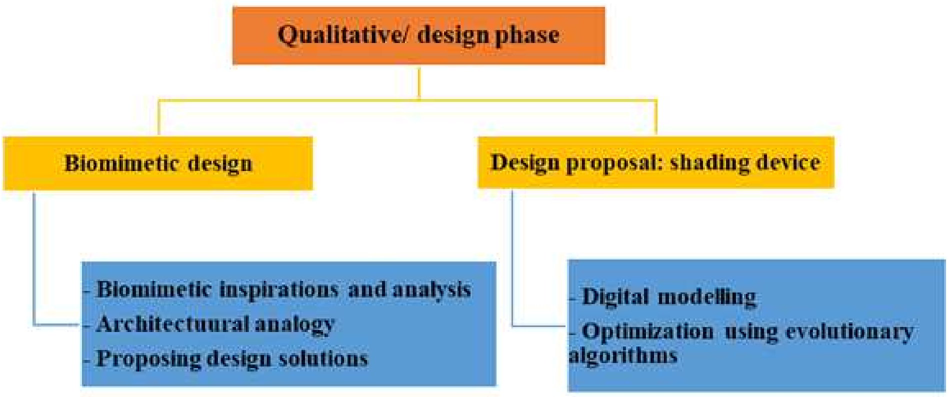

Figure 1.2: Qualitative/ design phase diagram (Author)

- Quantitative/ comparative analysis

  In this phase, we proceed to quantify the proposed design solutions, us-

ing parametric modelling and testing of the results. The design ideas are translated into mathematical relationships to build up the digital parametric model. A Visual Programming Language is used to model the design solutions (Grasshopper for Rhino 3D modeller) and to optimize the digital model using Evolutionary Optimization algorithms.
Series of experiments engages with a performance based design approach for integrating kinetic building's skins and environmental performance. The environmental softwares, which will be tested and employed for this investigation are Ecotect, energy plus, ladybug and honeybee plugins for Grasshopper and Climate Consultant. This is in order to study the performance of the kinetic building's skins throughout the selected design days. Both software systems are used and are integrated with generic evolutionary software called Galapagos as a tool to integrate different parameters (size of opening, geometry etc.). Then a comparative analysis will take place as the environmental performance of the skin of base-case office in hot arid region (reference case) is analysed before and after the new proposed skin. The results of the comparisons serve as a means to assess the degree of improvement that has occurred (Figure 1.3).

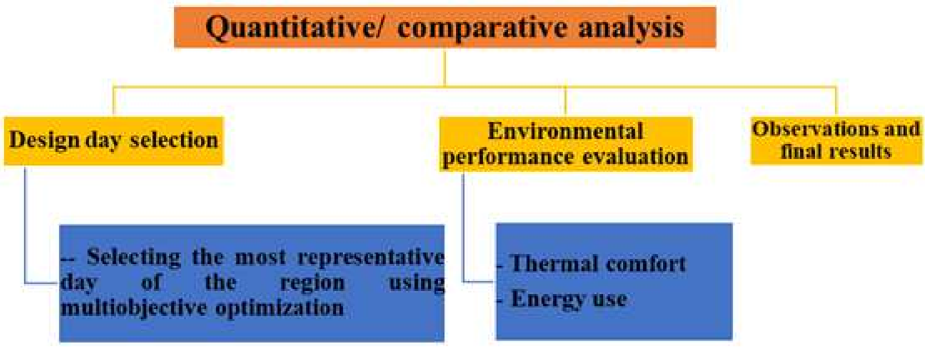

Figure 1.3: Quantitative/ comparative analysis diagram (Author)

1.6 STRUCTURE OF THE THESIS

The thesis is divided into two main parts as seen in Figure 1.4. The introductive chapter 1 starts with the research aim and objectives, the addressed problem, the scope of work, and the proposed methodology in order to achieve the stated objectives.

The first part of the thesis is a theoretical part "Advanced trends of building's skin design" and includes three chapters. The second chapter introduces the adaptive approach in architecture and develop a new classification system for adaptive building's skins to put forward the characteristics of these systems and how could we apply them in our designs. It presents the control system, mechanisms and different adaptive systems that exhibits properties that could be used in responsive designs.

In this chapter, different examples of adaptive building skins and adaptive building components that can be used in the building's skins are presented.

The third chapter, a thorough understanding of kinetic systems that are relevant to architecture and their usage is presented, enabling architects to think about the major aspects of kinetics and explore their potential for architectural applications and environmental control. In this context, the chapter presents a methodology for the definition and classification of different terms, concepts, and approaches in kinetic architecture. Moreover, it develops a framework of design strategies to identify different kinetic phases based on the main issues concerning the approach's impact on sustainability, each of these issues is explained separately, listing the main points and supporting it with examples.

The forth chapter has two main sections. The first section reviews existing literature and explores biomimicry information relevant for architectural design. It also seeks to provide a starting point for architectural designers and students to work with this subject, as a literature base to help architectural designers to know the biomimetic approach. We examine biomimetic potential effectiveness on architectural design. A framework is established to analyze different design approaches to biomimicry in architecture. However, the second section presents different point of views on definition and implementation of parametric design from design procedure lens in order to create platform for holistic design system. Therefore, new knowledge and skills that designers need to master the parametric and how they can learn and use it are discussed in this chapter. We demonstrated clearly how using patterns to think about and work with parametric modelling helps designers master the new complexity of the design systems.

The second part of the thesis is a practical part "Bio-kinetic design towards the optimization of the energy consumption". It starts with the chapter 5 that represents the qualitative / design phase. This part of the thesis sets out to the generation of the concept of the bio-kinetic design through the implementation of biomimetic design, parametric and kinetic design principles in the design of building's skin in hot and arid regions like the city of Biskra. This chapter includes biomimetic exploration, where certain design functions of the building skin are specified and the search for parallels in nature begins. Ideas from nature are categorized and then they are abstracted to see possible applications in architecture. It ends with chosen ideas to be applied in the design a shading device system for building's skin located in hot and arid region.

Chapter 6 concludes the bio-kinetic-computational approach presented in this thesis, it represents the quantitative/ comparative analysis phase. This chapter aims at testing the reliability and the environmental performances of the proposed Bio-kinetic shading device using the parametric tools as Grasshopper for Rhino, Ladybug plugin, Honeybee plugin, Energy plus, Ecotect. Outcomes are graphically presented in each case for clarity, easy understanding and comparison purposes.

The thesis concludes with chapter 7 that summarizes the obtained results, research contributions, perspectives and limitations. It also discusses the advantages and limitations of the proposed skin, the tools used and most importantly criticizes the design approach as a whole.

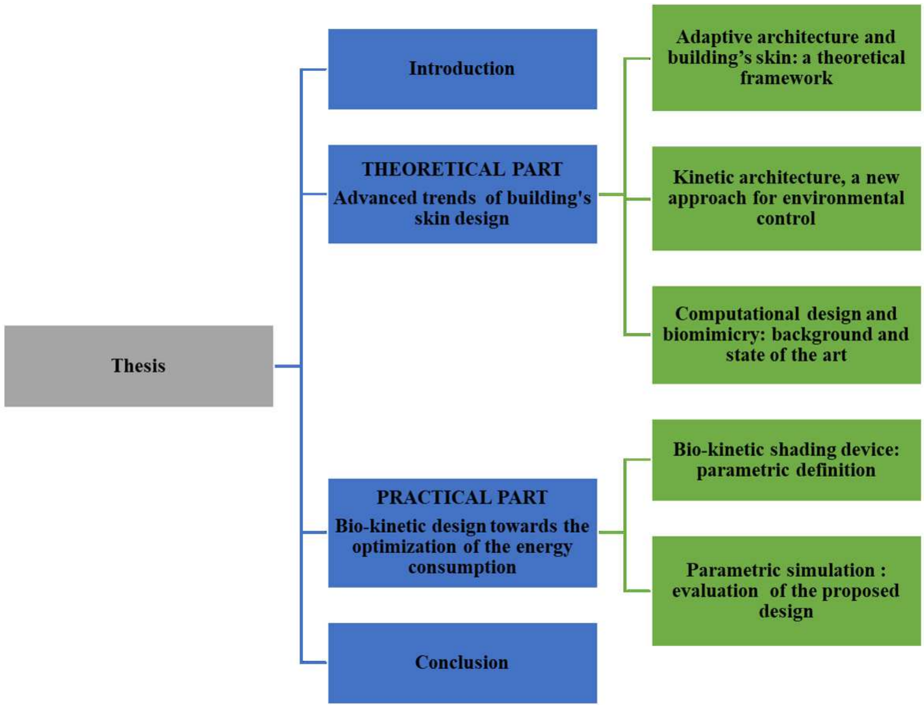

Figure 1.4: thesis structure (Author)

Part I

ADVANCED TRENDS OF BUILDING'S SKIN DESIGN

CHAPTER 2

ADAPTIVE ARCHITECTURE AND BUILDING'S SKIN: A THEORETICAL FRAMEWORK

" Architecture should speak of its time and place, but yearn for timelessness. "

- Frank Gehry

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2.1 INTRODUCTION

An expanded understanding of building performance acknowledges that all forces acting on buildings (climate, energies, information, and human agents) are not static and fixed, but rather mutable and transient. Architecture evolved in the belief that the static, permanent forms of traditional architecture are no longer suitable for use in times of major change. Therefore, designers need to develop a stronger design science approach and open the lines of communication between design and different science disciplines, which is critical. Science can find creative solutions and design can develop more innovative creations.

Adaptive architecture has potentials for using our natural resources in efficient way and for responding to the era's needs. Many design techniques and technologies, which aim to respond to the constantly changing needs, have appeared. The new paradigm shift in architecture has changed the architecture from a static form to a more responsive and dynamic form. It is supposed to be dynamic, adaptable and capable of being added to, reduced, or even being disposable, aiming to link past practices related to adaptive form with motion-based emerging technologies in a meaningful way and project into the inherent architectural possibilities.

The integration of motion into the built environment, results the aesthetics, design and performance of buildings that is of great importance to the field of architecture. Although the aesthetic value of virtual motion may always be a source of inspiration, its physical implementation in buildings and structures may challenge the very nature of what architecture really is. This has serious consequences for the building envelope whose design must transcend its role as mere protective wrapper separating inside from outside. Building's skins are increasingly developed as complex systems of material assemblies attuned to climate and energy optimization. The goal of this chapter is to introduce the adaptive approach in architecture and to develop a new classification system for adaptive building's skins to put forward the characteristics of these systems and how could we apply them in our designs.

2.2 ADAPTIVE ARCHITECTURE

2.2.1 DEFINITION OF ADAPTIVE ARCHITECTURE

Architecture evolved in the belief that the static, permanent forms of traditional architecture are no longer suitable for use in times of major change. Therefore, designers need to develop a stronger design science approach and open the lines of communication between design and different science disciplines, which is critical. Science can find creative solutions and design can develop more innovative creations [AlThobaiti 2014].

Faced with endless influencing parameters such as time, weather, functions, information, human needs, etc. architecture should be designed with multiple dimensions to face this infinity of forces. The design process should consider the adaptation to the changing conditions, which can be in terms of the building usage, environmental factors or even in the changes of sociological demands. The term 'adaptation' is commonly used in architecture in relation to the changing morphologies of the architectural artifact. These changing morphologies have been a result of timely changes and evolution of architecture as a social entity, technological product and as a practice.

Through years of architectural evolution, changes have occurred in notions of how buildings are conceived and built. The architectural morphologies adapt to the time, in which they are conceived and realized ([Kolarevic 2009]; [Kensek 2011]). Adaptive Architecture is concerned with buildings that are designed to adapt to their environments, their inhabitants and objects as well as those buildings that are entirely driven by internal data. The term is an attempt to incorporate what people imply when they talk about flexible, interactive, and responsive or indeed media architecture. Adaptive Architecture is not a well defined field of architectural investigation. It ranges from designs for media facades to eco buildings, from responsive art installations to stage design and from artificial intelligence to ubiquitous computing.

Adaptive Architecture brings together a number of different concerns stemming from a wide variety of disciplines, spanning Architecture, the Arts, Computer Science and Engineering among others [Maria 2008]. Whether buildings in this context are described as flexible, interactive or dynamic, they embrace the notion of Architecture being adaptive rather then being a static artefact, often with an emphasis on computer supported adaptation.

Adaptive systems combine the best of existing strategies: low energy use and control over building environments and they have the ability to adapt and interact with the surrounding environment and its variants, which include light, sound, wind, heat or with people [Elkhayat 2014a]. For instance, a building's energy requirements can be considerably lowered if its design can adapt to temperature fluctuations. An adaptive system that is modulated to control the volume and direction of heat flow in response to external and internal conditions can enhance comfort and energy performance [AlThobaiti 2014].

Holger Schnädelbach in [Schnadelbach 2010] has defined adaptive architecture as "*it is a multi-disciplinary field concerned with buildings that are designed to adapt to their environments, their inhabitants and objects as well as those buildings that are entirely driven by internal data.*"

The use of the term "Adaptive Architecture" must therefore be seen in this overall context and the following delineates between adaptable and adaptive: Adaptive Architecture is concerned with buildings that are specifically designed to adapt (to their environment, to their inhabitants, to objects within them) whether this is automatically or through human intervention. This can occur on multiple levels and frequently involves digital technology (sensors, actuators, controllers, communication technologies). Taking the above context into account, this definition and associated framework is therefore an attempt to incorporate a variety of approaches, such as those labelled flexible, interactive, responsive, smart, intelligent, cooperative, media, hybrid and mixed reality architecture ([Kronenburg 2007];[Bullivant 2005]; [Harper 2003]; [Streitz 1999]; [Zellner 1999]; [Schnabel 2007]).

The challenge of developing sustainable, adaptive, responsive architecture requires unconventional approaches to innovative knowledge about composition and dynamic interaction between the building and environmental conditions. A common aspect of robotic, kinetic, interactive or responsive architecture and smart buildings is to adapt intelligently to environmental changes like day light, wind, and temperature. The terms kinetic, interactive, robotic, and responsive architecture as well as smart buildings widely overlap and are used more or less synonymously or with a slightly different emphasis [Loonen 2010].

The concept of adaptable space means that it compliantly react to the supplies of any human activity from habitation, leisure, education, medicine, commerce and industry. The adaptation ranges from an interior, which is multi-use reorganized to a structure, has the ability to transform and programmatic response. It is capable to respond to various parameters with time. That is mean; time is an essential factor in the concept of adaptive architecture [Kensek 2011]. Therefore, adaptive architecture can be considered a responsive architecture adapting with time as demonstrated in Figure 2.1.

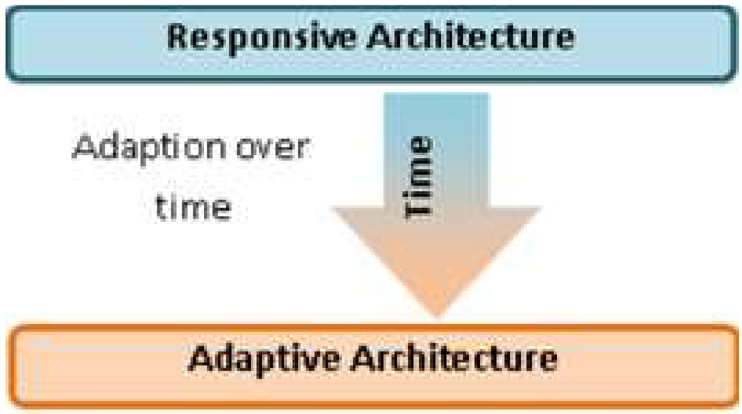

Figure 2.1: Responsive architecture to adaptive architecture over time

2.2.2 RELATED CONCEPTS AND APPROACHES

In literature, the term adaptive in the context of building is often associated with a long list of similar terms and concepts as shown in Figure 2.2. In this section, we presents the most known and the most used concepts in literature and the semantic frame.

Figure 2.2: Adaptive concept in literature

2.2.2.1 Intelligent Architecture

Intelligent architecture concept was introduced to control and manage buildings with a communication between building systems and users. This is attained by using high tech abilities to achieve user's needs, like comfort, productivity, energy saving, return investment, and life cost decreasing. The "building systems" includes all systems that control a building like HVAC, mechanical, structural, lighting control, access control, security, building management, maintenance, local networking, and energy management as illustrated in Figure 2.3.

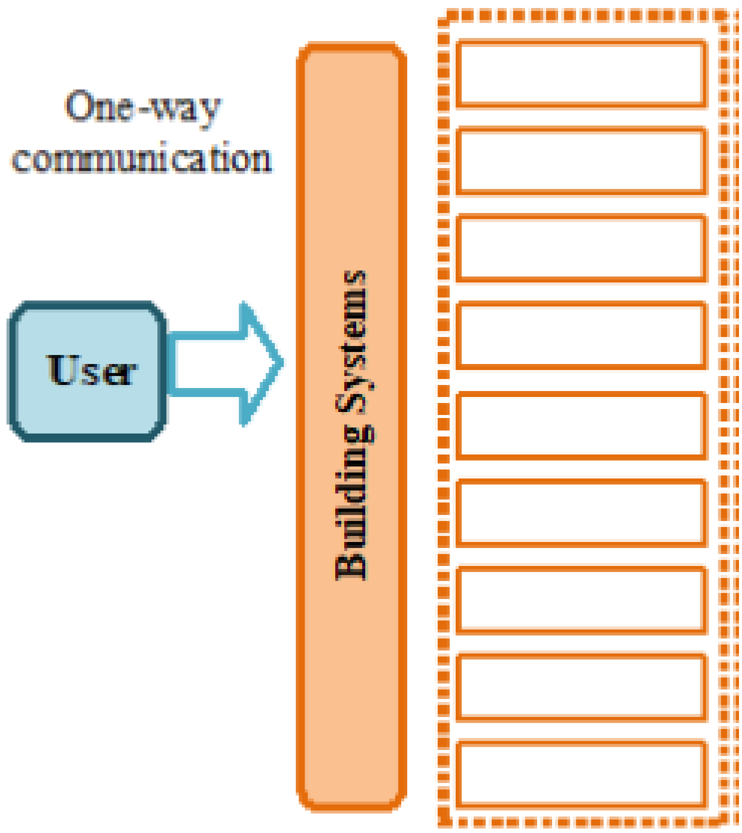

Figure 2.3: Intelligent Architecture concept

2.2.2.2 Interactive Architecture

It is defined as an interactive interface between humans and computers. It considered the building as an enclosure defines a space, which supports some activates. The building enclosures like walls, floor, and ceilings act as interactive spaces. This type of architecture doesn't deal with people as users but as participants [Elkhayat 2014b]. It is based on two ways communication between people and built components, which are divided to: input, processing and output (IPO) devices [AlThobaiti 2014]. The design space of interactive architecture can be categorized in three dimensions as shown in Figure 2.4:

- Sensible spaces

- Thinker spaces

- Responsive spaces can be changed

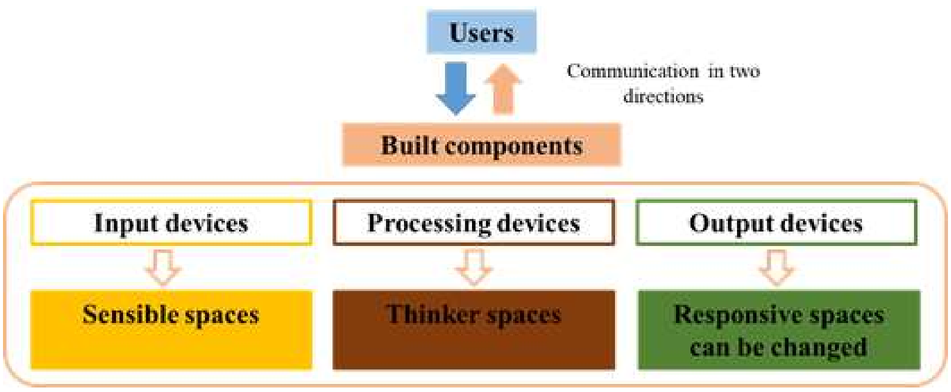

Figure 2.4: Interactive architecture concept

2.2.2.3 Responsive Architecture

Responsive architecture is defined as an active shape-shifting building system which is a response to environmental conditions and user activities. It consists of intelligent frames, systems and skins.

The building response is a change in its shape and physical properties by simulating bionic performances of human and natural systems as shown in Figure 2.5 [Kolarevic 2015]. Bionics means studying the design and performance of natural systems to design engineering systems and modern technology [Kirkeguard 2011].

Responsive architecture relates to elements that are moveable or transformable in terms of their purpose, their composition, their form and their meaning without reducing the overall structural integrity of the building [Schumacher 2010]. The concept of responsive architecture was introduced by Nicholas Negroponte in the late 1960s. He defined responsive environment as an environment that plays an active role, as a result and function of complex or simple computations to make a bigger or smaller degree of changes [Schumacher 2010]. The responsive building does not have to be intelligent unless its response is a result of an intelligent procedure [Kolarevic 2015].

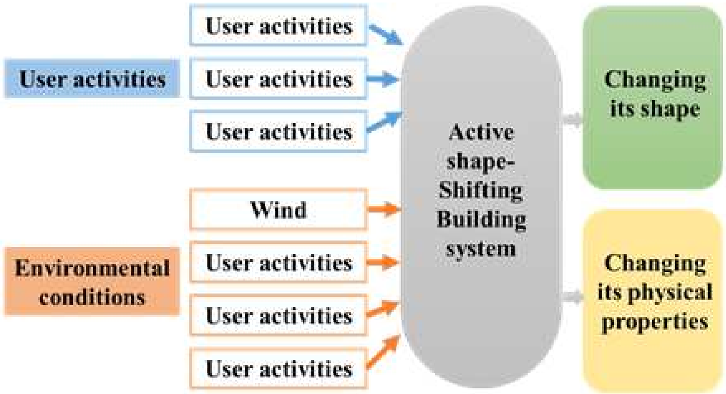

Figure 2.5: Interactive architecture concept

2.2.2.4 Kinetic Architecture

Kinetic architecture concept is the design of buildings with transformative and automatic elements. The building's shape is changed to match the people requirements and adapt to environmental conditions. This concept is well explained in chapter 3. Figure 2.6

presents the synthesis of different approaches and concepts and their relationship.

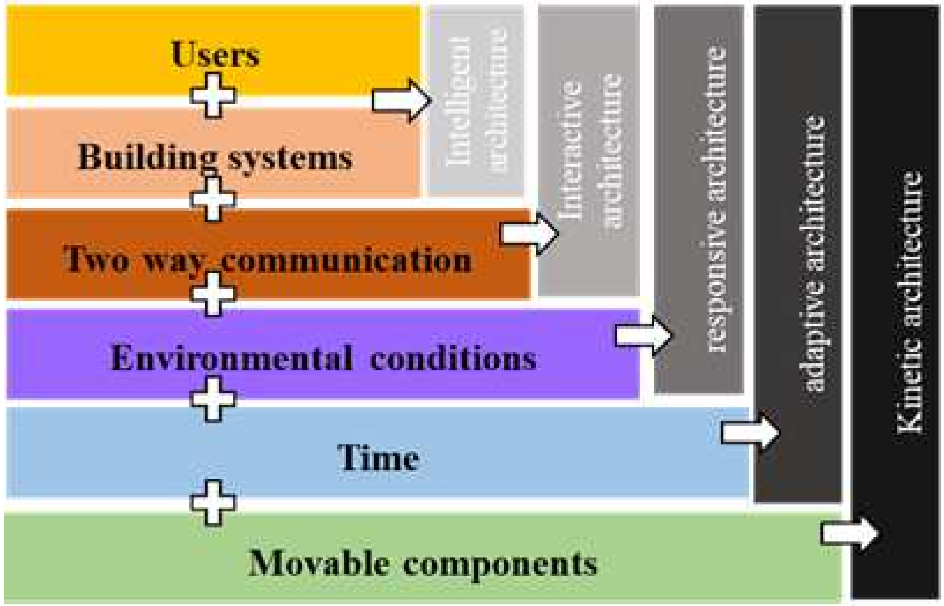

Figure 2.6: Interactive architecture concept

2.3 ADAPTIVE BUILDING'S SKIN

2.3.1 DEFINITION OF BUILDING'S SKIN AND ITS FUNCTIONS

The building's envelope is often referred to as the skin of the building that protects the core from environmental damage. Physical skin is one of the most versatile human organs aiding the metabolism, immune system, protecting the body from bacteria and regulating body temperature. The skin is a flexible surface, allowing movement and simultaneously acting as a surface for sensory perception (touch). Composed of a variety of complex systems and layers the skin acts as an active boundary between the inner core and the diverse environment outside.

The building's skin separates and protects juxtaposing environments but allows required transitions between the two spaces

[Gunderson 2015]. The building's skin is also the first image of the building [Michel-Alder 2006], which is viewed from both outside and inside, similar to the skin of people. It is a surface that is judged by occupants and the community.

The composition of the building's skin has a direct influence on the interior environment affecting comfort, energy and durability, productivity, as well as occupant and visitor happiness [Gunderson 2015]. As defined by Haggag [Haggag 2007], the building skin is crucial concept for energy efficiency. All components of the building skin need to work together to regulate the indoor environment. It is considered as a selective pathway for a building to work with the climate, responding to heating, cooling, ventilation, and natural lighting needs. It controls heat transfer, solar radiation, and airflow. It must balance requirements for ventilation and daylight while providing thermal protection appropriate to the climatic conditions [Reid 2001].

The building's skin is a multifunctional component; it provides stability, regulates air pressure and protects the interiors from direct environmental factors (sunlight, rain and wind). It plays a crucial role in saving or consuming energy, depending on its type and design ([Sozer 2010]; [Dugué 2013]). Architects and engineers need to consider many issues when designing envelopes like environmental issues, appearance, the quality of view and the occupant comfort, embracing a belief that the building's skin is increasingly the key component for improving the sustainability ([Zemella 2014]; [Ibanez-Puy 2018]).

2.3.2 DESIGN STRATEGIES FOR BUILDING'S SKIN

Skin design is a major factor in determining the amount of energy used in buildings [Haggag 2007]. Architects and engineers should integrate design of the building skin with other design aspects including material selection, daylight, heating, ventilation, and air-conditioning [Straube 1998]. In a hot and arid climate the key strategy is to control heat gain by avoiding excessive solar radiation penetration, while allowing reasonable daylighting levels and views. Below some essential design strategies for designing buildings skin:

- Building orientation can provide reductions to cooling loads through minimizing solar penetration through windows, minimizing solar absorption through walls and roofs.

- Building forms, volume, and orientation also have significant impacts upon the efficiency of the building skin.

- The amount of surface area, material choice and insulation strategies are key elements in buildings located in hot and arid regions. Where minimizing the ratio of outdoor surfaces of buildings to have a lower exposure to hot weather factors. Due to very hot temperatures, the building materials absorb heat from the sun, the energy is retained in the walls then gradually transferred to the inner spaces of the building, and where the absorbed temperature causes problems and the conditions inside the building prevents full comfort.

- Building envelope colour can influence thermal performance and reduce maximum indoor temperatures, thus reducing the need for mechanical ventilation and cooling. White surfaces absorb less solar radiation than dark surfaces, thus transferring less heat to internal surfaces by conduction and to indoor air through convection.

- Openings are also critical issue. The opening form, size and location vary depending upon the role they play in the building skin. Glazing systems have a great impact on energy efficiency. Appropriate glazing choices are varied, depending on the type of building skin, the use of the building, and the glazing placement on the facade. In a hot climate, the main strategy is to control heat gain by keeping solar energy from entering the indoor space while allowing reasonable visible light transmittance for views and daylight

- The orientation, placement and size of windows largely determines the heat gains. It must balance requirements for ventilation and daylight while providing thermal protection appropriate to the climatic conditions [Reid 2001].

Therefore, the building skin is a vital component to resolve the issues of adaptive architecture, as they are a medium through which intelligence can be imparted to the building system to respond to an environmental stimulus. Thus, key characteristic of an effective intelligent building's skin is its ability to modify energy flows through the building envelope by regulation, enhancement, attenuation, rejection or entrapment.

2.3.3 ADAPTIVE BUILDING'S SKIN; DEFINITIONS AND TECHNOLOGICAL EVOLUTION

Adaptive building's skin consist of multifunctional highly adaptive systems, where the physical separator between the interior and exterior environment is able to change its functions, features or behavior over time in response to transient performance requirements and boundary conditions, with the aim of improving the overall building performance [Loonen 2015]. Furthermore, these building's skin systems can seize the opportunity to save energy by adapting to prevailing weather conditions, and support comfort levels by immediately responding to occupants needs and preferences [Loonen 2013]. In other words, adaptability can be understood as the ability of a system to deliver intended functionality, considering multiple criteria under variable conditions, through the design variables changing their physical values over time [Ferguson 2007].

An adaptive building's skin has the ability to repeatedly and reversibly change some of its functions, features or behavior over time in response to changing performance requirements and variable boundary conditions [Basarir 2017]. This technology is not a well defined field of architectural research, it ranges from artificial intelligence to passive design, from responsive art installations to media building's skins.

For years, architects and building scientists have envisioned the possibility that future buildings would possess envelopes with a certain type of adaptive response to changing environmental conditions. In 1975 N. Negroponte [Negroponte 1976] introduced the concept of responsive environment, capable of playing an active role, initiating to a greater or lesser degree changes as a result and function of complex or simple computations. In 1981, Mike Davies proposed the idea of 'The polyvalent wall', an envelope system where several functions can be integrated into one layer [Davies 1981]. However, only in recent years, technological research has been investigating new experimentation frontiers capable of reaffirming the osmotic quality of a process of exchange that concerns energy flows that have passed and exchanged right through the envelope [Altomonte 2004].

These studies are new research to demonstrate if a vertical closure surface can be equipped with systems designed to ensure the dynamics required to the managed energy flows in the same way as a biological organism. From the screening system of the Arab World Institute by Jean Nouvel to the dynamic screenings of Al Bahar Towers by Aedas Architects, the new frontiers of innovation in architecture are oriented towards proposing new models of approach in which the "building organism" is also capable of autonomously ensuring the comfort of its users. In this sense, the evolution and dissemination of Information Technology Control (ITC) systems (from home automation to Building Management Systems (BMS)) to transfer the potential of systems equipped with artificial intelligence to the building scale, has ensured the regulation of space also in the absence of human users and in relation with a whole series of requirements that guarantee optimisation from the functional and physical perspective of the built space.

Adaptive building's skin is considered the next milestone in building's skin technology and receiving increasing attention by researchers and producers [Basarir 2017]. It is the last frontier of contemporary architectural and technological research, which is more and more related to the wish of designing new dynamic envelope models, which, with the help of sensors, system components for energy production and smart materials, contributes towards reducing the building's energy demand. These are technological solutions that, as previously mentioned, are capable of managing energy flows by altering the properties of fixed devices (smart materials) or by controlling (manually or automatically) moving parts (e.g. sunshades, windows, ventilation outlets, etc.) in relation to the type of user and complexity of the building. This envelope typology is marked by dynamic anisotropy that is the capacity to offer different solutions for the different exposures of the building, where a change in the structure modulates the various environmental flows according to the climatic conditions of the place, including external climatic-environmental conditions.

Given the complexity of the topic and multiple variables affecting the performance of these systems, a characterization was carried out in terms of technologies and purpose, as described in Figure 2.7, where the first column represents the purpose of building's skin/components with adaptive capacity. These purposes can be related with thermal comfort, energy performance, indoor air quality (IAQ) and visual and acoustic performance, among other requirements (Figure 2.8).

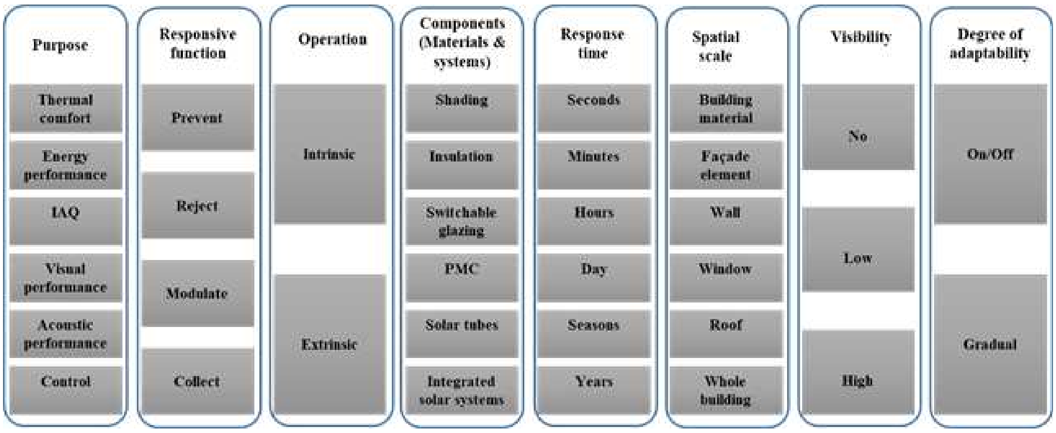

Figure 2.7: Overview of characterization concepts for building's skin adaptivity (adopted from [Loonen 2015])

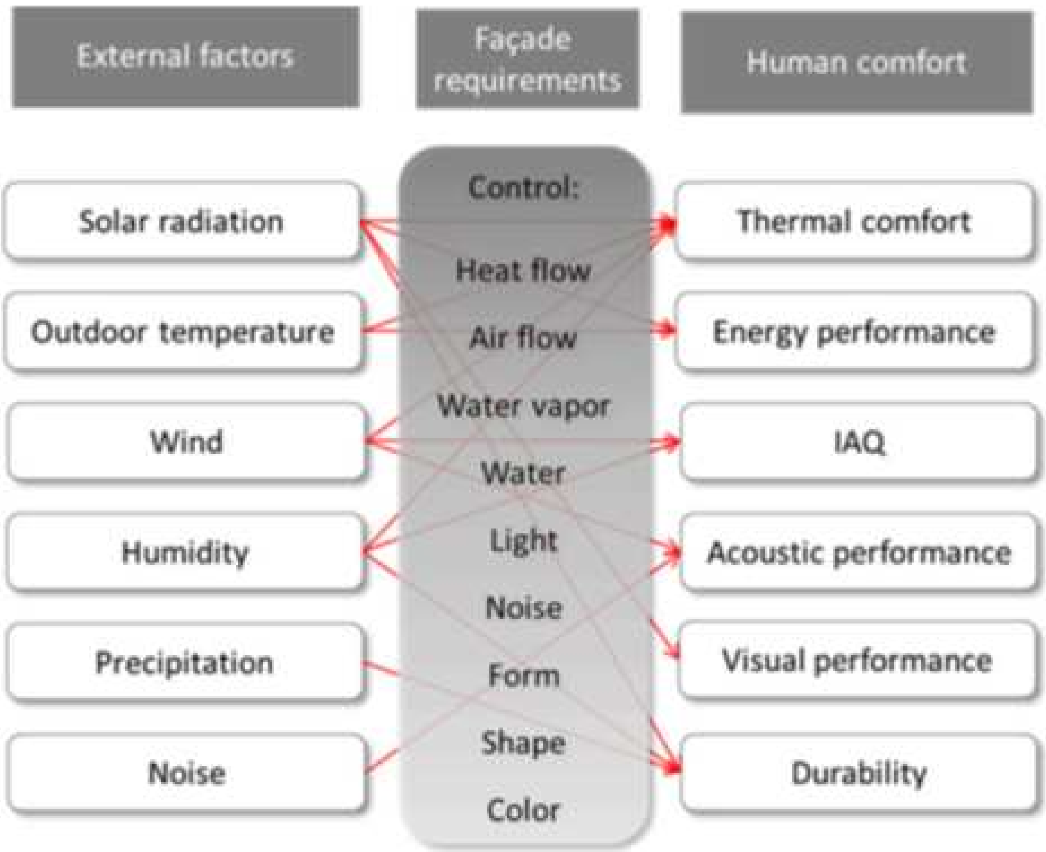

Figure 2.8: schematic role of adaptive building's skin [Aelenei 2018b]

2.3.4 CONTROL SYSTEMS FOR ADAPTIVE BUILDING'S SKIN

The control mechanisms of adaptive building's skin could be divided into two different system types, the open loop system Figure 2.9 and the closed loop system Figure 2.10. A sensor, a processor and an actuator build up an open loop system. [Addington 2005] The reaction of the sensor is read and interpreted by the processor, which in turn sends a signal to the actuator to preform according to a predefined logic. The sensors register the ambient conditions in their surrounding medium [Hanna 2014]. They can be sensitive to changes in heat, moisture, pressure etc.., and are classified following which one of these stimuli that they react upon. The actuator is the part of the system that converts the processed data into a mechanical, physical or chemical action.

The control unit is suitable if we wish to connect the adaptive envelope to a central building control system and if we want to allow users to interact with and influence its actions. The difference between the closed loop system and an open loop system is that the closed loop system also constitutes of a control unit that can measure the output action. The collected information could then be used as feedback to the processor [Addington 2005].

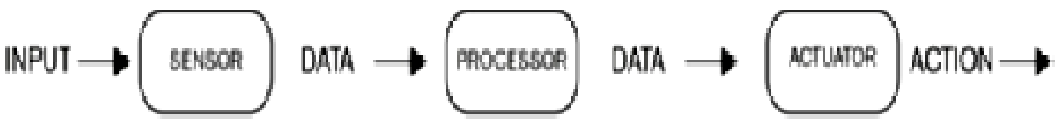

Figure 2.9: Diagrammatic concept of open loop system [Hanna 2014]

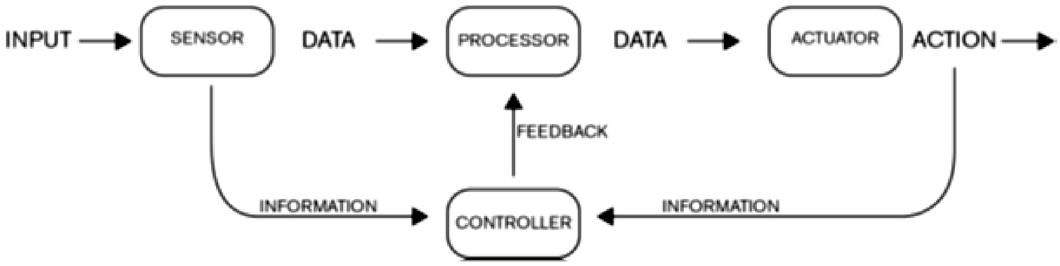

Figure 2.10: Diagrammatic concept of closed loop system [Hanna 2014]

These different control systems can be implemented in different ways giving rise to different typologies of responsive architecture, which are stated below.

- Material systems: the development of physical kinetic systems or the like are often developed within structural and mechanical engineering and material sciences.

- Informational systems: the development of physical sensor systems, which to an increasing level can observe and send continuous information further to a processing system, which then actuate into behaviors passing information back to the environment.

- Processing systems: the development of physical processing systems, which filter and decide from large amounts of sensor information and stored information. These are often associated and developed within computational science.

- Behavioural systems: the development of logic and behavioural gestures, patterns and systems, often associated with artificial intelligence sciences based upon computational and neurological sciences [Kirkeguard 2011].

2.3.5 MECHANISMS FOR ADAPTIVE BUILDING'S SKIN

There are two levels of mechanisms that drive the adaptive behavior; micro level and macro level but combinations are also seen

[Hanna 2014].

2.3.5.1 Macro-level

This mechanism can be seen with the naked eye and it is often associated with motion of various kinds like folding, sliding, rolling, hinging, etc. The driving principal behind a macro-level adaptive mechanism is usually an electromotor, which is triggered by an input from a sensor and driven with external energy input (Figure 2.11).

