Intelligent and Adaptive Façade System: The Impact of Intelligent and Adaptive Façade on The Performance and Energy Efficiency of Buildings

Mohanned M. Al Thobaiti

University of Miami, m.thobaiti@gmail.com

Follow this and additional works at: http://scholarlyrepository.miami.edu/oa_theses

Recommended Citation
UNIVERSITY OF MIAMI

INTELLIGENT AND ADAPTIVE FAÇADE SYSTEM: THE IMPACT OF INTELLIGENT AND ADAPTIVE FAÇADE ON THE PERFORMANCE AND ENERGY EFFICIENCY OF BUILDINGS

By

Mohanned Al Thobaiti

A THESIS

Submitted to the Faculty of the University of Miami in partial fulfillment of the requirements for the degree of Master of Science in Architecture

Coral Gables, Florida

August 2014
UNIVERSITY OF MIAMI

A thesis submitted in partial fulfillment of
the requirements for the degree of
Master of Science in Architecture

INTELLIGENT AND ADAPTIVE FAÇADE SYSTEM:
THE IMPACT OF INTELLIGENT AND ADAPTIVE FAÇADE ON THE
PERFORMANCE AND ENERGY EFFICIENCY OF BUILDINGS

Mohanned Al Thobaiti

Approved:

John Onyango, Ph.D.                                         Jean-Francois Lejeune
Assistant Professor of Architecture                           Professor of Architecture and
                                                          Director of Graduate Studies

Juhong Park, Ph.D.                                         M. Brian Blake, Ph.D.
Assistant Professor of Architecture                           Dean of the Graduate School

Esbar Andiroglu
Adjunct Lecturer of Engineering
President of Energy Sciences, Inc.
The integration of nature and technology always represents a rich combination of developed and innovative elements to serve the environment. Building performance depends not only on the operation of individual elements in the building but also on how they behave as integrated systems to satisfy the user demands. In architecture, usually projects are consist of different stages of design process, and several factors need to be considered among this cycle, such as climate, building shape, comfort levels, materials and systems, occupant health and security. Therefore, advanced technologies became a significant discourse that caught the interest of many professional fields. The building envelope is particularly important, as it is the starting point of energy efficiency measures, and the main determinant of the amount of energy required for heating, cooling and ventilation. In order to be able to deal with the different energy saving alternatives, a strong foundation of knowledge need to be addressed to the architects and engineers. Hence, understanding the nature of a specific system in the ecosystem can provide us with intelligent solutions that could fulfill the multipurpose functions.

The study focuses on the dynamic kinetics and adaptive facades system, and its impact on the quality of the interior environment, as well as the whole building energy efficiency and performance in the warm humid climate. Investigation was carried through fabric
gain energy modeled box of 4ft x 4ft x 4ft in Autodesk ecotect, and for various dynamic shading devices (horizontal, vertical, and grid) for a south facing façade. Also, Physical models experiments with the same settings were conducted as part of this study to validate the outcomes from the simulation runs. In the first case analysis, representations have shown for HVAC energy consumption and temperature changing average during a course of a day – hourly basis – with overall KWh consumption for each hour on June 19\textsuperscript{th} – 20\textsuperscript{th}. The outcomes revealed that the use of smart shading comparing the to the non-shaded condition results in energy saving of about 34\% – 40\%. 

ACKNOWLEDGEMENTS

I would never have been able to finish my thesis without the guidance of my committee members, help from friends, and support from my family and wife.

My experience at University of Miami has been nothing short of amazing. Since my first day at UM, I have been given unique opportunities and taken advantage of them. Throughout two years, I have learned that there are those who build tools and those who use them; my passion is in creating the tools used in cutting edge research. This thesis presents the lessons learned in creating one of those special tools: Intelligent Façade System. This research is the result of support by many people, who I wish to thank. But this thesis is also the result of many experiences I have encountered at UM and at King Saud University before.

I would like to express my deepest gratitude to my advisor, professor John Onyango, for his excellent guidance, caring, patience, and providing me with an excellent atmosphere for doing research. I would like to thank him for letting me experience the research of Intelligent Façade system in the field and practical issues beyond the textbooks, and patiently corrected my writing. Ever since, Onyango has supported me not only by providing a research assistantship, but also academically and emotionally through the rough road to finish this thesis.

I would like to thank Professor Juhaog Park for his willing to help and give his best suggestions in creating the study models. Many thanks also to Adrián Alfonso the manager of the model shop for helping me collect the materials and tools for building the study models. My research would not have been possible without their helps.
I would also like to thank my parents, and five siblings. They have always been supporting me and encouraging me with their best wishes. During the most difficult times when working with this study, they gave me the moral support I needed to move on.

Finally, I would like to thank my wife, Maha. She has been a source of love and energy ever since, and she has always been there cheering me up and stood by me through the good times and bad.
# TABLE OF CONTENTS

**LIST OF FIGURES** .......................................................................................................................... viii  
**LIST OF TABLES** ........................................................................................................................... x  

**Chapter 1** INTRODUCTION .............................................................................................................. 1  
1.1 Overview ........................................................................................................................................ 1  
1.2 Research Problem ............................................................................................................................ 1  
1.3 Research Analysis ............................................................................................................................ 4  
1.4 Design Components .......................................................................................................................... 4  
1.5 Responsive and Dynamic Facades in Gulf Region ......................................................................... 6  
1.5.1 Dynamic Control Systems ......................................................................................................... 6  
1.6 Aims of the Research ....................................................................................................................... 7  
1.7 Objectives of the Research .............................................................................................................. 7  

**Chapter 2** Investigation .................................................................................................................... 10  
2.1 Overview ........................................................................................................................................ 10  
2.2 Adaptation ...................................................................................................................................... 11  
2.3 Biological Pattern ............................................................................................................................ 12  
2.4 Biomimetic ..................................................................................................................................... 14  
2.5 Benefits of Studying the Natural Patterns ....................................................................................... 16  
2.6 Dynamic System ............................................................................................................................. 17  

**Chapter 3** Intelligent-Adaptive Façade .............................................................................................. 21  
3.1 Overview ........................................................................................................................................ 21  
3.2 Intelligence in Architecture ............................................................................................................. 21  
3.3 Basic Principle of Adaptive Skin ..................................................................................................... 25  
3.4 Performance of Intelligent Kinetics Facade ................................................................................. 27  
3.5 Typology of Kinetics in Architecture ............................................................................................. 29  
3.6 Modeling Intelligent Kinetics ......................................................................................................... 30  