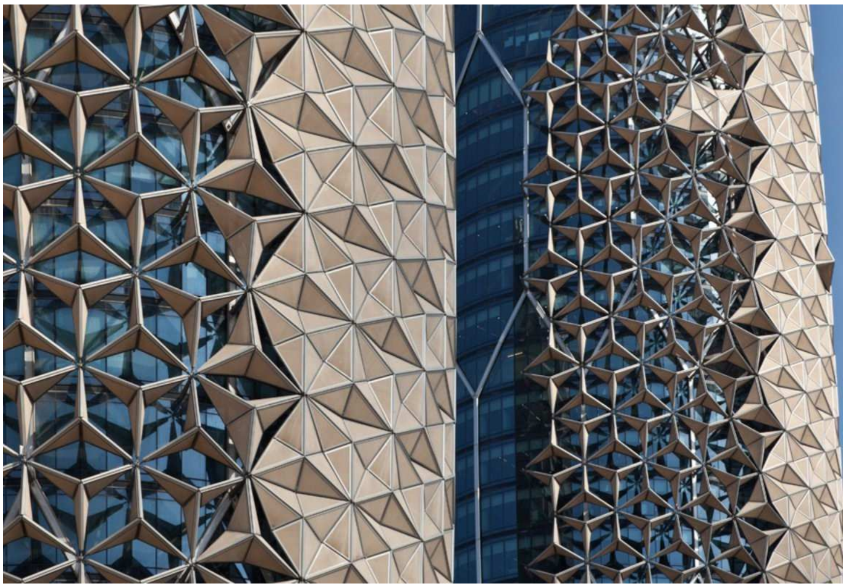

Figure 2.11: Example of a macro-level adaptive system at Al Bahar towers.

2.3.5.2 Micro-level

Micro-level changes occur in a smaller scale. The change occurs within the material itself, for example the arrangement of water molecules when the water transits from the fluid phase to the solid phase (ice) as seen in Figure 2.12. This change in a material's properties could be applied as an invisible change in the envelope that alters for example the thermal properties or it can be used as a motor to drive a larger system.

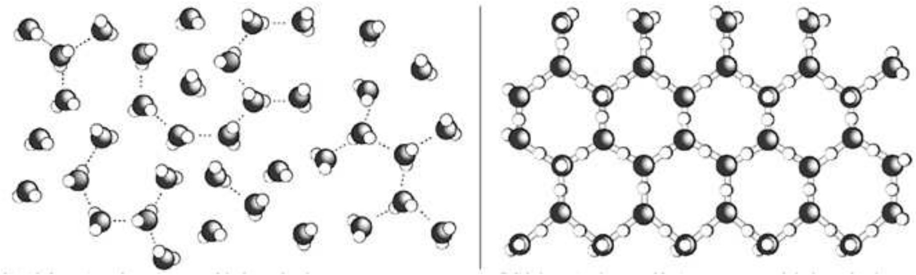

Figure 2.12: Molecule configuration of water as fluid and ice (Right: solid phase. Left: liquid phase) [Hanna 2014]

2.3.6 ADAPTIVE SYSTEMS

Several existing systems for adaptive buinding's skin, most fall into the macro level of mechanisms, exhibiting large changes that usually are governed by computerized control systems. In this section, we present the most used systems that are adaptive to different environmental parameters.

2.3.6.1 Responding to solar radiation

Adaptive systems that react to different levels of solar radiation is by far the most seen adaptive facade solution. There are examples of micro, macro and combined systems, but computer controlled macro systems are the most common. The adaptive solar shading systems can take on many different shapes and forms, there are external and internal systems, different kinds of blinds and shutters ([Weston 2010]; [Hanna 2014]) but also more innovative examples both when it comes to shape and appearance but also in terms of driving mechanism Figure 2.13.

A common way to reduce the solar heat gain is to use windows that have an additional coating. These coating can be of different kinds but with one thing in common, they can under influence of high levels of radiation, [Addington 2005] high temperature or an electric current [Mehrabian 2013] change their transparency and thus reflect the heat radiation, not allowing it to enter into the room [Hanna 2014]. This is an example of a micro level system that is commonly used, but today it has the drawback of not being able to over rule.

Figure 2.13: Adaptive building's skin responding to solar radiation

2.3.6.2 Responding to thermal loads-Variable U-values

Another adaptive solution is to allow the U-value of the wall to alter according to the heat loads from the surroundings (Figure 2.14). This could be achieved in a number of different ways, for example by introducing a controlled airflow in the wall stratification [Hagentoft 2013] or by the use of deployable insulation panels that can be moved to a configuration that is suitable for the current surrounding conditions [Hanna 2014].

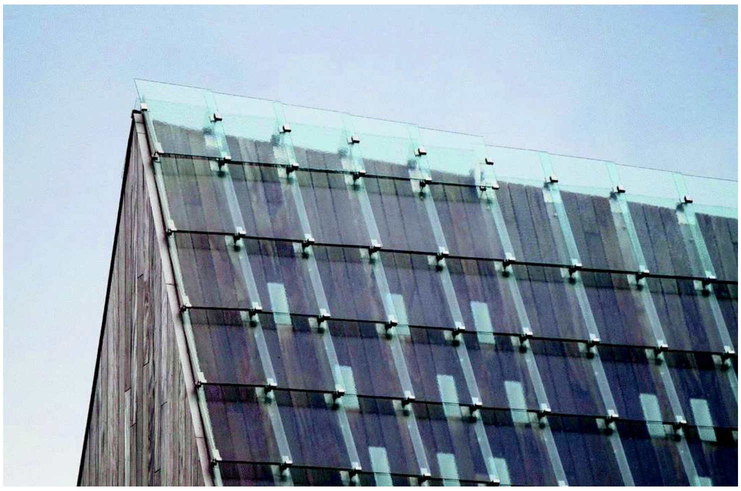

Figure 2.14: Adaptive building's skin with biomaterials

2.3.6.3 Responding to moisture contents

There are several different concepts that use the response to water as mechanism for change. Material similar to that of the well-known fabric Gore-Tex does not change per say but behaves differently depending on the phase of the water [Hanna 2014]. It allows vapor to exist and enter but block liquids from passing through material. In addition, others that instead grants liquids unlimited access while refuse to let vapor through the membrane, so called hygrodiodes. While Gore-Tex is a Polytetraflourethylene (PTFE) based polymer the hygrodiodes is a layered construction that allows water to pass through the means of capillary suction in a felt material. [Hagentoft 2013] There are also material that change depending on the relative humidity in the surrounding.

2.3.7 ADAPTIVE BUILDING'S SKIN CLASSIFICATION APPROACH

Some research projects as COST action TU 1403, IEA Annex 44 and FACET-project examine the adaptive behavior of building's skins and provide a systematic characterization of adaptive building's skins for future trends of adaptive building's skins and development. In this section, we present a classification approach of adaptive building's skins adopted from [Basarir 2017]. This approach is based on the change event (Figure 2.15), which can be characterized with three elements: agent of charge (Trigger for the change that occur), mechanism of charge (path of the system) and the effect of change (the difference between the states before and after a change has taken a place).

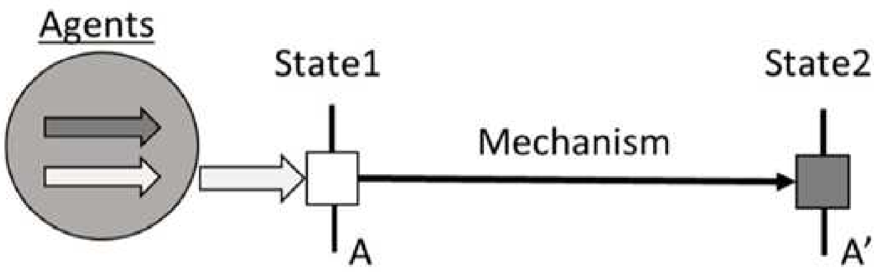

Figure 2.15: definition of a change as state transition [Ross 2008]

The classification approach represents adaptive building skins in comprehensive way; it is structured in 15 variables of change description:

-Elements of adaptation: the elements that adapt are driven by the agent of adaptation or what adaptive buildings react to (Figure 2.16).

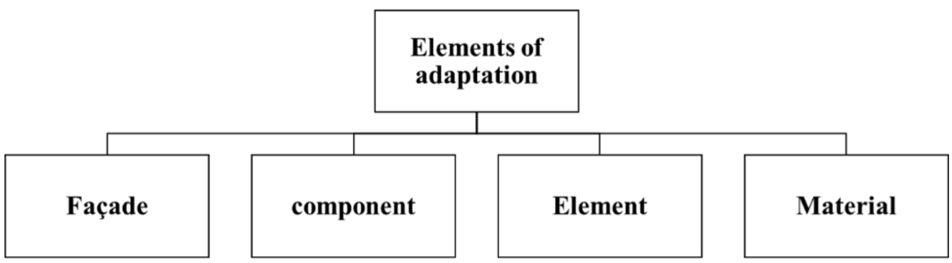

Figure 2.16: the different elements of adaptation

-Agents of adaptation: Building's skins are designed to be adaptive in reaction to a trigger and an agent of adaptation (Figure 2.17) [Schnadelbach 2010].

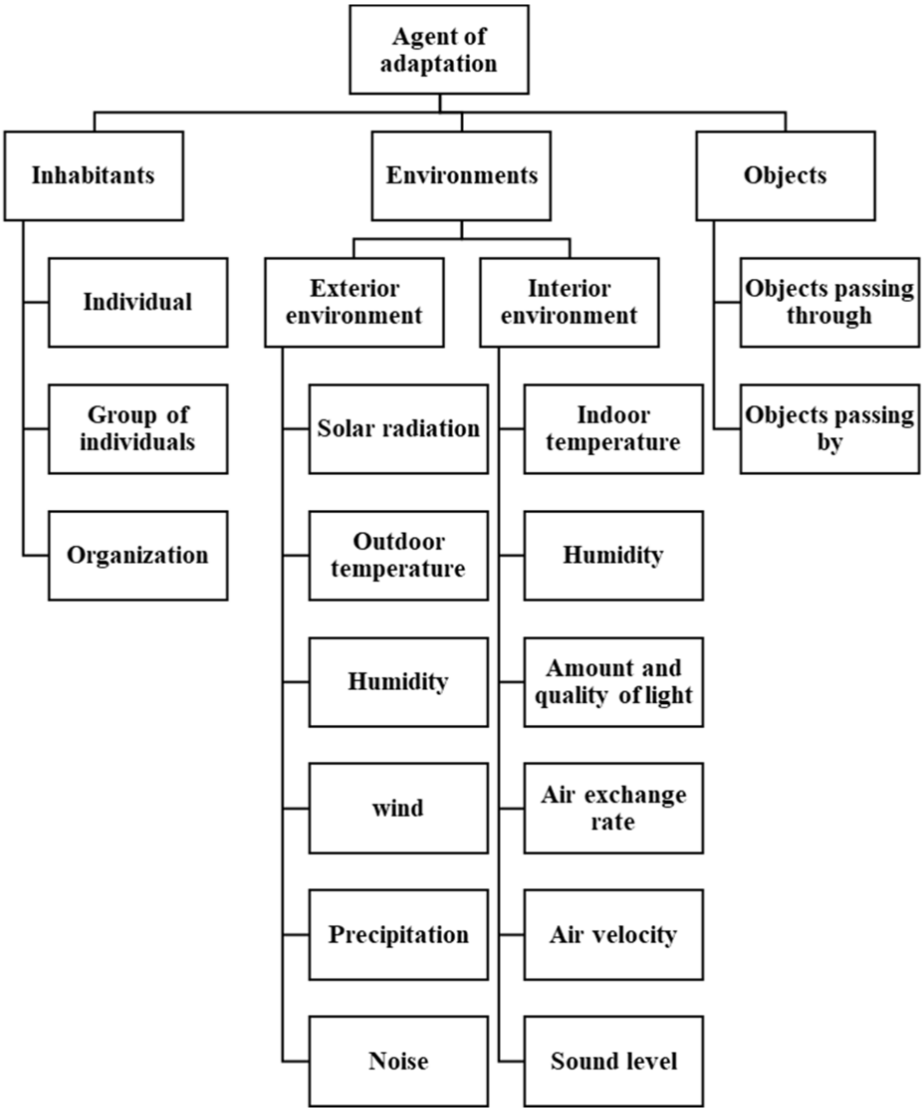

Figure 2.17: triggers and agents of adaptation

-Respond to adaptation agent: adaptive building's skins are able to respond to adaptation agent either in static or dynamic way (Figure 2.18) [Ogwezi 2011].

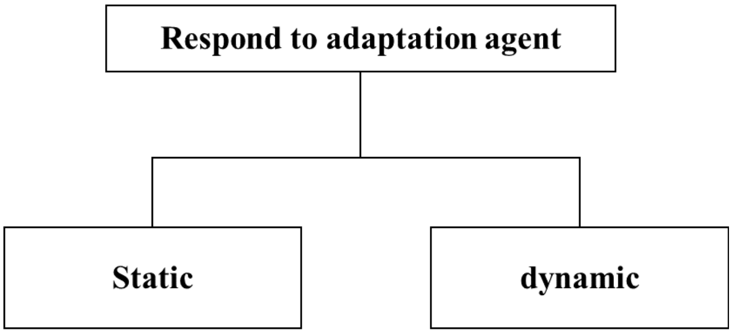

Figure 2.18: ways of response to adaptation agent

-Type of movement: It defines movement pattern according to positional displacement (Figure 2.19) [Herzog 2004].

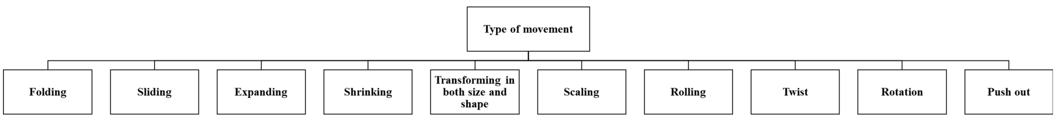

Figure 2.19: ways of response to adaptation agent

-Size of spatial adaptation: defines the dimensions of the spatial change that occurs during adaptation (Figure 2.20).

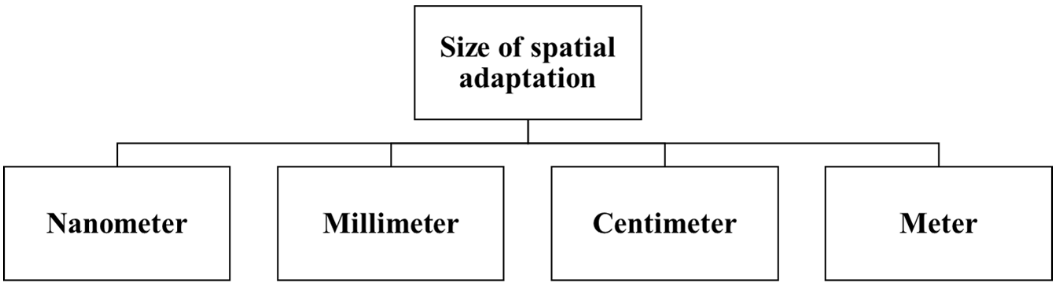

Figure 2.20: ways of response to adaptation agent

-Limit of motion: defines the maximum size of the motion provided by the adaptive system (Figure 2.21) [Ramzy 2011].

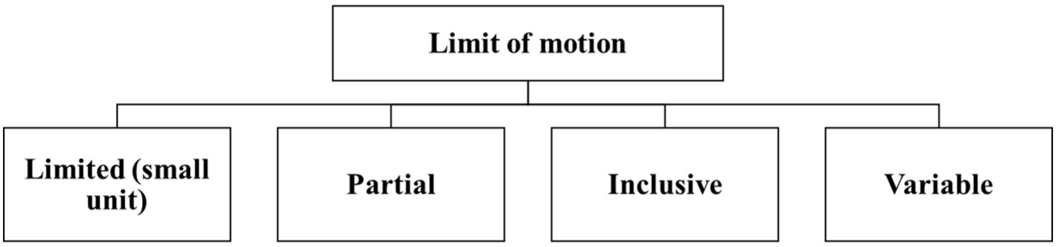

Figure 2.21: limit of motion

-Structural system for dynamic adaptation: four main categories of adaptive building's skins can be determined according to their structural system (Figure 2.22) [Kirkeguard 2011].

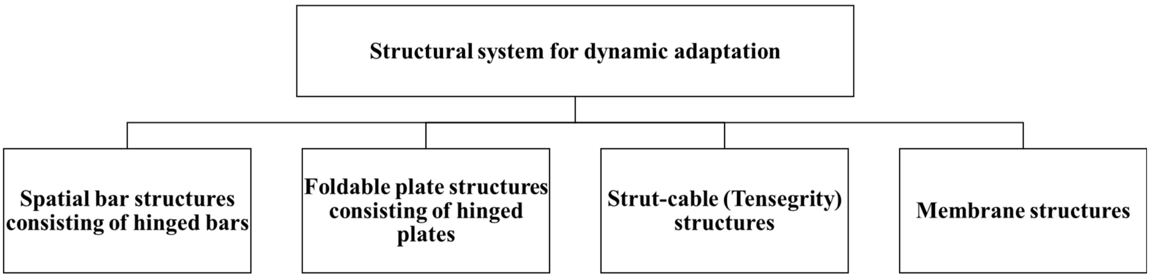

Figure 2.22: structural system for dynamic adaptation

-Type of actuator: it defines how the adaptive behavior is activated on the building's skin, and the different types of actuators are presented in Figure 2.23 [Kolarevic 2015].

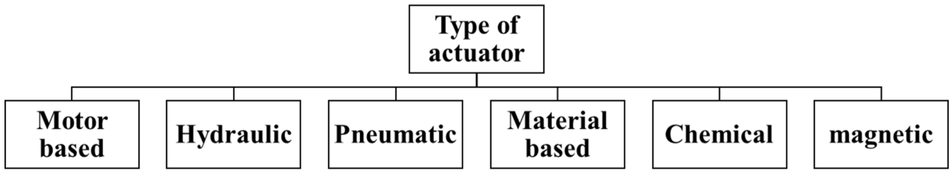

Figure 2.23: type of actuator

-Type of control: Figure 2.24 presents the various ways that an adaptive building's skin may be controlled [Fox 1999].

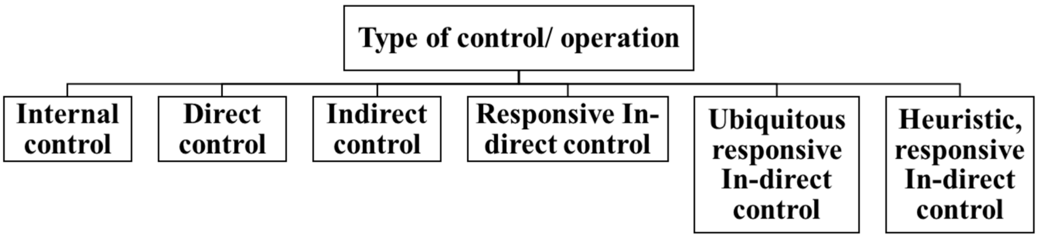

Figure 2.24: type of control and operation

-System response time: response time refers to the temporal scale at which the actions of adaptive building's skin effectively take place [Feuerstein 2002]. The time scales varies from short periods to long ones (Figure 2.25).

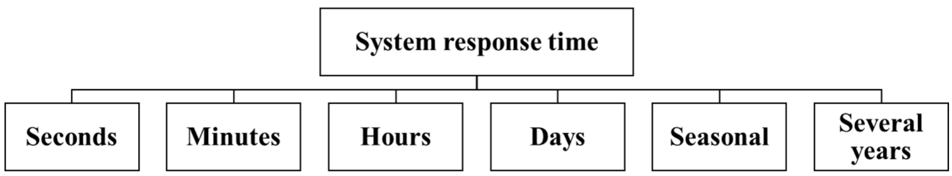

Figure 2.25: system response time

-System degree of adaptability: adaptativity takes place between two states of building's skins either gradually, directly and hybrid (Figure 2.26).

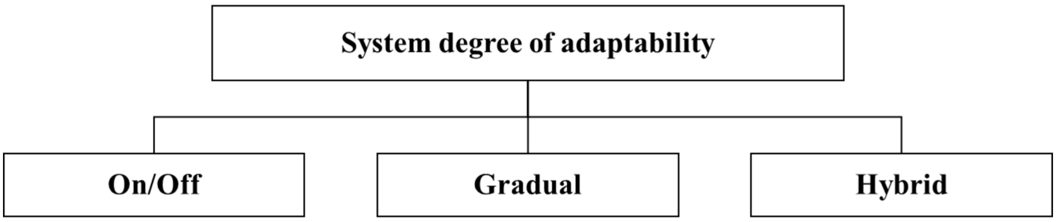

Figure 2.26: system degree of adaptability

-Level of architectural visibility: the architectural and visual expression of adaptive building's skins are identified in Figure 2.27.

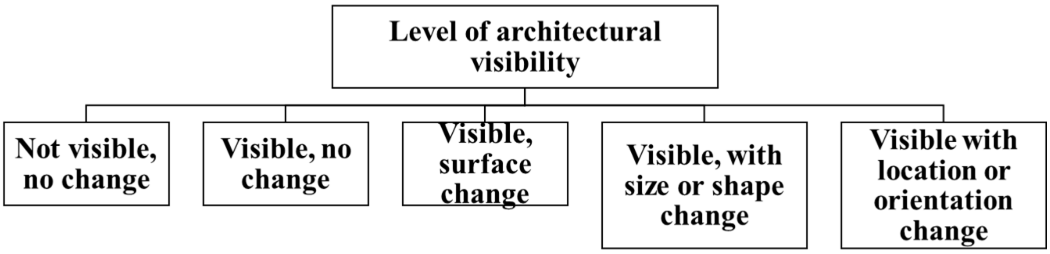

Figure 2.27: level of architectural visibility

-Effect of adaptation: It defines what short of alterations occur in the characteristics of the building's skin between the states before and after the adaptive change has taken place (Figure 2.28) [Loonen 2015].

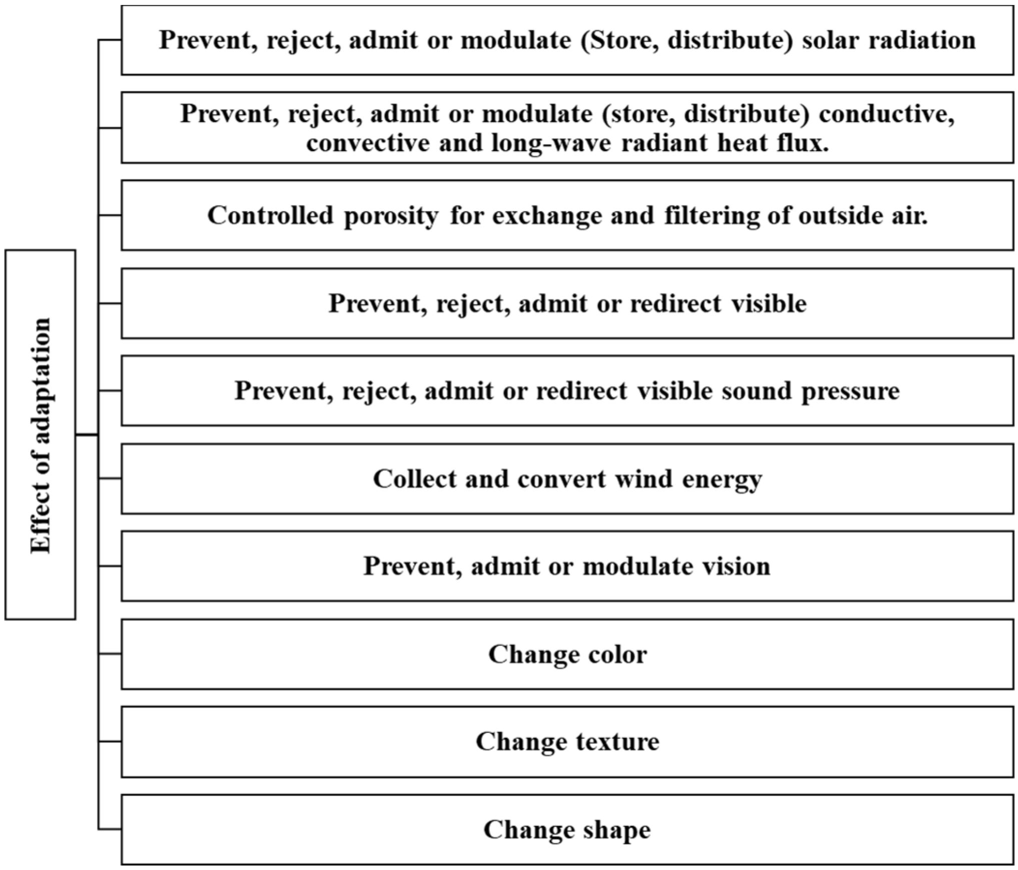

Figure 2.28: different effect of adaptation

-Degree of performance alteration: it refers how much difference the adaptation makes in regard of human needs and interaction with the building context (Figure 2.29).

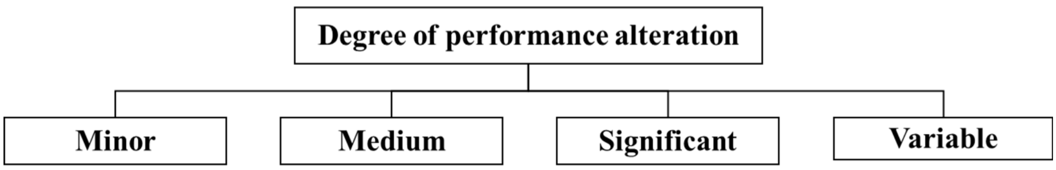

Figure 2.29: degree of performance alteration

-Level of system complexity: the complexity is related to the amount of information used in defining the system. It is determined by the number of unique elements in the system and their interactions (Figure 2.30) [Hubka 1998].

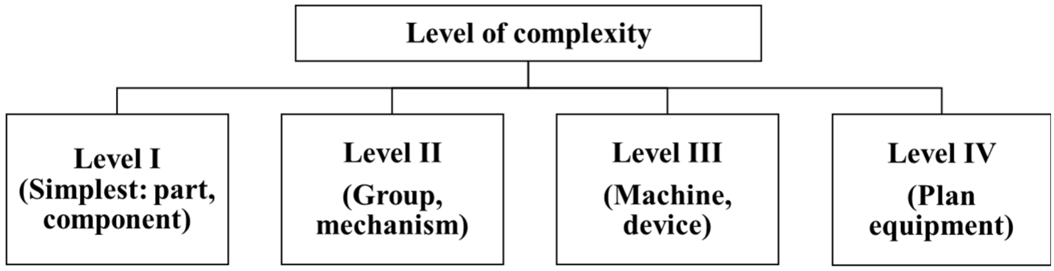

Figure 2.30: level of system complexity

Based on the previous classification approach, we can divide adaptive building's skin into three categories. In this regard, the database case studies were classified, related to the following definitions (Figure 2.31):

- Material: a material can be in different states of refinements such as raw, extruded or coated. In addition, materials that are inseparable combined, such as bi-metals, belong to his category. Examples of these types of material are: Polymer, Bi-metal, steel, wood, phase change material [Aelenei 2018a].

- Component: a component is an assembly of a different set of elements. It forms a complete constructional or functional unit as part of a building's skin. For example, we can define as component systems an insulated glass unit but also a window frame including glazing or a sun-shading device.

- Building's skin-system: a building's skin system is composed of different transparent or opaque structural or technical components. It fulfils all basic technical building's skin functions such as insulation, rain and wind tightness. Example of building's skin systems are: curtain wall; prefabricated module;

double skin building's skin; ventilated building's skin, etc.

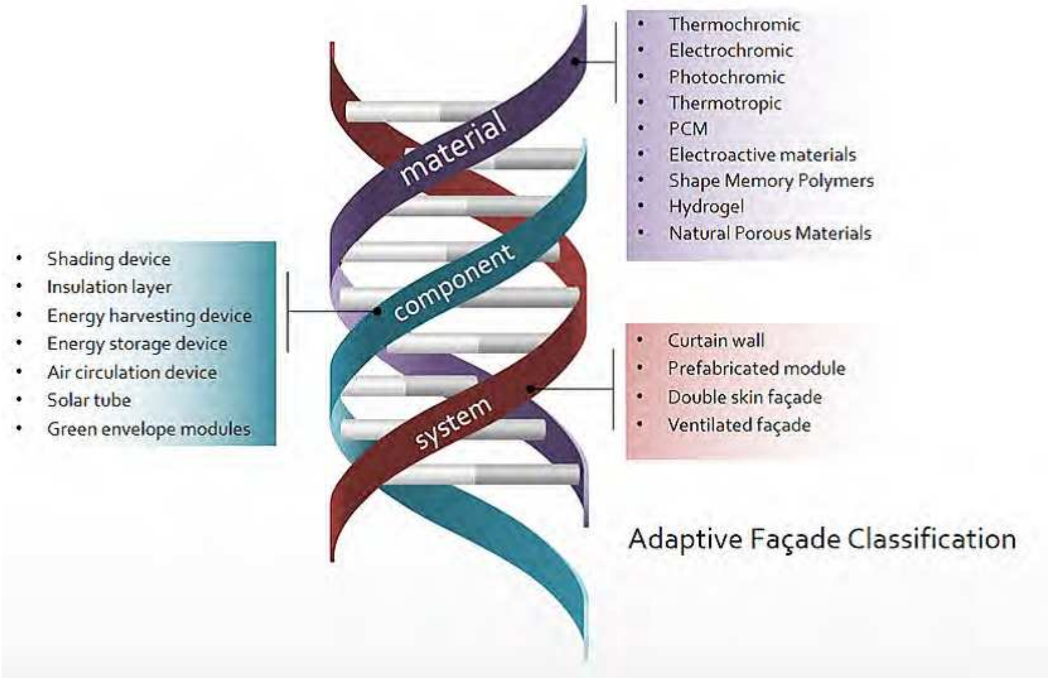

Figure 2.31: diagram of adaptive building's skin categories

2.3.7.1 Adaptive Building's skin Materials

Materials in the built environment play a major role in operational energy consumption and structural optimization as they are defined by boundary conditions. These materials functions sets the operational performance requirements for building component interfaces as an integrated building's skin system.

Thermal, visual comfort demands are driven by the prerequisite to moderate climatic regional environments for shelter. To maintain thermal comfort the building envelope acts as a boundary working with mechanical service systems (heating/cooling, lighting) to regulate internal surrounding temperature. In opaque envelopes the technological methods of achieving good thermal insulation is well researched and advanced. However, to achieve visual comfort and contact to the outside environment, at least part of the building skin needs to be transparent. Translucent components can also contribute to visual comfort by allowing ingress of daylight while redirecting it in a way to avoid harsh shadows. By allowing, the ingress of solar irradiation into the building comes with heat gain issues that require measures against overheating in warm conditions. Hence, thermal insulation properties of the current state-of-the-art in transparent and translucent building envelopes are rather poor in comparison to those of opaque elements [Senem 2018].

The most controllable form of adaptivity can be reached with materials that can be adapted by an 'extrinsic' stimulus such as an electromagnetic field or a pressure change applied to the material. Examples are electrochromic glazing, liquid crystal devices and vacuum insulation that can be switched by a controlled change in the gas partial pressure within the insulation element.

To optimally harness the adaptability of such materials, they need to be integrated into special devices that allow the application of the corresponding 'extrinsic' stimuli. Another class of adaptive materials reacts to an 'intrinsic' stimulus, i.e. a change of a parameter directly relevant for comfort and energy balance of the building such as light intensity, temperature, moisture for example. The characterization of these materials include photochromic glasses, thermo-opaque or shape-memory materials ([Senem 2018]; [Aelenei 2018a]). As an intrinsic environmental stimulus is used to trigger the change in material properties in this case, the integration of the material into a building is usually much simpler than for extrinsically stimulated additivity. However, the adaptively of a facade relying on such a material is autonomous and cannot be extrinsically controlled. Materials that depend on a strong deformation cycle of geometry shape change for adaption without fatigue of failure is a prerequisite for this grouping. Tables 2.1; 2.2 present the analysis of the most prominent adaptive building's skins materials examples.

	Regenerable PV with hydrogel, Hyung-Jun Koo and Orlin D. Velev	NITINOL (NITI)	Facade panels incorporating cement-based batteries,2015 Dr Niall Holmes	MIcrofluid Glass, 2015 M.E.Alston
Building Information	Energy generation, All climates types, All building's skins orientation	Shape memory; alloy; kinetic; temperature; reactive, All climates types, All building's skins orientation	Cement-based batteries; cathodic protection; reinforced concrete; pv	Biosystem, energy, adsorption, conductance, solar modulation device prototype glazed facades new built + refurbishment All climates types, All building's skins orientation
Technology readiness level	Technology validated in lab	Commercial product/Existing building	Technology validated in lab	Technology concept formulated/Design Proposal
Function/ Goal	Energy management (harvesting, storing, supply)	Visual comfort, Appearance (aesthetic quality)	Energy management (harvesting, storing, supply)	Thermal comfort Visual comfort Energy anagement (harvesting, storing, supply) Energy generation
Type of material	Electrochromic: dye-sensitized solar cells	Shape Memory Polymer: Nichel-titanium (NiTi)	Photochromic: Concret	Photochromic Polymers
Material family	Reversible colour / Opacity change	Shape Changing Materials	Cement-based batteries	Reversible colour / Opacity change

Table 2.1: Adaptive building's skin materials case studies analysis (Author)

Type of shading device		Bi-directional transmission control		
Material effect	chemical infusion of organic dye u-FGPV	Shape Memory Material	charging and recharging using photovoltaic	heat flow transport
Type of trigger (Input)	energy enhance performance function of PV	Thermal (e.g. outdoor air temperature)	elements embedded steel corrosion	Electromagnetic (e.g. solar radiation)
Type of actuator (output)	Chemical	Mechanical	Electrical	Thermal
Type of switchable glazing	Photoelectrochemical oxidation to reduce accelerated photo degradation for enhanced photovoltaic functionality			Fluidglass
Control / Operation type	photovoltaic of u-FGPV in a closed structure	Intrinsic (auto reactive)	Intrinsic (auto reactive)	Intrinsic (auto reactive)
System response time	depending on dye infusion into network, changes response time of PoDM regeneration	Seconds	Days	Seconds
System degree of adaptivity	Gradual	Gradual	On/off	On/off
Degree of spatial adaptation	Nanometers	Nanometers		Nanometers
Levels of visibility	Visible, no surface change (smart glazing)	Visible, size or shape change (shutters,flaps, dynamic facade element	Visible, no surface change (smart glazing)	Not visible (heat storage, phase change materials)

Table 2.2: Adaptive building's skin materials case studies analysis continued(Author)

2.3.7.2 Adaptive Building's skin Components

Adaptive building's skins can provide improvements in the building's energy efficiency and economics, through their capability to change their behavior in real time according to indoor-outdoor parameters, by means of materials, components and systems. A component can be defined as an assembly of different set of elements. In this regard, it forms a complete constructional or functional unit as part of a building's skin (for example an insulated glass unit but also a window frame including glazing or a sun shading device). Unlike the adaptive building's skins solutions analyzed in the WG1 database, most of the component case studies are still in the development, prototype and lab test phases. This demonstrates that the research is constantly aimed at the optimization and development of new and advanced solutions that can be used in this construction sector [Senem 2018].

One of the aim of the adaptive components is to react to external stimuli with low-environmental impact and low-cost. In this regard, an understanding of how materials changes with environmental exposure is vital for successful long-term architectural application. Moreover, the study of durability and life cycle of these same components becomes crucial to make future applications sustainable. It is interesting to notice that many adaptive components are directed not only to efficiently contribute to the energy balance of the building and the reduction in energy consumption, but also towards aspects of multimedia communication, where building building's skins become a means of relating to the city and its inhabitants. Tables 2.3; 2.4 present the analysis of the most prominent adaptive building's skins components examples.

	HYGROSCOPE, Centre Pompidou, Paris, 2012 Achim Menges Architect	InDeWaG, BAYREUTH (DE), 2015 Dieter Brüggemann	KUMORIgami, MILAN 2016 Pesenti, Masera, Fiorito	BIPV Adaptive Flakes, Milan 2016 Enrico Sergio, Mazzucchelli, Luisa Doniacovo
Building Information	Moisture Sensitive; parametric; wood; kinetic; autoreactive	Fluid Flow Glazing Systems; Insulating Glazing; Daylight All climates, All orientations	Origami, Parametric, Kinetic, Adaptive Shape Memory Alloy All climates, East, South, West	Bipv, Adaptive Flakes, Shading System, Hygromorphic Materials, Timber All climates, East, South, West
Technology readiness level	Prototype demonstration	Prototype demonstration	Technology concept formulated/ Design Proposal	Technology concept formulated/ Design Proposal
Function/ Goal	Visual comfort	Thermal comfort Visual comfort Energy management (harvesting, storing, supply) Indoor air quality Energy generation	Visual comfort Appearance (aesthetic quality)	Visual comfort Energy generation
Type of component system	External skin	Curtain wall (stick) Energy harvesting device	External skin	Curtain wall (stick) Energy harvesting device
Technological features	Mobile screens for controlling solar radiation	High-performance innovative materials and systems for absorbing and storing solar energy	Mobile screens for controlling solar radiation	-High- performance innovative materials and systems for absorbing and storing solar energy -Mobile screens for controlling solar radiation

Table 2.3: Adaptive building's skin components case studies analysis(Author)

Type of shading device	Bi-directional transmission control		Deployable screen	Flake that changes its shape
Type of material	Wood	Fluidglass	translucent polypropylene, opaque methyl methacrylate, NiTinol springs	Wood PV
Material effect	Bi-material effect		Heat-joule effect	Bio-material effect
Type of trigger (Input)	Air quality (humidity, CO2 concentration, etc)	Air temperature	Optical (e.g. daylight level, glare)	- Thermal (e.g. outdoor air temperature) - Air quality (humidity, CO2 concentration, etc)
Type of actuator (output)	Mechanical		NiTinol springs	-Thermal -Outdoor climate
Type of switchable glazing		Fluid glass		
Control/ Operation type	Intrinsic (auto reactive)	Intrinsic (auto reactive)	Intrinsic (auto reactive) Possibility to switch by using electricity	Intrinsic (auto reactive)
System response time	Gradual	On/Off	Gradual On/Off	Gradual
Degree of spatial adaptation	Micrometers	Micrometers	Centimeters	Millimeters
Levels of visibility	Visible, size or shape change(shutters, flaps, dynamic facade elements)	Visible, no surface change (smart glazing)	Visible, size or shape change (shutters, flaps, dynamic facade elements)	Visible, size or shape change (shutters, flaps, dynamic facade elements)

Table 2.4: Adaptive building's skin components case studies analysis continued(Author)

2.3.7.3 Adaptive Building's skin Systems

Building's skin systems have been transformed from passive technological solutions to active systems capable of producing renewable energy and, above all, able of changing the building in a dynamic and adaptive system, in terms of the spatial configurations and behaviour of its external skin, to improve indoor comfort conditions [Senem 2018]. Thanks to the presence of smart materials and/or automated systems with varying degrees of complexity the building thereby becomes a dynamic system, which can be likened to a living organism, in which each part reacts to external and internal input, adapting to the surrounding space with the aim of regulating the energy balance necessary for it to function [Aelenei 2018b]. Tables 2.5; 2.6 presents the analysis of the most prominent adaptive building's skins systems examples.