**Chapter 4** Low-Energy Buildings .................................................................................................... 32  
4.1 Overview ........................................................................................................................................ 32  
4.2 Energy Efficiency Features ............................................................................................................. 34  
4.3 Energy Efficiency Initiatives ........................................................................................................... 34  
4.4 Climate Change Issues .................................................................................................................... 36  
4.5 Solar Energy and Selective Surfaces ............................................................................................... 37
4.6 Solar Gain Processes at Glazing ................................................. 38
4.7 Sun Path Diagram ..................................................................... 40
4.8 Concept of Daylight Deflection .................................................. 44
4.9 Solar Shading Design ................................................................. 45
4.10 Consequences on Building Energy Efficiency ......................... 46

Chapter 5 Design Tools and Methods ............................................. 48
5.1 Overview ................................................................................. 48
5.2 Design Components ............................................................... 48
5.3 Simulation for Kinetic Response ............................................... 49
5.4 Simulation Method .................................................................. 52
  5.4.1 Simulation Conditions ....................................................... 52
5.5 Simulation Parameters ............................................................ 54
5.6 Visualization of Some Simulated Schemes ............................... 58

Chapter 6 DATA ANALYSIS METHOD Diagrams and Charts .......... 60
6.1 Overview ................................................................................. 60
6.2 Kinetic Scenario Compilation Method ...................................... 60
6.3 Dynamic Simulation Analysis .................................................. 61
  6.3.1 Horizontal Louvers .......................................................... 62
  6.3.2 Vertical Louvers ............................................................... 65
  6.3.3 COMBINED CONFIGURATION Horizontal and Vertical .... 68
6.4 Kinetic Scenario for Actuation Pattern ..................................... 70
6.5 Validity of Simulation Results for Design Decision Making .... 72
6.6 Physical Scale Models Versus Dynamic Simulation Models .... 73
6.7 Physical Model Experiments Analysis ...................................... 74
  6.7.1 Horizontal Louvers .......................................................... 75
  6.7.2 Vertical Louvers ............................................................... 76
6.8 Kinetic Scenario for Actuation Pattern ..................................... 78
6.9 Experiments Conclusion ......................................................... 79
6.10 Analysis Conclusion ............................................................... 80

Chapter 7 CONCLUSION AND FUTURE WORK .......................... 83
7.1 Conclusion .............................................................................. 83
7.2 Scope and Limitations ............................................................. 85
7.3 Future Work ........................................................................... 86
  7.3.1 Occupants' Behavior ......................................................... 86
LIST OF FIGURES

Figure 1-1: The energy consumption by sectors in Saudi Arabia ........................................ 3
Figure 2-1: The intelligence of human skin ................................................................. 13
Figure 2-2: Bird’s wing ......................................................................................... 16
Figure 2-3: Pentagram of the functional architectural process .............................. 19
Figure 3-1: The process of the adaptive feature through the intelligent façade. ... 23
Figure 3-2: The definition of the intelligent building qualities .............................. 24
Figure 3-3: External view of Mashrabiya ............................................................. 26
Figure 3-4: Panel for Mashrabiya ..................................................................... 26
Figure 4-1: The annual energy consumption in Saudi Arabia ............................. 33
Figure 4-2: The average temperature for Riyadh ............................................. 37
Figure 4-3: Visualization of solar radiations ...................................................... 39
Figure 4-4: Visualization of solar radiations ...................................................... 40
Figure 4-5: The sun path diagram for Miami ..................................................... 41
Figure 4-6: The sun path diagram for the city of Riyadh .................................. 42
Figure 4-7: The annual sun path diagram for Miami ......................................... 43
Figure 4-8: The experimental model for the study ......................................... 44
Figure 4-9: Visualization for louver geometry ............................................... 46
Figure 4-10: Without ventilation ..................................................................... 47
Figure 4-11: With ventilation .......................................................................... 47
Figure 5-1: Visualization for the horizontal louvers ....................................... 51
Figure 5-2: Visualization for the vertical louvers .......................................... 51
Figure 5-3: The dimensions of the space used in the simulation .................... 53
Figure 5-4: Solar angles..................................................................................................................56
Figure 6-1: Illustration for the non-shaded KWh consumption ...............................................62
Figure 6-2: Visualization for the Horizontal louvers ............................................................63
Figure 6-3: Representation of all Horizontal tilt angles. ....................................................64
Figure 6-4: Comparison between the Horizontal and the Non-Shaded..............................65
Figure 6-5: Visualization for the Vertical louvers.................................................................66
Figure 6-6: Representation of all Vertical tilt angles. ..........................................................67
Figure 6-7: Comparison between the Vertical and the Non-Shaded.................................68
Figure 6-8: Visualization for the combined (grid) louvers...................................................69
Figure 6-9: Comparison between the combined (grid) and the Non-Shaded......................70
Figure 6-10: Comparison between all conditions KWh consumption. ..................................71
Figure 6-11: The experimental models...................................................................................73
Figure 6-12: Kill A Watt – Data logger...................................................................................75
Figure 6-13: Comparison between the Horizontal and the Non-Shaded............................76
Figure 6-14: Comparison between the Vertical and the Non-Shaded.................................77
Figure 6-15: Comparison between the combined (grid) and the Non-Shaded....................78
Figure 6-16: Comparison between all conditions.................................................................79
LIST OF TABLES

Table 5-1: Tilt angle combinations those used for all simulation runs. ..........................57
Table 6-1: The non-shaded KWh consumption in the simulation runs.........................61
Table 6-2: The performance of all dynamic configurations........................................71
Table 6-3: The performance of all dynamic configurations........................................80
Table 6-4: The results of all dynamic configurations performance..............................81
CHAPTER 1 INTRODUCTION

1.1 Overview

Sustainable and green technologies in the building industry are in an ongoing explosive development. These technologies are basically going toward practical application and production; as a result, a need for creating critical examination has arisen to infuse these technologies into the present system. However, there is a futuristic structures danger that architects and engineers create under the name of efficiency. A question then arises, how do we incorporate the diversity of innovative products that successfully archive both engineering goals and aesthetic aspects into a building’s systems? Basically, in building design the fundamental strategy begins by identification of the extensive array of requirements, then unify them to form multifunctional elements in order to create buildings that provide protected and comfortable environment to satisfy its human occupants. One of the main purposes of all new technological developments is to provide better living and working conditions for the users. Also, to avoid that feeling like we are walking into a machine. These technologies and building solutions in particular need to be humanized and interpreted to a well-designed space considering all our human senses. Ultimately, the technology should be critically examined when it is applied to a building to ensure that it complies with its objectives as well as the human comfort.

1.2 Research Problem

There is a high level of energy consumption and subsequent severe environmental problems in some developing regions such as in the Middle East that has the second largest energy use intensity level in the world (World Energy Council, 2012). Fossil fuels
that produced from building is accounted for most of the energy consumption in the region, which causes considerable amounts of greenhouse gas (GHG) emissions, and, indeed, buildings account for almost 40% of final energy consumption and related GHG emissions in most countries. However, in Saudi Arabia (where the study was initially geared toward) the situation is even worst, this number goes much higher and reaches almost 80% of the total energy consumption. Moreover, during the period of 1971-2004, residential buildings in Middle East accounted for the second largest regional producer of CO₂ emissions (Bahrami, 2008).