	Al bahar towers, Abu Dhabi (AE), 2012 Aedas Architects	Swisstech convention center western facade, Lausanne, 2014 Michael Grätzel	Campus kolding, Kolding, 2014 Henning Larsen Architects	Selfie facade, florence (IT), 2017 Interuniversity Research Centre
Building	Mashrabiya; Double	Dye-Sensitized Solar	Shading Device,	Energy Saving
Information	Skin Facade Shading Device PTFE	Cells; Vertical Shading Devices; Convention Center	Dynamic And Adaptive Envelope, Energy Saving South, East, West	Renewable Energy; Bipv; Pcm; Nanomaterials New build South face
Technology readiness level	Commercial product/Existing building	Commercial product/Existing building	Commercial product/Existing building	Commercial product/Existing building
Function/ Goal	Thermal comfort Visual comfort Acoustic comfort Appearance (aesthetic quality)	Visual comfort Appearance (aesthetic quality) Energy generation	Thermal comfort Visual comfort Appearance Personal users control	Thermal comfort Visual comfort Acoustic comfort Energy management Mass transfer control Indoor air quality Appearance Energy generation
Type of facade system	Responsive building's skin	Active building's skin	Kinetic building's skin Interactive building's skin Responsive building's skin	Smart building's skin

Table 2.5: Adaptive building's skin systems case studies analysis (Author)

Technological features	-Mobile screens for controlling solar	High-performance innovative materials	-Mobile screens for controlling solar	High-performance innovative materials
	radiation - Building automation systems for the	and systems for absorbing and storing solar energy	radiation - Building automation systems for the	and systems for absorbing and storing solar energy
	management		management	
	of plants and elements of the building skin		of plants and elements of the building skin	
Type of material	PTFE	Photovoltaic (Dye-sensitized	Aluminium	-Phase Change Materials
		solar cells)		-Ceramics - BIPV
Type of shading device	triangulate units	Blinds with slat angle control	Shading with dual-axis tracking	Screens / roller shades
Material effect	/	Electroactive material	/	Phase Change
Type of trigger (Input)	Optical (e.g. daylight level, glare)	Electromagnetic (e.g. solar radiation)	Electromagnetic (e.g. solar radiation)	Thermal Optical
Type of actuator (output)	Mechanical	Electromagnetic	Mechanical	Mechanical Thermal Chemical
Control/ Operation type	Intrinsic (auto reactive)	Intrinsic (auto reactive)	Intrinsic (auto reactive) Extrinsic (requires external control)	Extrinsic (requires external control) external control)
System response time	Minutes	Seconds	Seconds, minutes, hours	Minutes
System degree of adaptivity	Gradual	On / Off	Gradual	Gradual
degree of spatial adaptivity	Centimeters	Nanometers	Centimeters	Nanometers
Levels of visibility	Visible, size or shape change (shutters, flaps, dynamic facade elements)	Not visible (heat storage, phase change materials)	Visible, size or shape change (shutters, flaps, dynamic facade elements)	Not visible (heat storage, phase change materials)

Table 2.6: Adaptive building's skin systems case studies analysis continued(Author)

2.4 CONCLUSION

Delivering building with adaptive features is a discourse, taking place in our profession that helps to overcome some of the serious issues that the environment is experiencing. This chapter presented a background research into adaptation approach in architecture and building's skin.

The results from the literature study within the context of this chapter were introduced and divided into two distinct parts; adaptive architecture, in which the approach and the different related concepts were presented and defined. The second part was about adaptive building's skins, their control system, mechanisms and different adaptive systems that exhibits properties that could be used in responsive designs. In this chapter ,different examples of adaptive building skins and adaptive building components that can be used in the building's skins were presented.

Chapter 3

KINETIC ARCHITECTURE: A NEW APPROACH FOR ENVIRONMENTAL CONTROL

" Architecture is a visual art, and the buildings speak for themselves."

- Julia Morgan

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3.1 INTRODUCTION

This chapter provides a review on kinetic design in architecture and kinematics. The objective of this chapter is to understand kinetic architecture and propose a conceptual framework for kinetic approach in architecture. A thorough understanding of kinetic systems that are relevant to architecture and their usage is presented, because it enables architects to think about the major aspects of kinetics and explore their potential for architectural applications and environmental control. In this context, the chapter presents a methodology for the definition and classification of different terms, concepts, and approaches in kinetic architecture. Moreover, it develops a framework of design strategies to identify different kinetic phases based on the main issues concerning the approach's impact on sustainability, each of these issues is explained separately, listing the main points and supporting it with examples. Previous and ongoing research work conducted by different researchers on this aspect are presented. Key observations from the reviewed studies are summarized at the end of this chapter.

3.2 KINEMATICS: DESIGN OF MOTION

3.2.1 KINEMATICS DEFINITION

Kinematics is a branch of classical mechanics. It concerns the study of motion (points, bodies (objects), and systems of bodies (groups of objects)) without regard to forces that cause them to move. Kinematics, as a field of study, is often referred to as the "geometry of motion" and is occasionally seen as a branch of mathematics [Erdman 1991]. The most important aim of kinematics is to create and design the desired motions of the subject mechanical parts and then mathematically compute the positions, velocities and accelerations that those motions will create on the parts [Norton 2004].

The term kinematic is the English version of A.M. Ampére's cinématique, which he constructed from the Greek kinema ("movement, motion"), itself derived from kinein ("to move"). Kinematic and cinématique are related to the French word cinéma, but neither are directly derived from it. However, they do share a root word in common, as cinéma came from the shortened form of cinématographe, "motion picture projector and camera," once again from the Greek word for movement and from the Greek grapho ("to write") ([Hertel 1966]; [Muller 1996]).

3.2.2 APPLICATION OF KINEMATICS AND ITS DESIGN PROCESS

Determining the kinematic configuration needed to provide the desired motions is the first task in solving any machine design problem. Without solving the kinematic issues, forces and stress analyses could not been done ([Bayram 2003]; [Erdman 1991]). Virtually, any machine or device that moves contains one or more kinematic elements such as linkages, cams, gears, belts. A bicycle is a simple example of a kinematic system containing a chain drive to provide torque multiplication and simple cable- operated linkages for braking.

Kinematic research has been devoted to the definition of several design processes intended to provide means to structure the unstructured problem and lead to a viable solution. Norton Robert in ([Norton 2004]; [Kimbrell 1991]) presented 10 steps of kinematic design process: identification of need, background research, goal statement, performance specifications, ideation and invention, analysis, selection, detailed design, prototyping and testing, and production.

- Identification of need

  Often we have to identify what we need, and this statement will be brief and lacking in detail, it will fall far short of providing us with structured problem statement.

- Background research

  This is the most important phase in the process. In this phase, we have to gather information on the relevant physics and the other aspects of the problem.

- Goal statement

  Once the background of the problem area as originally stated is fully understood, we recast the problem into a more coherent goal statement, it should be concise, be general and couched in terms of functional visualization.

- Performance specifications

  In this phase, we have to formulate a set of performance specifications (task specifications) in order to specify how the goal is to be accomplished.

- Ideation and invention

  Several techniques have been developed to enhance or inspire creative problem solving. The ideation and invention step can be broken down into four sub-steps: idea generation, brainstorming, problem statement.

- Analysis

  In this phase, we analyze and examine the performance on the design. Further iteration will be required as problems are discovered from the analysis. Repetition of as many steps in the design process as necessary must be done to ensure the success of the design.

- Selection

  After the technical analysis step, we select the most optimal design for detailing, prototyping and testing. The selection process involves a comparative analysis of the available design solutions. We have to consider a variety of factors in a decision matrix (Figure 3.1) to help us in the selection process.

	Cost	*Safety*	*Performance*	*Reliability*	*RANK*
Weighting Factor	.35	.30	.15	.20	1.0
Design 1	3 / 1.05	6 / 1.80	4 / .60	9 / 1.80	5.3
Design 2	4 / 1.40	2 / .60	7 / 1.05	2 / .40	3.5
Design 3	1 / .35	9 / 2.70	4 / .60	5 / 1.00	4.7
Design 4	9 / 3.15	1 / .30	6 / .90	7 / 1.40	5.8
Design 5	7 / 2.45	4 / 1.20	2 / .30	6 / 1.20	5.2

Figure 3.1: an example of a decision matrix [Norton 2004]

- Detailed design

  In this step, we create a complete set of assembly and detail drawings of each and every part used in the design specifying the dimensions, materials...From this drawings a prototype test model will be constructed for physical testing.

- Prototyping and testing

  In this step, we actuate the model or the prototype and observe its function and performance.

- Production

  In this phase, we will be ready for the production and manufacturing the final version of the design.

3.3 KINEMATIC FUNDAMENTALS

In this section, we present definitions of a number of terms and concepts fundamental to the synthesis and analysis of mechanisms.

3.3.1 DEGREES OF FREEDOM (DOF)/MOBILITY

A mechanical system's mobility (M) can be classified according the number of the degrees of freedom (DOF) that it possesses. The system DOF is equal to the number of independent parameters (measurements) that are needed to uniquely define its position in space at any instant of time [Norton 2004].Figure 3.2 shows a pencil lying into a flat paper; three parameters are required to completely define the pencil's position on the paper: two linear coordinates (x,y) and one angular coordinate (θ) to define the angle of the pencil with respect to the axes. This system of the pencil in the plane then has three DOF. If the pencil exists in a three-dimensional world, in this case we will need six parameters to define its six DOF: three lengths (x,y,z) and three angles (θ, ϕ, α) [Bayram 2003].

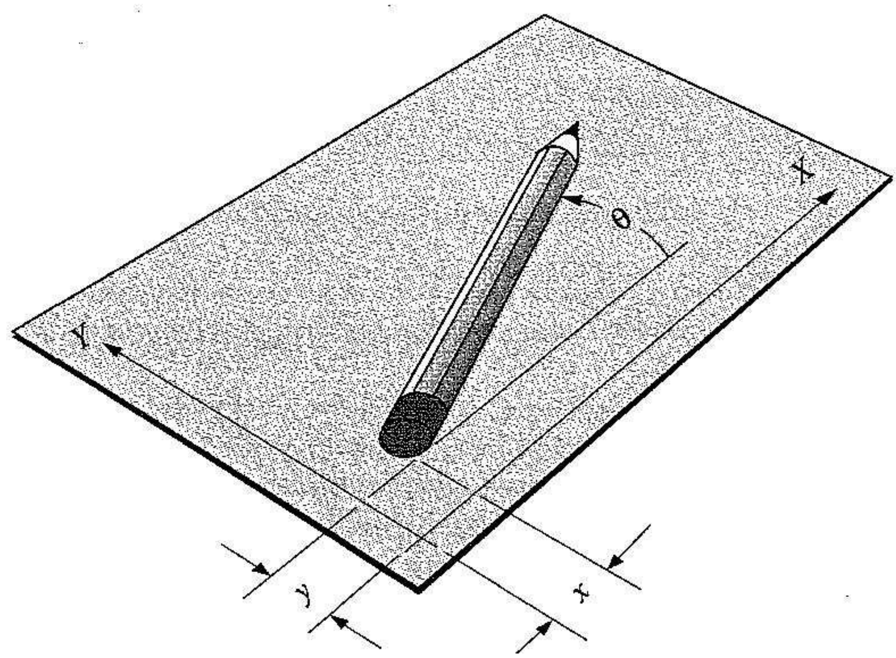

Figure 3.2: a pencil in a plane with three DOF

3.3.2 TYPES OF MOTION

A rigid body free to move within a reference frame will have complex motion, which is simultaneous combination of rotation and translation. In three-dimensional space, there may be rotation about any axis of three principal axes and also simultaneous translation along the three axes.

- Pure rotation

  The body possesses one point (center of rotation) that has no motion with respect to the "stationary" frame of reference. All other points on the body describe arcs about that center. A reference line drawn on the body through the center changes only its angular orientation.

- Pure translation

  All points on the body describe parallel (curvilinear or rectilinear) paths. A reference line drawn on the body changes its linear position but does not change its angular orientation

- Complex motion

  A simultaneous combination of rotation and translation. Any reference line drawn on the body will change both its linear position and its angular orientation. Points on the body will travel nonparallel paths, and there will be, at every instant, a center of rotation, which will continuously change location.

3.3.3 LINKS, JOINTS AND KINEMATIC CHAINS

Linkages are the basic building blocks of all mechanisms. Linkages are made up of links and joints [Korkmaz 2004]. A link, as shown in figures (Figure (3.3), Figure (3.4), Figure (3.5)) is a rigid body that possesses at least two nodes that are points of attachment to other links, binary link (Figure 3.3), it is one link with two nodes, ternary link (Figure 3.4) is a link with three nodes, and quaternary link (Figure 3.5) is a link with four nodes [Norton 2004].

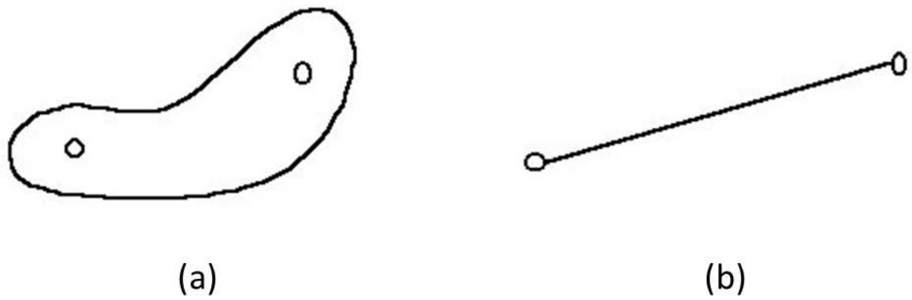

Figure 3.3: Binary link (a) Typical Form, (b) Skeleton Diagram

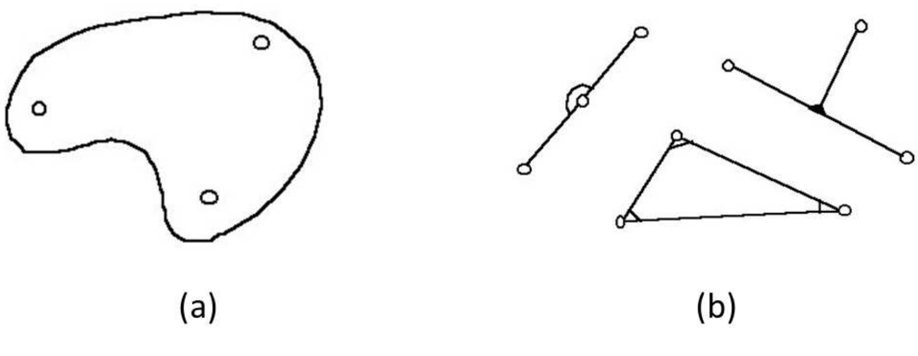

Figure 3.4: ternary link (a) Typical Form, (b) Skeleton Diagram

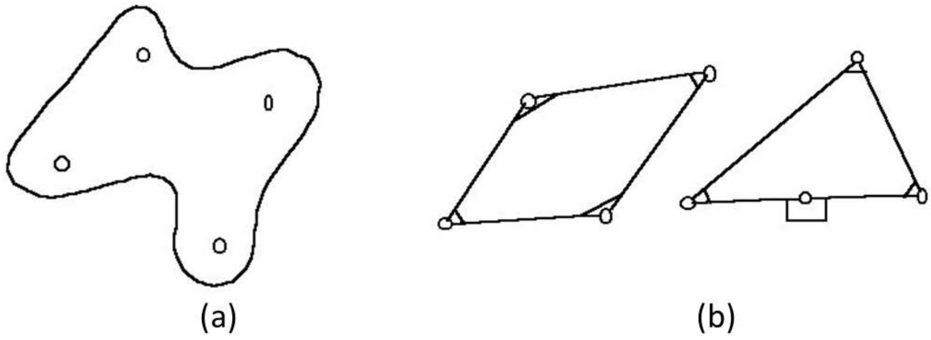

Figure 3.5: quaternary link (a) Typical Form, (b) Skeleton Diagram

A joint is a connection between two or more links (at their nodes), which allows motion between the connected links. Joints are also called kinematic pairs, they can be classified in several ways:

- By the type of contact between the elements, line, point or surface.
- By the number of degrees of freedom allowed at the joint
- By the type of physical closure of the joint: either force or form closed.
- By the number of links joined (order of the joint).

Norton in [Norton 2004] described joints with surface contact as lower pair and joints with point or line contact as higher pair. Figure 3.6 presents the six possible lower pairs, their degrees of freedom and their one-letter symbols. The revolute (R) and the prismatic (P) pairs are the only lower pairs usable in a planar mechanism. The screw (H), cylindric (C), spherical (S) and flat (F) lower pairs are all combinations of the revolute and prismatic pairs and are used in spatial 3D mechanisms.

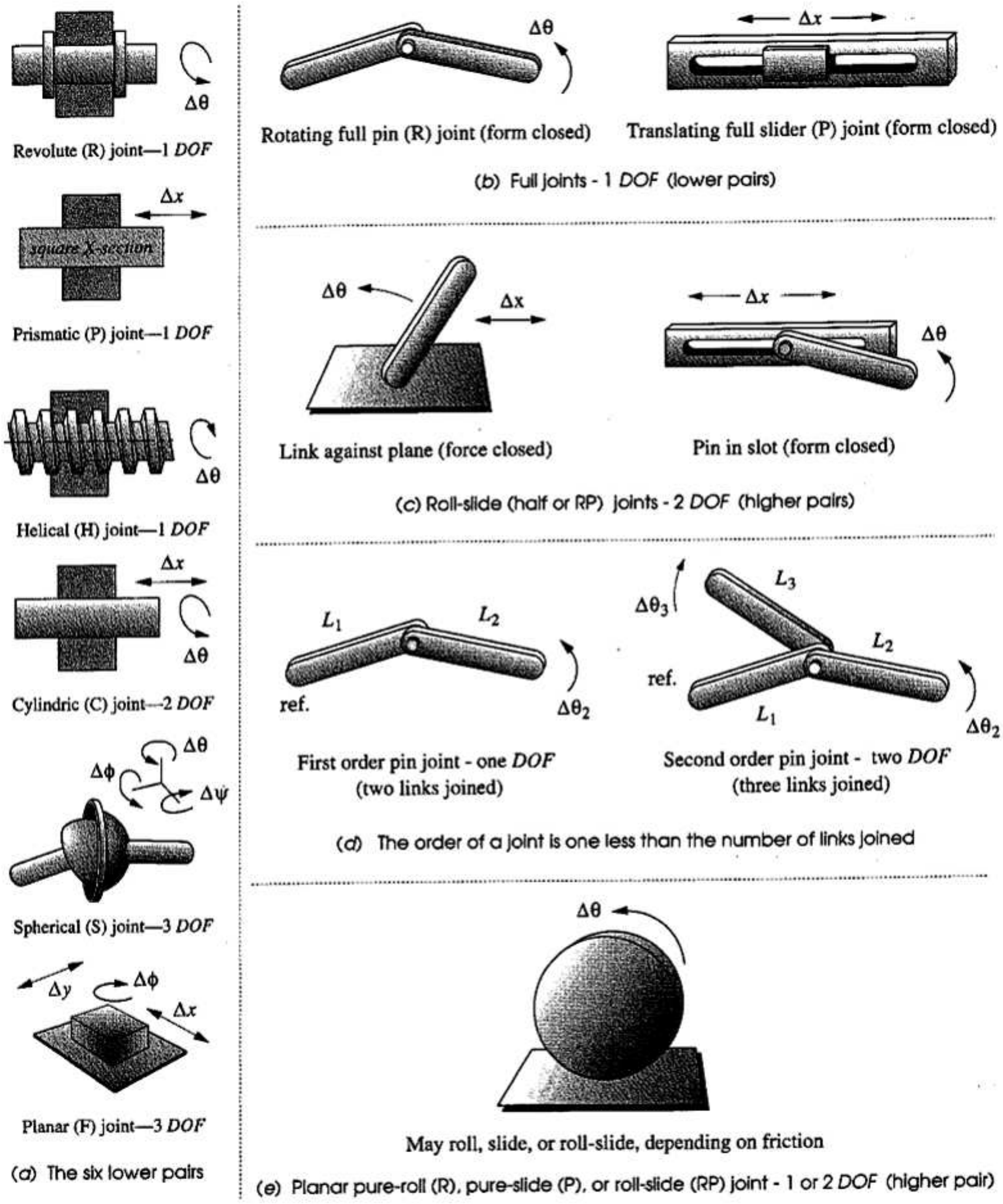

Figure 3.6: Joints (pairs) of various types [Norton 2004]

Kinematic chain is defined as an assemblage of links and joints, interconnected in a way to provide a controlled output motion in response to a supplied input motion [Norton 2004]. If the links are connected in such a way that no motion is possible, it results in a locked chain or structure (Figure 3.7).

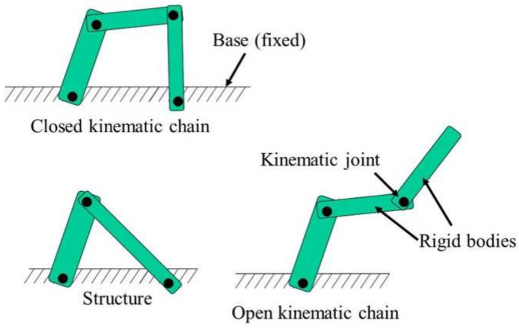

Figure 3.7: open and closed kinematic chains

In case when at least one link is grounded or attached to the frame of reference, the kinematic chain will be called mechanism [Norton 2004]. This means that the motion of any one link in the kinematic chain will give a definite and predictable motion relative to each of the others. Usually one of the links of the kinematic chain is fixed in a mechanism. According to Norton definition [Norton 2004], a machine is a collection of mechanisms arranged to transmit forces and do work.

If, for a particular position of a link of the chain, the positions of each of the other links of the chain can not be predicted, then it is called as unconstrained kinematic chain and it is not mechanism. All mechanisms are Kinematic chains but not vice versa (Figure 3.8).

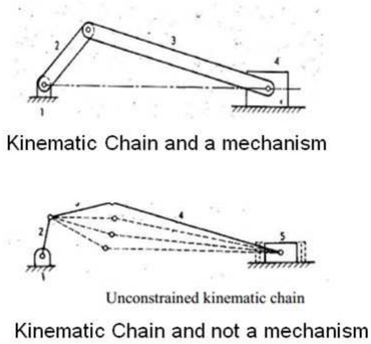

Figure 3.8: the difference between the kinematic chain and the mechanism [Norton 2004]

3.4 KINETIC DESIGN IN ARCHITECTURE

3.4.1 KINETIC DESIGN DEFINITION

Kinetics deals with the forces or torque applied on a body [Norton 2004]. It focuses on the causes of different motions of objects such as in case of rotational motion, force or torques is dealt with kinetics [Soha 2012]. Kinematics focuses on the velocities, acceleration and position of objects. Kinematics does not consider the masses of the object. Table 3.1 presents the difference between kinetics and kinematics.

3.4.2 KINETIC ARCHITECTURE DEFINITION

Integrating intelligent features into the architecture of a building is a discourse taking place in the architecture profession [ElSheikh 2011]. According to Willian Zuk and Roger Clark [Zuk 1970] the kinetic architecture is where "the architectural form could be inherently being dispenceable, deformable, expandable or capable of kinetic movement". However, [Fox 2009] describes it as " either transformable objects with dynamically occupy predefined physical space, or moving physical objects that can share a common physical objects that can share a common physical space to create adaptable spatial configurations". If the building could mediate our needs and the environment outside: its demand on physical resources could be slashed. If it could transform to facilitate multi-uses; its function would be optimized. If a building could adapt to our desires: It would shape our experience" [Fox 2003].

Kronenberg in [Kronenburg 2008] defines kinetic architecture as buildings or building components with variable mobility, location and / or geometry. Hornby in [Hornby 2010] states that, kinetic architecture refers to the design of buildings that are produced by movement.

When implicating kinetics in architecture, the design will be a continuous process that will not stop when the building is erected [Elzanfaly 2009].

Kostas Terzidis [Trezidis 2003] also defined kinetic architecture as "*The integration of motion into the built environment, and the impact such results has upon the aesthetics, design, and performance of buildings may be of great importance to the field of ar-*

Difference Between	Kinetics and Kinematics
Kinetics	Kinematics
Deals with the causes for the motions of the object	Deals with the position, acceleration, speed of an object
Takes into consideration the mass of the object	Doesn't take into consideration the mass of the object
Its practical applications can be found	Its application can be found in the study
in the designing of automobiles	of the movement of celestial bodies
It takes forces explicitly into account	It doesn't take forces explicitly into account
It does not have more mathematical expressions	It has more mathematical expressions
It is also known as dynamics	It is called with the same name
This topic is used in various branches of science such as biology, chemistry and physics	This topic is used in physics, mechanics in terms of engineering

Table 3.1: difference between kinetics and kinematics

chitecture. While the aesthetic value of virtual motion may always be a source of inspiration, its physical implementation in buildings and structures may challenge the very nature of what architecture really is".

3.4.3 HISTORICAL CHRONOLOGY OF THE KINETIC ARCHITECTURE

Kinetic architecture is not new [Elzanfaly 2009]. This ideology has appeared at least since the XIII century, where Leonardo Da Vinci designed numerous kinetic structures. He designed a crane, which, can move and lifts heavy weights (Figure 3.9).

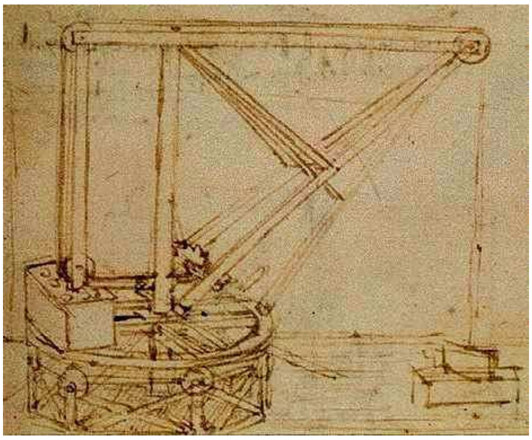

Figure 3.9: sketches of the crane (Source: https://sites.google.com/a/mynbps.org/ninas-old-fab-lab/ib-design-tech-year-1/strategies for innovation individual exercise)

Traced back to the middle ages or earlier, we found that drawbridges were the most popular form of kinetic architecture (Figure 3.10). Yet it was only in the early 20th century that architects began to widely discuss the possibility for movement to be enabled for a significant portion of a buildings' superstructure [Asefi 2010]. In the first third of the 20th century, interest in kinetic architecture was one of the stands of thought emerging from the Futurism movement [Laracuente 2015]. Various papers and books included plans and drawings for moving buildings.

For the first few decades of the 20th century, kinetic architecture was almost entirely theoretical, but by the 1940s, innovators such as Buckminster Fuller began experimenting with concrete implementations, though his early efforts in this direction are not regarded as very successful.

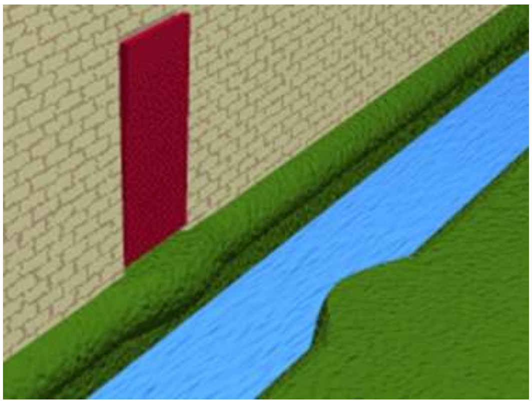

Figure 3.10: drawbridge: an early instance of kinetic architecture

According to the portal theartstory.org, the kinetic art as a proto-disciplinary approach to bionics and as a movement would not start until 1954 (Figure 3.11). The kinetic art has traced its origins from XIX century's impressionism and the beginning of the XX century's futurism [Laracuente 2015]. In presenting works of art which moved, or which gave the impression of movement (from mobile, mechanical sculptures to Op art paintings, which seemed to rotate or vibrate in front of the eyes). Kinetic artists offered us some of the most quintessential expressions of modern art's concern with presenting rather than representing living reality. It Kinetic art grew into a lively avant-garde after the Second World War.

The Kinetic art movement was the first to offer works of art which extended in time as well as space. This was a revolutionary gesture: not only because it introduced an entirely new dimension into the viewing experience, but because it so effectively expressed the new fascination with the interrelationship of time and space

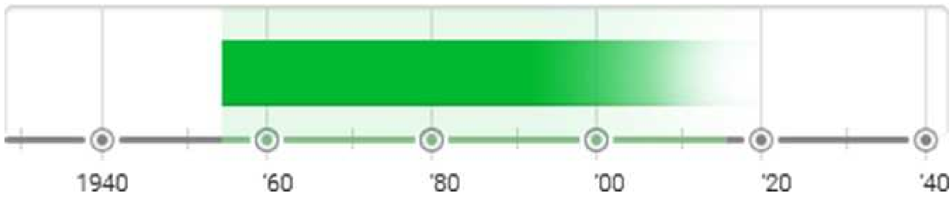

Figure 3.11: Kinetic art timeline and years of influence

which defined modern intellectual culture since the discoveries of Einstein.

The book of William Zuk "Kinetic architecture" [Zuk 1970] inspired a new generation of architects, to design an increasingly wide range of actual working kinetic buildings. Assisted by new concepts such as Fuller's Tensegrity and by developments in robotics, kinetic buildings have become increasingly common worldwide since the 1980s. Architect Jose Leonidas Mejia, created the concept in its region in 1989 with a deepen application on transforming structures [Laracuente 2015]. Figure 3.12 shows a timeline for the major historical kinetic structure projects and books in the 20th century, including Heroons's walking City in the 60's and ending with Rajaa Issa's book "Essential algorithms and data structures" in 2020 [Rajaa 2020].

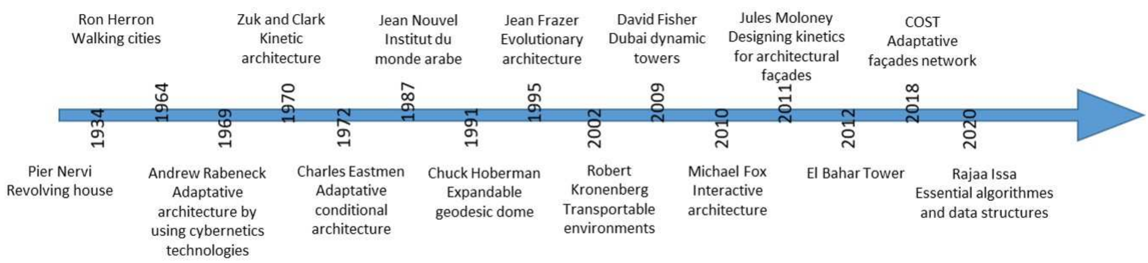

Figure 3.12: a timeline for the major historical kinetic structure projects and books in the 20th century (Author)

3.5 INTERACTIVE MOVEMENT AND ITS PRINCIPLES IN KINEIC ARCHITECTURE

In this section, we present the interactive movement as one of the leading factors of contemporary ways of expression in architecture. The evolution of architecture from static and stability to dynamic and movement has been followed by changes in the architectural thought ([Elkhayat 2014a]; [Fox 2010]). The kinetic architectural language has been found as some new concepts have emerged, and so modulation vocabulary uses have been introduced, materials and construction methods have evolved and uses of computer and multimedia in architecture have developed. Elkhayat in [Elkhayat 2014a] introduced the design principles of interactive movement that would be applied in kinetic architecture.

- Time

  Time refers to really existence of phenomena. It always accompany movement and material, if the place has three dimensions, the dimension of time is one to forward [Schumacher 2010].

- Physics and balance

  Mechanics is a science, which follows physics, and it is one of extensive sciences dealing with movement of objects and their causes. A branch of Mechanics is "Dynamics", which deals with objects under effect of forces that often follows statics study [Meriam 1998].

- Speed and acceleration

  A part of movement is the speed at which movement takes place. Without speed, or a change between two different states there is no movement. Movement results from a change in position from a stationary condition via acceleration and deceleration to a new stationary condition [Schumacher 2010].

- Form and serial repetition

According to [Schumacher 2010], specific forms characterize moving things like all things. Nevertheless, the definition of form is more complex than with static objects as its form changes with movement. The serial repetition of movable building elements is very common in architecture. The way in which elements are coupled in series can have a great effect on the overall appearance [Elkhayat 2014a].

- Mass and weight

  Elkhayat in [Elkhayat 2014a], states that large masses are more difficult to set in motion as well as to halt once moving. As ever in architecture, the mass of an element needs to be taken into account in terms of both construction as well as design. For architects, the need to consider the implications of mass in the design of moving architectural elements is comparatively new.

- Complexity and Scale

  Complex temporal and spatial sequences in the transformation of an object can also be used as a means of design. Movement has been and will continue to be integrated into architecture at all scales and orders of magnitude. The scale of the movable element (its order of magnitude in relation to the scale of the human being) has a determining effect on the complexity: the technical realization of movement.

- Mystery and interaction

  Some movements generate interest precisely because one cannot see where they come from or how they work [Schumacher 2010]. Interaction is a kind of action that occurs as two or more objects have an effect upon one another.

Interactive Architecture is a processes-oriented guide to creating dynamic spaces and objects capable of performing a range of pragmatic and humanistic functions. These complex physical interactions are made possible by the creative fusion of embedded computation (intelligence) with a physical, tangible counterpart (kinetics) [Moloney 2011]. Interactive Architecture includes contributions from the worlds of architecture, industrial design, computer programming, engineering, and physical computing. Interactive Architecture examines this vanguard movement from all sides, including its sociological and psychological implications as well as its potentially beneficial environmental impact ([Elkhayat 2014a]; [Fox 2010]).

3.6 ACTUAL MOVEMENT IN ARCHITECTURE

3.6.1 TYPOLOGIES OF ACTUAL MOVEMENT IN ARCHITECTURE

El Khayat in [Elkhayat 2014a] divided the typologies of actual movement in architecture into five types, considering that the movement is one of all the branchesof mechanical physics:

- The movement of rigid architectural elements.
- The movement of deformable architectural elements.
- The movement of soft and flexible architectural elements.
- The movement of elastic architectural elements.
- Pneumatic forms.

3.6.1.1 MOVEMENT OF RIGID ARCHITECTURAL ELEMENTS

Any mechanical movements is based mainly on two types of movement: Rotation, Translation and a combination of the two. Nevertheless, where the joint is located and without considering gravity, this classification is used [Elkhayat 2014a]. As architects and building designers, the function of the movement is considered rather than the precise mechanical or theoretical elaboration of a sequence of movements (Figure 3.13).

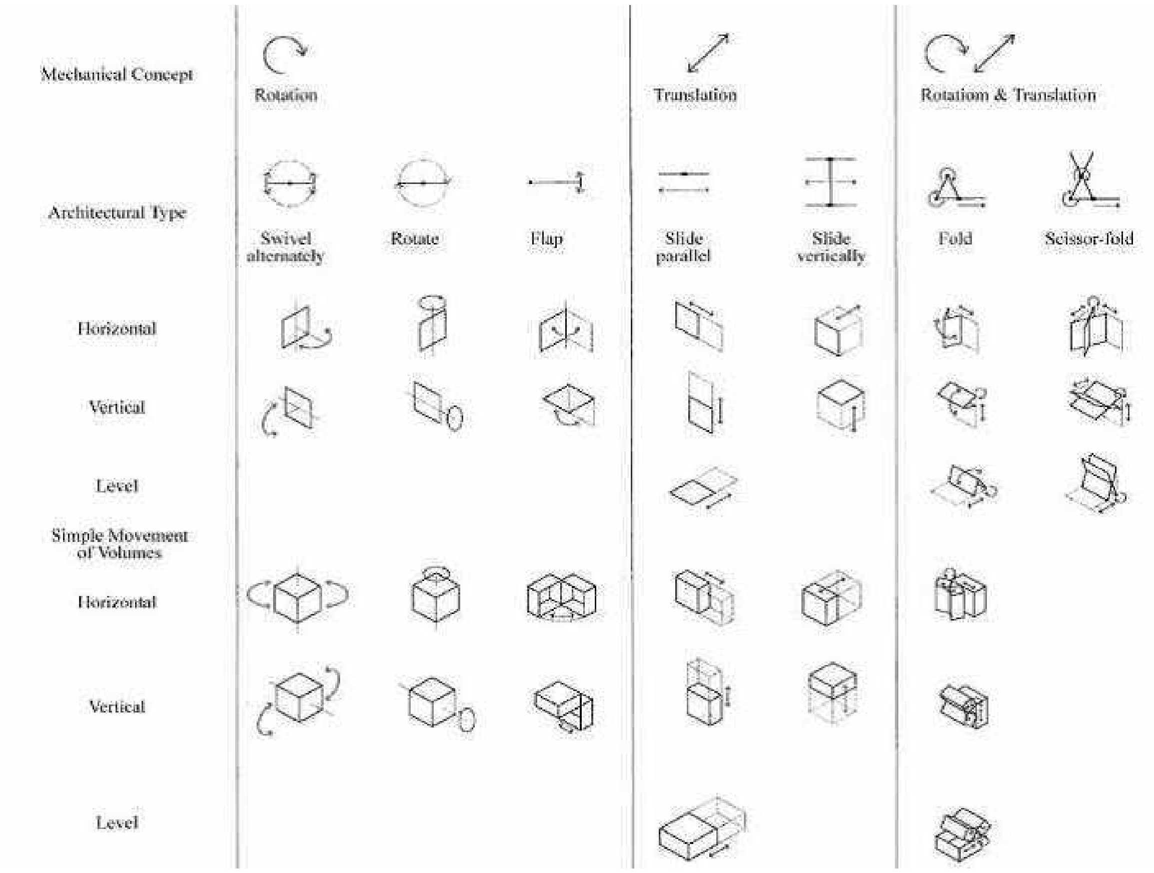

Figure 3.13: movement of rigid architectural elements [Elkhayat 2014a]

3.6.1.2 MOVEMENT OF DEFORMABLE ARCHITECTURAL ELEMENTS

Elkhayat in [Elkhayat 2014a] states that deformable architectural elements play an important role in small-scale movements in particular and in the flexible transformation of larger surfaces (Figure 3.14). In this case, formal and spatial transformations are not the product of different specific and temporal constellations of essentially rigid, unchanging building elements, as discussed above, but instead result from movement within the element or the material itself. Depending on the specific material properties and combinations of the materials, used one differentiates between soft and flexible bodies and elastic bodies. Substances and plastic materials that deform irreversibly under force are rarely used in architecture [Schumacher 2010].

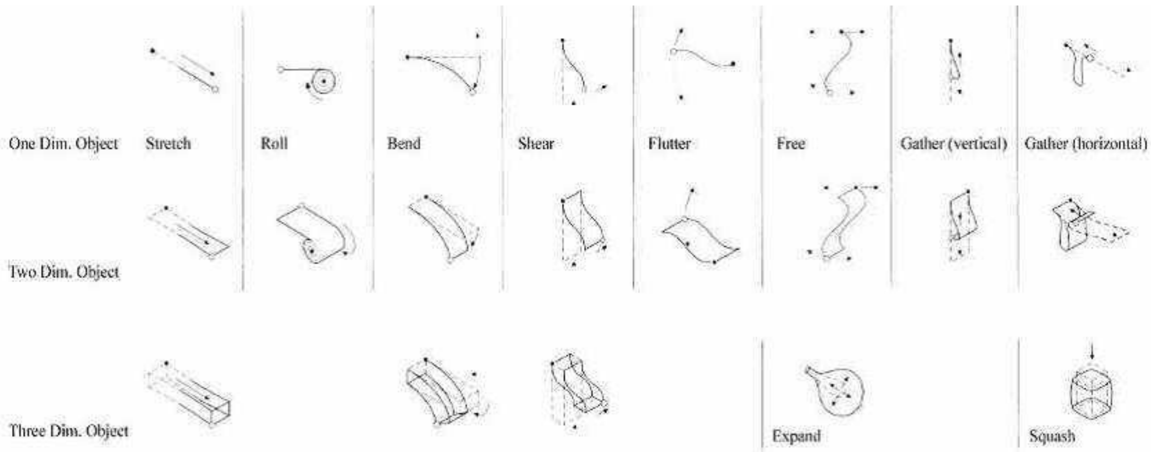

Figure 3.14: Types of the movement of deformable architectural elements [Schumacher 2010]

3.6.1.3 MOVEMENT OF SOFT AND FLEXIBLE ARCHITECTURAL ELEMENTS

Flexible architectural elements are able to change shape permanently when external forces are applied without losing their overall formal consistency. Soft and flexible architectural elements can be divided into two types: Linear and Flat elements. Linear examples include fibers, cords or ropes; flat examples include textiles and woven or knitted fabrics. Elastic materials are used extensively in architecture, most commonly in the form of textiles [Elkhayat 2014a]. Textiles and membranes are extremely light and flexible in relation to the surface area they can cover. They are particularly well suited for creating strong visual and spatial divisions with a minimum amount of energy input and are used in combination with a whole vocabulary of hanging, rolling, gathering or pleating systems [Kronenburg 2007]

3.6.1.4 MOVEMENT OF ELASTIC ARCHITECTURAL ELEMENTS

As Elkhayat mentions in [Elkhayat 2014a], in contrast to flexible or supple materials, elastic materials are able to regain their original form after deformation without the need for additional external force. In theory, elastic materials offer a variety of architectural applications, however most elastic materials are not available on the market at the necessary size, durability or visual quality. The use of this group of materials is therefore restricted to small-scale elements and less design-related functions, for example steel springs or rubber dampers [Schumacher 2010].

3.6.1.5 Pneumatic forms

Flat deformable materials can be transformed into three-dimensional objects by inflating them under pressure. As with air balloons, pneumatic constructions are rarely able to oscillate elastically between two different forms of expansion but instead change between two different defined states: inflated and deflated. Deflated pneumatic forms occupy very little volume and can be stored away in a very small space and when sufficiently inflated, they acquire the desired spatial form [Elkhayat 2014a].

3.6.2 ACTUAL MOVABLE ARCHITECTURE COMPONENTS

Actual movable architecture consists of a number of interrelated elements and dynamic transition structures (Figure 3.15). However, it is not required that all items mentioned above to move in movable buildings.

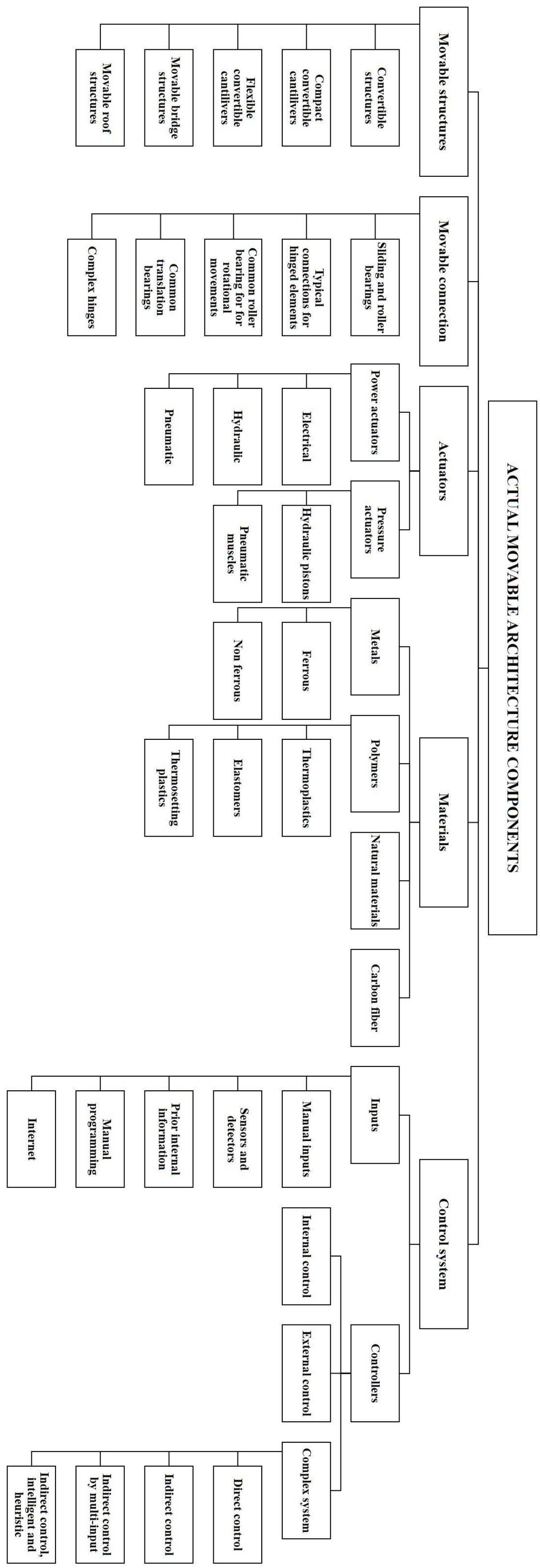

Figure 3.15: actual movable architecture components (Author)

3.7 KINETIC DESIGN KEY ELEMENTS

In this section, we present general mechanical and technological principles to design an intelligent kinetic design in architecture. These principles are divided into three general categories, which are structural innovation and materials advancement, embedded computation, and recently adaptable architecture.

3.7.1 STRUCTURAL INNOVATION AND MATERIALS ADVANCEMENT

Dealing with structures should not be independently when developing kinetic systems. Soha in [Soha 2012] states that for best structural solutions, ways and means are highly considered. The ways of kinetic structural solutions may include folding, sliding, expanding, and transforming in both size and shape, among others. While the means of kinetic structural solutions may include pneumatic, chemical, magnetic, natural or mechanical means [Fox 1999].

As a result of recent technological innovation, manufacturing technologies have evolved to the degree where creating intelligent kinetic architectural solutions became effective and feasible. These kinetic systems depend upon advanced computer control technology as well as high quality manufactured kinetic parts. New materials may include ceramics, polymers and gels, fabrics, metal compounds and composites, nano materials, and plastics, which can help creating highly intelligent responsive kinetic systems. Developing materials technology helped in facilitating creative solutions not only for kinetic structural systems but also for membrane systems, tensegrity systems, as well as thermal and acoustic systems [Laracuente 2015].

3.7.1.1 Kinetic structures typologies in architecture

Motion structures have long been in use and they remain today at the forefront of scientific endeavor [Megahed 2016]. They are easy to assemble, easy to use and easy to store and, consequently, are in constant demand to overcome engineering problems that exist in all walks of life. Several typologies or classes for kinetic structures are found in literature. According to Michael Fox [Fox 2009] kinetic structures in architecture are classified in three general categories:

Embedded kinetic structures

Embedded Kinetic structures are defined by Michael Fox [Fox 1999] as "systems that exist within a larger architectural whole in a fixed location." The primary function is to control the larger architectural system or building, in response to changing factors (human and environmental factors). Controlling the larger architectural system or building in response to changing factors is the main function and role of embedded kinetic structures.

This type of kinetic structures is the most developed of the three categories and always coupled with computational control.

Deployable kinetic structures

While embedded structures are fixed in their location (Figure 3.16), deployable kinetic structures are defined by Michael Fox in [Fox 1999] as " *structures that typically exist in a temporary location and are easily transportable. Such systems possess the inherent capability to be constructed and deconstructed in reverse* ".

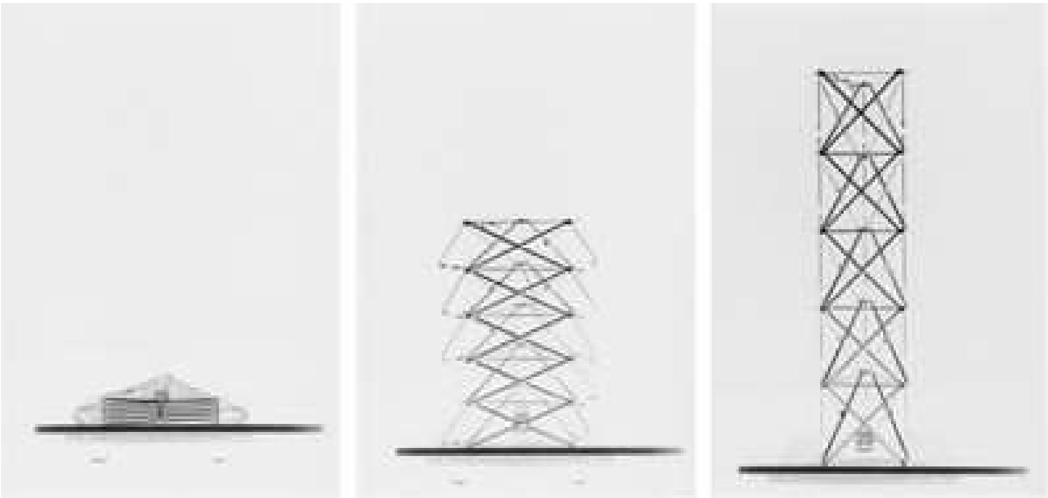

Figure 3.16: Deployable morphing structures

Deployable structures are capable of transforming from a small, closed or stowed configuration to a much larger, open or deployed configuration. It is in the fully deployed configuration that they are able to perform their architectural function; they are designed for typically small to medium scale applications. As defined by [Gantes 1991] " *these structures that can be transformed from a closed compact configuration to a redetermined expanded form in which they are stable and can carry loads*".

Deployment describes the transformation these structures carry out from a small, tight and compact configuration to an unfolded and open one reaching a state in which the structure is stable and able to carry loads. Numerous attempts for classifying deployable structures over the past 30 years, a timeline of the key literature relating the authors to the period during which their work was published (Figure 3.17). The authors shown in the timeline are not the only ones to write about deployable structures during the period considered but were selected as representing the most consistent and unifying pieces of work with regard to classification. Other authors allude to classifications of deployable structures in the introduction to their research or carry out a classification of a specific type of deployable structures [Fenci 2017].

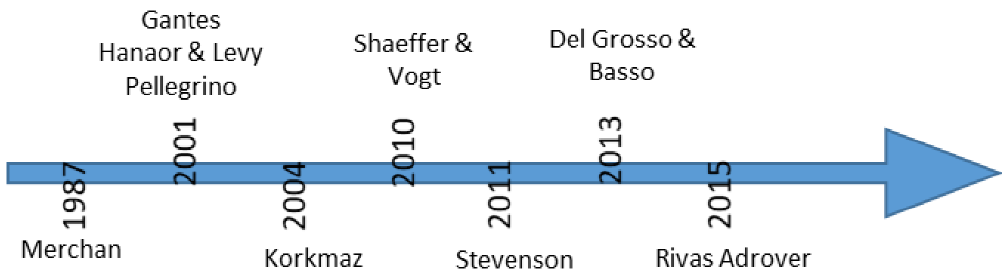

Figure 3.17: timeline of deployable structures reviews and classifications (Author)

One of the first classifications of deployable structures is done by Carlos H. H. Merchan in [Merchan 1987] the author proposes a general classification stating himself that only the most important structure types are presented, as shown in (Figure 3.18).

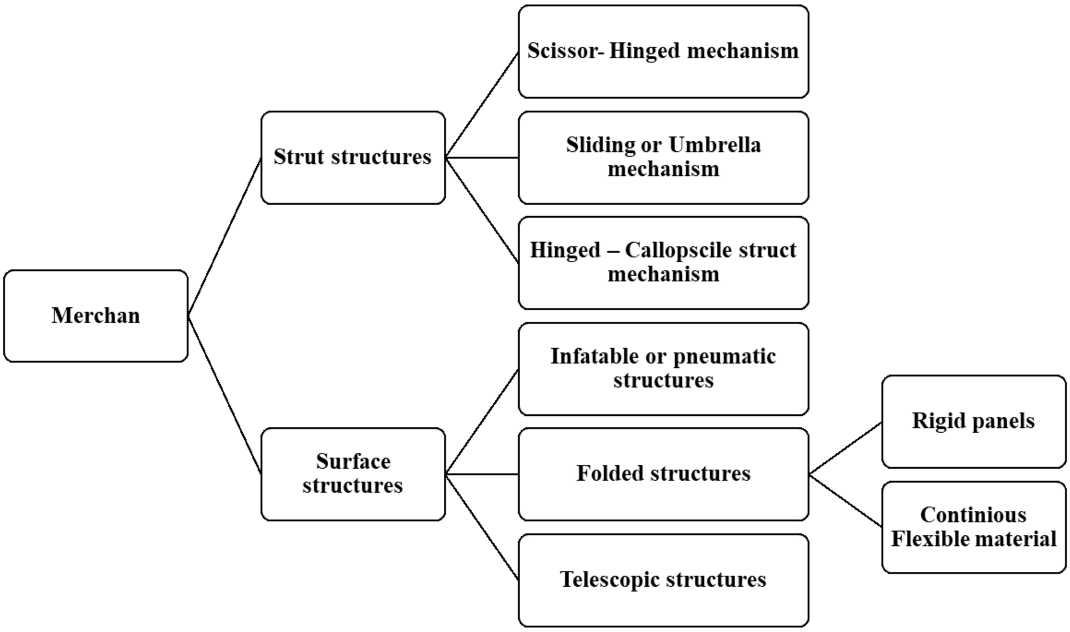

Figure 3.18: classification by Merchan (Author)

Gants in his book: "Deployable Structures: Analysis and Design" identified two classes for deployable structures (Figure 3.19): Earth-based structures and deployable structures for space applications [Gantes 1991].

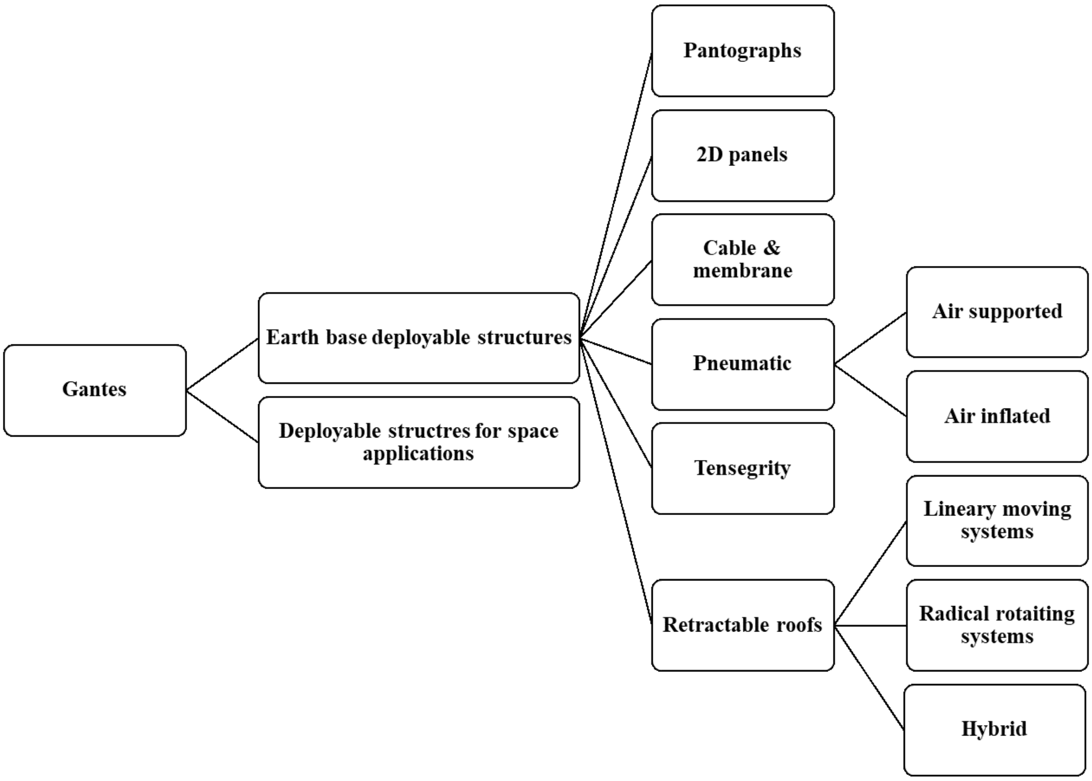

Figure 3.19: classification by Gantes (Author)

While Pellegrino offers, a list of structures able to withstand large geometrical deformations grouped together (Figure 3.20). Its work is valuable as it approaches the subject of structural form from a motion perspective, and the classification criteria is not explicit.

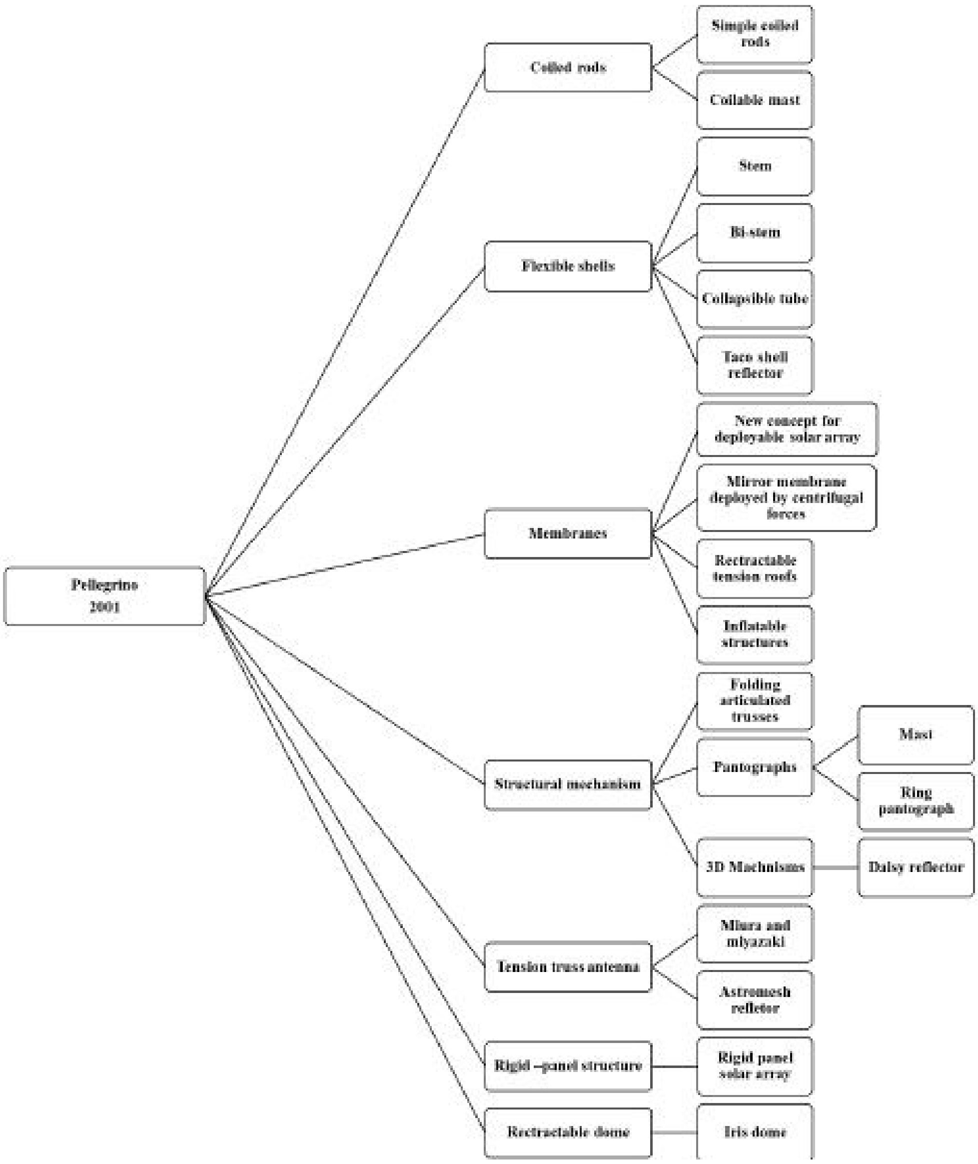

Figure 3.20: classification by Pellegrino (Author)

A detailed classification for deployable structures is produced in 2001 by the researchers Levy and Hanaor in [Hanaor 2001]. The authors generated a two-way distinction: morphological and kinematic (Figure 3.21). Morphological sub-categories are skeletal or lattice structures and continuous or stressed-skin structures, while kinematic sub-categories are rigid link systems and deformable components. A further parameter is added relatively to the previous classifications based on the way in which deployment occurs: the kinematic properties.

A deployable structure requires the whole structural system or at least some of its elements to be able to change their geometry. This requirement leads to the field of mechanism-like structures or, in other words, Variable Geometry Structures (VGSs). This kind of structures can be designed such that they possess kinematically indeterminate states [DelGrosso 2013]. VGSs can be classified according to their structural system. In doing so, four main groups can be distinguished; these structural systems have been classified by their morphological and kinematic characteristics by Hanaor and Levy. This classification is presented in Figure (Figure 3.21).

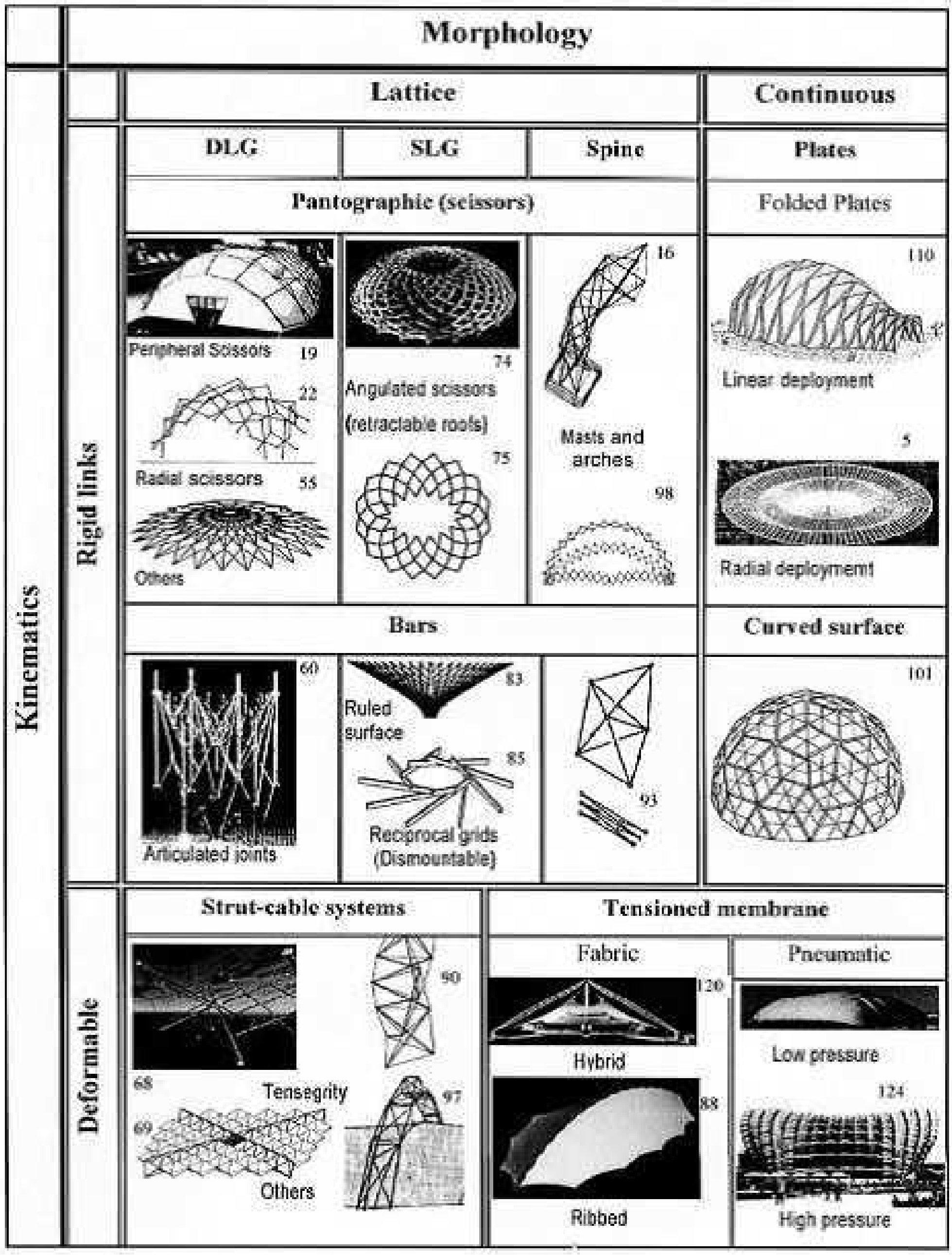

Figure 3.21: classification of VGSs on the basis on their morphological and kinematic characteristics [Hanaor 2001]

The classification of deployable structures of Korkmaz [Korkmaz 2004] is based on the definition Fox and Yeh [Fox 1999] of kinetic architecture as comprising buildings, or components, with variable location and mobility in space and / or variable configuration and geometry. This classification is more appropriate for architectural field. Taking the above definition as a starting point, kinetic structures are considered with regard to when the motion takes place, making the concept of 'time' a key parameter for the classification (Figure 3.22).

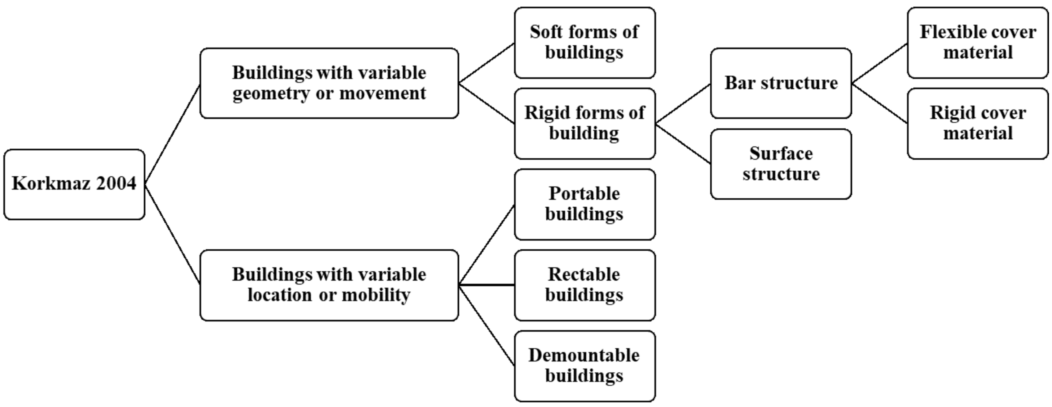

Figure 3.22: classification by Korkmaz (Author)

Schaeffer and Vogt in [Schaeffer 2010] in their classification have differentiate between movement of rigid materials and deformable ones. For rigid materials, they state that there fundamentally are three basic types of movement: rotation, translation and a combination of the two. However, the way in which a structural assembly moves at a macro-scale may differ from the topology of movements that occur at a detailed level: on a macro-scale, the structure transforms from a flat configuration to an open three-dimensional one. However, on a micro-scale, the topology of movement is different. However, the classification of Stevenson [Stevenson 2011] is based on the morphology criteria , destinated for architectural application (Figure 3.23).

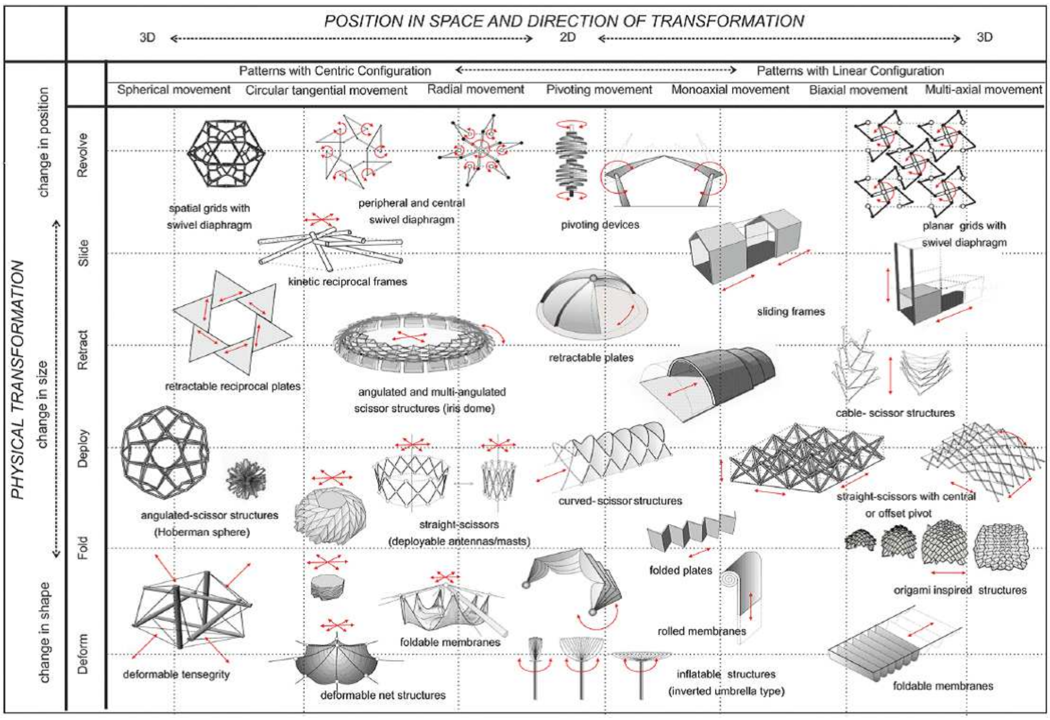

Figure 3.23: classification by Stevenson

Dynamic kinetic structures

Michael Fox defines these structures, as "Dynamic kinetic structures also exist within a larger architectural whole but act independently with respect to control of the larger context. Such can be subcategorized as Mobile, Transformable and Incremental kinetic systems" [Fox 2009]. This type is the most used of the different typologies of kinetic structures. It could include small architectural elements as well as large ones (doors, windows, louvers, movable partitions, furniture and ceilings...). Recently these structures are becoming increasingly automated and intelligent as a result of the technological innovation and advances. Dynamic kinetic systems are sub-categorized into (Figure 3.24) [Fox 2003]:

- Mobile systems: systems that could be physically moved within an architectural space to different locations.

- Transformable systems: are those capable of changing shape to take on a different spatial configuration and can be used for space-saving or utilitarian needs.

- Incremental kinetic systems: are those that can be added to a subtracted from a building.

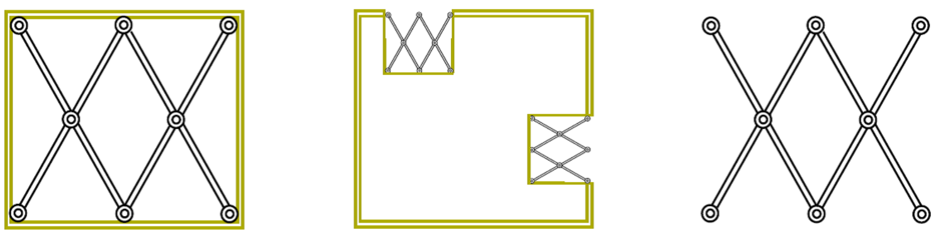

Figure 3.24: diagram of kinetic typologies in architecture [Fox 2009]

William Zuk and Roger Clark in [Zuk 1970] introduced five kinetiscism (typologies):

- Kinetically controlled static structures

- Dynamically self-erecting structures

- Kinetic component

- Reversible architecture

- Incremental architecture

Where in the first four typologies, design decisions for future changes must be made prior to the erection of the original form that is why they are described by the authors as "closed system kinetics". The rest of the typologies can be opened to accept new, outside elements which may not have existed at the time of the formal inception.

While Maziar Asefi [Asefi 2010] has devided the kinetic typologies into two categories (Figure 3.25): Transformable tensile structures (consisting from transformable tensile membranes and transformable compressive- tensile architectural structures) and transformable bending and compression structures (consisting from spatial bar structures and spatial frame structures).

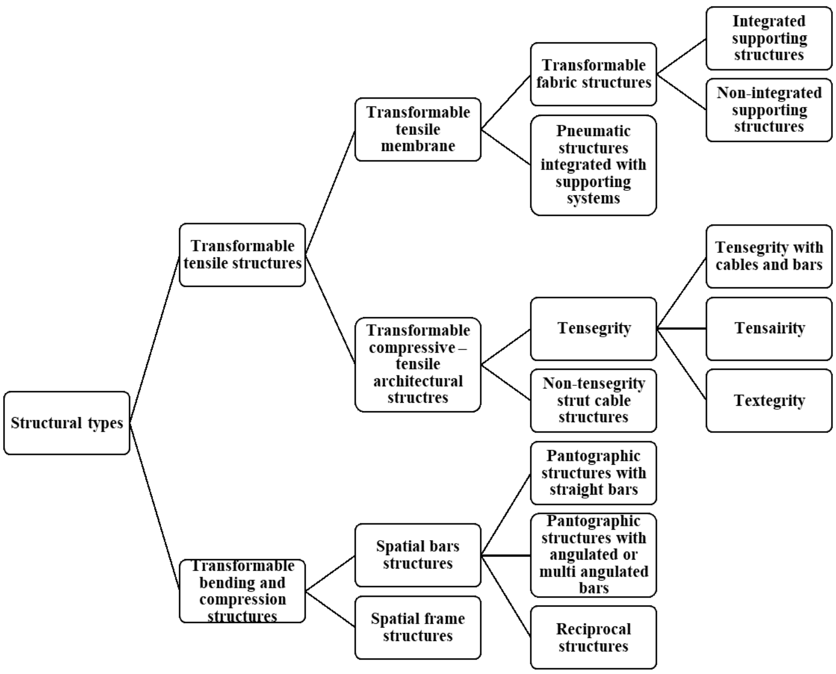

Figure 3.25: classification of transformable architectural structures [Asefi 2010]

Another kinetic typologies classification is introduced by Michael Schumacher in his book "Move: Architecture in motion-dynamic components and elements" based on motion types of buildings and building elements (Figure 3.26) [Schumacher 2010].

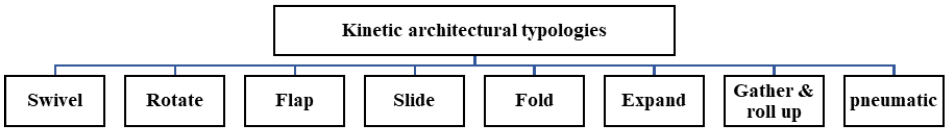

Figure 3.26: Kinetic typologies classification according to Michael Schumacher [Schumacher 2010]

3.7.2 EMBEDDED COMPUTATION (INTELLIGENCE IN ARCHITECTURE)

Computation is the most important feature in a kinetic feature. It controls the required change and motion for the components. Users and inhabitants of architectural space can have environments that change and adapt according to information gathered by means of computation and sensing technologies. This is the importance of kinetics as well as embedded computation. The importance of embedded computation is not only for the ability to sense change in the environment but also for its ability to control the response to this change. Embedded computation is the combination of computational processors and information gatherers such as sensors, cameras, and microphones [Soha 2012].

3.7.3 ADAPTABLE ARCHITECTURE

Kinetic architecture is built on both embedded computation (intelligence) and the physical counterpart (structural engineering and kinetics), which satisfies adaptation within human and environmental interaction. The combination of these two areas will make it possible for any environment to reconfigure itself, to automate physical change, to respond, react, adapt, and interact. Adaptability is defined as the flexibility of space to face changing demands on the system. Adaptability in built projects was either embedded in the logic of the creation of a system such as manually adjustable modular panels and structure systems by Fuller, or embedded in the logic of the kinematics such as manually adjustable awnings and domes by Calatrava and Hoberman [Soha 2012].

Past kinetic projects were adaptable although they relied on their user to manually change the size, color, shape, or location of an object that made up the space in respect to the new demands. The difference between those past kinetic projects and new ones is that in new projects spaces are being interactive with their ability to sense information from the users or the environment and then adapt themselves. Adaptable architecture may range from interior organizational disposition to external environmental mediation to complete structure transformability/transformation. According to [Soha 2012], adaptable architecture is divided into four categories, which are living, working, entertainment, and public environments.

3.8 CONCEPTUAL FRAMEWORK FOR KINETIC ARCHITECTURE

In this section, we present a conceptual framework (Figure 3.27) that requires us and any researcher to specify what is going to be studied and what will be neglected. It also assumes existence of relations between the key variables. This conceptual framework is based on the previous research on classification and establishes a new type of classification ([Elkhayat 2014b]; [Asefi 2011]; [Elrazaz 2010]; [Fouad 2012]; [Fox 2010]; [Kirkegaard 2009]; [Kolarevic 2015];

[Kronenburg 2014]; [Moloney 2011]; [Osorio 2014]; [Parkes 2009]; [del Valle 2005]; [Megahed 2016]). It acts as a guide map that links the key elements of kinetic classification.

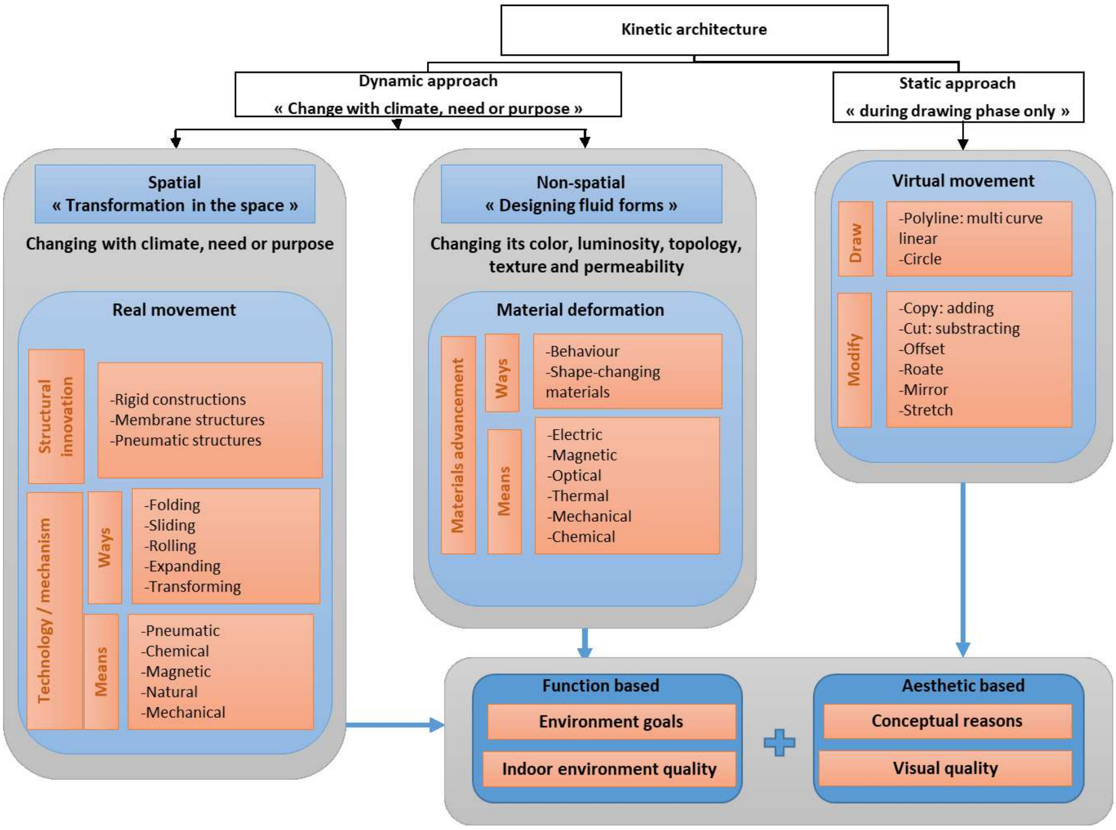

Figure 3.27: Conceptual framework of kinetic architecture (adopted from [Megahed 2016])

3.9 SUSTAINABLE VISION OF KINETIC ARCHITECTURE

This section focuses on dealing with sustainability through the applications of a kinetic system in architecture. Tables (3.2, 3.3) presents analysis of some kinetic case studies that are aiming to enhance sustainability by their designs.