Therefore, because of the emerging need for finding innovative and proper solutions, this study came to investigate the most efficient technological solutions for buildings in warm climates of Middle East countries, especially in Saudi Arabia, and hot humid climatic region of South Florida. The research literature review revealed that buildings in gulf countries have high levels of energy consumption and related emissions particularly in residential and commercial sectors. Referring to the Saudi Energy Efficiency Center (SEEC), the residential and commercial sectors account for about 80% of the total final energy consumption, and these sectors are also the largest contributor of CO₂ emissions (Figure 1-1).
Building owners can avoid the hazards of this energy distraction, and capitalize on opportunities by investing in energy efficiency measures. Examples are lighting, building envelope construction, and/or air conditioning, all of which of these building components can optimize the building performance and the overall energy cost. A lot of research has shown good results in term of energy and greenhouse gas savings that if energy efficiency techniques have been taken into consideration on buildings. As a result, the economic and efficient outcomes of these implementations will determine which technology is the best fit to be chosen and to what extent the investments are undertaken.

When technology is integrated with nature, it would always result in productions that remarkable and intelligent, dynamic, and of course, more efficient product. One of the most innovative and highly efficient technologies nowadays is the intelligent envelope shading system, when, in some cases, the system works in response to the varying environmental conditions. This thesis is an investigation on the responsive and dynamic facade system and its impact on the quality of the interior environment in addition to
information on energy efficiency in buildings and climate change. This research represents an investigation about utilizing intelligent and dynamic shading system to optimize the building energy performance in office buildings. It will be carried out through analyzing results from dynamic energy simulation and experimental work on models built at University of Miami during the month of June 2014.

1.3 Research Analysis

Building energy consumption can be reduced by range of improvements that can be implemented to the building envelope. These, for example, include enhanced designs, advanced construction methods, improved insulation, and inspection techniques aimed at achieving envelopes with high R-values. Therefore, high-performance facades with developed techniques and equipments allow daylighting to reach inside the space while minimizing any extra cooling/heating loads. In addition, results in tighter envelope design and structure, which causes reductions in air infiltration. Moreover, the use of smart architectural objects on the skin, would scatter and reflect UV, enhance visibility, and reduce solar gain and radiation or minimize unwanted heat loss to the night sky.

Accordingly, any improvements to the building envelope must take into consideration the potential undesired consequences in both durability and indoor environmental quality, which will eventually enhance occupants’ comfort and survive our globe.

1.4 Design Components

Almost all projects pass through different design stages, and many factors need to be taken into account during those phases, such as the local climate, building shape, comfort levels, materials and systems, occupant health, and security. Building performance
depends not only on the performance of individual elements, but also on how they perform as integrated systems and users behavior.

The building envelope particularly is very important as it is the starting point of energy efficiency standards. Also it is the main determinant of the amount of energy required for heating/cooling and ventilation. Specifically, it defines how much heat is transmitted through “thermal bridges” (which breaches insulation and allow heat to flow in or out) and how much natural light and ventilation can be used (Larsen et al, 2011).

Currently, the sector of energy saving is in growing cycle, and existing technologies are rapidly changing, and that refers to the extensive research and development. As a result, architects and engineers must be knowledgeable and aware to make holistic distinction between the energy saving alternatives to assess different sustainable strategies. The main goal should be to rationally integrate and express these systems to produce more efficient products. Oftentimes, the nature of a particular system or technique could lead to solutions that are more intelligent and mutually satisfy multipurpose functions. For example, the energy-collecting devices can lend themselves to serve more than one purposes; they can collect both electrical and thermal energy (PVT), and work on an insulating envelope that can both heat gain/lose into the interior. This approach applies also on the intelligent envelop of the building. Therefore, the technology of dynamic and smart façades can be engineered with features that serve as a sunshade, light shelf, a façade treatment, a water harvester, or a wind diverter (Dyson et al, 2011). Most importantly, this approach of doing several things at once will not necessarily end with poor result as the expense of doing one thing. In fact, the main objective of the
multifunctional and intelligent solutions is to not compromise the individual functions, and the final solution should be better than the sum of the parts.

1.5 Responsive and Dynamic Facades in Gulf Region

As mentioned previously, intelligent shading systems are featured of having visual and thermal properties that can be dynamically changed in response to exterior climatic conditions, occupant preferences, and the requirement of the building energy management system. Thus, it could be used to reduce peak electric energy loads by 20-30% in commercial buildings and increase daylighting benefits, as well as improving indoor comfort, which potentially enhances the productivity of the overall buildings performance (Dyson et al, 2011). These technologies work to manage the demand of energy use in building and provide maximum flexibility in the performance. Therefore, buildings’ utility will be used to help the community’s goal of producing more efficient and advanced building performance with minimal impact on the environment and energy resources. Ultimately, this flexibility will enhance the users’ decision and independency to dynamically control envelope possibilities for heating/cooling loads and lighting loads to fit their own comfort.

1.5.1 Dynamic Control Systems

Dynamic control system is an automated system that provides industrial solutions for some time to convey the actuated and responsive reactions to passive processes. Applying such a technology to a buildings’ façade and integrate it with intelligent features will develop an adaptive system that transmit a higher level of performance while reducing the negative impact of the environmental conditions and the consumption
resources (Dyson et al., 2011). As a consequence, designing any façade system should take advantage of all surrounding conditions and resources to develop intelligent techniques that observe occupants’ behavior and achieve a performative envelope that enhances energy efficiency, adaptivity, and aesthetics.

In general, from the perspective of awareness context, adaptive façade implies that the intelligent objects and components will be featured with enhanced abilities to communicate and interact with environmental conditions and user behavior, and respond to changes in external climatic circumstances. Therefore, the situational information can provide the users with applications to accomplish its process and adjust its functions.

1.6 Aims of the Research

The primary goal of this study is to investigate the effect of a state-of-the-art technology on the operational energy use of buildings through using dynamic blinds as a secondary skin. This will be carried out through dynamic simulation using Autodesk Ecotect and validated with experimental physical models. The research could provide designers with informative decisions on their approaches to meet the design goals for energy efficiency, productivity, and sustainability.

1.7 Objectives of the Research

As previously mentioned, buildings are responsible for approximately 80% of total energy use in Saudi Arabia, and as the construction sector is booming, the absolute figure rising rapidly. Thus, it is crucial to act sooner, since buildings can make a major
contribution to solve the issues of the climate change and reduction in energy use and CO₂ emissions.