Today's life is dynamic, therefore the space we are living in should be dynamic as well, adjustable to our needs that change continuously to our concept of design andour mood [Elrazaz 2010]. Kinetic buildings can follow the rhythms of nature and can change direction and shape from spring to summer, from sunrise to sunset and adjust themselves to the weather so; buildings will be alive ([Asefi 2011];[Elrazaz 2010]). Kinetic architecture will allow architects to develop realistic consideration of human and environmental conditions. The result will be architecture of unique and wholly unexplored applications that address the dynamic, flexible and constantly changing activities of today and tomorrow.

Adaptive response to change must intelligently moderate human activity and the environment and build on the task of enhancing everyday activities by creating architecture that extends our capabilities [Moloney 2011]. It is difficult to see if advanced kinetic architectural systems are far on the horizon or inevitably in the very near future. To extrapolate the existing into a future vision for architecture is a conundrum residing in the hands of architects directing the future of their profession. Therefore, architects need to grasp a vision that will harness technology transfer from "outside" fields and prevent contradictions in human interaction with the built environment [Elrazaz 2010].

Type			Kinetic example	Description of kinetic design key elements
Static Approach	Draw	Polyline	Central China TV, Beijing, China	Rising from a common platform, two towers lean towards each other and finally merge in a perpendicular, 75-m cantilever. The facades reveal the irregular geometry of the building's steel structure whichreflect the distribution of forces under different load conditions
		Circle	City Hall London, UK	The circular shape achieves optimum energy performance by maximizing shading and minimizing the area exposed to direct sunlight
	Modify	Copy	The Cube, Beirut, Lebanon	The concept for the tower is simple but effective. The copy and add concept reaches the maximum allowable height to produce flexible floor plans to optimize breath taking views of Beirut and the Mediterranean
		Cut	Crescent Moon Tower Dubai, UAE	The structure is designed as a crescent, a symbol of energy and power. This moon shaped building, which literally cuts across the skyline proposed to present a major symbol of the Islamic faith
		Offset	Scottish Exhibition and Conference Centre, Glasgow, UK	External shell takes a flat sheet material to clad a series of framed hulls, which wrap around the disparate elements. These overlapping, aluminium -clad shells create a distinctive profile on the skyline
		Rotate	Massar Children's Discovery Centre Damascus, Syria	The proposed structure represents the rose petals that rotate around the central atrium to create an amazing scenography of light into the interior spaces
		Mirror	Emirate Tower, Dubai, UAE	The two adjacent towers, which rise to 355 m and 309 m, respectively, is situated in a mirror-shaped to provide an iconic profile
		Stretch	The Gherkin Building London, UK	The structure has a steel frame with circular floor plans and a glass facade which is essentially an elongated, curved, shaft with a rounded end that is reminiscent of a stretched egg

Table 3.2: analysis of the sustainable vision of some kinetic case studies (Author)

Type			Kinetic example	Description of kinetic design key elements
Dynamic Approach	Spatial	Rigid	Rotating Skyscraper Dubai, UAE	The tower is designed to be self-sustaining, up to79 wind turbines will be fitted to each floor. Each floor is designed to rotate independently around the core by means of power generating wind turbines, resulting in a changing shape of the tower
		Membrane	One Ocean – Thematic Pavilion for EXPO 2012 Yeosu, South Korea	Bionic façade with kinetic glass fiber reinforced polymers (GFRP). Opening and closing moveable lamellas in succession allowschoreography of wave-like patterns to be created along the entire length of the building
		Pneumatic	The Media-TIC building Barcelona, Spain	Facades made of ETFE (ethylene tetra fluoro ethylene) air cushions that provide pneumatic shading. The cushions consist of three layers of plastic with two air chambers between them that can be inflated or deflated as needed
	Non-spatial	Material deformation		Dynamic façades based on ETFE cladding by nearly 3000 bubble-like pneumatic cushions of all sizes supported by a polyhedral steel-framed structure. It built upon 'the soap bubble' theory resulting media facades shine in the sunlight like a pearl in water

Table 3.3: analysis of the sustainable vision of some kinetic case studies (Author)

3.10 CONCLUSION

In this chapter, a new approach for environmental control was presented. kinetic architecture is not a new concept, it has been infrequently applied until recently. The progress in science and technology has affected all aspects of building design and construction. This has enabled kinetic architecture to make a spectacular comeback and challenge the traditional form of architecture. Kinetic structures offer the means to significantly expand the functional and performance-related features of traditional and static architectural solutions. This can be realized only if the buildings can transform by use of kinetics without losing the fundamental strengths of traditional architecture.

Kinetic approaches offer a wide range of possibilities for architecture. They can be used as indoor elements. They can appear as a part of the building's structure, or even as the whole structure. The main motivation for moving toward kinetic architecture lies in the increasing demands for comfort, flexibility, adaptability, as well as the need to use natural resources more prudently. In some cases, there are multiple reasons for using kinetics. The most common reason is the need to control and use space and material by function sharing, and the ability to change geometry's appearance.

Ultimately, kinetic approaches provide designers with the creative means to solve problems using technological advancements. Installing kinetic systems in buildings will increase costs; on the other hand, if these systems are employed for energy efficiency by maximizing the use of sunlight and natural ventilation, the buildings' running costs will reduce in the long run.

For architects, it is important to highlight that design strategies framework should provide a methodology of kinetic structures, thus helping in formulating and selecting the most suitable techniques and methods that can be used. While much has been accomplished, it is also clear that a number of serious obstacles remain, which must be overcome before implementation possibilities of kinetic concepts can be realistically assessed. Architects should realize that creating motion does not change our understanding of architecture and that it may actually make architecture more functional and exciting for the users.

Chapter 4

COMPUTATIONAL DESIGN AND BIOMIMICRY: BACKGROUND AND STATE OF THE ART

" The style finally closes the transitional period of uncertainty that was engendered by the crisis of modernism and that was marked by a series of short lived episodes including post-modernism, deconstructivism, and minimalism. Parametricism is the great new style after modernism."
- John Hernaldez

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4.1 INTRODUCTION

Biomimicry is an applied science that derives inspiration for solutions to human problems through the study of natural designs, materials, structures and processes. Many fields of study benefit from biomimetic inspirations, such as agriculture, medicine, engineering, and architecture. The growing interest in biomimicry suggests that architects must become more aware that nature has much to offer in order to improve the way our designs and buildings function. Biomimicry already achieved and realized some of the advanced and efficient technologies in materials and products, however, it is still largely unrealized in the architectural design

Architects and designers, while applying this approach in their designs, they change the way approaching the architectural design and architectural forms from finding process and manufacturing. In this case, computation will be used in all the phases of the building: design, construction and management. Therefore, the exploration and adoption of new techniques and methods for design and manufacturing, including parametric design approaches, performance-based design approaches and digital manufacturing techniques, are necessary. The application of computational tools in the design process speeds the design process and offers to the designer a free space of imagination while exploring new complex building's shapes by integrating all the design phases into one comprehensive model.

Coupling the biomimetic design with parametric approach needs a transformation in modes of thinking, which, would be the main agenda toward designers and architects. A brief overview of biomimicry in computational design is presented, since computational tools are intended to be used in the application of biomimetic design. Examples of how such a biomimetic-computational approach can be applied are also demonstrated. Based on this literature review, the chapter ends with defining the design approach and focus points that will be addressed in the rest of the thesis. We present novel techniques that enhance architects' contribution to building processes based on parametric design creation. This allows a deeper comprehension of the design objectives and aids designers in their decisions to find solutions.

4.2 BIOMIMETIC DESIGN IN ARCHITECTURE

4.2.1 UNDERSTANDING BIOMIMICRY

Biomimicry means the imitation of life, the word coming from a combination of the Greek roots bios (life) and mimikos (imitation).

According to Khelil [Khelil 2018] Biomimicry is the study of nature's most successful developments and then imitating these designs and processes to solve human problems. The idea is that, during its 3.8 billion years of research and development, nature has evolved highly efficient systems and processes that can inform solutions to many of the waste, resource efficiency and management problems that we now grapple with today [Elghawaby 2010].

Biomimetics, a name coined by Otto Schmitt in the 1950s for the transfer of ideas and analogues from biology to technology, has produced some significant and successful devices and concepts, but it is still in its infancy and still needs time to become fully integrated into popular thinking and popular design. The biologist Julien Vincent describes it as "*The abstraction of good design from nature*" [Vincent 2006]. The architect Michel Pawlin defines Biomimicry as "*mimicking the functional basis of biological forms, processes and systems to produce sustainable solutions*" [Pawlyn 2011]. The Biomimicry institute posit that Biomimicry is the science and art of emulating nature's best biological ideas to solve human problems [Badarnah 2012].

In 1997 Janine M. Benyus published a book about biomimicry, that book popularized this concept and made it well known. Benyus is the founder and the Board President of the Biomimicry

Institute, and also a co-founder of Biomimicry Guild. She is also a Natural Sciences writer, innovation consultant, author as well as teacher and lecturer at the University of Montana. She has degrees both in Natural Resource Management and in English Literature/Writing from Rutgers University where she graduated with highest honors. In 1997 Benuys was awarded the Rachel Carson Environmental Ethics Award and in 2007 she was honored by the Time magazine as "Heroes of the Environment" where the most innovative and influential protectors of the planet are honored [OmAmarson 2011].

Due to the fact that biomimicry is an inspirational source of possible new innovation and because of the potential it offers as a way to create a more sustainable and even regenerative built environment [Khelil 2015]. Biomimicry, where flora, fauna or entire ecosystems are emulated as a basis for design, is a growing area of research in the fields of architecture and engineering [Benyus 2002].

4.2.2 BIOMIMICRY MOTIVATIONS

Nowadays, humans can explore and investigate the living world and all the natural phenomena more precisely thanks to the technological advancements. The Biomimetic investigation and the emergence of Biomimicry as research area increase human capacity to understand and mimic nature [Khelil 2019].

Maibritt Pedersen Zari School of Architecture, Victoria University, Wellington, New Zealand [Zari 2012], said that "Mimicking organisms or ecosystems is an expanding field of research in both academic and design discourse" [Zari 2012]. According to her, there are three main motivations behind investigating Biomimicry:

1. Biomimicry for innovation
   Biomimicry can be seen as a source of innovation in the creation of new materials and technologies. Most biomimetic investigation relate to this reason and they are not necessarily

aiming to improve the ecological performance of human technology. Rather, they are about novel approaches to technical problems, increased performance capabilities. This brand of research is related particularly to robotics, computing and materials technologies that have no focus on sustainability issues.

2. Biomimicry for sustainability
   There is a rise in interest in the potential of biomimicry as a way to create more sustainable materials, products, built environments, and engineering solutions. Biomimicry can improve the environmental performance of human technologies and the built environment [Pawlyn 2011]. The act of mimicking an organism in design is in itself a means to achieve greater sustainability. One of the crucial dissimilarities between biomimicry-for-sustainability and biomimicry-for-innovation, is that biomimicry-for-sustainability have a tendency to recognize the importance of mimicking not just organisms but also the underlying processes, strategies and systems of ecosystems, to lead to more sustainable outcomes. Biomimicry-for-sustainability is not focused exclusively on the creation of new and novel technologies, but on the altering of the underlying foundations of design ([Zari 2007]; [Feuerstein 2002]).

3. Biomimicry for human well-being
   The third motivation for exploring biomimicry comes from examining whether design based on an understanding of the living world could contribute to increasing human psychological wellbeing,due to its inherent relationship to the concept of Biophilia [Zari 2012].

4.2.3 BIOMIMETIC DESIGN STRATEGIES

No general approach has been developed for Biomimetics, although a number of people are at this time developing methods for searching biological literature for functional analogies to implement

[Finsterwalder 2011]. Although it is well known that design and engineering are rendered much easier with use of the biomimetic theory, every time we need to design a new technical system we have to start afresh, trying and testing several biological systems as potential prototypes and striving to make some adapted engineered version of the biomimetic device. Moreover, the transfer of a concept or mechanism from living to non-living systems is not trivial. A simple and direct replica of the biological prototype is rarely successful, even if it is possible with current technology ([Khelil 2015]; [Badarnah 2008]). Some form or procedure of interpretation or translation from biology to technology is required. More often than not, the technical abstraction is possible only because a biologist has pointed out an interesting or unusual phenomenon and has uncovered the general principles behind its functioning. Only then does the biological principle become available outside biology f or biomimetic use. The result is often unexpected and the final product seldom resembles the biological prototype ([Vincent 2006]; [Freya 2011]).

We present here a logical framework that we believe exposes some important underlying methods and approaches to Biomimicry.

4.2.3.1 BIOMIMICRY 3.8 LIFE'S PRINCIPLES

The Biomimicry Institute and the Biomimicry Guild, along with many partners,have distilled a collection of scientific research to create a summary of the most fundamental principles conductive to life [Stokoe 2013].

Life's Principles (Figure 4.1) are design lessons from nature. Based on the recognition that Life on Earth is interconnected and interdependent, and subject to the same set of operating conditions, Life has evolved a set of strategies that have sustained over 3.8 billion years. Life's Principles represent these overarching patterns found amongst the species surviving and thriving on Earth

[Khelil 2016].

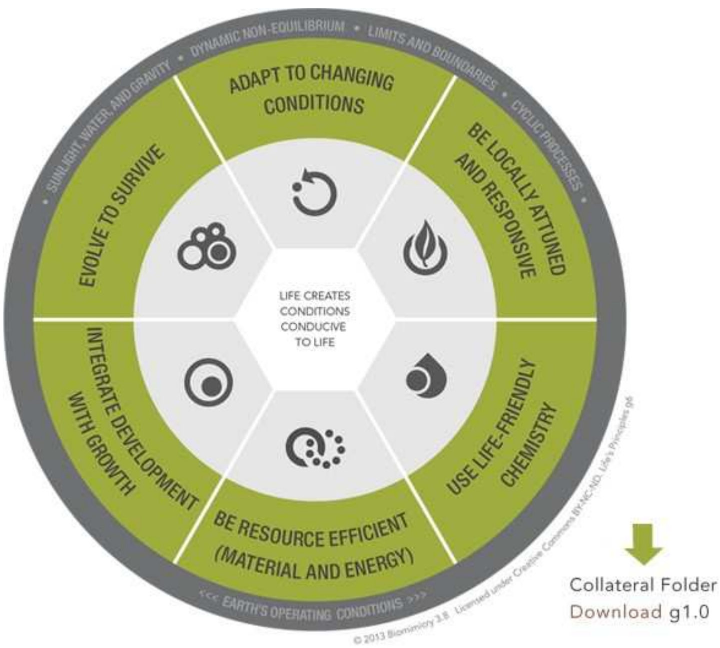


Figure 4.1: The fundamental principles conductive to life (Source:©2014 Biomimicry Group)

Life integrates and optimizes these strategies to create conditions conducive to life. By learning from these deep design lessons, we can model innovative strategies, measure our designs against these sustainable benchmarks, and allow ourselves to be mentored by nature's genius using Life's Principles as our aspirational ideals.

Life's principles Sustainability Wheel (Figure 4.2) illustrates the holistic overriding principles, patterns and solutions utilized by nature to create highly sustainable, non-intrusive environments. The aim of life's principles is to create products, processes, and policies inspired by nature to create a new way of living (Biomimicry 3.8, 2011). This method helps to identify a problem, to explain it, to find a suitable solution and concludes with a Biomimetic design.

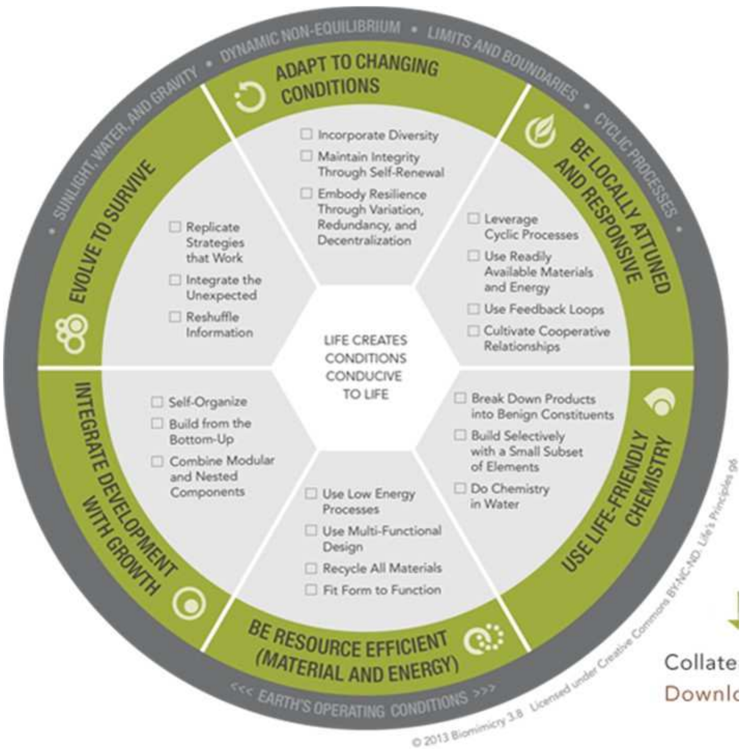


Figure 4.2: Life's principles Sustainability Wheel (Source:©2014 Biomimicry Group)

4.2.3.2 BIOMIMICRY DESIGN SPIRAL: A TOOL FOR INNOVATION

The Biomimicry Institute has provided a tool aiding innovative design using the biomimicry process. The biomimicry design spiral (Figure 4.3) provides a clear process to follow in order to produce a design inspired by nature that utilizes solutions found in nature to solve problems in innovative ways [Khelil 2019].

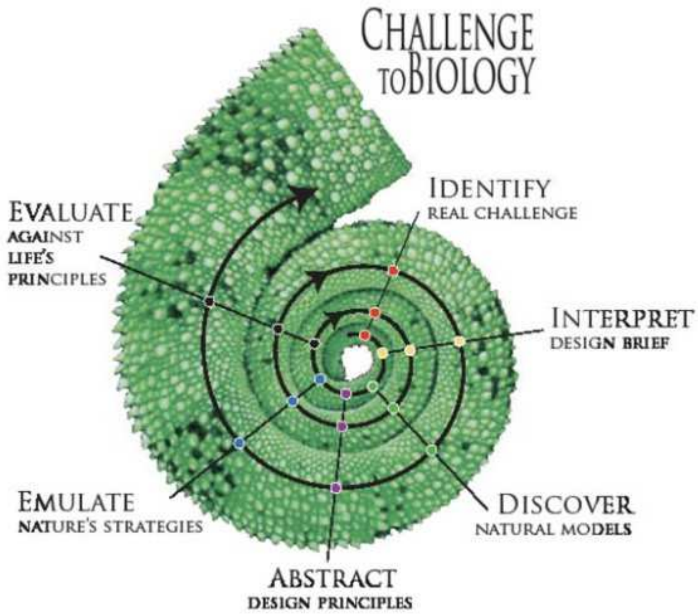


Figure 4.3: Biomimicry design spiral developed by the Biomimicry Institute (Source:©2014 Biomimicry Group)

4.2.3.3 BIOMIMICRY TAXONOMY STRATEGY

AskNature is an online inspiration source for the biomimicry community set up by the biomimicry institute. Nature's most elegant ideas organized by design and engineering function. Information organized on AskNature uses a classification system known as the Biomimicry Taxonomy: in order to organize how organisms meet different challenges.

The Biomimicry Taxonomy (Figure 4.4) provides a novel way to approach our next innovation challenge sustainably. We have to look to the taxonomy as a tool when we first approach our design challenge, using its framework to ask questions of nature. For example, if we are trying to make less toxic pigments, "ask" a Morpho butterfly how it creates its color. If we want to manufacture tough, lightweight building materials without unsustainable high pressures and temperatures, "ask" a toucan how it manages impact with its strong and light beak.

AskNature offers two ways for us to ask questions of nature: Search and Explore. Explore enables us to quickly find strategies by function using a table of contents organized by the Biomimicry Taxonomy. With Search, we can ask questions like those posed above - for example, "How does nature stay dry?".

4.2.3.4 TYPOLOGICAL ANNALYSIS (TA) STRATEGY

TA examines nature at three levels of mimicry: the organism, the behavioral and the ecosystem [Stokoe 2013].

- Organism : specific flora or fauna, mimicking either the whole organism,or a particular feature.
- Behaviour: translation of an aspect of how an organism relates to its environment, or larger context.
- Ecosystem: emulating or recreating the common principles that allow an ecosystem to successfully function.

Each of these three levels is further categorized into five dimensions to consider different aspects of design that may be emulated in an organism or a system [Zari 2007].

- Form: shape
- Material: properties
- Construction: arrangement or composition

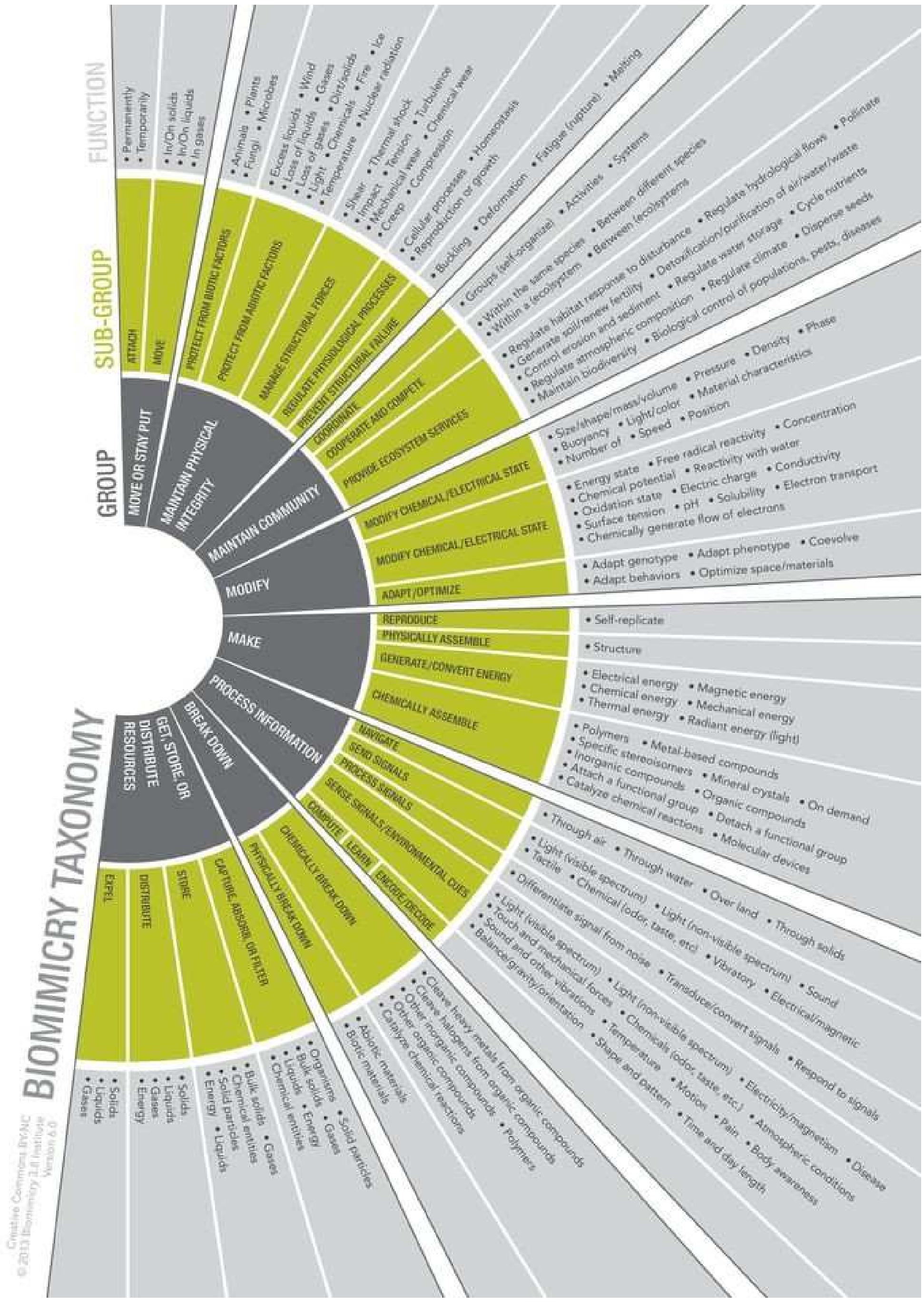


Figure 4.4: The biomimicry Taxonomy (Source: The Biomimicry institute)

- Process: mechanism
- Function: application

According to Gamage and Hyde [Gammage 2012] TA is a framework to explain the application of Biomimicry at these different levels, and attempts to clarify the potential of using Biomimicry as a tool to increase the regenerative capacity of the built environment. This can be used by designers to utilize Biomimicry as a methodology for improving the sustainability of the environment as an effective approach.

Table 4.1 shows a framework for the application of biomimicry using TA. This example looks at a emulating the beaver [Stokoe 2013].

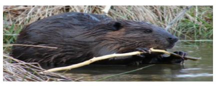
LEVEL		DIMENSIONS	ASPECTS
ORGANISM		FORM	The site is shaped like a beaver.
		MATERIAL	The site is made from a material that mimics a beaver skin or hair.
		CONSTRUCTION	The site is constructed in the same way as a beaver, ie it goes through various growth cycles.
		PROCESS	The site works in the same way as an individual beaver, ie it issemi-aquatic and functions in both dry and aquatic environments.
		FUNCTION	The site functions like a beaver in a larger context; their excrement is re-introduced to the environment providing nutrients for plant life.
BEHAVIOUR		FORM	The site looks like it was made by a beaver: a replica of the beavers dam.
		MATERIAL	The site is made from the same materials that a beaver builds with, using twigs and mud as the primary material.
		CONSTRUCTION	The site is made in the same way a beaver would build his lodge or dam, working at night and self-built.
		PROCESS	The site works in the same way as a beavers dam would ; covering their lodges with fresh mud, when frozen in winter it becomes hardened.
		FUNCTION	The site functions In the same way that it would if made by beavers; providing both protection against predators and access to food in winter.
ECOSYSTEM		FORM	The site looks like an ecosystem that a termite would live in ie. a riparian zone with stream bed.
		MATERIAL	The site is made from the same kind of materials found in a riparian ecosystems; woodland and water.
		CONSTRUCTION	The site is resembled in the same way as a (beaver's) ecosystem; principles of succession and increasing complexity over time.
		PROCESS	The site works in the same way as a (beaver's) ecosystem; it captures and converts energy from the sun, and stores water.
		FUNCTION	The site is able to function in the same way that a (beaver's)ecosystem;would and forms part of a complex system by utilizing the relationships between processes it is able to participate in the hydrological,carbon, Nitrogen cycles.

Table 4.1: Example: a landscape that emulates a beaver (STOKOE, 2013).

4.2.3.5 BIOTRIZ APPROACH

BioTRIZ uses the methodology of TRIZ to abstract design information from natural systems and give designers a tool that allows that knowledge to be applied to engineering design without requiring that designers possess extensive knowledge of biological systems. The development of BioTRIZ was led by Dr. Vincent of the University at Bath. Like TRIZ, BioTRIZ condenses design information into a contradiction matrix that lists inventive principles (IPs)used to solve conflicts between system parameters.

TRIZ is a Russian collection of tools and techniques of engineering problem solving, developed by Genrich Altshuller and Rafik Shapiro [Altshuller 1999] that ensures accurate definition of a problem at a functional level and then provides strong indicators towards successful and often highly innovative solutions. It was named TRIZ, the acronym of Teorija Reshenija Izobretatel'skih Zadach. The acronym is usually translated into Theory of Inventive Problem Solving [Vincent 2002]. One of the most popular tools is a look-up table made up of 39 opposing features (parameters, variables) of engineering systems such as strength, weight, speed, volume, temperature, ease of manufacture and versatility. The claim is that if you define your problem in its terms, the TRIZ contradiction matrix will point you to a handful of principles that have been found to resolve the trade-off. Altshuller and his colleagues reportedly found 40 such inventive principles from the study of 3 million patents.

TRIZ identifies 39 system parameters that designers may wish to optimize as well as forty inventive principles (IPs) that can be used to resolve design challenges. The set of conflicts and solutions is presented as a 39 by 39 "contradictions matrix" in which each row and column corresponds to a system parameter and each cell lists the IPs that other designs have used to solve the conflicting parameters of the cell's row and column.

However, while TRIZ shows designers how design problems have been solved in technical and engineering designs, BioTRIZ shows how those problems are solved by natural systems. BioTRIZ is based on the analysis of approximately 500 biological phenomena with over 270 functions and 2500 contradictions. One other important difference between TRIZ and BioTRIZ is that BioTRIZ groups the 39 system parameters of TRIZ into six fields of operation: substance, structure, space, time, energy, and information. Consequently,the conflict matrix for BioTRIZ is only a 6 by 6 matrix. However, BioTRIZ does retain the 40 IPs used in TRIZ. The procedures used to apply BioTRIZ to a design problem are identical to those used for TRIZ.

To make the best use of BioTRIZ, Vincent proposed the following five-step methodology.

- Define the problem in the most general way
- List both desirable and undesirable properties and functions.
- Analyze and understand the problem and so uncover the main conflicts or contradictions.
- Find the functional analogy in biology.
- Bridge from natural to technical design.

4.2.4 DESIGN APPROACHES TO BIOMIMICRY IN ARCHITECTURE

Through a comparative literature review, and an examination of existing biomimetic technologies we can define distinct approaches to biomimetic design, each with inherent advantages and disadvantages.

Approaches to biomimicry as a design process typically fall into two sets.

1. Design referencing biology: first, we define the human need or the design problem, and then we explore the ways other organisms or ecosystems solve this.

2. Biology influencing design: we identify a particular characteristic or function in an organism or ecosystem and then we translate it into a human design context.

4.2.4.1 DESIGN REFERENCING BIOLOGY

Throughout literature review, this approach was found to have different designation, such as -Design looking to biology [Zari 2007], -Top-down Approach [Knippers 2009] and -Problem-Driven Biologically Inspired Design [Goel 2009] all referring to the same meaning. It is the most common approach to biomimicry.

When designers look to organisms or ecosystems for solutions they are first required to identify problems and then to match these problems to organisms that have solved similar issues. Generally, to access to this immense encyclopedia of biological and ecological knowledge, we have to consult scientists in the field of biomechanics or biology like biologists, zoologists, ecologists... However, this approach must be led by designers who must identify initial aims and parameters for the design.

4.2.4.2 BIOLOGY INFLUENCING DESIGN

When biological knowledge influences human design, the collaborative design process is initially dependent on people having knowledge of relevant biological or ecological research, rather than on determined human design problems. The translation from a biological context can be intentional or accidental. This approach also have different naming such as Biology Influencing Design, Bottom-Up Approach and Solution-Driven Biologically Inspired Design [Zari 2007].

4.2.5 LEVELS OF BIOMIMICRY

The information embedded in each organism can be found in many levels, which is summarized in Table 4.2, possible features that can be concluded from an organism and its biomimicry are analyzed using three levels (Figure 4.5). Each level is concerned with a layer of the design of an organism [Khelil 2015]. The first includes aspects and properties of a creature as a whole unit. The second includes other features that focus on the relationships between an organism and its living community. The third level highlights systems and eco-solutions that can be concluded from relationships between an organism and its context/environment. Within each of these levels, a further five possible dimensions to the mimicry exist. The design may be biomimetic for example in terms of what it looks like (form), what it is made out of (material), how it is made (construction), how it works (process) or what it is able to do (function).

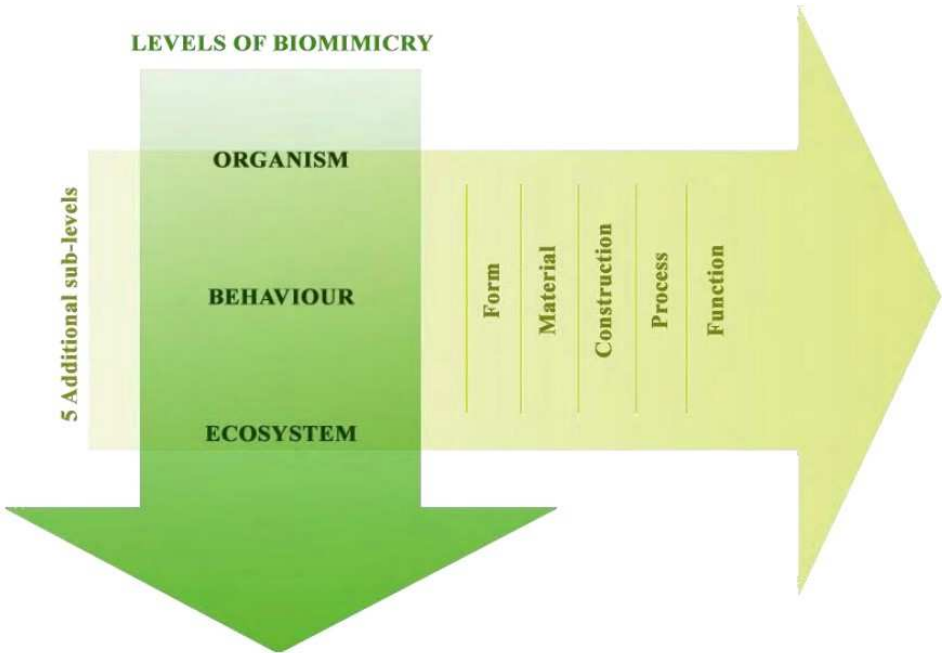


Figure 4.5: Levels of Biomimicry [Khelil 2015]

M. Pedersen Zari attempted to clarify the various levels and dimensions of biomimicry and proposed a framework for understanding its application. This is applicable to both approaches (design looking to biology, and biology influencing design).

Levels of Biomimicry	Aspects of the levels
Organism features (Features of the organism itself	Formal attributes include shape, color, volumetric treatment, transparency, rhythm.
	Organization and hierarchy of parts and systems.
	Structure, stability and gravity resistance.
	Construction materials and process.
	Mutation, growth and life cycle.
	Function and behavior.
	Motion and aerodynamics.
	Morphology, anatomy, modularity and patterns.
	Probability and mobility.
	Self-assembly.
	Healing, recovery, survival and maintenance.
	Homeostasis the balances internal systems while external forces change.
	Systems that include organ, digestive, circulatory, respiratory, skeletal, muscular, nervous, excretory, sensory and locomotive systems.
Organism- community relationship (The organism's relationship to its community of similar organisms as well as other creatures that it may deal with).	Survival techniques.
	Interaction with other creatures.
	Transgeneration knowledge transfer and training.
	Hierarchy of community members.
	Group management and coordination.
	Communication.
	Collaboration and teamwork.
	Self- protection.
	Sensing, responding and interaction.
	Risk management.
Organism-environment relationship (How an organism fits in its biome and environment).	The contextual fit.
	Adjustment to change.
	Response to climate by cooling, heating and ventilation solutions.
	Response to context by, for example, camouflage, self-protection and self-cleaning.
	Adaptation to ecosystems includes adjustment to various light or sound levels, shading, and self-illumination.
	Shelter building.
	Limited resource management such as adaptation to lack of water, light or food.
	Waste management. Input/ output/ process cycling.

Table 4.2: A Framework for the Application of Biomimicry adapted from [Zari 2007]

4.2.6 PRINCIPLES OF BIOMIMICRY IN DESIGN

The previously topics explained the principles of biomimicry in the ecosystem. From that, a set of specific principles were selected as there are providing a basis for further study in designing purpose and method within the limitations of available technology and knowledge. The approaches of biomimicry as a design process generally fall into two categories as seen before. In the view of [Mazzoleni 2013], [Elnokali 2012], the designers will look to the living world solutions as the methods to identify problems and match these to organisms that have similar issues in their design. Based on that, there are several principles of biomimicry that will inspire the designer in the process of design by getting the inspiration from nature and making it better to the surroundings and also as the interaction between human and living organism. The selected principles of biomimicry in design are: adaptation, material as system, evolution, emergence, form and behavior.

The five principles are generated from the previous principles of biomimicry in ecosystem. The first principle is adaptation, the ecosystem can adapt and evolve at different levels and rates, so we can change environments by behavioral adjustments. Basically, adaptation is the evolutionary process that makes a population feels comfort and better suited with its habitat. It also can be referred to a feature process which includes the organism to survival by accepting naturally the current situations that to get involved in successfully.

The next principle in design is material as systems that comes from ecosystems optimize the system rather than its components. The biological material systems are self-assembled that makes weak materials become strong structure and the used properties are totally different from the classical engineering of traditional man-made structures. The other principle of design in biomimicry is evolution, which comes from the ecosystem principle that adapts and evolves at different levels too.

The adaptation and evolution will allow the whole ecosystem and organism to continue constantly dynamic in cyclic environment that they existed in it. The variety and perfection of natural forms will produce the result of relentless in experimentation of evolution. Moreover, the analogy of evolutionary architecture does not mean to be taken without imply the development of natural selection. In addition of that, the grows of living form is a complex process that contributes in the genotype with variables contribution in environmental dependencies that also comprises the genetic constitution of an individual and the interaction between the genotype and the environment is the product that is evolutionary formed [ElAhmar 2016].

As have been discussed in the ecosystem principle that ecosystems are diverse in components, relationship and information, emergence is a principle in the design that is complex and works in various hierarchies, the emergent will effects the tendencies to occur in that design process. All multiples variations of biological form is a form of evolution that should not be thought separately from the structure and materials. The emergent performance comes from complex hierarchies of material within natural structures.

The last principle biomimicry in design is form and behavior that is generated from the ecosystem principle, ecosystem that optimize the system rather than its components. It explains the emphasized call between functions and form that produce the result of equally important between form and behavior. It emerges from the process that produces, elaborates and maintains the structure forms of biological organism and the complex process consist of the exchange between the organism and ecosystem. The choice of these principles is done due to literature review of previous studies on biomimicry in attempt to link them with current research in the design part.

4.3 PARAMETRIC AND COMPUTATIONAL DESIGN IN ARCHITECTURE

Parametric design enables the exploration of alternative designs within a single representation using parameters and associative relationships to control geometric and constructive aspects of the design, especially the kinetic design. In performance-based design, performance goals with respect to various aspects, such as comfort and structure, are explicitly developed and updated during the design, and assessed and guarded throughout the design process. Digital manufacturing enables innovative design exploration through physical prototyping during the design process, and mass-customization of non-standard architecture towards industrialization in a cost- effective manner. In this section, we approach the definition of the parametric design, the process of its application in architecture.

4.3.1 PARAMETRICISM AS A STYLE

Parametricism is a term for a new call epochal global style of architecture covering all the design disciplines including urbanism, architecture, interior design, graphic design, product design, and even fashion design and has become an important benchmark in design education as well. The term 'parametricism' was coined by Patrik Schumacher, partner at Zaha Hadid Architects, who promoted it as the natural successor to post-modernism. According to Schumacher [Schumacher 2016]: *"The style finally closes the transitional period of uncertainty that was engendered by the crisis of modernism and that was marked by a series of short lived episodes including post-modernism, deconstructivism, and minimalism. Parametricism is the great new style after modernism."*

Schumacher theorised that, in becoming the dominant single style for avant-garde architectural practice, parametricism is able to articulate increasingly complex social processes and institutions.

In terms of aesthetics, the style is characterised by the elegance of ordered complexity,of fluidity and seamless curvatures that are reminiscent of systems found in nature.

Schumacher [Schumacher 2016] identified the defining heuristics of parametricism as being both positive (dogmas) and negative (taboos):

- Positive heuristics consider the parametrical malleability of all forms, with systematic inflection, gradual differentiation and correlation.

- Negative heuristics include the avoidance of classical architectural characteristics such as geometric shapes like squares, triangles and circles, as well as the avoidance of the simple repetition of elements.

The term after its advent in 2008 has developed a global movement that has become mature in the body of technology and contemporary issues on architecture and urbanism [Chokhachian 2014]. Additionally, through the past fifteen years digital media computational tools in architecture were implemented in different methods and affected the entire field of architecture construction and design. Digital media were practical only as a representational tool for presenting ideas, at the beginning.

With developing digital tools and technology, architecture has faced new tools for diverse activities within architecture design process in digital media [Schnabel 2007]. Furthermore, parametric design has its roots in the digital media improvement, animation techniques, and computational tools of the mid-1990s. The style has been introduced and emerged in recent years by advancement of innovative parametric design systems. Nowadays, the single and dominant style for practice of contemporary architecture is "Parametricism" ([Schumacher 2009]; [Chokhachian 2014]).

Parametricism implies that all elements and aspects of an architectural composition or product are parametrically malleable;

and the style owes its original, unmistakable physiognomy to its unprecedented use of computational design tools and fabrication methods. All design parameters are conceived as variables that allow the design to vary and adapt to the diverse, complex and dynamic requirements of contemporary society [Schumacher 2016].

Parametricism links elements, architecture and urbanism as a set of design criteria which forms a complete 'system' of values, that might include the way people move through the building, their frequency of encounter, their dwell times, and so on. These values are linked in a similar way to a spreadsheet, with one value change causing a change in all other related values. Accordingly, the ultimate goal of parametricism is that a computer could calculate every factor imaginable and deliver a building that responds to and reflects all of them, thereby achieving architecture based on rational scientific data as opposed to intuitive artistic judgements.

A central criticism of parametricism is that it sometimes foregoes the requirement that a building appropriately responds to the context of its site, for instance in terms of topography, local culture, economics, etc. Many of the most celebrated buildings that have been designed using parametric techniques have been accused of being capable of belonging anywhere with little-or-no attachment to the specific area.

Another criticism is that parametricism is an opaque, pseudo-intellectual facade for the formal preferences of certain architectural practices, luring clients into spending on unnecessarily expensive buildings for the few who can afford them, and with results, which fail to deliver on promises, in either form or function.

4.3.2 PARAMETRIC APPROACH IN DESIGN

Parametric systems have emerged as a fundamental keystone in architectural design during the last decades, marking the rise of a new area of study that engages with design cognition, computation and generative principles in contemporary design practice [Dino 2012].

Parametric systems are principally based on algorithmic principles.

Several definitions of the parametric design are found in literature, from scholars and practicing architects. Parametric design is an innovative approach to digital design that allows the generation of shapes with complex geometry from the exploitation of a large amount of data[Khelil 2020a]. These data can be of environmental, acoustic, structural, social, urban type. This approach makes it possible to generate and control complex and evolving forms but requires at the same time a significant mastery of the artistic and technical challenges linked to the design of these forms.

Parametric design allows the articulation of procedures for solving both well-defined problems with a clear target, and complex ill-defined problems having several workable solutions. While the former can be regarded rather as a deterministic approach suitable for well structured problems, it is the second type that is more representative of the creative design process. Design problems offer no single best solution, but a class of satisfactory solutions [Simon 1996]; [Dino 2012]). Therefore, the designer needs to be able to define, redefine and change the design problem in the light of the solution while navigating within this design space of possible solutions [Dino 2012].

Similarly, the ability to investigate a large number of design alternatives is critical to finding successful designs, and "a main distinguishing mark of expert designers compared with novices is the creation of comparatively more alternative problem formulations" [Akin 2001]. Furthermore, design is considered as an iterative divergence / convergence process, where designers are supported and encouraged to generate the widest possible range of concepts, and then to explore, evaluate, and modify these ([Liu 2003]; [Dino 2012]).

Parametric modeling can facilitate a wider search area for design exploration by allowing the automatic generation of a class of alternative design solutions. It offers obvious advantages for engineering and manufacturing processes, now architects emerge to apply these methods in their creation of design suggesting solutions at an earlier stage of the process. A change in an input parameter generates a simultaneous change in the form, generating variations on the form while maintaining the underlying coherence of the schema [Rajaa 2020].

Parametric architecture and design question the new roles of architects and designers who are no longer simple creators of forms and spaces, but rather coordinators of an organic and complex process capable of interpreting and transforming data, they emerge to apply these methods in their creation of design suggesting solutions at an earlier stage of the process.

The parametric design is seen by Fran Gehry as a system affording inputs and inputs and outputs and that generates design spaces and mechanisms to arrive at a solution. However, Axel Kilian discusses parametric design as a process of choosing appropriate set of parameters with the most sufficient correlation to fulfill the design problem requirements. Hernaldez has broader perspective on parametric design as a process and he admits, *"parametric design is the process of designing in environment where design variations are effortless, thus replacing singularity with multiplicity in the design process"* [Chokhachian 2014]. Moreover, in systematic perspective parametric modeling system allows designers and architects to model classes of design and parts of the process. In other word, the project and the process are in parallel system, which could possibly lead to the solution [Woodbury 2011].

Parametric design system makes possible the communication and transformation between a built environment‘s geometric frame and physical or other parameters ([Chronis 2012]; [Chokhachian 2014]). The advantage of parametric design is to plan and synthesize the overall requirements and relationships of many design elements into one form. This process allows the designer to investigate variety of possible solutions quickly. Another key aspect in the usage of parametric design enablers in the design practice is the assortment of rules and the transformation of design problems and associated references into parameters, features and dependencies [Chokhachian 2014].

Parametric design enables very complex constructions, flexible design and production without making mistakes. Two main categories of the computer-aided design are enlisted by Gero in [Gero 1995]:

- The representation and production of the geometry and topology of designed objects: relating to the general use off-the-shelf CAD tools that aim to increase the efficiency or aim to automate design and drafting activities.

- The representation and use of knowledge to support or carry the synthesis of designs: giving birth to novel generative approaches that regard computation as an aid to the design process and to explore design ideas.

According to [Grobman 2008], today parametric design applications are used in architecture mainly for the following purposes:

- Design of building elements: building elements, as opposed to entire buildings, do not require a complex set of constraints in order to follow all the interconnections defined by the brief. Therefore, building elements can be designed entirely parametrically, without limitations of computer power or human perception. In this sense, building elements are designed in a similar manner to mechanical and industrial design objects. Moreover, no architectural parametric software that integrates material properties has been developed so far, which means that the design has to be performed using applications developed for industrial and mechanical designers. Software programs often used for this purpose are CATIA, Pro-engineer and Solidworks [Grobman 2008].

- Optimization of building elements: this refers to the optimization of elements like facades to fit materials and manufacturing demands using parametric applications mainly designed for industrial design or mechanical, structural engineering.

- Development of design alternatives: parametric design has been employed in a limited way for several years. Usually used for the design of geometrically complex buildings, parametric design is a tool that enables the modification of the geometry without the need to redraw the entire building. In terms of cost effectiveness, the time invested developing the custom made parametric model is worthwhile because it saves time that would have been spent on redrawing the building after geometrical changes and on drafting sections and plans that are produced automatically from the parametric model [Grobman 2008].

4.3.3 COMPUTATION-BASED DESIGN APPROACH IN ARCHITECTURE

Computational systems have emerged as a fundamental keystone in architectural design during the last decades, marking the rise of a new area of study that engages with design cognition, computation and generative principles in contemporary design practice [Dino 2012]. Architecture has always embraced innovative ideas, materials, and techniques. Contemporary architecture is no exception. The emerging computation-based design approaches, known as Computational Design (CD), differ significantly from the previous ones since they ground the design representation in its computational logic instead of its geometric aspects [Caetano 2019]. Both design theory and practice are changed by computational design. In this section, we contextualize it by presenting the evolution of CD tools, and the CD design techniques mostly used by architects.

Computational design is an excellent means of dealing with complexity, traditionally this approach has been applied mainly to place projects whose obvious visual complexity demanded it, buildings with highly sculptural forms, intricate facades and so on that would be next to impossible to design through any other means. However, all projects are complex in their own way, and can benefit from automation to handle that complexity.

The development of computer-aided design has two main areas according to ([Gero 1995]; [Dino 2012]): "the representation and production of the geometry and topology of designed objects" and "the representation and use of knowledge to support or carry the synthesis of designs". While the first category relates to the general use off-the-shelf CAD tools that aim to increase the efficiency or aim to automate design and drafting activities, the second has given birth to novel generative approaches that regard computation as an aid to the design process and to explore design ideas.

Development in available software enabled the shift from computer aided design processes (CAD) to computational design processes [ElAhmar 2016]. In CAD,forms are created by modelling geometric entities (such point, lines, solids, surfaces, etc.) which are defined only by their coordinates. In this case, the software is only a digital alternative to the previously used manual tools such as pencil and T-square, making it easier to edit, erase, copy, and so on [ElAhmar 2014]. Even after the introduction of NURBS geometries which enabled the creation of more complex forms, these forms are still the result of a set of drawing commands where the computer plays a passive role. In computational design however, form is created by a set rules and relationships. Achim Menges defines computation as *"the processing of information and interactions between elements which constitute a specific environment; it provides a framework for negotiating and influencing the interrelation of datasets of information, with the capacity to generate complex order, form, and structure."* [Menges 2011]. So in this case the role of the computer is extended to be a more active player in the design process.

Generative, Bio morphogenetic, Parametric and algorithmic design are all synonyms and sub-disciplines for computational design, aiming to use artificial intelligence and advanced mathematics. Computational design is different from computer-aided-design CAD. It is more about using the algorithmic thinking to explore limitless iterations of forms, problem solving, complex geometric calculations and rationalization. Its application can cover several aspects such as industrial design and simulation.

4.3.4 ALGORITHMIK THINKING

An algorithm is a clear set of instructions which received data as input, processes them and provides its answer in output, aiming to fulfill a clearly defined purpose in a finite number of steps [Kazemi 2015]. An algorithm takes one value or a set of values as input, executes a series of computational steps that transform the input, and finally produces one value or a set of values as output [Dino 2012]. Algorithms can solve an extensive variety of computational problems including but not limited to sorting and searching, data structure operations, combinatorial problems, numerical problems (including random number generation), and computational geometry ([Cormen 2001]; [Dino 2012], [Rajaa 2020]).

Cormen in [Cormen 2001] defines the algorithm as a value or set of values as its input, shows some of the measurable stages that converts or changes the input and finally produces one or some values as output. The power of algorithms in solving multiple measurable problems including but not limited to categorizing and searching, operation associated with the information configuration, solving combinatorial and numerical problems, such as producing random numbers and measurable geometry [Kazemi 2015]. Chang defined three instructions that perform basic operations as follows [Chang 2003]:

- Sorting (displaying instructions respectively);

- Choosing (choosing instructions for the user and then displaying explanations);

- Repetition (repeating instructions in the form of linear or return).

Algorithms can computationally generate and manipulate design entities such as geometric form, design variables, data structures that contain numeric or geometrical entities, mathematical expressions and operations, and logical operations. This level of control over design in a 3D modeling environment allows the designers extend functionality, or evaluate certain conditions and respond appropriately. Therefore, an algorithm can effectively deal with the complexities of design much beyond form with precision, and translate these into architectural properties.

Algorithmic design is a design method where the output is achieved through well defined steps [Rajaa 2020]. Regardless of its complexity, all algorithmic solutions have three building blocks: input, key process, and output (Figure 4.6).

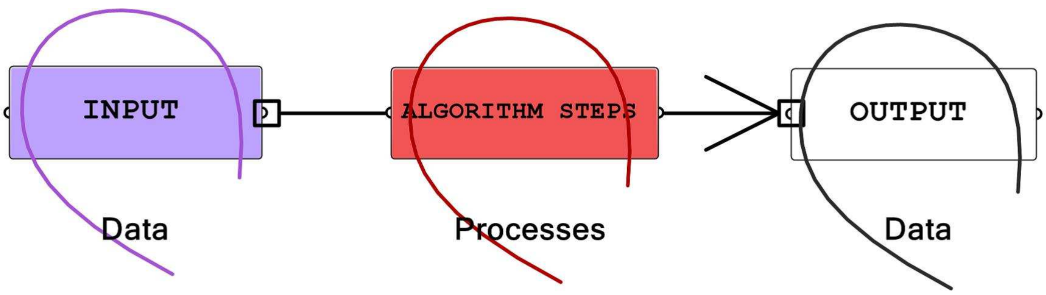


Figure 4.6: The building blocks of algorithmic solutions [Rajaa 2020]

Rajaa in [Rajaa 2020] has defined four logical steps process for designing algorithms:

- Output: clearly identify the desired outcome

- Key processes: identify key steps to reach the outcome

- Input: examine initial data and parameters

- Intermediate input and processes: define intermediate steps to generate missing data

Although algorithmic thinking, the process of finding a structure of paths or steps to be taken in order to solve a problem or a number of correlated problems, serves as the creative core of programming. Algorithms apply combinations of reasoning, data processing and calculation actions to transform the input into the output. A finite number of relatively simple algorithms may constitute compound-complex algorithms. Thus, the role of thinking is to discover the profundity of the question, turn its very roots into solvable problems, and assemble an orchestra of algorithms, which should be intelligible and executable for the expected performers. The performers could be computers, people, mechanical tools, etc.

Kazemi in [Kazemi 2015] states that, in algorithmic architecture it is attempted to make the parameters affecting the physical behavior of building (such as structure and materials) in the process of continuous analysis affect the architecture on time and reform the design in the feedback loops. Algorithmic design allows architects to explore the complex geometric designs and space to develop solutions to complex geometric and architectural space. Algorithmic design consists of a set of variables and a set of relationships that defines a form that the form can be manipulated by changing certain parameters and setting data ([Rajaa 2020], [Kazemi 2015]).

Parametric design is a subcategory of algorithmic design, and is strictly based on an algorithmic construct. Computationally speaking, there is no difference between algorithmic and parametric systems; algorithms by default operate on parameters, and a parametric system's fundamental component is the algorithm itself, called the schema or definition. However, different from algorithmic design, parametric systems emphasize the explicit and direct manipulation of the parameter values in order to induce a change on the design artifact. This simple difference between a purely algorithmic versus parametric design manifests itself only during the design process, where the designer changes the parameter values in order to manipulate the design geometry in search of the optimal design solution.

4.3.5 ARCHITECTURAL PARAMETRIC MODELLING

4.3.5.1 PARAMETRIC MODELLING PROCEDURES AND SYSTEMS

The term parametric conceptual modeling is used to characterize a particular design or process that uses conceptualism in architectural design [Hardi 2013]. It is an abstraction that filters unnecessary details and simplifies the object while elements of components and relations among them are determined. The representations at this stage should support various interpretations of design elements while simultaneously allowing them to be adjusted using multiple methods [Emdanat 1998]. Parametric modeling is a mode of operation of current computer-aided design software. It is a question of defining an entity by parameters, which can be modified easily. In this way, the definition of the models to be simulated is easily changed. The parameters can be of several types: intrinsic (lengths, angles), Cartesian (coordinates relative to a coordinate system), situational (distance, angle between 2 elements) [Hardi 2013].

When architects alter parametric values to explore various alternative solutions for a particular problem, the model will respond to modifications through automatically updating itself without deleting or remodeling any elements [Stavric 2011]. According to Burry and Murray [Burry 1997] *"parametric modeling software is invaluable for both preliminary and developed design where there is a need for the definition, manipulation and visualization of complex geometry".*

Some of the most significant goals of parametric modeling are:

- Flexibility
- Adaptability
- Modification without the need to delete or remodel
- Providing solution spaces to be explored
- Less time consuming
- Quick in responding to changes and updating of the whole model
- Working with the historical based system where designers can come back at any stages.

The design parameters control the geometry in particular, and not the predefined shapes. In addition, different geometric shapes and configurations can easily be obtained by different parameter values [Kolarevic 2003]. This is why parametric design has changed the role of architects, from designing the geometry itself towards the production of the geometry from the rules predefined by the designer. Parametric models have two variable components [Benbacha 2017]:

- Parameters: geometric relations and numbers
- Constraints: constant fixed elements

Modeling in the parametric approach requires defined values; these are often expressed through mathematical equations. For this, parametric design has an active role in design based on environmental quality. The established parameters become tools that automatically meet our simulation requirements in order to obtain adequate solutions during the optimization process ([LaBelle 2008]; [Benbacha 2017]).

Computing tools and particularly parametric design tools can help in the refined and dynamic coordination of interdisciplinary intelligence that has been transmitted through various analytical tools and techniques [Kocaturk 2011]. Consequently, parametric systems simplify a multiple interaction between the geometry, which is the representation of the primary design, and the requirements of the symbolic design [Dino 2012]. Parametric design tools highlight a collection of design methods. With the possibility of transforming ordinary design techniques, once, by computer-aided design (CAD), or by the proposal of generative techniques [Akin 1990].

Hardi in [Hardi 2013] has presented a new approach to parametric in the conceptual design phase. They state that the nature and complexity of the conceptual design stage as well as the demand to generate various design solutions within the same model without the need for programming knowledge led to the idea of incorporating Parametric Design (PD) with Design Procedures (DP) and other significant generative methodologies to introduce a new approach in the name of Parametric Design Procedures (PDPs). This incorporation can be seen as taking viable aspects of PD and DP to overcome the limitations of parametric modeling and DP. PDPs use parameters (e.g. initial shapes, variables, operations, numbers and relationships) as inputs, and calculate them through an encapsulated mathematical process to interactively generate and explore solutions for the design problem.

Lecky-Thompson in [Lecky 2006] defines a procedure as *"a named block of code, like a subroutine, but with some additional features. For example, it can accept parameters, which might be input, output, or pass-through."*[Lecky 2006]. PDPs use encapsulated codes in the form of visual features without the need to use scripts. Unlike DP, which only supports generative forms, which are designed for, PDPs support all kind of designs, which means that a parameterized model can be used for many formal explorations. In spite of using initial shapes as parameters, in PDPs shapes have the 2D and 3D transformation capability of other shapes, including non-closed shapes 'which is a condition in Design Procedures that shapes must be closed'. This addresses topological and geometrical transformation limitations of PD and DP [Hardi 2013].

Architects can also switch between operations such as extrusion, rotation, scaling, twisting, etc. to generate completely different instances within the same model, and explore more options. PDPs works with a historical based platform, and a designer can come back to any particular step to do further modifications [Hardi 2013]. Moreover, Architects have the entire control over the generation procedures thus the generation procedure will allow the combination of automated and non-automation computational procedures. In other words, design instances can be generated interactively via altering parametric values from the beginning to the end of the design process.

This approach supports the generation of all kinds of non-Euclidean forms and curvilinear surfaces, which are needed for architectural design in this digital age. Although, the PDPs approach is a computation methodology, the conceptual design process usually starts with some initial steps which are rather manually performed [Hardi 2013]. These include the identification of problems and goals, and initial sketching of 2D shapes and 3D forms which can be moved into a digital environment using the PDPs approach to generate and explore forms. In this context, these constrains can be considered as inputs to the computational framework. Figure 4.7 shows the system of PDPs as a computational methodology to form generation.

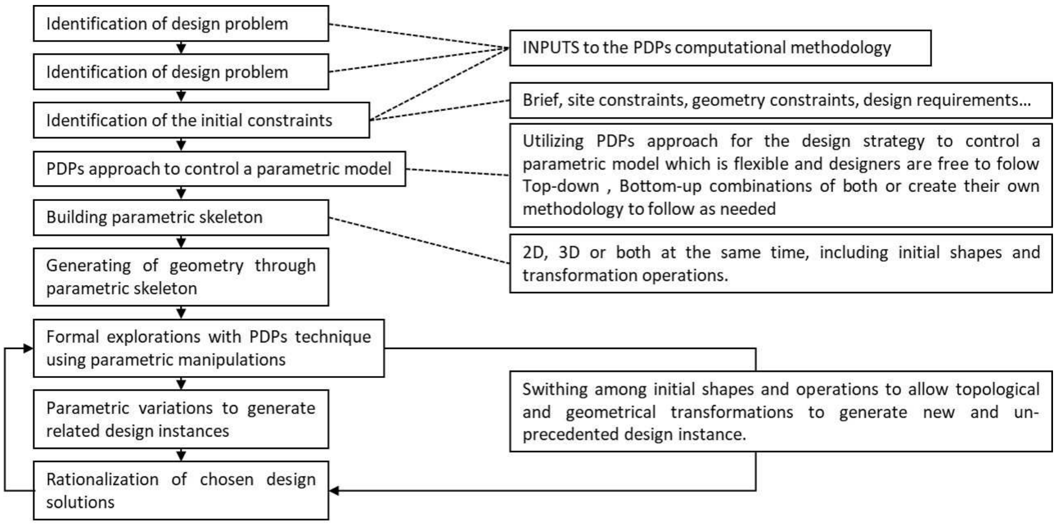


Figure 4.7: System of PDPs as a computational methodology to generative-forms of the conceptual parametric design [Hardi 2013]

4.3.5.2 PARAMETRIC MODELLING TOOLS FOR KINETIC DESIGN

As the use of computers spread among architectural practice, a growing exchange of knowledge among the disciplines of programming and architecture took place. Architects are becoming more interested in personalising available tools by re-writing their code to build more customised solutions for their design problems. A number of Text-Programming Languages (TPLs) such as RhinoScript and Processing and Visual Programming Languages (VPLs) such as Grasshopper are becoming increasingly used. Each of these two types has its advantages and drawbacks depending on the task at hand. For example, one of the most important differences between them is that TPLs are only one-dimensional while VPLs are two-dimensional or more, which makes their use much more intuitive and user-friendly and therefore it requires less background knowledge than TPLs. On the other hand, VPLs might be difficult to understand and keep track of a script if it becomes too big as they become quite 'messy' with lots of connecting wires between different components. Users must continuously organise their script to avoid losing track of it. Another drawback of VPLs is the absence of advanced abstraction means which forces users sometimes to rely a lot on copying and pasting leading to redundancy in their scripts [Leitao 2012].

- Autodesk 3D Max

  It is a parametric 3D modeling tool for architects, graphic designers, and simulators. 3D Max's geometry engine produces 3D forms that rely on modifiers and wired variables.

- Autodesk Revit

  The name Revit is short for "Revise it"; meaning you can start modeling any building in as much detail as you like while you're able to fully revise every element along the way and have the relevant pieces adjusted automatically. It practically allows us to make changes up to the most substantial scope possible. Therefore, it has the essential characteristic of parametric architecture natively built-in the platform. It is much more than a geometric simulation environment in that it comprises architectural rendering tools, an extensive repository of building components, and the framework for any BIM-oriented project; So rather than just a building, you can model the construction process with all its time and cost requirements.

- Catia

  CATIA (Computer Aided three-dimensional Interactive Application) was used by architect Frank Gehry to design some of his award-winning curvilinear buildings such as the Guggenheim Museum Bilbao Gehry Technologies, the technology arm of his firm, have since created Digital Project, their own parametric design software based on their experience with CATIA.

- Autodesk Maya

  Autodesk Maya is a 3D computer graphics software originally developed by Alias Systems Corporation (formerly

Alias|Wavefront) and currently owned and developed by Autodesk, Inc. It is used to create interactive 3D applications, including video games, animated film, TV series, or visual effects. Maya exposes a node graph architecture. Scene elements are node-based, each node having its own attributes and customization. As a result, the visual representation of a scene is based on a network of interconnecting nodes, depending on each other's information. Maya is equipped with a cross-platform scripting language, called Maya Embedded Language. MEL is provided for scripting and a means to customize the core functionality of the software, since many of the tools and commands used are written in it. MEL or Python can be used to engineer modifications, plug-ins or be injected into runtime. User interaction is recorded in MEL, allowing novice users to implement subroutines.

- Autodesk Dynamo
  Dynamo is an open source graphical programming environment for design. Dynamo extends building information modeling with the data and logic environment of a graphical algorithm editor.

- GenerativeComponents
  GenerativeComponents, parametric CAD software developed by Bentley Systems, it was first introduced in 2003, became increasingly used in practice (especially by the London architectural community) by early 2005, and was commercially released in November 2007. GenerativeComponents has a strong traditional base of users in academia and at technologically advanced design firms; GenerativeComponents is often referred to by the nickname of 'GC'. GC epitomizes the quest to bring parametric modeling capabilities of 3D solid modeling into architectural design, seeking to provide greater fluidity and fluency than mechanical 3D solid modeling; Users

can interact with the software by either dynamically modeling and directly manipulating geometry, or by applying rules and capturing relationships among model elements, or by defining complex forms and systems through concisely expressed algorithms. The software supports many industry standard file input and outputs including DGN by Bentley Systems, DWG by Autodesk, STL (Stereo Lithography), Rhino, and others. The software can also integrate with Building Information Modeling systems. The software has a published API and uses a simple scripting language, both allowing the integration with many different software tools, and the creation of custom programs by users. This software is primarily used by architects and engineers in the design of buildings, but has also been used to model natural and biological structures and mathematical systems. Generative Components runs exclusively on Microsoft Windows operating systems, and in English. Bentley Systems,Incorporated is offering GC as a technology preview of GC as a free download. This is a version of GC that no longer requires Bentley's MicroStation software for it to run, and that has features and a user interface focused on computational design.

- Marionette

  Marionette is an open source[citation needed] graphical scripting tool(or visual programming environment) for the architecture, engineering, construction, landscape, and entertainment design industries that is built into the Mac and Windows versions of Vectorworks software. The tool was first made available in the Vectorworks 2016 line of software products. Marionette enables designers to create custom application algorithms that build interactive parametric objects and streamline complex workflows, as well as build automated 2D drawing, 3D modeling, and BIM workflows within Vectorworks software. Built in the Python programming language, everything in Marionette consists of nodes which are linked together in a flowchart arrangement. Each node contains a Python script with predefined inputs and outputs that can be accessed and modified with a built-in editor. Nodes are placed directly into the Vectorworks document and then connected to create complex algorithms. Since Marionette is fully integrated into Vectorworks software, it can also be used to create entirely self-contained parametric objects that can be inserted into new and existing designs.

- Modelur
  Modelur is a parametric urban design software plug-in for Trimble SketchUp, developed by Agilicity d.o.o. (LLC).. Its primary goal is to help the users create conceptual urban massing. In contrast to common CAD applications, where the user designs buildings with usual dimensions such as width, depth and height, Modelur offers design of built environment through key urban parameters such as number of storeys and gross floor area of a building. Modelur calculates key urban control parameters on the fly (e.g. floor area ratio or required number of parking lots), delivering urban design information while the development is still evolving. This way it helps taking well-informed decision during the earliest stages, when design decisions have the highest impact.

- Archimatix
  Archimatix is a node-based parametric modeler extension for Unity 3D. It enables visual modeling of 3D models within the Unity 3D editor.

- Rhinoceros 3d
  Commercial 3D computer graphic and computer-aided design application developed by Robert McNeel & Associates. It is based on NURBS mathematical modeling, which focuses on generating mathematically precise representation of curve

and freeform surfaces within computer graphics as different to polygon mesh-based application.

- Grasshopper 3D

  The VPL Grasshopper for Rhino 3D modelling (Figure 4.8) is a plug-in that is developed specifically for modeling algorithm-based parametric forms. It is a visual programming language developed by David Rutten at Robert McNeel & Associates [Rajaa 2020]. It operated within Rhinocerous 3D modeller, which offers the visual algorithms and parametric modelling. The program is capable of creating custom designed programs that can extend the functionality. Various type of analysis ranges from sound, structural, design optimization and controlling Arduino are just a few tasks that can be operated within the Grasshopper software. It allows complicated generation of algorithmic patterns for the model [ElAhmar 2016]. It has several advantages:

  - The highly interactive and visual interface is among the most important.
  - The immediate visual feedback makes it easy to detect defects and adjust accordingly.
  - Input parameters could be easily adjusted at any point, and the resulting form is immediately altered.
  - The wide variety of free plugins for Grasshopper, which are usually programmed by architects and tackle specific problems encountered in design practice. These plugins could work together and freely exchanging data with one another. This is due to the software's capabilities created by David Rutten, which formalize the exchange of data around simple collections of basic geometric primitives. This 'geometric content- based' data exchange is in contrast to BIM's 'assigned attribute-based' data structures, and is a simplification that enables plug-ins to easily work

together [Davis 2013].

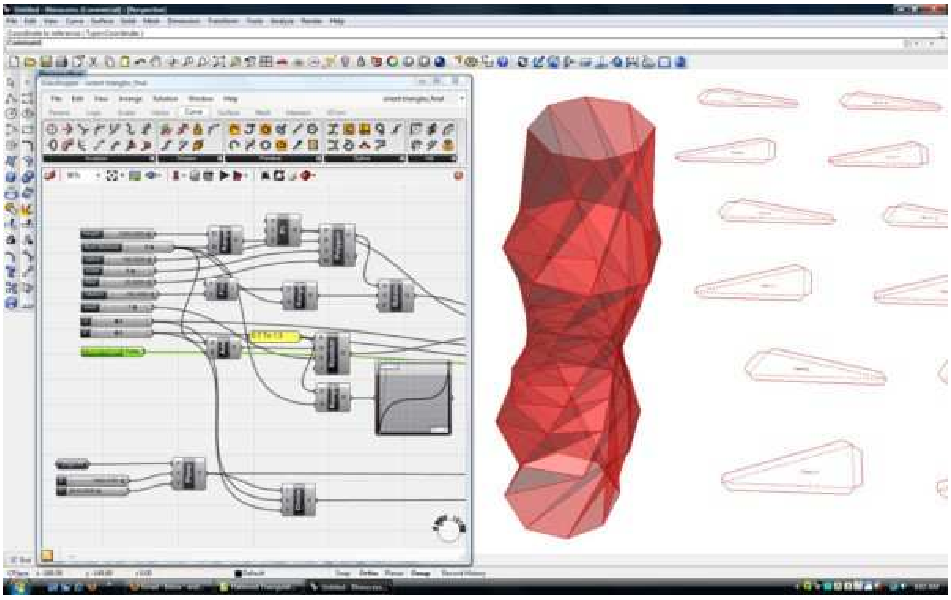


Figure 4.8: Grasshopper plug in for Rhino interface

4.3.6 PARAMETRIC PERFORMANCE ANALYSIS TOOLS FOR KINETIC DESIGN

4.3.6.1 Plug-in for environmental analysis

The applications of 'Ladybug', 'Honeybee', 'Geco' and 'Heliotrope-Solar', in the 'Grasshopper 3D' environment, can be extended to generate responsive and kinetic architecture (Dynamic Facades), where the building envelopes adapt to natural systems, such as the dynamic movement of the sun. These environmental analysis plugins enable architects to build much more balanced, green and sustainable structures, by coming up with various innovations on the buildings to leverage the external weather conditions to the maximum.

- Ladybug plugin

  An open source parametric plugin called "Ladybug" is used to support further environmental analysis inside the

Rhinoceros/Grasshopper Interface (Figure 4.9). Ladybug imports standard "Energy Plus Weather" files (EPW) into Grasshopper 3D and brings with it, a wide variety of 2D and 3D interactive graphics to conduct accurate environmental studies for the form generation of the building. It simplifies the process of analysis and automates the calculations, whilst providing easy to understand graphical visualizations in the 3D modeling interface of Grasshopper. It further allows users to work with validated energy and daylighting engines such as "EnergyPlus", "Radiance" and "Daysim", effectively allowing to the architect to make better design choice [Sadeghipour 2013].

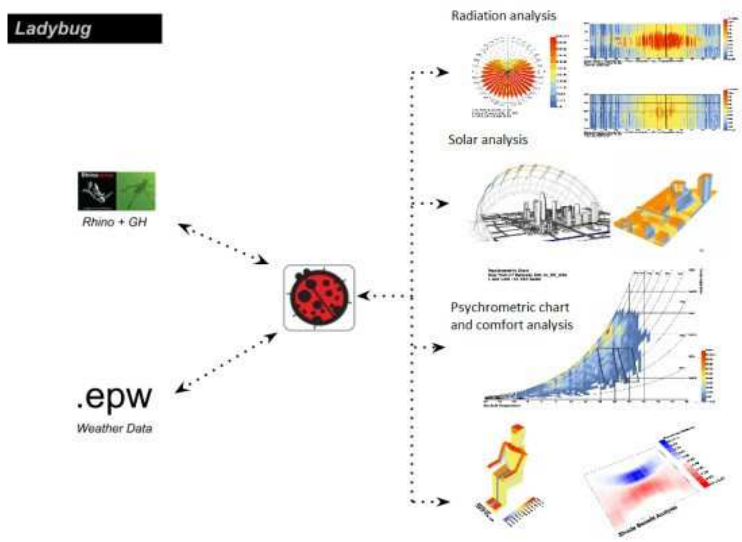


Figure 4.9: ladybug environmental analysis plugin

- Honeybee plugin

  Honeybee is another parametric plugin for Grasshopper which also connects Grasshopper3D to "EnergyPlus", "Radiance", "Daysim" and "OpenStudio", for building energy consumption & daylighting simulation (Figure 4.10).

- Geco plugin

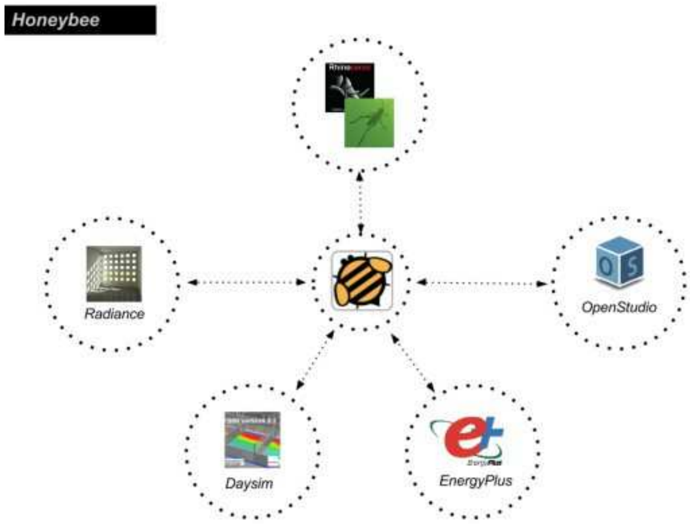


Figure 4.10: Honeybee environmental analysis plugin

Geco (Figure 4.11) allows one to export and actively collaborate effectively with another software called Ecotect, in order evaluate one's design with various the performance data, which Geco again makes possible to import the results as feedback, back into Grasshopper. Now, Ecotect is a visual software for architects, which enables them to test environmental performance issues and simulate various environment and climatic conditions in order to design more green and efficient parametric structures.

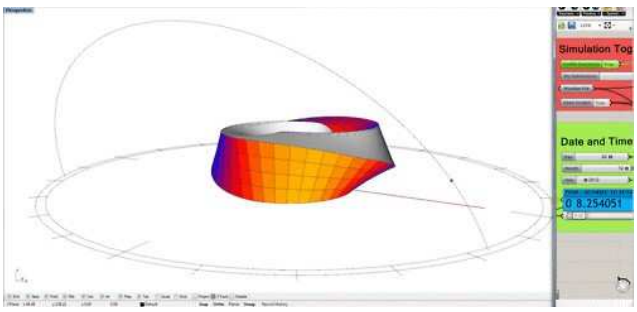


Figure 4.11: Geco environmental analysis plugin

- Heliotrope-Solar plugin

It is a Grasshopper plug-in for manipulating geometry based on the dynamic position of the Sun Figure 4.12. The tool calculates the apparent position of the sun (using vector physics) at specified dates and times of the day, and uses this data to compute and provide a variety of components for parametrically manipulating the design based on the position of the sun on those specified dates. It is used to create solar-aware designs, to deduce the position of rendering lights & to design shading devices for the structure.

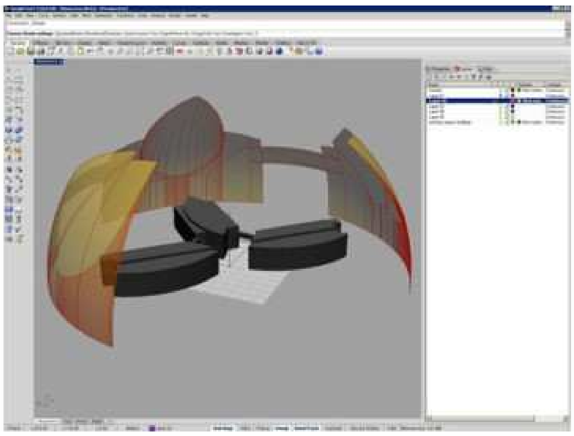


Figure 4.12: Heliotrope-Solar environmental analysis plugin

4.3.6.2 Plug-in for structural analysis

Structural systems are formed by the interpretation of lines, curves and points as structural elements and forces, through custom components. All the data analyzed is then exported from Rhinoceros to a FEM (Finite Element Method) analysis software like "SOFiSTiK". The software uses a numerical technique for finding approximate solutions to boundary value problems for partial differential equations harnessed from the prior structural analysis. It basically breaks down a complex problem into simpler parts and then begins to calculate and solve them. This "part to whole" approach truly eliminates a large margin of error and compliments for a much more accurate structural analysis, aiding in a much more robust, stable and balanced parametrically designed structure.

- Kangaroo Physics plugin

  Structural Engineers use the Kangaroo Physics plugin (Figure 4.13) inside Grasshopper for interactive real simulation, generating form, optimization and analysis of structural components and constraint introspection.

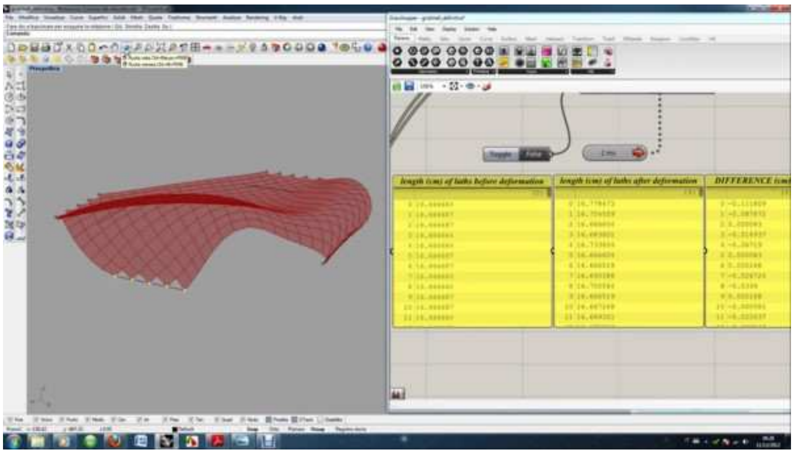


Figure 4.13: Kangaroo Physics structural analysis plugin

- Karamba plugin

  Parametric design plugins like "Karamba" (Figure 4.14) define new horizons in the field of structural engineering. Karamba is an interactive structural analysis plugin in the parametric environment of Grashopper 3D. This plugin makes it extremely simple to combine parameterized complex geometric forms, load calculations, finite element analysis, etc. It provides accurate analysis of spatial trusses, frames and shells at the early design stage. The user is able to create basic 'pin-jointed' planar systems, from which graphic statics are generated and analyzed, to understand the available degrees of freedom in these systems, in order to leverage them structurally.