This can be done immediately because there is adequate knowledge and technologies that help to cut down the buildings’ energy use and increase the level of comfort at the same time. However, there are barriers that prevent us from start doing any immediate action, such as financial, organizational, and lack of perception, so there are three approaches can help to overcome them:

- Reduce the energy consumption in buildings through using new and more efficient technologies.
- Encourage people and stakeholders in adopting integrated approaches that promise to sherd responsibility and liability toward better building performance and more sustainable to their communities.
- Encourage the behaviors of building users and professionals by educate and motivate them so they can respond to the market opportunities and increase the potential of the existing technology.

Therefore, the objective of this study came to investigate the potential overcome through implementing an intelligent system as a secondary skin on buildings, and as a part of this thesis that was done by the following:

1. Model a unit box to determine its operational energy use in Miami, Florida.
2. Use the model to simulate the air conditioning energy use of the box without any shading settings.
3. Use the model to simulate the air conditioning energy use of the box with
static louvers configuration.

4. Use the model to simulate the air conditioning energy use of the box with
dynamic louvers configuration.

5. Compare and analyze the results of (4) with (2) and (3) and draw the
conclusions.

As a result, the hypothesis is if the dynamic louvers are applied to a building envelope,
then there will be a noticeable reduction in energy use in comparison to the non-shaded
and static configuration.
CHAPTER 2 INVESTIGATION

Delivering building with intelligent features is a discourse taking place in the profession. Oftentimes, nature provides us with smart solutions that help to overcome some of the serious issues that the environment is experiencing. This chapter will present a background research into adaptation approach along with the biological paradigm in architecture.

2.1 Overview

This section provides a complete literature review of the investigated topic and its attributes. Given the investigation of two related topics, (1) the biological paradigm; the approach of biomimetic and mimicking nature for architectural benefits, and (2) intelligent-adaptive skins. The literature review of both topics addresses the definition of intelligence adaptation within the framework of the study, the use of intelligent skins as shading component, the performance of smart shading in reducing the energy use and enhancing the quality and quantity of light in office spaces.

Before proceeding further, some points need to be covered in order to express the correlation between intelligent skins and shading enhancement. The context of each point is directly related to the intelligence and adaptation of a building skin and its ability to respond to environmental changes. Therefore, providing a solid background to the following points creates a strong foundation for explaining shading enhancement through the use of intelligent systems:
• The adaptation approach.
• The biomimetic inspirations.
• What is intelligence?
• The concept of intelligent-adaptive systems.
• Intelligence and environmental controls.

2.2 Adaptation

In contemporary architecture, one of the significant and concerning studies are that research involves dealing with surfaces (Picon, 2010). Therefore, designing components that can be assembled to create skin geometry that is responsive to certain environmental conditions, and attached to building’s façade is a primary interest in building sustainable and adaptive architecture. Adaptive systems, or in other word “kinetic system” are engaged in the surface generation scheme and are most likely connected to inextricably digital architecture and computational fabrication design. The feature of these systems consists of three-dimensional layers to operate the two-dimensional skin elements. These operational components are embedded in the skin and attached to the material system used. On the other hand, the conventional design embodies the skin systems and the standard materials with the regular operations, where the materials selection is limited to the response condition, and its properties are fixed (Maragkoudaki, 2013).

The skin does not necessarily perform multifunctional program, yet it works according to the natural properties of the material, and hence it is possible for the skin to perform only one type of response per system, such as shading or ventilation. Exploration of these solutions results from the ongoing need for more environmentally viable solutions caused
by the transfer of the heating and ventilation regulation once controlled by centralized systems. Therefore, innovative and intelligent research is been conducted, based on biological and technical forms, to provide the external layer of the building with evolitional solutions.

2.3 Biological Pattern

Man is in ongoing challenge lifecycle with nature and is always attempting to accomplish the best state of living. In addition, he is consistently trying to learn and discover Mother Nature throughout the history, as well as perceiving and gaining new experience, which assist in achieving better and efficient state of life. Humans have acquired knowledge by observing nature and transmitted the outcomes to the benefit of several science applications, which helps to enhance the environment and behaviors in more efficient and effective way. This is because nature is always the best reference for solving problems we face in our life, and any structure that has been built based on natural fundamental is most likely have high standard of efficiency.

Basically, the integration between man-made systems and natural systems is essential to create an optimal and effective structure, and nature can be the best source for ideal designs and approaches. In the meantime, architecture and biology are capable of using information from the nature to build structures that are more bonded to the nature, which shows the possibility of designing and create buildings that are well suited for the main purpose of the design (Maragkoudaki, 2013). It is therefore possible to look at nature and mimic its principles to develop a dynamic envelope shading system and improve the level of comfort for users as well as more friendly with the environment.
Studying living organisms has inspired scientists and engineers by not only their design morphology, but also their structure principles. As a result, instead of being interested in the building structure only, these researchers that involve natural intelligence have taken the interest to the building’s skin. Accordingly, the goal is to implement the principles that have been found in the nature on buildings components to upgrade a holistic design approach. For instance, the human skin works to protect the internal organs against the physical, chemical and bacterial threats (Figure 2-1). This example is a good representation to understand the behavioral function of the building’s skin. It adapts to temperature and humidity, can feel the slight touches, and can repair itself. These reactions happen after an intelligent perception and movements of the skin’s cells. The skin made up of many layers and contains enormous amount of elements that keeps the body free of any infections and many climatic conditions. This is exactly what happens on the building skin, where the skin plays an essential role in protecting and guarding the building against the environmental factors that threaten the internal space.

Figure 2-1: A representation to show the intelligence in how human skin retain and protect the internal organs. Source: http://www.caecilian.org/wp-content/uploads/2010/04/skin-graphics.jpg
Humans have always tried with persistence to dominate the natural world, which has isolated them and limited their abilities against the extension of the Biomimetic. However, they have became more knowledgeable and aware to the danger of neglecting the importance of the living organism, so this battle against the natural behavior has started to disappear. In addition, the collaboration between the nature and human being through the technology has been generating new paths of hypothesis. Adaptive and dynamic façades incorporate the responsiveness and integrated the performance typically found in living organisms, and producing a smooth and organic movement demonstrating clearly its association to biological systems.

2.4 Biomimetic

Nature always represents valuable sources for the built environment, and has always been a mindful motivator for the survival mankind. Many studies have investigated and consciously looked on the ecosystem and nature as inspirational resources for our environment uses. At the top of these studies is what called “Biomimetic,” Also known as “Biomimecry”. Miriam Webster defines biomimetics as:

The study of the formation, structure, or function of biologically produced substances and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones (Wiebe, 2009).

In late-20th century Biomimicry became a formal study area. Then, it became popular in the later period of the 1990s by the biologist Janine M. Benyus after her influential book “Biomimicry: Innovation Inspired by Nature” (1997), which provided a comprehensive focus on Biomimicry. However, if we look throughout the history, nature was a crucial
reference for many inventors back then. For example, in the 9th century the Andalusian inventor Abbas Ibn Firnas had mimicked the bird biological system and designed a winged structure from that. His designs have inspired the Italian artist and inventor Leonardo da Vinci in the 15th century. Leonardo DaVinci went with mimicry a little further; he created drawings that been influenced from birds to picture an imagination of flying machines. In the 20th century, the brothers Wright had spent time studying and analyzing birds in flight and implemented some of those principles to their airplane prototype.