- BullAnt plugin

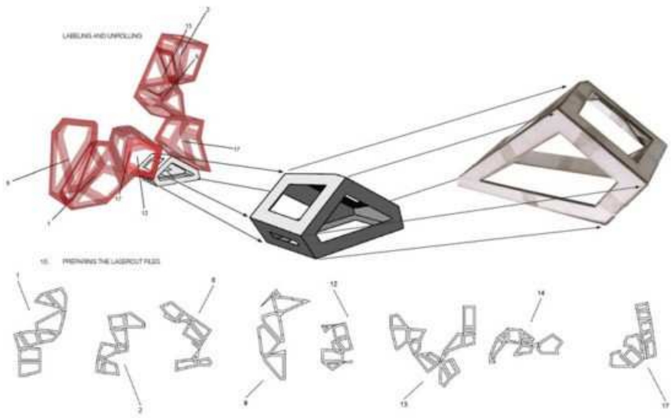


Figure 4.14: Karamba structural analysis plugin

It is a Grasshopper3D plug-in (Figure 4.15) , primarily for Architects and Engineers. It features unique tools, which enhance and extend the capabilities of parent program. It features an array of commands including mesh relaxation & inflation, automation in symmetry, tessellation, structural analysis (modeling and sketching) and parametric generation in Grasshopper. It also features geodesic dome & curve network processing

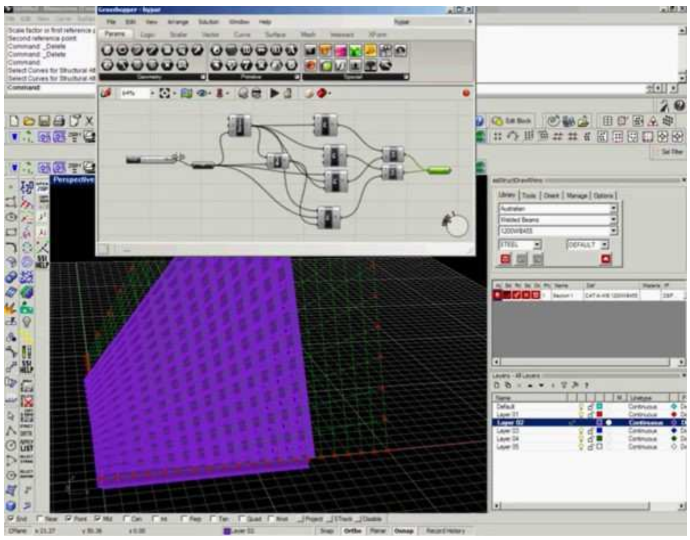


Figure 4.15: BullAnt structural analysis plugin

- Hummingbird plugin

It expands Grasshopper's capabilities by adding a set of components which help in the conversion and creation of Revit files which contain supported geometric algorithms for the Rhino modeled file. In other words, a complex parametrically designed geometry, can be designed in a BIM software, to make the structure much more practical, before presenting or proposing it. Hummingbird (Figure 4.16) basically allows a bi-directional workflow in between Autodesk Revit and Rhinoceros 3D, removing the need to create reference objects. This also helps in better visualizing and analyzing the structural components.

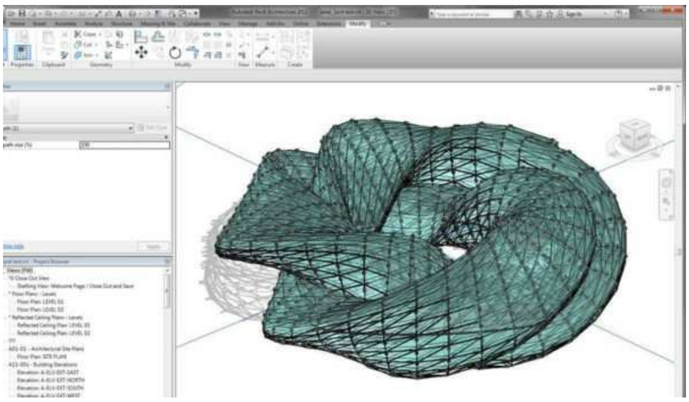


Figure 4.16: Hummingbird structural analysis plugin

- Mantis plugin

Mantis is a plugin for grasshopper (Figure 4.17), which directly links Rhinoceros and Mathematica. Mathematica is a tool for technical computing, used by mathematicians, engineers and analysts. It is renowned as the world's best application for computations

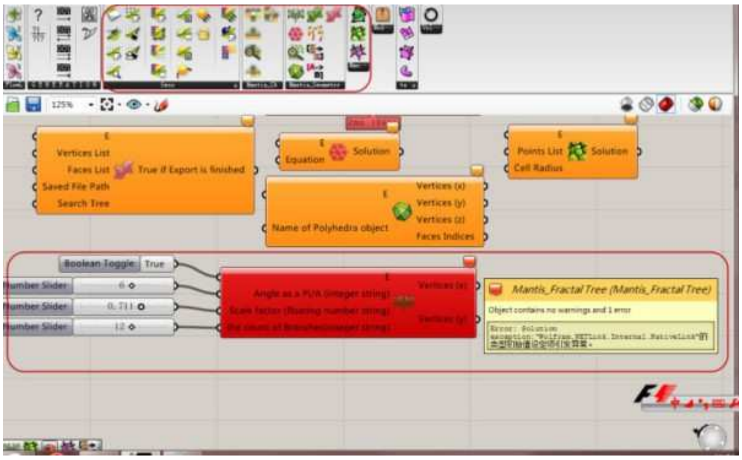


Figure 4.17: Mantis structural analysis plugin

4.4 CONCLUSION

Coupling biomimicry with parametric and computational design needs a transformation in modes of thinking, which, would be the main agenda toward designers and architects. A brief overview of biomimicry in computational design was presented, since computational tools are intended to be used in the application of bio-kinetic design in the second part of this thesis.

This chapter discussed how a natural language approach facilitates the identification of biological analogies. A framework for understanding biomimicry has been developed. This kind of literature review was elaborated on distinct strategies to biomimetic design that have been evolved, and was used to discuss the distinct advantages and disadvantages inherent in each as a design methodology. We were aiming to clarify the various types of biomimicry that commonly exist or could be explored in the future, so that distinctions between different kinds of biomimicry and their potential sustainability outcomes could be made.

From the discussion on the above study, it can be concluded that the nature also can give an impact to the world of architecture. The approach of biomimetic design in architecture was introduced. It represented a literature reviewing phase that addressed the origins of design inspired by nature, the relationship between nature and architecture, and the different biomimetic design methods. It also discussed the main biological principles followed by nature in order to understand how such principles can relate to architectural design. Then a particular focus was made on different biomimetic design strategies.

In order to shift into digital and computational thinking, the first step is to build up computational knowledge and basic awareness on parametric issues, so in this chapter we presented different point of views on definition and implementation of parametric design from design procedure lens in order to create platform for holistic design system. Therefore, new knowledge and skills that designers need to master the parametric and how they can learn and use it were discussed in this chapter. We demonstrated clearly how using patterns to think about and work with parametric modelling helps designers master the new complexity of the design systems.

Examples of how such a biomimetic-computational approach can be applied were demonstrated. Based on this literature review, the chapter ended with defining the design approach and focus points that will be addressed in the rest of the thesis. We presented novel techniques that enhance architects' contribution to building processes based on parametric design creation. This allows a deeper comprehension of the design objectives and aids designers in their decisions to find solutions.

Part II

BIO-KINETIC DESIGN TOWARDS THE OPTIMIZATION OF THE ENERGY CONSUMPTION

Chapter 5

BIO-KINETIC DESIGN AND COMPUTATION

” There is a duality between engineering and nature, which is based on minimum use of energy. This is because animals and plants, in order to survive in competition with each other, have evolved ways of living and reproducing using the least amount of resource. This involves efficiency both in metabolism and optimal apportionment of energy between the various functions of life. A similar situation obtains with engineering, where cost is usually the most significant parameter. It seems likely, then, that ideas from nature, suitably interpreted and implemented, could improve the energy efficiency of our engineering at many levels.”

- Julient Vincent

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5.1 INTRODUCTION

After reviewing biomimetic, adaptive, kinetic and parametric approaches in Part One of this thesis, The second part contains the qualitative and quantitative phase. It starts with chapter five that represents the qualitative / design phase (as explained in the introductive chapter). This part of the thesis sets out to the generation of the concept of bio-kinetic design. We implement the biomimetic design, parametric and kinetic design principles in the design of building's skin in hot and arid regions like the city of Biskra as case of the study to evaluate the introduction the parameterization of buildings skins as a valuable strategy for reducing energy consumption in these regions.

The city of Biskra, located in Algeria is chosen for its representativeness of hot and arid environments in the country. It has a rigorous climate characterized by very hot, dry summer and cold winter. Its characteristics are unfavorable for achieving thermal comfort. Harsh climatic characteristics of the region and this proliferation of mass concrete and wide paved streets has contributed to the deterioration of the microclimate of the city. The temperature of the asphalt surfaces can reach 353 °K because of its color and horizontality. We provide more details about this region in chapter 6.

In this research, we treat one of the sick building syndrome symptoms of this region, which is thermoregulation, through mimicking the impressive natural adaptation methods found in fauna and flora. It is not a simple mimicking of nature but rather than it searches beyond the form towards a better understanding of its adaptation principles. Therefore, we try to reformulate a new design concept for building's skin shading device system in buildings through proposing a strategic methodology as a bio-problem solver for supporting the design as a step towards creating the conceptual model.

The ultimate goal of this research is to assess building's skin parameterization and adaptiveness through developing bio-kinetic shading elements for further application in a typical office room skin located in hot and arid regions. The reference office is meant to act as a baseline for comparative analyses. The reference office represents a somewhat typical 'shoebox' model as is commonly used for conceptual design explorations. Figure 5.1 presents the diagram of the used parametric design methodology of the bio-kinetic shading system proposal. In this chapter, only the first step is proceeded and presented, however the second step is presented in Chapter 6.

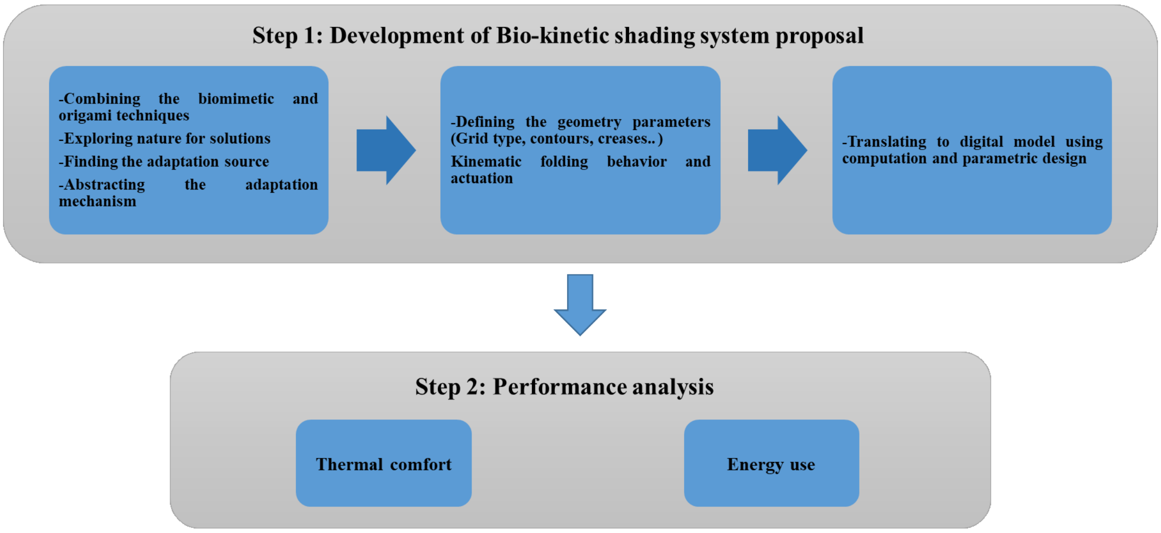

Figure 5.1: Diagram of the parametric design methodology of the bio-Kinetic shading system proposal (Author)

This chapter includes biomimetic exploration, where certain design functions of the building skin are specified and the search for parallels in nature begins. Ideas from nature are categorized according to the main heat transfer method by which thermoregulation occurs, and then they are abstracted to see possible applications in architecture. It ends with chosen ideas to be applied in the design a shading device system for building's skin located in hot and arid region.

5.2 BIOMIMETIC INSPIRATIONS AND ANALYSIS

With the aim to resolve thermoregulation problems in hot and arid regions, we have started looking to nature to find solutions and some adaptations strategies aiming to minimize heat gain or maximizing heat loss through heat transfer methods.

The applied biomimetic design methodology is a problem-based approach, which means it starts by defining specific design challenges and then search for parallels in nature. More specifically, this chapter will focus on the searching phase in an attempt to prepare a list of possible solutions that either reduce heat gain or increase heat loss to adapt to hot climatic conditions. In the following section, fauna and flora will be addressed and analyzed to explore some of the strategies, which they have in general to aid in thermoregulation. Figure 5.2 presents the scope of this chapter within the biomimetic process.

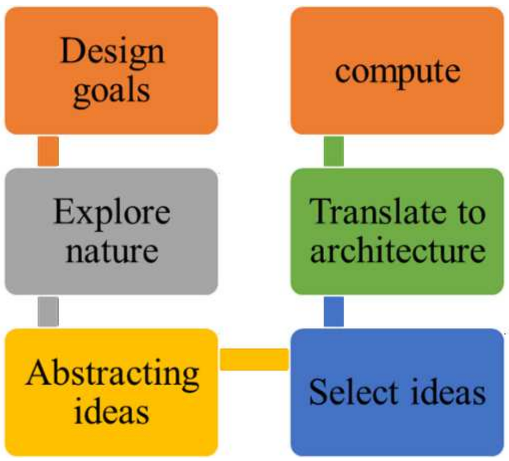

Figure 5.2: scope of the chapter within the biomimetic process (Author)

In this chapter, the biomimetic design process starts as a mean of exploration for innovative ideas for thermoregulation problems in building skins. Thermoregulation is the ability of an organism to keep its body and environmental temperature within certain boundaries, even when the surrounding temperature is very different. Efficient thermoregulation solutions can be extracted from thermoregulation strategies found in nature, or carried out by living organisms. Living organisms maintain the thermal comfort of their habitats in narrow ranges in order to survive.

A systematic knowledge about adaptation in nature and how the different types of natural organisms adapt to environmental changes, by providing great thermoregulation strategies, is presented, where the biomimetic approach is used as the tool that externalizes the responsive connectedness between nature and built environment. In addition, it establishes the design framework to implement this responsive connectedness in the adaptive skin system. Approaches to biomimicry typically fall into two categories. The 'design referencing biology' and 'biology influencing design'. The first approach is followed in order to find new methods ,systems and biological strategies to optimize the selected challenge, mimicking the nature by looking to its systems and process in order to learn how natural systems can overcome the same design problem.

5.2.1 BIO-DESIGN METHODOLOGY FOR BUILDING'S SKIN DESIGN

The bio-brainstorming methodology [Khelil 2015] is adopted, a selective tool to identify the relevant systems and strategies in nature, in order to find new alternatives for the thermal comfort in buildings and then the energy optimization and saving. The aim of this methodology is to explore and extract mechanisms found in nature, for potential application in innovative building skins. The methodology is basically dealing with the exploration process and organisms investigation, and the results in leading architects to a concept design.

An amount of steps are carried out: definition of the challenge and its functions, explore biological challenges similar to the identified technical challenge, discover creatures and natural organisms, Select the pinnacles that do the needed roles for extracting the main principles and processes, build Taxonomies to obtain Brainstorm ideas, evaluate the ideas, transform the best ideas into designs, build physical models, evaluate and validate them. These steps and phases (Figure 5.3) are presented in tables, and figures that provide a selective tool, which leads to a concept design of the living building. This methodology is basically dealing with the exploration process and organisms' investigation, and the results in leading architects to a concept design [Khelil 2018].

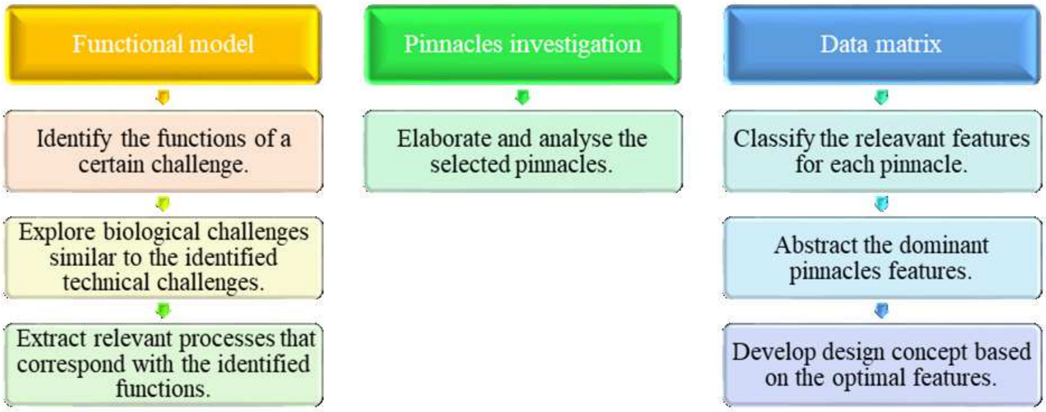

Figure 5.3: flow chart of the design methodology showing the several phases

Initially, we define a design challenge that we are wondering to resolve. This methodology contains three levels of abstraction, the functional model, pinnacles investigation, Data matrix.

5.2.1.1 Thermoregulation functional model

Thermoregulation is the capability of an organism to retain its body and environmental temperature within certain limits, even when the surrounding temperature is very different. Natural thermoregulation strategies present very promising solutions to inspire us, where the living organisms aiming to survive preserve the thermal comfort of their habitats and surrounding.

The thermoregulation in organisms has several mechanisms and strategies. According to Badarnah [Badarnah 2012], the investigation and exploration of heat regulation in nature is based on four initial functions: gain, retain, dissipate, and prevent. Each function incorporates different processes (Figure 5.4).

Radiation, convection, evaporation and conduction are four mechanisms of heat exchange between the environment and the organism. Radiation is the emission of electromagnetic "heat" waves. Heat radiates from the sun and from dry skin the same manner. When a mammal sweats, evaporation removes heat from a surface with a liquid [Edney 1971]. Convection currents of air remove heat from the surface of dry skin as the air passes over it [Bahamon 2007]. Heat can be conducted from one surface to another during direct contact with the surfaces, such as an animal resting on a warm rock [Douglas 1978] .

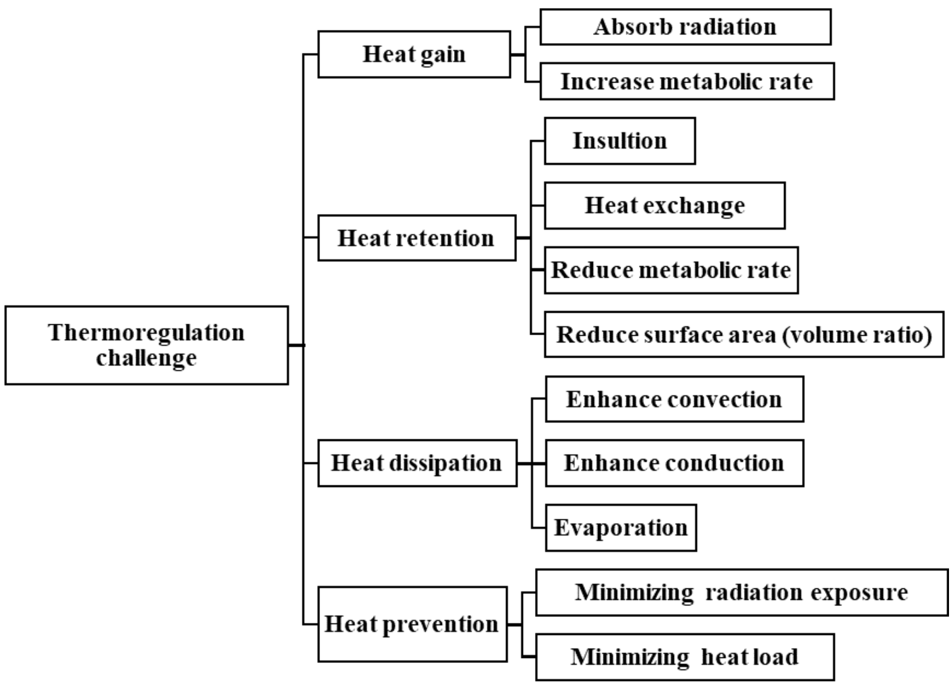

Figure 5.4: thermoregulation functional model (Author)

The main concern of this research is thermoregulation in hot climates where the design goal is the minimization of heat gain and maximization of heat loss through the building skin. Heat is transferred by one of four processes: radiation, conduction, convection, evaporation. Therefore, the output of the searching phase of living organisms will be categorized depending on the means by which they regulate heat, which is one of these four processes. Then each pinnacle (organism) will be analyzed in order to understand exactly how did it regulate heat, then its strategy would be simplified and abstracted to facilitate the identification of the potential corresponding architectural feature(s).

5.2.1.2 Thermoregulation pinnacles investigation

Thermoregulation in animals Thermoregulation in animals runs along a spectrum, in general, they can be classified as ectotherms or endotherms; they can either be homeothermic, poikilothermic, or both [Clench 1966]. An ectotherm is an organism in which internal physiological sources of heat are of relatively small or quite negligible importance in controlling body temperature (Figure 5.5). Since ectotherms rely on environmental heat sources, they can operate at economical metabolic rates.

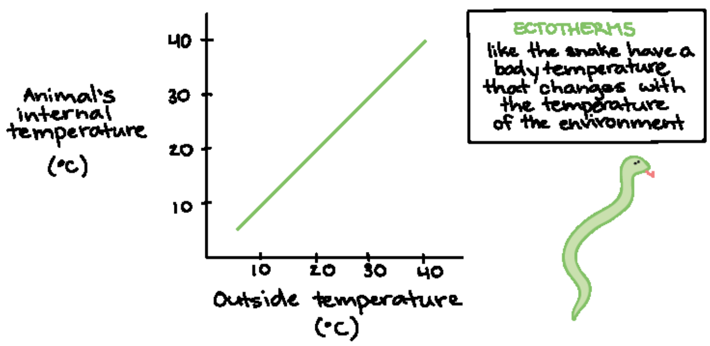

Figure 5.5: examples of ectotherm animals

They usually live in environments in which temperatures are constant, such as the tropics or ocean. They have developed several behavioral thermoregulation mechanisms, such as basking in the sun to increase body temperature or seeking shade to decrease body temperature [Badarnah 2012]. Ectotherms use external sources of temperature to regulate their body temperatures; they are colloquially referred to as "cold-blooded" even though their body temperatures often stay within the same temperature ranges as warm-blooded animals [Casey 1976]. Iguanas and rattlesnakes, like most other reptiles (along with most fishes, amphibians, and invertebrates) are ectotherms (Figure 5.6).

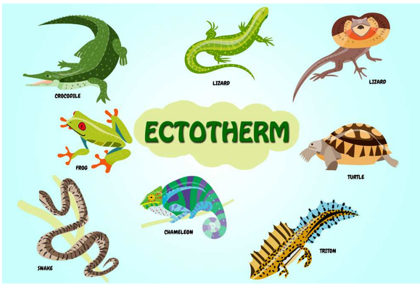

Figure 5.6: examples of ectotherm animals

In contrast to ectotherms, endotherms regulate their own body temperature through internal metabolic processes and usually maintain a narrow range of internal temperatures (Figure 5.7). Heat is usually generated from the animal's normal metabolism, but under conditions of excessive cold or low activity, an endotherm generates additional heat by shivering. Many endotherms have a larger number of mitochondria per cell than ectotherms [ElAhmar 2016]. These mitochondria enable them to generate heat by increasing the rate at which they metabolize fats and sugars. People, polar bears, penguins, and prairie dogs, like most other birds and mammals, are endotherms.

Endothermic animals must sustain their higher metabolism by eating more food more often. For example, a mouse (endotherm) must consume food every day to sustain high its metabolism, while a snake (ectotherm) may only eat once a month because its metabolism is much lower.

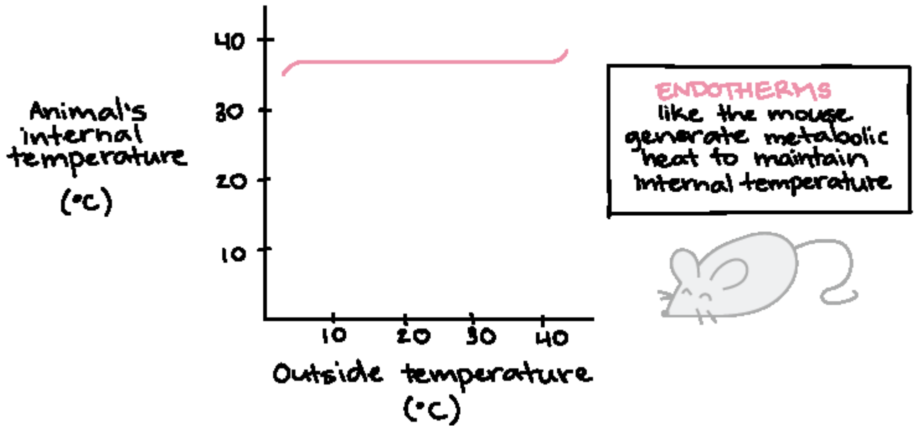

Figure 5.7: thermoregulation of endotherms

Endothermy and ectothermy refers to the way in which organisms generate heat, homeothermy and poikilothermy refers to the stability of their core temperatures (Figure 5.8). A poikilotherm is an organism whose internal temperature varies considerably. It is the opposite of a homeotherm, an organism, which maintains thermal homeostasis. Poikilotherm's internal temperature usually varies with the ambient environmental temperature, and many terrestrial ectotherms are poikilothermic [Casey 1976].

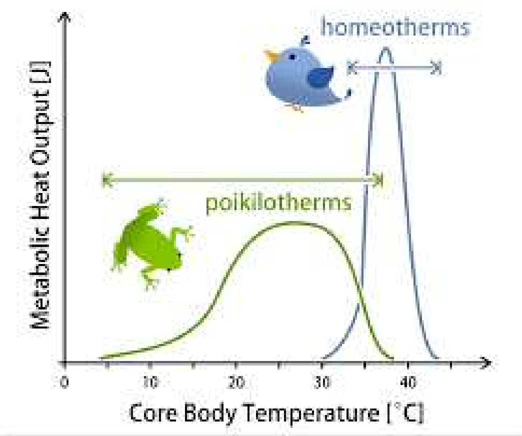

Figure 5.8: thermoregulation of homeothermy and poikilothermy organisms

Poikilothermic animals include many species of fish, amphibians, and reptiles, as well as birds and mammals that lower their metabolism and body temperature as part of hibernation or torpor. Some ectotherms can also be homeotherms. For example, some species of tropical fish inhabit coral reefs that have such stable ambient temperatures that their internal temperature remains constant (Figure 5.9).

Heat can be exchanged between an organism and its environment through four mechanisms (Figure 5.10): radiation, evaporation, convection, and conduction. Radiation is the emission of electromagnetic "heat" waves. Heat radiates from the sun and from dry skin the same manner. When a mammal sweats, evaporation removes heat from a surface with a liquid. Convection currents of air remove heat from the surface of dry skin as the air passes over it. Heat can be conducted from one surface to another during direct contact with the surfaces, such as an organism resting on a warm rock.

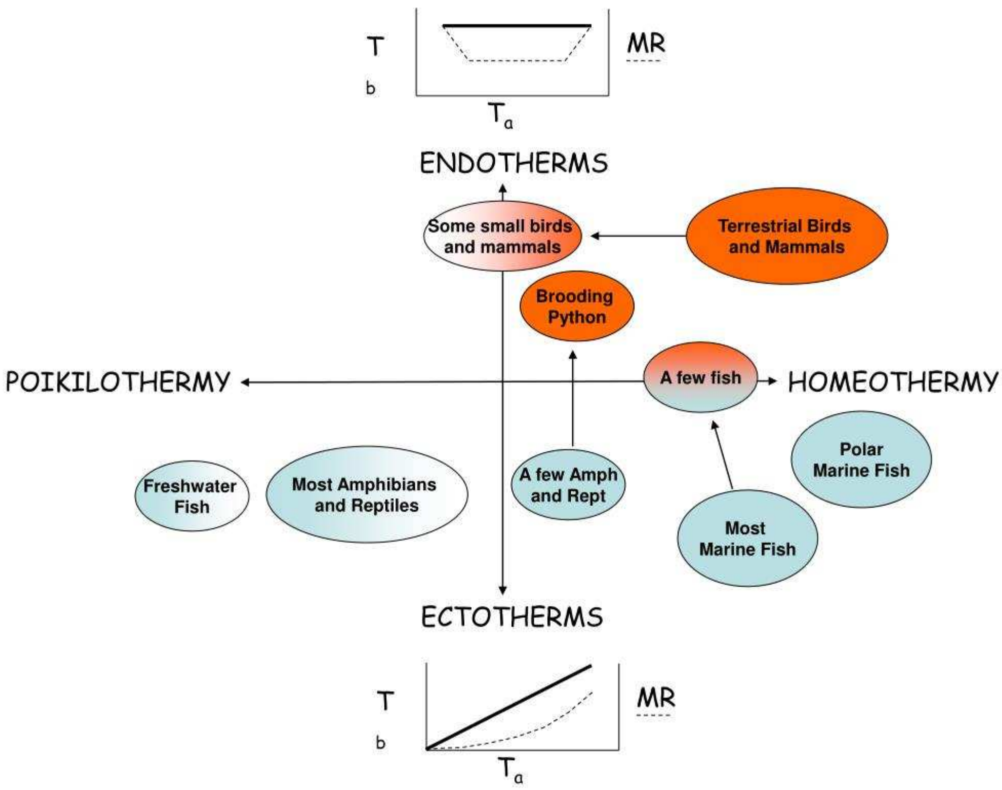

Figure 5.9: classification of different organisms depending on their thermoregulation strategies

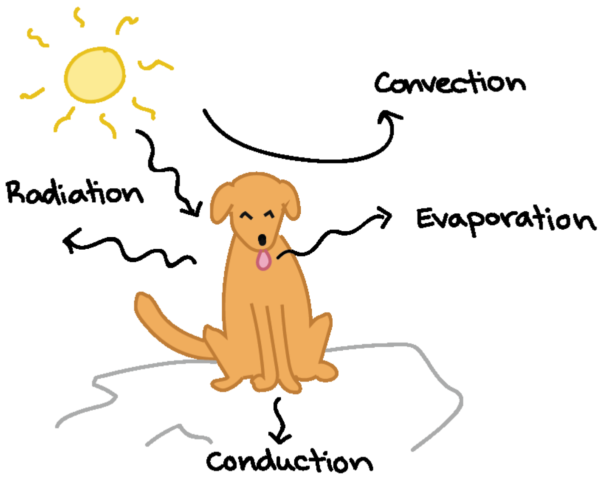

Figure 5.10: classification of different organisms depending on their thermoregulation strategies

Three categories of thermoregulatory mechanisms are abstracted from the analysis of the thermoregulation in animals:

1. Changing behavior: For instance, elephants spray themselves with water to cool down on a hot day, and many animals seek shade when they get too warm. On the other hand, lizards often bask on a hot rock to warm up, and penguin chicks huddle in a group to retain heat. Some ectotherms are so good at using behavioral strategies for temperature regulation that they maintain a fairly stable body temperature, even though they don't use metabolic heat to do so.

2. Increasing metabolic heat production: Endotherms have various ways of increasing metabolic heat production, or thermogenesis, in response to cold environments. One way to produce metabolic heat is through muscle contraction and shivering increase muscle activity and thus boost heat production. Nonshivering thermogenesis provides another mechanism for heat production. This mechanism depends on specialized fat tissue known as brown fat, or brown adipose tissue. Some mammals, especially hibernators and baby animals, have lots of brown fat. Brown fat contains many mitochondria with special proteins that let them release energy from fuel molecules directly as heat instead of channeling it into formation of the energy carrier ATP.

3. Controlling the exchange of heat with the environment: Animals also have body structures and physiological responses that control how much heat they exchange with the environment:

   a Circulatory mechanisms, such as altering blood flow patterns: the body's surface is the main site for heat exchange with the environment. Controlling the flow of blood to the skin is an important way to control the rate of heat loss to (or gain from) the surroundings.

- Vasoconstriction and vasodilation

  In endotherms, warm blood from the body's core typically loses heat to the environment as it passes near the skin. Shrinking the diameter of blood vessels that supply the skin, a process known as vasoconstriction, reduces blood flow and helps retain heat (Figure 5.11).

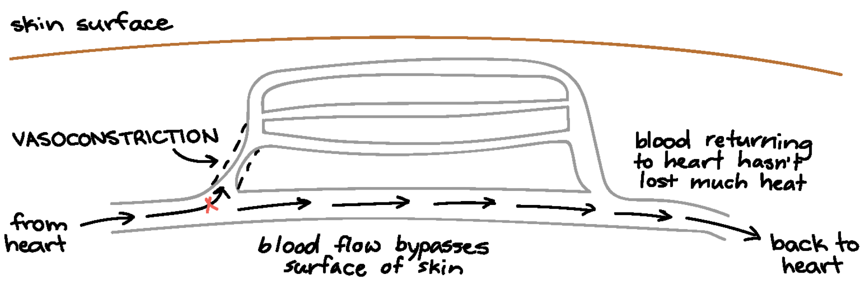

Figure 5.11: vasoconstriction mechanism

  On the other hand, when an endotherm needs to get rid of heat, these blood vessels get wider, or dilate. This process is called vasodilation. Vasodilation increases blood flow to the skin and helps the animal lose some of its extra heat to the environment (Figure 5.12).

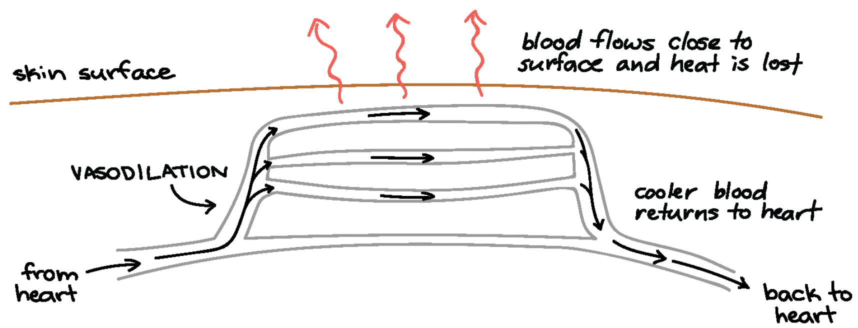

Figure 5.12: vasoconstriction mechanism

- Countercurrent heat exchange

  Many birds and mammals have countercurrent heat exchangers, circulatory adaptations that allow heat to be transferred from blood vessels containing warmer blood to those containing cooler blood (Figure 5.13).

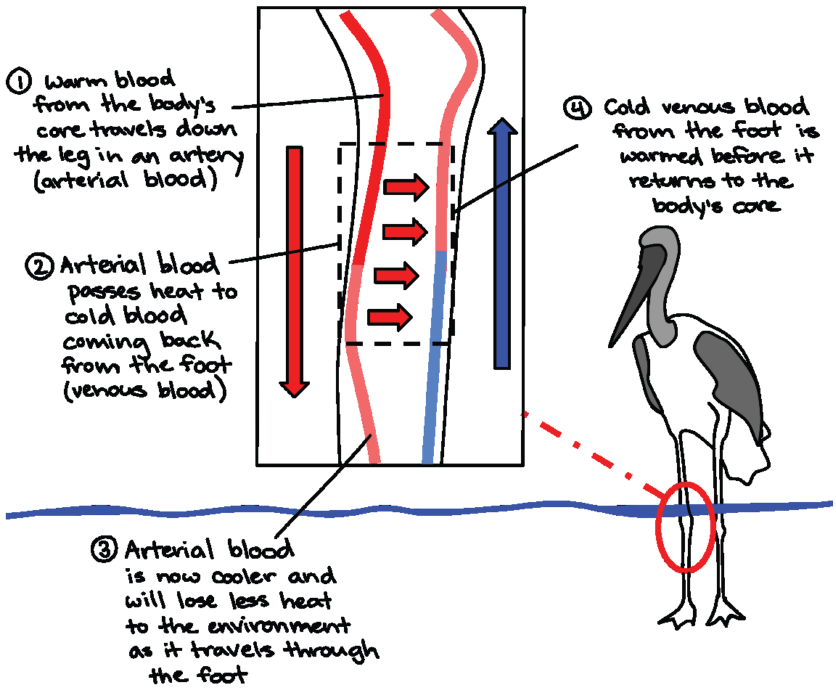

Figure 5.13: countercurrent heat exchange mechanism

b Insulation, such as fur, fat, or feathers: Another way to minimize heat loss to the environment is through insulation. Birds use feathers, and most mammals use hair or fur, to trap a layer of air next to the skin and reduce heat transfer to the environment. Marine mammals like whales use blubber, a thick layer of fat, as a heavy-duty form of insulation (Figure 5.14).

Figure 5.14: Left, a pigeon fluffs its feathers for warmth; right, human goosebumps are an attempt to increase insulation by trapping air near the skin

c Evaporative mechanisms, such as panting and sweating: Land animals often lose water from their skin, mouth, and nose by evaporation into the air. Evaporation removes heat and can act as a cooling mechanism. For instance, many mammals can activate mechanisms like sweating and panting to increase evaporative cooling in response to high body temperature.

- In sweating, glands in the skin release water containing various ions. Only mammals sweat (Figure 5.15).
- In panting, an animal breathes rapidly and shallowly with its mouth open to increase evaporation from the surfaces of the mouth. Both mammals and birds pant, or at least use similar breathing strategies to cool down (Figure 5.15).

Figure 5.15: Left, a pigeon fluffs its feathers for warmth; right, human goosebumps are an attempt to increase insulation by trapping air near the skin

Table 5.1 presents a taxonomy of bio-thermoregulative strategies of animals for further application to design bio-kinetic building's skin in hot and arid regions responding to the most critical functional requirements of envelopes. The selected pinnacles apply specific processes with a variety of factors to ensure the thermoregulation.

Architects and engineers, for enhancing environmental adaptation, choose the relevant strategy from the taxonomy with the corresponding processes, and procedures to identify morphological means for adaptation for resolving their challenge. Alternatively, they can combine several processes.

Thermo-regulation challenge	Functional requirements of buildings skin	Abstracted strategies			
		Pinnacles	Functions	Process	Factor
	Control heat flow	The shell of desert snails	Prevent	Minimize heat load	Layers insulation
		nightjars	Dissipate	Evaporation	Temperature
		free-tailed bats	Dissipate	Enhance conduction	Circulation (blood)
		Pelicans	Retain	Reduce convection	Circulation
		Alligators	Dissipate	Evaporation	Temperature
		Tuna Dolphins flippers	Retain	Heat exchange	Morphology
		-mammals (warm blooded animals) -Honeybees	Gain	Increase metabolic rate	Shivering / Vibrating
		Spiders (Micrathena gracilis)	Gain	Absorb radiation	Orientation
	Control air flow	-Termite mound -Zebra	Dissipate	Enhance convection	Airflow: Pores, air passages.
		Great egret	Dissipate	Evaporation	Airflow rate
		The Burrow of the prairie dog	Retain	Heat exchange	Morphology
		Wood ant (Formica rufa)	Dissipate	Enhance convection	Airflow : holes
	Control light / solar radiation	Chuckwalla	Gain	Absorb radiation	Surface area
		Lizard	Gain	Absorb radiation	Posture/ Orientation
		The shell of desert snails	Prevent	Minimize irradiation	Morphology
		Elephant skin	Dissipate	Minimize irradiation	Reflectance
		Skink	Dissipate	Minimize irradiation	
		Camel	Dissipate	Minimize irradiation	Volume/ surface area
		Wood ant (Formica rufa)	Dissipate	Minimize irradiation	Orientation, morphology
		Polar bear (Ursus maritimus)	Gain	Absorb radiation	Surface area

Table 5.1: Taxonomy of bio-thermoregulative strategies of animals for bio-kinetic building's skins in hot and arid regions (Author)

Thermoregulation in plants Trees, plants, flowers and succulents are flexible structures that are sensitive to climatic conditions and as a response, they have evolved a number of techniques and features that aid in overcoming such situations. These features aid in thermal regulation either by minimizing heat gain, or maximizing heat loss [ElAhmar 2016]. We analyze leaves, trees and flowers, In order to explore some of the strategies, which they have in general to help in thermoregulation.