In general, Biomimicry defines the bond between living organism and product design, and is the reference of ideas that produce innovative designs based on well-engineered systems that exist in nature. It focuses on utilizing the common mechanism in the ecosystem to form and build optimal structure through mimicking and learning from nature based on ecological literacy. Ecological literacy means to “understand the principles of organizing the natural ecological systems, and using them to create stable manmade constructions” (Taghzade et al, 2013). Thus, it is possible to seek excellence from nature and get inspirations by looking at ideas from various perspectives. For example, we can get inspired from natural forms of living creatures, their influential geometry, their arithmetic proportions, their evolutionary processes, ecosystems, adaptation behavior, etc. All these aspects lead to achieving extraordinary results with high efficiency implementation.
2.5 Benefits of Studying the Natural Patterns

Studying nature can provide architects with key points to utilize in architectural design; for instance, imitating the bird’s wings and its structure does not only lead to creation of flying machine, but also to solutions that potentially can be an inspiration for designing a stable ecosystem and harmonic architectural façade elements (Figure 2-2).

One of the physiological functions of bird’s feathers is to create insulation, which represents the protection mechanism of the climatic conditions. In birds, the insulation enhances with the increase in feather volume and its unique arrangements in the skin, which makes birds more protected at very low temperatures through dead pores (Patrick, 1989). The open and covered areas on bird’s body are arranged to create the perfect balance in its weight, have better compatibility between body movement and feathers, and most importantly, help the body to retain its perfect temperature (Maragkoudaki, 2013).

Figure 2-2: Views of bird’s wing describing the functionality of each of its parts. Source: Jamal Ara, http://www.4to40.com/geography/index.asp?p=Birds_V1
From that examples and many others, the information provided from studies of nature could lead to superior performance in buildings, making them more efficient, and provide better quality of life and living conditions. Therefore, to concentrate on buildings’ façades only, skin components that have been designed by such solutions can be fulfilled by the following primary benefits (Maragkoudaki, 2013):

1. Implementing elements on building’s façade that have the ability to change or rotate shading devices during course of a day;
2. Decreasing the waste of heat during winter time by blocking/catching cold air through elements on the façade;
3. Improving the efficiency of the building through reducing the increased consumption in energy, which increases the risks on the environment and ecosystem;
4. Decreasing the financial costs that caused by potential energy consumption.

In conclusion, by mimicking the nature, the building’s skin system could provide ability to transform over time through incorporating intelligent systems that undergo purposeful changes in accordance to external and environmental conditions. These adaptive systems have the ability of inherent movement in their structure and operate dynamically as actuators combined with electronic sensors at low energy supply.

2.6 Dynamic System

Over the past few decades, architects have adapted dynamic systems on many façade systems, not only for particular environmental purposes, but also for interactive capabilities. As a result, having movable components on a building’s façade was a
turning point in the 1980s when they were first used (Wigginton, 2002). However, we can denote to a façade as “interactive” without processing “kinetic” capabilities (El Sheikh, 2011). Media façades, for example, are one type that uses flare of light as architectural elements system and socially interactive components. Even sometimes they are considered to be sustainable when they use solar panels as renewable source for energy. There are many other types in the field that present interactive designs and include wall pattern designed by some architects for a purpose of social interaction, in which a wall has the ability to respond to an occupant’s motion. However, since the main objective of this type of façade systems is only to address artistic and aesthetic issues, they are irrelevant to our current environmental needs.

There is a great demand for intelligent and responsive-based designs. These are regulated through the means of perception, processing, and response; in order to achieve both occupants’ comfort level and high building efficiency among their functioning. However, in many cases now, building performance is seen more like a machine box, and designers started investigating the possibilities to activate buildings’ façades with elements that are generated in response to human and natural stimuli. Therefore, the profession in performative architectural fields needs to restructure the approaches of conventional kinetic systems to benefit from today’s technology, and go beyond the traditional single function design, which would eventually lead to comprehensive and effective building production.

Integrating intelligent features into the operation of a building is a subject that caught the interest of the architectural professions, and always façades that are capable to process intelligent features are denoted to as “intelligent skin” (Wigginton, 2002). The conception
of intelligent skins touches not only the energy performance, but also the aesthetic aspects of design. This combination has caught the interest of many interactive architectural professionals who are concerned about adaptive building and attempt to utilize intelligence to transform façade components in response to environmental conditions. Thus, the function of optimal intelligent architecture is an integration of form and technology that has inspired from nature without neglecting the aesthetic part of a building (Figure 2-3).

![Pentagram of the functional and integrated intelligent features for the architectural process.](image)

Since the façade of buildings is an important element in architecture, its design is strongly influenced by changes in architectural trends, especially in terms of its system and geometry. That became widely used in iconic architecture, and this approach can clearly be seen in many buildings when they incorporate complexity of geometry into their designs as well as their structures. Most importantly, this geometric complexity in buildings should not neglect the need of better energy efficiency performance, yet when art and science are combined, it presents optimal solutions to support undertaken efficiency in design approach through advanced technological settings.
As a consequence, to develop the profession and improve our environment, it is significant that we learn from the past, investigate the current, and innovate solutions for the environmental demands. Therefore, it is better to start rethinking rather than refining old design approach in order to solve certain problem. This requires that we utilize the existing technologies to develop and customize techniques for the sake of solving behavioral and performative issues.
CHAPTER 3 INTELLIGENT-ADAPTIVE FAÇADE

3.1 Overview

The 1980s was the beginning of using the word “intelligent” together with the word “smart” to describe the advanced techniques in the buildings (Wigginton, 2002). Since then, buildings façades have become incorporated in their more advanced features that are also known as “intelligent building skin”, and skin of buildings has come to represents a great part of the building elements. Hence, the intelligent features in such a façade require integration of responsive dynamic capabilities, which allow for changes in the façade’s configuration based on daily and seasonal stimuli, and considering the surrounding environmental context in order to reduce the energy consumption and increase the building efficiency.

Therefore, the complexity of intelligence comes from its irregular variability and its influence from nature and cognitive abilities (El Sheikh, 2011). As a result, the meaning of intelligence varies and can be manipulated in accordance to designer’s intentions and ideas, but all definitions address the impact of ecosystem and natural world in term of behavior and reasoning.

3.2 Intelligence in Architecture

There is a wide discussion taking place in the related professions regarding implementing intelligence to buildings in the form of building’s systems, smart façade, sensors, materials, or even the structure of the building itself. In addition, people are not passive organism, so they often create the initiatives for the intelligence in buildings, and are
habitually changing their environment to fit their needs depending on their psychological, biological, physical, and behavioral surroundings.