Leaves are physical and biological entities with a huge variation in shapes and sizes, indicating that it is a part of an adaptive response to different climates, and different microclimates within the same tree or plant [Schuepp 1993].

They only absorb the energy required for photosynthesis (which is a sensitive process and occurs within a temperature range between 30 and 40 degrees Celsius) and the energy required for the tensile water transport upwards along tree barks [Henrion 2009]; [Zahr 2010]).

El ahmar Salma in [ElAhmar 2016]states that it is worth noting that leaves depend on two types of convective heat loss; thermally-driven (free) convection in the form of upward flows, and wind-driven (forced) convection represented in lateral air movement, which is the most effective. From the pinnacles analysis, five strategies are found that are likely to decrease the effect of full sunlight in warm climates.

a Size

Optimal leaf size in different situations ranging from mesic (moisture-abundant) to xeric (dry) environment, and from sunny to shady situations (Figure 5.16). The stippled area indicates the range of habitats likely to be encountered in nature [Givnish 1976]. Smaller and narrower leaves have evolved as they have thinner boundary layers (BL) (a thin zone on the surface of a leaf where air does not move due to surface friction. For transpiration to take place, water vapour must pass this

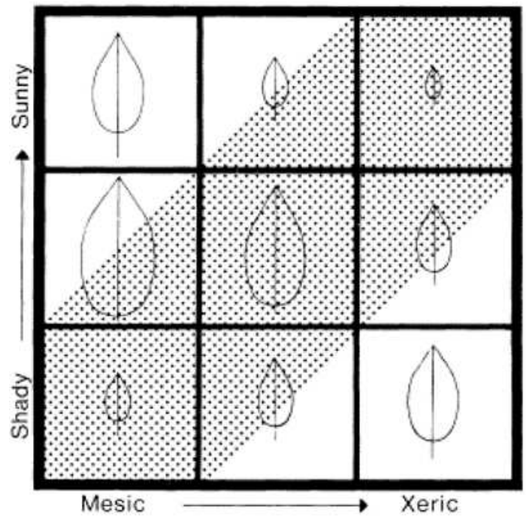

Figure 5.16: Optimal leaf size in different situations ranging from mesic to xeric environment, and from sunny to shady situations [Givnish 1976]

layer to reach the atmosphere) [ElAhmar 2016]. The bigger and wider the leaf, the thicker the boundary layer becomes and therefore resistance to transpiration increases ([Schuepp 1993]; [Givnish 1988]), and therefore less resistance and more heat loss by convective dissipation as seen in Figure 5.17.

b Shape

The shape of the leaf also has a role, as temperature on a given point on a leaf increases approximately with the square root of the distance from an edge [Vogel 2009]. Therefore, this distance decreases if a leaf is lobed, dissected or pinnate and narrow in addition to being smaller in size (Figure 5.18). Lobes and serration in leaves decrease the boundary layer resistance and improve free convection ([Schuepp 1993]; [ElAhmar 2016]).

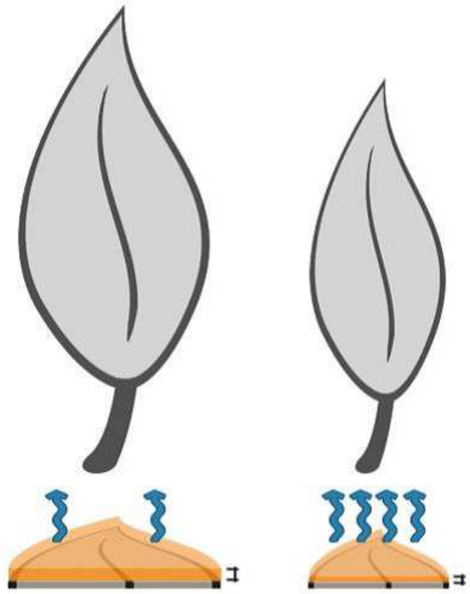

Figure 5.17: Smaller leaf size decreases the boundary layer resistance hence improving free convection [ElAhmar 2016]

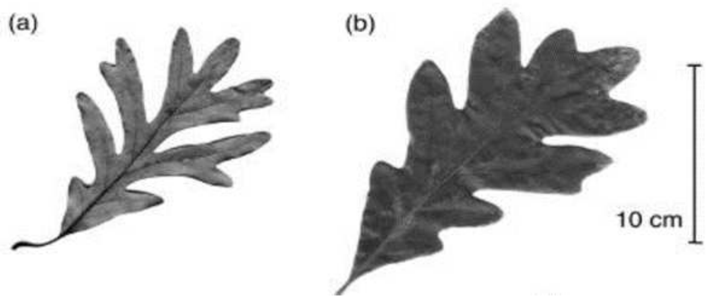

Figure 5.18: difference between a sun leaf (left) and a shade leaf (right) of white oak (Quercus alba). Sun leaf is smaller and more lobed [Vogel 2009]

El ahmar in [ElAhmar 2016] states that around 73% of leaves took the lobed form in winter, while in summer they were only 12% (Figure 5.19). A trick that un-dissected or un-lobed leaves have evolved by time to overcome excessive heat gains in the summer is producing phytochemicals, which lures certain types of insects to produce non-lethal holes in its blade. These holes permit buoyancy-driven convective airflow through the leaf rather than around it (Figure 5.20). Leaf tearing has also been observed in large leaves such in the banana (Musaceae) in hot environments as a similar protective mechanism [Schuepp 1993].

Figure 5.19: difference between a cordate leaf (left) and a lobed leaf (right). Lobes improve free convection [ElAhmar 2016]

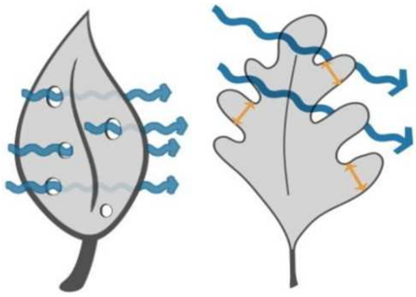

Figure 5.20: Holes (left) and lobes (right) in leaves decrease the distance to the closest edge and decrease the boundary layer resistance and improve free convection [ElAhmar 2016]

Another observation regarding the form of leaves is that some have evolved a folded form that enables young leaves to fit inside small buds [ElAhmar 2016]. This form allows self-shading and hence reduces heat gain. There are numerous folding patterns in plants [Patil 2007]; among the well-known is common beech (Fagus sylvaticus) as seen in Figure 5.21, and hornbeam (Carpinus betulus) leaves. The leaves have a central primary vein and secondary parallel veins arranged symmetrically about the main one [Kobayashi 1998]. This folding pattern is the inspirational source of a two-dimensional expandable array proposed by Miura (1980) for the design of a solar pattern, and is still inspiring researchers today [ElAhmar 2016].

Figure 5.21: Holes (left) and lobes (right) in leaves decrease the distance to the closest edge and decrease the boundary layer resistance and improve free convection [ElAhmar 2016]

c Orientation

The effects of changing orientation are usually seen in un-lobed leaves (Figure 5.22). They tend to avoid near-horizontal positions reduces incident radiation in addition to improving convection between the leaf blade and surrounding air [ElAhmar 2016]. Mangrove leaves are a good example where sun leaves are almost vertical while shade leaves are almost horizontal. Some leaves are capable of rotating throughout the day to adjust their position and reduce heat gain such as the Alibizzia (julibrissin) leaves [Vogel 2009].

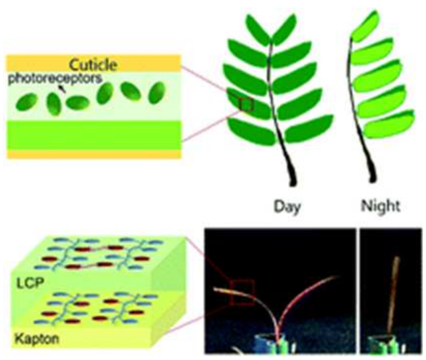

Figure 5.22: Alibizzia (julibrissin) leaves

d Leaf surface

Another way of reducing incident radiation is by decreasing absorptivity. Silvery and shiny leaves have around 20% less absorbance than others [Vogel 2009]. Thus, the presence of a waxy coating for reflection proves useful. Pubescence (leaf hair) as shown in Figure 5.23, has been observed as a feature of plants in arid climates, because they reduce the heat load of leaves by increasing the reflectance from the leaf surface, which reduces amount of radiation, absorbed [Ehleringer 1976]. Pubescence also affects the leaf boundary layer in different ways. Widely distributed hair decreases the effect of this layer's resistance, while dense hair traps the air and therefore the boundary layer thickens [Schuepp 1993]. Stomata distribution is another very important aspect that

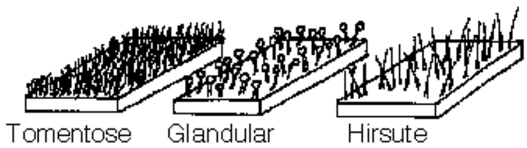

Figure 5.23: numerous possibilities of leaf pubescence [Wilson 2016]

leaves have evolved, since sun leaves general have more stomata per unit area than shade leaves [Vogel 2009]. Increased stomata mean better heat loss through transpiration. Figure 5.24 presents a Schematic cross-section through leaf indicating a reflective upper surface either by was or pubescence to minimize incident radiation. Stomata openings in the lower side are responsible for evaporative cooling.

e Venation system

According to [ElAhmar 2016], venation systems (Figure 5.25) have two main functions, which are transporting substances from one point to another with the least investment in energy and mass and sustaining the mechanical behavior and structural support of leaves ([Kull 1994]; [Nebelsick 2001]).

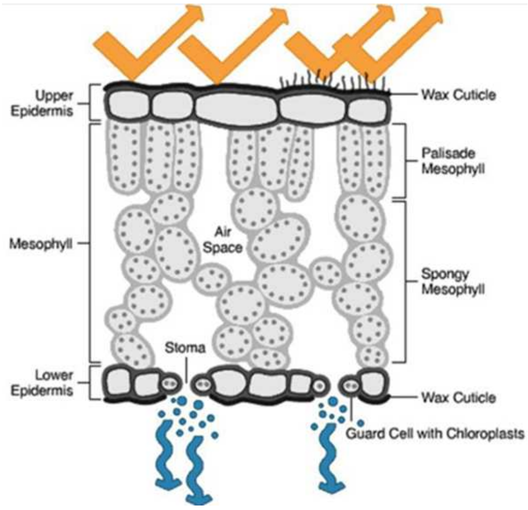

Figure 5.24: Schematic cross-section through leaf with Stomata openings [ElAhmar 2016]

Figure 5.25: Leaf venation system

Table 5.2.1.2 introduces a taxonomy that lists the most appropriate strategies found in plants that could be applied in the design of bio-kinetic building's skin in hot and arid regions and responding to the most critical functional requirements of envelopes. The selected pinnacles apply specific processes with a variety of factors to ensure the thermoregulation.

Chapter 6

PARAMETRIC EVALATION OF THE PROPOSED BIO-KINETIC SHADING DEVICE

" You never change things by fighting the existing reality. To change something, build a new model that makes the existing model obsolete."
- - Buckminster Fuller

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the average temperatures are low, with a temperature of 5.4 °C

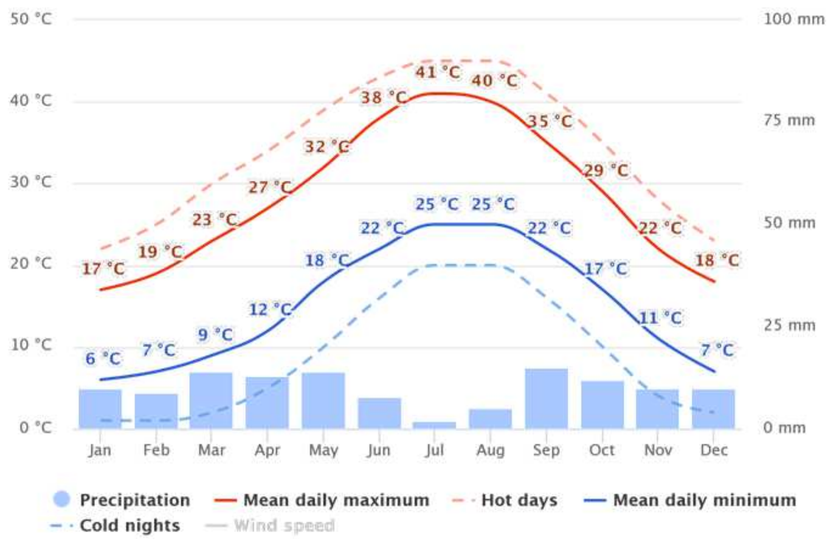

Figure 6.2: Average temperatures and precipitation

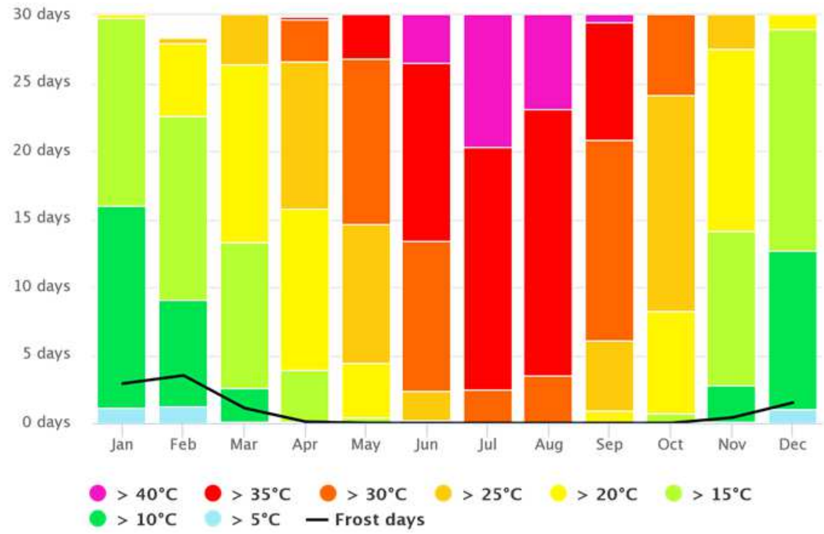

Figure 6.3: Maximum temperatures

The city of Biskra is characterized by very low relative humidity, this is due to the lack of water surfaces and the surrounding vegetation cover, on the other hand the effect of the oases around the city and the gardens remains insignificant to the effect of solar radiation and warm winds. The average relative humidity is 26.2% during the month of July, with a minimum average value of 16.78% recorded from April to August, it increases to reach the value of 76.7% in December with an average maximum of 70.1% in November.

According to the climate data, the prevailing winds come from the South and the Southwest during the summer and from the North, North-East, during the winter and the spring (season of the dusty winds). Average speeds vary from 3.9 to 6 m / s with an average of 4.4 m / s, the period of dusty winds is between March and May (Figure 6.4).

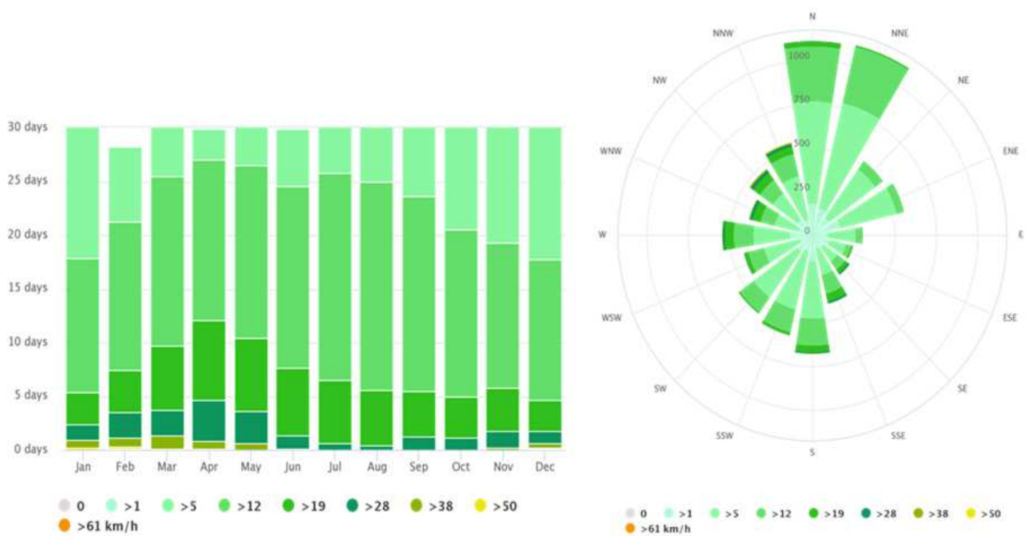

Figure 6.4: Wind speed and wind rose

Biskra receives very small amounts of precipitation (Figure 6.5)(Figure 5), with an annual average of 127.9 mm, because the Tell Atlas marks a barrier between north and south, opposes rainy clouds, which explains the scarcity of rainfall in this area. Climate analysis reveals that the climate of Biskra is very hard, especially in summer because of:

- Intense solar radiation,
- Very high temperatures,
- The scarcity of rains,

The climate of the region is hot and dry.

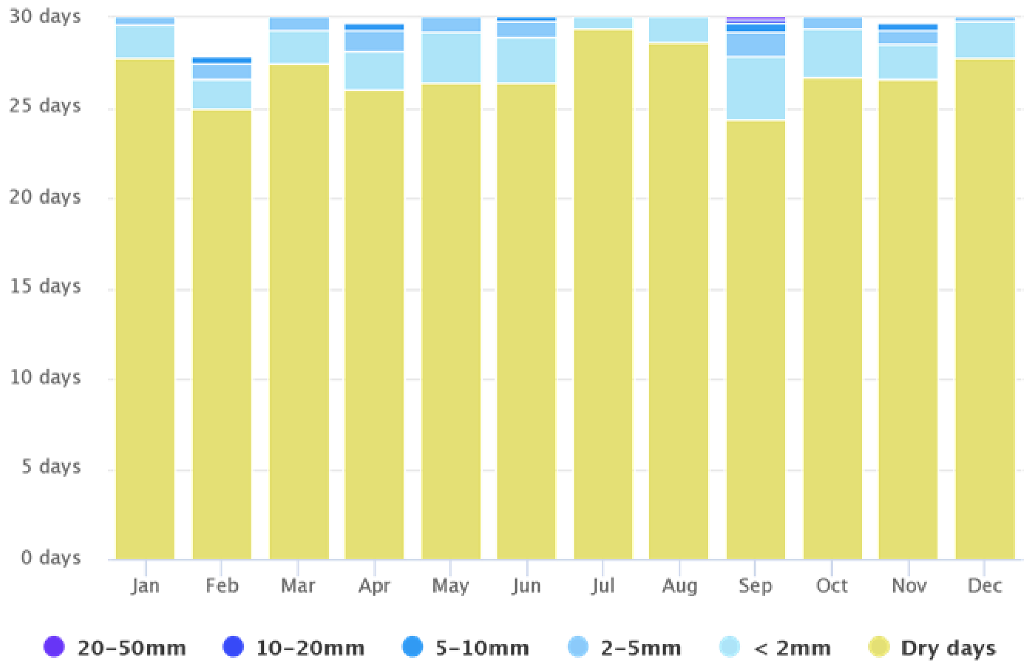

Figure 6.5: Precipitation amounts

Climate analysis reveal that the climate of Biskra is a harsh climate, characterized by a hot and dry summer with very intense solar radiation. For this, a bioclimatic analysis was carried out by applying the Mahoney tables and the Szokolay psychometric chart and using a powerful application in the bioclimatic analysis "Climate Consultant 5.5" which provides detailed and precise data on the local climate as well as the passive strategies that can be used during the sketching phase.

We can distinguish from the results obtained from the analysis of the psychometric diagram of the city of Biskra:

- 20.5% of the year in the comfort zone.
- 20.7% needs sun protection for different windows.
- 25.4% needs indirect evaporative cooling.
- 7.6% needs cooling with natural ventilation.
- 18.4% needs a high mass with direct passive solar gain

The bioclimatic analysis of the city of Biskra indicates that most of the year lies outside the thermal comfort zone (only 20.5% of the year is in comfort), and by the same analysis it was confirmed and concluded that the strategy of protection of solar radiation direct, is one of the most popular requirements to approach thermal comfort conditions and to minimize energy consumption in buildings in this region during the summer period.

6.2.3 DESIGN DAY SELECTION BASED ON PARETO MULTIOBJECTIVE OPTIMIZATION

Using "Meteonorm 7" software, we extracted a typical year data representing a decade (2009-2019), where the year 2015 presents the typical year for the city of Biskra and it is materialised with a specific format TMY3 weather file.

The design day is selected from the 365 days in 2015. The selected design day weather file consists of detailed data of 24 hourly values of climatic criteria parameters: temperature, solar radiation. These weather parameters have an influence on the energy and thermal performance of a building [Ishino 2005]. Besides acting as control criteria in the selection of a design day, these criteria offer clues for interventions to reduce discomfort in occupied zones.

The selection is based only on daily averages of temperature and solar radiation parameters, thus the selected day is the day having the maximum temperature (t) and the maximum solar radiation (in the hot period) and the minimum temperature (t) and the minimum solar radiation (in cold period). In this context, the problem is defined as research, from the research space (set of 365 days), the days d_1^* and d_2^* that make these two criteria in their maximum and minimum values, respectively. To optimize (maximize or minimize) simultaneously these criteria, the multiobjective optimization (MO) techniques are used in the problem of the design day selection.

In multiobjective optimization problems (MOP), we have two or more objective functions to be optimized at the same time, instead of having only one. Therefore, there is no unique solution to multiobjective optimization problems, but instead, we are aiming to find all of the good trade-off solutions available (the so-called Pareto optimal set). A solution xp is a Pareto optimal solution if no objective function can be improved without worsening at least one other objective function. Such solution is not unique, and the set of the Pareto optimal solutions are known as the Pareto front.

Several bio-inspired optimization techniques have been developed for MO problems, the most known is genetic algorithm (AG). The nondominated sorting genetic algorithm II "NSGA-II" [Deb 2002] is the most popular genetic algorithm for solving MOP.

The NSGA-II is a multi-objective optimization algorithm that tries to identify non-dominated solutions that represent different trade-offs between multiple objectives. It is a modified GA that simulates the natural selection procedure. In the classical GA, at

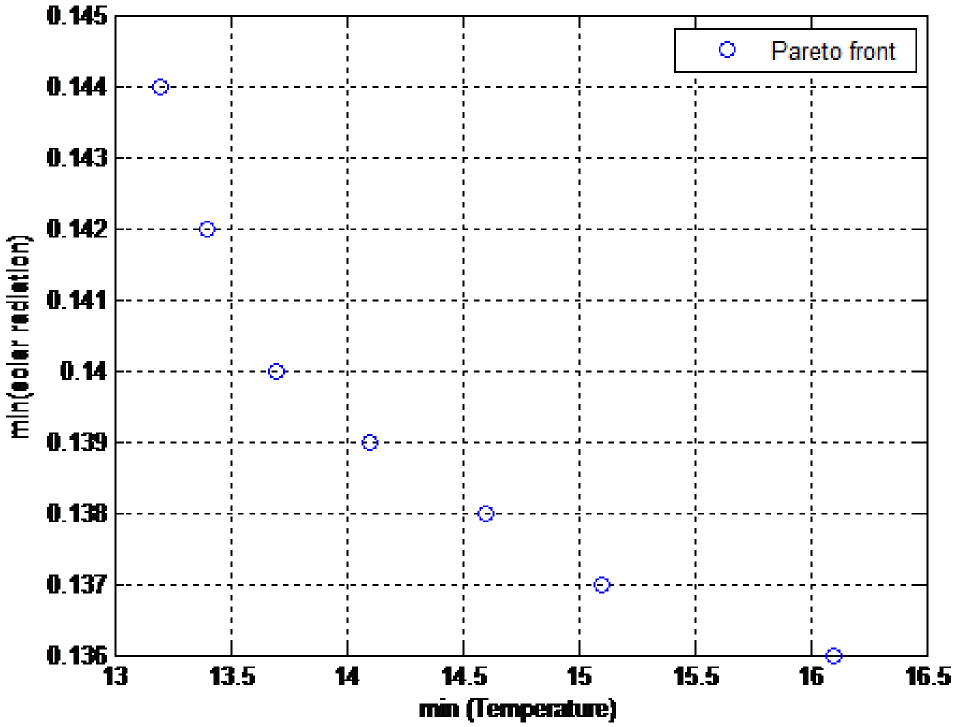

Figure 6.7: Pareto front found by NSGA-II, in the case of the minimization of two criteria: temperature (°C) solar radiation w/m^2 (Author)

The day (d_2^*)	1	2	3	4	5	6	7
	26Jan	13Dec	14Feb	31Jan	01Jan	25Dec	17Mar
Min Temperature $T°$(daily average)	13.2	13.7	15.1	14.1	13.4	14.6	16.1
Min Solar radiation w/m^2(daily average)	0.144	0.140	0.137	0.139	0.142	0.138	0.136

Table 6.2: set of the Pareto optimal solutions (in the case of the minimization of two criteria) (Author)

Based on our initial objectives, we select two design days from the set of the Pareto optimal solutions. The first design day "DD1" is 22nd July that represents the brightest (High solar radiation) and the hottest day. The second design day "DD2" is 1^{st} January, it represents the most overcast and the coldest day.

the proposal three patterns of contraction have been considered 25%, 50%, 75%.

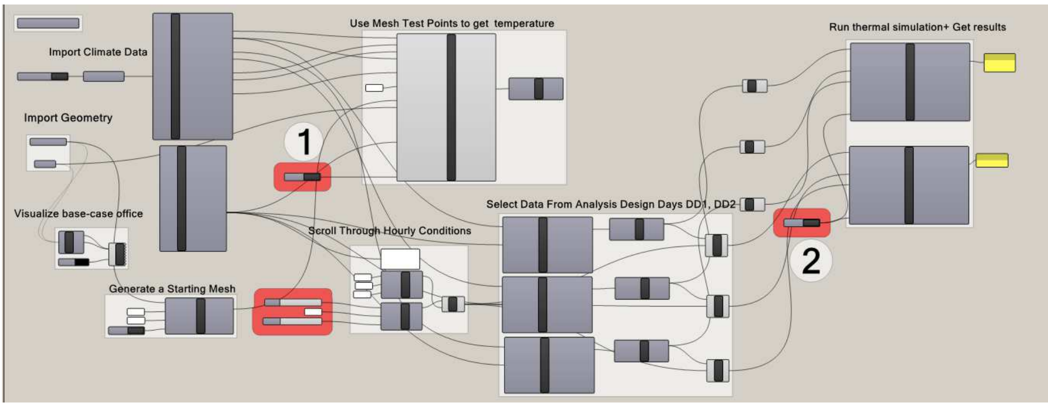

Figure 6.8: Parametric algorithm to analyze the thermal behavior (Author)

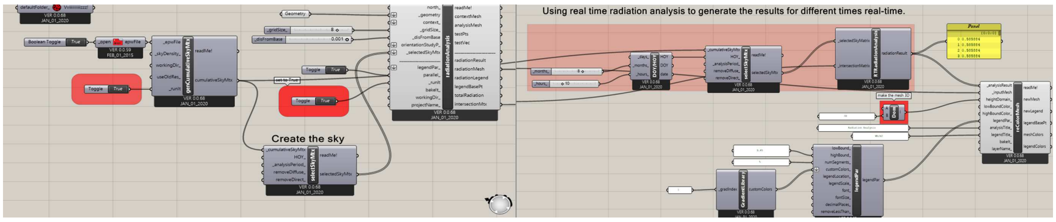

Figure 6.9: Parametric algorithm to analyze solar gains (Author)

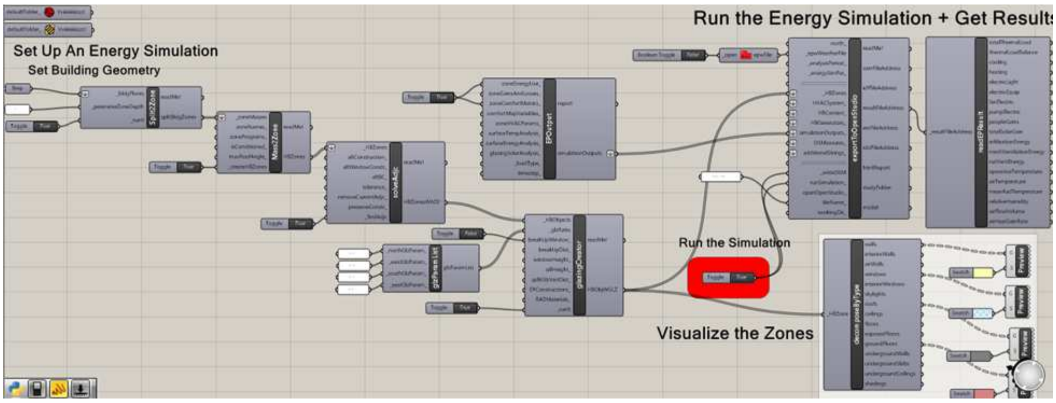

Figure 6.10: Parametric algorithm to analyze the energetic behavior (Author)

East orientation

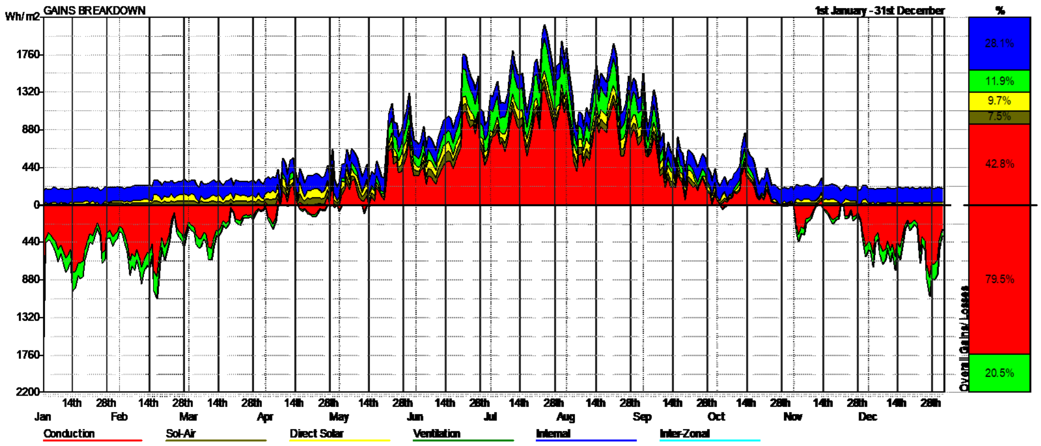

Figure 6.17: base-Case annual gains with without shading panel (glazing only)(Author)

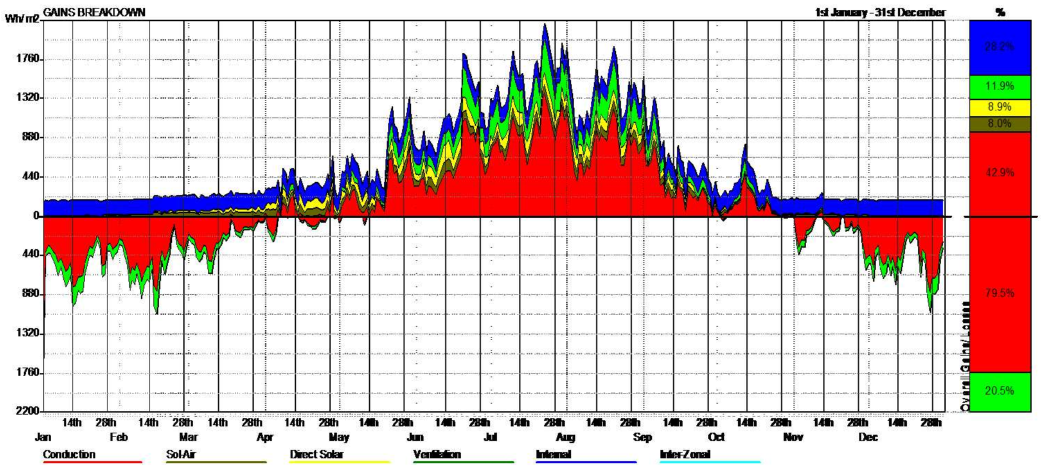

Figure 6.18: base-case annual gains with shading panel (partially opened 25%)(Author)

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RESEARCH ACTIVITIES:

Publication:

- S. Khelil, N. Zemmouri, 2018, BIOMIMETIC: A NEW STRATEGY FOR A PASSIVE SUSTAINABLE VENTILATIONSYSTEM DESIGN IN HOT AND ARID REGIONS. International Journal of Environmental Science and Technology. https://doi.org/10.1007/s13762-018-2168-y

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1. S. Khelil, A. Khelil, E. Cubukcu, A PARAMETRIC APPROACH TO OPTIMIZE THE ENVIRONMENTAL PERFORMANCE OF URBAN STREETS IN IZMIR, International Symposium of Architecture, Technology and Innovation (ATI), Izmir. (2020)
2. S. Khelil, A. Khelil, K. Korkmaz, N. Zemmouri, RAISING THE EFFICIENCY OF DEPLOYABLE BUILDING FACADES WITH BIOMIMETICS FOR HOT AND ARID REGIONS, International Symposium of Architecture, Technology and Innovation (ATI), Izmir. (2020)
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RÉSUMÉ

L'enveloppe du bâtiment joue un rôle important dans l'efficacité énergétique du bâtiment, en particulier dans les économies et la consommation d'énergie. Les concepteurs doivent prendre en compte de nombreux problèmes lors de la conception de l'enveloppe du bâtiment, pour éviter de gaspiller de grandes quantités d'énergie et pour maintenir le confort à l'intérieur, en particulier dans les régions chaudes et arides où l'intégration de systèmes de protection solaire est fortement recommandée. Cette thèse aborde le problème de la conception de l'enveloppe de bâtiments économes en énergie dans le contexte de climats chauds comme celui de la ville de Biskra.

A travers cette recherche, on vise à évaluer l'introduction de la paramétrisation dans le design de l'enveloppe des bâtiments comme une stratégie précieuse pour réduire la consommation d'énergie et améliorer le confort thermique intérieur dans ce climat. Cette étude tente de définir et d'appliquer une méthodologie de conception biomimétique-computationnelle pour étudier et analyser les organismes naturels en termes de leur comportement en matière de thermorégulation. En outre, la recherche présente une taxonomie biomimétique explorée et analysée afin de servir de mini-banque de données pour les architectes ou les concepteurs intéressés par cette approche de conception afin résoudre les problèmes de thermorégulation.

Les éléments d'ombrage bio-cinétique et Paramétrés sont développés pour une application ultérieure dans une enveloppe de bâtiment en explorant et en extrayant les mécanismes de thermorégulation trouvés dans la nature. Cette recherche est insérée dans la typologie de la technique générative des structures déployables, où nous avons combiné le biomimétisme avec l'origami basé sur une méthodologie paramétrique pour concevoir un dispositif d'ombrage adaptatif interagissant avec la lumière du soleil.

L'enveloppe du bâtiment est conçue de manière paramétrique à l'aide du langage de programmation visuelle Grasshopper pour Rhino 3D Modeller.
Afin d'évaluer la performance de la proposition en termes d'efficacité énergétique et de confort thermique tout au long des design days sélectionnés, on l'applique à la façade d'un bureau à Biskra qui sert à un cas de référence. Les résultats d'expérimentation sont prometteurs et montrent l'avantage de la proposition. L'objectif principal visé dans cette thèse est atteint avec succès. Les résultats montrent que l'utilisation de la paramétrisation de l'enveloppe du bâtiment et les inspirations biomimétiques représentées dans la morphologie cinétique de l'origami rigide sont importantes pour réduire la température et la consommation d'énergie. La méthodologie utilisée peut générer des concepts de design avec un défi initial défini par le concepteur. De plus, cette étude ouvre de nouvelles perspectives pour de nouvelles solutions possibles pour l'enveloppe du bâtiment afin de développer une base fonctionnelle en architecture : biomimétique, cinétique, orientée par le climat et soucieuse de l'environnement.

Mots clés: Architecture Cinétique, Biomimétisme, Conception Paramétrique, Design Day, Efficacité Energétique, Enveloppe Du Bâtiment, Régions Chaudes Et Arides, Optimisation, Thermorégulation.

ملخص

تلعب واجهة المبنى دورًا مهمًا في كفاءة الطاقة في المبنى، خاصةً من ناحية توفير الطاقة أو استهلاكها. يحتاج المصممون إلى مراعاة العديد من المشكلات عند تصميم واجهة المبنى، لتجنب إهدار كميات كبيرة من الطاقة والحفاظ على الراحة الداخلية خاصة في المناطق الحارة حيث يوصى بشدة بدمج أنظمة الحماية الشمسية. تتناول هذه الرسالة مشكلة تصميم واجهات المباني الموفرة للطاقة في سياق المناخات الحارة مثل مدينة بسكرة. يحاول البحث تحديد وتطبيق منهجية تصميم المحاكاة المستوحاة من الطبيعة -الحاسوبية لدراسة وتحليل الكائنات الطبيعية من حيث سلوكها فيما يتعلق بالتنظيم الحراري. علاوة على ذلك، يقدم البحث تصنيفًا مجمّعًا لأفكار المحاكاة المستوحاة من الطبيعة التي تم استكشافها وتحليلها من أجل توفير بنك بيانات للمهندسين المعماريين أو المصممين المهتمين بنهج التصميم هذا في معالجة مشاكل التنظيم الحراري .

تم اقتراح عناصر التظليل الحركية مستوحاة من الطبيعة للتطبيق في واجهة المبنى من خلال استكشاف واستخراج آليات التنظيم الحراري الموجودة في الطبيعة. يتم إدراج هذا البحث في تصنيف التقنية التوليدية للهياكل القابلة للنشر، حيث قمنا بدمج المحاكاة المستوحاة من الطبيعة مع الطي الورقي بناءً على منهجية معلمية لتصميم جهاز تظليل متكيف يتفاعل مع ضوء الشمس. تم تصميم واجهة المبنى بشكل أساسي باستخدام لغة البرمجة المرئية **Grasshopper** لـ**Modeller3D Rhino**.

من أجل تقييم أداء الاقتراح من حيث كفاءة الطاقة والراحة الحرارية طوال أيام التصميم المختارة، تتم مقارنته بأداء واجهة مكتب في بسكرة بصفته حالة مرجعية. تظهر نتائج التجارب الواعدة ميزة الاقتراح حيث تظهر النتائج أن الإلهامات المستوحاة من الطبيعة الممثلة في مورفولوجيا الأوريغامي الصلبة الحركية مهمة في تقليل درجة الحرارة واستهلاك الطاقة. تم تحقيق الهدف الرئيسي المقصود في هذه الأطروحة بنجاح. يمكن للمنهجية المستخدمة توليد مفاهيم تصميم جديدة. بالإضافة إلى ذلك، يفتح هذا التصميم وجهات نظر جديدة للحلول الممكنة لواجهة المبنى من أجل تطوير أساس وظيفي في الهندسة المعمارية: المحاكاة المستوحاة من الطبيعة، الحركية، التصميم الموجه مناخيًا والوعي البيئي.

الكلمات المفتاحية: واجهة المبنى، محاكاة الطبيعة، كفاءة الطاقة، يوم التصميم، المناطق الحارة والجافة، العمارة الحركية، التحسين، تصميم المعلمات، التنظيم الحراري.