In architectural intelligence, there is a distinction between automation and integration in building, since objects and elements are often referred to be intelligent when they are enhanced with automated features in their controlling system (Fox and Kemp, 2009). By the same token, the term “intelligent” is often used to describe the automation function in a certain space through a computerized system such as opening and closing the windows’ curtains or turning on/off the air-conditioning or the lights (El Sheikh, 2011). Therefore, while the users are operating these actions manually, they would not be considered as intelligent since the system of reasoning progress is absent. On the other hand, the intelligent system passes through certain process from the beginning of the inputs till the generation of the outputs.

In this research, intelligence is related to human characteristics in the building energy performance to provide better indoor environment based on different paradigms, and through investigating building’s skin. Although occupants’ behavior is a very important factor for building’s operation, some buildings tend to incorporate adaptive and responsive features that function based on environmental and climatic conditions only without giving consideration to occupants’ preferences. Thus, an intelligent building can be exemplified as a one living organism, where the users resemble the internal organs, and the building’s envelope represents the skin of the external organs. The body of the organism is adapted to suit the purpose of protecting the internal environment to ensure that organs perform well. Similarly, one the objectives of the building is geared toward providing an optimal level of comfort for the occupants. Therefore, the users behavior is
the dominating factor for better efficiency in the building performance, even though if it varies based on the conditions of the space and its environmental surroundings. Developing buildings with intelligent features should achieve better performance by implementing the following processes (El Sheikh, 2011):

- Creation of a relationship between the occupants’ behavior and indoor space condition.
- Provision of automatic adjustments in response to environmental changes and occupant’s requirements.
- Generation cost-effective modifications based on changes on tasks and users behavior.

The operation of intelligent buildings should be treated as if they possess smart features and some cognitive abilities that allow them to perceive data, analyze it, and respond with an appropriate reaction (Figure 3-1). This process is applicable to building’s operation within its different criteria, between which is the environmental performance of spaces (El Sheikh, 2011). Therefore, the energy performance of a space or a building could be drastically enhanced by considering and embedding the occupant’s behavior and the changes of the environmental conditions data into its intelligent-cognitive system (Figure 3-2).

Figure 3-1: The process of the adaptive feature and data flow through the intelligent façade.
Brian Atkin has identified three aspects that should be considered on intelligent buildings (Atkin, 1993):

- Building should know what is happening inside and immediately outside.
- Building should decide the most efficient way of providing a convenient, comfortable, and productive environment for the occupants.
- Building should respond quickly based on occupant’s preferences.

![Diagram of Building Intelligence](image)

Figure 3-2: The definition of the intelligent building qualities by Mervi Hemanen. Source: Clements-Croome, 2004.

As previously mentioned, responsive skin and intelligent system would adapt the building to the external climatic and environmental changes and consider the level of occupant’s comfort to achieve better performance and efficiency. But that doesn’t mean that buildings without intelligent features do not perform well in term of energy efficiency. Environmental approaches have been implemented in the profession before the advent of advanced and intelligent technologies through the integration of passive principles into the design to enhance the building’s performance. Therefore, understanding the importance of these principles in the existing passively designed buildings provides a
strong foundation of acknowledge, which, eventually, addresses to high effective implementation in the intelligent-adaptive building field.

3.3 Basic Principle of Adaptive Skin

Building’s façade works as an environmental filter to protect the interior environment against unfavorable climatic changes. Therefore, the most efficient envelope must lead to better energy reduction, sufficient daylighting, adequate ventilation, and excellent quality in indoor environment. Throughout history, many prototypes of building’s façade have been designed to illustrate the importance of the filtered envelope. *Mashrabiya* is one example that aims to provide solution for privacy issues in the Middle Eastern countries, and provides better indoor environments by dealing with thermal and daylighting matters, as well as protecting occupants from the adverse environmental conditions. It is a traditional wooden element that has been used in the Middle Eastern architecture, such as Saudi Arabia and Egypt from the middle ages until the mid twentieth century (Feeney, 1974). The special form of *Mashrabiya* with operable windows allows the cool air to flow through the screen to the interior space, and cast shades to protect the space from the hot sunrays (Figure 3-3), (Figure 3-4).
Figure 3-3: External view of mashrabiya on the Bayt Al-Suhaymi building in Cairo, Egypt.

Figure 3-4: Panel for Mashrabiya to show the solid and void pattern.
Bearing in mind the severe weather conditions in the Middle East, Arabs were leaders in inventing environmental solutions for their architecture. And *Mashrabiya* is one of the most efficient prototypes that have been applied on most commercial and residential buildings to comply with environmental occupant’s comfort purposes beside its cultural value (Kenzari, 2003). Since this approach was successful and influenced people in the profession, a further step has been taken toward more advanced technology that can be embedded in building’s skin with intelligent features that dynamically respond to the environmental stimuli.

**3.4 Performance of Intelligent Kinetics Facade**

There is a wide range of unfavorable environmental conditions that buildings experience, so that requires innovative solutions to be embedded in the building’s envelope which possess intelligent features that are capable to dynamically respond to the occupants’ demands as well as the climatic and environmental changes. One type of these intelligent and advanced technologies is the kinetics façades. In this technology, the building’s skin represent flexible and adaptable abilities that constantly changes its behavior to meet the occupants’ expectation according to the indoor optimization conditions and based on the users’ behavior. Hence, it is a technology that represents part-of-all of building intelligent system, and can be implemented as an effective element that is bonded to responsiveness and interaction of building’s performance. In addition, it can be implemented as a secondary skin layer to work independently as a primary system. For instance, the operable windows represent a basic example of the primary system, when they open and close based on individual needs, and an external secondary skin of series of louvers is
separated from the main skin and can be operated independently in response to climatic changes (Michael and Fox, 2009).

There are number of buildings that have used advanced technologies to improve their performance; however, just few of them operate efficiently and meet the targeted standard. That refers to the lack of developing intelligent-cognitive applications in buildings to correspond with the real life stimuli. Therefore, they can only accomplish particular tasks, and are not able to operate the same way human or living organism do.

The mechanism of kinetic technology and responsive façade in early stages was based on set of pre-defined commands with no existence for reasoning and processing to respond to unforeseen natural forces (El Sheikh, 2011). However, we cannot consider the only dynamic system as an intelligent or kinetic, because such a system works with the motion of the sun in order to prevent the direct solar light inside the space. In this system the sun altitudes are already known, and the designer can provide the equations and program them into the system to make it actuate accordingly in the same routine every day. Therefore, it is only a single-input that has been dealt with, whilst many other important inputs have not been considered and they are strongly affect the occupants in term of comfort level and productivity, such as enhancing daylighting, protection from the sun, generation of electricity, heat/cool collection and rejection, etc., (Wigginton, 2002).

Therefore, the users’ input is a problematic issue for making a building responds and interact in smart way with the daily operation of human’s demands. For example, people usually prefer to find sufficient daylighting in their office spaces during work period. Even though the quality of luminous inside the space is a crucial factor, they rarely
question the level of adequate lighting based on their comfort needs. And for better satisfaction inside a space, many designs have been created to provide alternatives for issues such as controlling the lighting and the blinds manually via a remote control to adjust tasks and activities in the place. Thus, I argue that if there is an intelligent façade system that is capable to recognize occupants’ demands and automatically respond to their activities and needs, it would enhance the performance of the building in terms of energy efficiency, and satisfy the occupants comfort. In intelligent kinetic façade system, accounting for how much shading and daylighting is needed for the space based on time and place as variables is a significant factor, as well as the ability to automatically detect and recognize the occupant behavior, and that what makes it intelligent (Wang, 2009). This is one approach of many, and intelligent kinetic system is not the only way to achieve good building performance.

3.5 Typology of Kinetics in Architecture

Kinetics in architecture is a vital discourse and a technology that can be integrated in different aspects to buildings; one important form is its integration into the building’s façade with dynamic features. Therefore, many buildings have adopted kinetic elements on their façade configuration, and as a matter of fact, in intelligent architecture not only does the building respond based on users’ behavior, but also the users learn from building’s behavior. Meaning that users experiences can influence the architectural environment, and likewise, the architectural environment can teach the users how to practice their activities in a more effective way. For instance, a smart shading system with series of louvers is capable to adjust its configuration to overcome the direct sunlight that cause over illumination when hits the working plane. At this point, the users will
recognize that the sun position is unfavorable at this time of a day during the year. It is important to provide this information as feedback to the occupants on how they would interact with this situation.

The mechanism of intelligent system in a building’s façade could be based on knowledge or sensors, or both. Sensors are very important elements for human interaction and intelligent architecture due their capability in detecting data from surrounding’s stimuli such as sunlight, motion, and temperature, and translate these data as real actions to provide better environmental performance (El Sheikh, 2011).

3.6 Modeling Intelligent Kinetics

The high demand for better performance and more efficient buildings has resulted in the emergence of technologies that are adaptable and capable to enhance the effectiveness of the environment. Kinetic façade is one approach that provides technique beyond the conventional strategies in term of skin design. In the case of designing a skin using advanced techniques, some designers prepare framework of variables and parameters to generate a list of results. From this perspective, intelligent kinetic model is very similar except for the final result where there is no final form due to the variety of forms that are going to occur based on different conditions over the building’s life cycle (Moloney, 2011).

The use of dynamic and kinetics system as a secondary skin would provide more creative geometrical forms and designs besides the possible enhanced energy performance. This diversity of characteristics and configurations will impact on the functionality and aesthetic of the building. In addition, the current trend is to integrate the sustainability
and kinetic into one large system. This does not mean that the system is built entirely for sustainable purpose, but it also serves aesthetic and cultural values. As a result, incorporating computer tools and softwares is a significant method for modeling intelligent-responsive façade in order to achieve these goals.

Modeling kinetic architecture is a very distinct and complicated work, and most of the effort in this area is still in experimental labs and firms that are specializing in building technology. The difficulty in this process is in the stage of inputting parameters that characterize the natural features and human interactions to the intelligent skin and make it behave like human being and recognize the behavior of the occupants. In this study, the intelligence has been incorporated to the simulation through a single task presentation of adjusting the desired quality of shading and quantity of HVAC energy use to the internal performance quality. Taking into account the human comfort level, a set of parameters have been conducted on the simulation based on pre-designed equations for solar changes, which gives opportunity to test the intelligent façade system against the users preferences in different scenarios.
CHAPTER 4 LOW-ENERGY BUILDINGS

There are arguments within the profession that many of the purported benefits of passive low-energy design are not actually being achieved in real practice (Nutt, 1994). However, buildings with intelligent-responsive skin system still do make a significant contribution in reducing the overall energy use, and assist in maintaining and improving internal comfort levels (Jong-Jin, 1993). A background about energy issues in Saudi Arabia and initiatives along with climatic and solar analysis are discussed in this chapter.

4.1 Overview

Energy efficiency gained a significant interest after the 1973 Arab oil embargo, and that was a wake-up call for all economies on how vulnerably their situation was toward the expanded need of oil. The Kingdom of Saudi Arabia (KSA) is one of the countries that blessed with abundance oil and minerals, and it is the largest oil exporter because of its large oil reserves. In addition, it has the fourth largest gas reserves, but most importantly, it has a significant amount of solar resource that can contribute in producing renewable energy (Anwar, 2013).

The capacity of electricity generating in Saudi Arabia is around 58,000MW; however, this barley meets the emerging demand of the industrial and residential electrical requirement. Currently, there is a huge ongoing spending on the capital of new power stations, which is on growing pace as seen in Figure 4-1 of 8% increase since the year of 2002 and expected to reach the level of 10% by the year 2023 (Anwar, 2013).
Saudi Electricity Company (SEC), the main utility provider, has plans in place on the basis that an investment of around $8 billion a year would be required for the sector to keep pace with consumer demand. However, the needs of a fast developing industrial sector are becoming more urgent. As a result, the SEC’s 2013 capital expenditure is now likely to be closer to US$10 billion annually. The higher and faster levels of actions are urgent because power consumption is increasing faster than anticipated. Moreover, Saudi Arabia needs to find new ways of bridging a growing energy gap that threatens to have impact on its development goals.

Attempting to face the potential energy crisis, KSA is evaluating how it will manage and develop its power sector in the near future. By shifting electricity generation and water desalination plants away from oil towards gas and renewable sources of energy, KSA aims to reduce the amount of crude oil burnt to fuel its power stations (Anwar, 2013).
This will help free up more of the country’s primary energy resources for export. Some analysts believe it is possible that all Saudi electricity could be powered by renewable energy by the second half of the century (Sioshansi, 2013). If new energy policy is vigorously pursued by KSA, it is likely to become one of the largest provider of Renewable energy technologies, especially for solar power.

4.2 Energy Efficiency Features

The amount of energy needed to provide the desired services of heating, cooling and lighting becomes rather circular. For example, if sufficient natural lighting can be provided at least for the hours when the sun is shining without resorting to artificial lights, then electricity consumption can be reduced without affecting comfort or productivity. In Saudi Arabia perhaps the biggest problem facing the energy supply sector is the large seasonal variation in electricity consumption. In the hot summer season, there is increasing in energy demand for air conditioning, especially by the residential and commercial sectors. Therefore, to overcome the danger of overloaded usage of energy, modifications must be implemented on the buildings to achieve the better use, such as natural lighting, the building’s orientation, location and design of windows, shading louvers.

4.3 Energy Efficiency Initiatives

A number of energy efficiency and conservation initiatives have been taken by various agencies in response to the increasing demand of electric power, and to help ensure security of supply. There are several steps to reduce the energy demand have been taken by the Saudi Arabian Standards Organization (SASO) with standards for the use of
advanced insulating materials in the construction of all new commercial buildings. Another important initiative that must be taken in consideration is the adoption of high-end technologies that would help to save energy and plays a significant role on the aspect of energy saving. As mentioned previously, building’s façade is one of the largest contributor on energy consumption, and by implementing new technologies on our buildings’ façades, we will provide a crucial impact to stand in front of the potential energy crises in Saudi Arabia.

With supportive policies, pricing, regulations, standards, and enabling technologies that inform, motivate, and engage customer participation and influence consumer behavior; there is considerable scope for optimism. Energy efficiency must be considered as a main contributor in energy saving and buildings’ performance for many reasons. One reason, and According to the UK Energy Center (UKERC, 2009), the production of crude oil will have past its peak by the year 2031 and the subsequent two decades will see a ‘terminal decline’ in the global oil production. This will need to be replaced by renewable resources if global energy demand is to continue on its upward trend.

The second reason is that energy efficiency directly reduces negative environmental effects associated with the consumption of fossil fuels. Consequently, improvements in energy efficiency often have a positive business case, as saving energy means saving money. This reflects starkly on many other environmental protection measures considered by policymakers, companies, and consumers.
4.4 Climate Change Issues

It is essential for this study to understand the context of the place. The capital of Saudi Arabia, Riyadh was the initial location for conducting the study for this research. Therefore, data for Riyadh was collected as will be presented below. However, due to time limitation, the direction of the site was moved to Miami, and the entire study has been conducted in the campus of University of Miami.

Riyadh is well known for having hot desert climate, it is extremely hot during the summer months, approaches 55 °C (131 °F) occasionally, and has an average temperature in July of 44 °C (111 °F) [Figure 4-2]. The winters, on the other hand, are a combination of warm and cold, and windy during some nights. The overall climate is arid, and the city experiences very little rainfall, especially in summer; however it receives a fair amount of rain in March and April. It is also experiences many dust storms, which is often so heavy that visibility is under 30 ft.
4.5 Solar Energy and Selective Surfaces

There is a spectral distribution of wavelengths from the solar radiation that reaches the earth, and the relationship of the wavelength to temperature is inversely proportional, so that, for example, the wavelength of 400nm corresponds to 7500 Kelvin and the wavelength of 2400nm corresponds to 1250 Kelvin (Jankovic, 2012). To determine how individual materials respond to solar radiation, each material surface properties consist of absorptance, reflectance, and emittance. Absorptance is defined as a fraction of absorbed radiation at the surface relative to radiation absorbed by the black body. Reflectance is a fraction of reflected radiation from the material surface, while Emittance is a fraction of emitted radiation, relative to radiation emitted by the black body (Jankovic, 2012).
The types of the absorption surfaces can be defined by using the surface properties of materials, the corresponding temperature, and the spectral distribution of solar radiation. Absorptance rate is equivalent to emittance rate in materials with conventional surfaces. In other words, that gain and lose of energy are the same for the materials with conventional surfaces, and in the term of solar absorption they are not the ultimate materials to use (Jankovic, 2012). By the same token, materials with selective surface properties have high absorptance at high radiation temperatures (low wavelengths) and low emittance at low radiation temperatures (high wavelengths). For example, definition for the relationship of selective surfaces; absorptance of 6000K is greater than emittance of 60K, which means that absorptance at radiation temperatures of 6000°C is higher than emittance at temperatures of 60°C that are likely to occur at material surfaces as result of heating by solar radiation (Szokolay, 2008). As a result, selective surface materials absorb more than they emit, meaning they are better suited for the absorption of solar radiation than the conventional surfaces.

4.6 Solar Gain Processes at Glazing

Jankovic, (2012) points out that part of the incoming solar radiation ($I_o$) will be reflected ($I_r$) to outside from the outer surface of the glazing, while some will refract through the glazing. Part of the refracted rays will get absorbed in the glazing ($I_a$) and part will be transmitted into the interior space ($I_t$). The absorbed fraction will be consumed through heat losses to the outside ($I_{co}$) and to the inside ($I_{ci}$). The total amount of heat gain ($I_g$) will therefore consist of the transmitted solar radiation and the absorbed solar radiation that is transferred by convection to the inside ($I_g = I_t + I_{ci}$). Figure 4-3 shows this process for a single layer of glazing, and for multiple layers of glazing as shown in Figure
The type of glass will impact on the result of the amount of reflected, transmitted and absorbed solar radiation. For instance, reflective glass will reflect more than clear glass, and tinted glass will absorb more than clear glass. Therefore, the amount of heat melt into the outside may be higher or lower than the amount of heat melt into the inside; all that depending on the type of glass.

Figure 4-3: Visualization of how solar radiations reflect, transmit, and absorb through the single glazing layer. Source: Jankovic, 2012.
4.7 Sun Path Diagram

Sun path diagram is useful in determining the solar angles and the tilt angle of the louvers at different times of a day and month on particular latitude. This information is also important for the site analysis; however, for the purpose of this study, I will use the sun path diagram only for solar shading design. Some simulation tools such as IES VE, and Autodesk Ecotect can also create Sun path diagram, and these are able to generate diagrams for many locations around the world. The diagram in Figure 4-5 was obtained from Autodesk Ecotect for the Miami, while Figure 4-6 represents the city of Riyadh. The outer circle in the sun path diagram represents the horizon, the clockwise scale marked, shown in degrees, on this circle represents azimuth. Date lines run as arcs across the diagram. The intersection between the date and time line indicates to a particular hour on the corresponding date. The concentric circles in the diagram represent the sky grid and correlate with the solar altitude angles (Jankovic, 2012).
Stereographic Diagram

Location: 25.8°, -80.3°

Figure 4-5: The sun path diagram for Miami from Autodesk ecotect.
By understanding the details of the sun path, we will be able to calculate the altitude and azimuth of the sun on any specific date and time in any location over the world. It is therefore easy to predict the sun movement, the best building orientation, and generate diagrams to demonstrate the sun's location and the optimal range of the annual shading, which are all used to determine the best tilt angle for the louvers at any time of a day.

The amount of sun rays hitting the space and the illumination inside the environment can be calculated by using numbers from charts, equations, and tables. However, these results
impacted significantly depending on the orientation of space, location, and month, day and time of the year (El Sheikh, 2011). As an illustration, the blue line on the horizontal plane in Figure 4-7 represents the exposure area of the sun during the summer time, while the red line represents the sun range during the winter, which has a shorter period.

Figure 4-7: The annual sun path diagram for Miami. The high angle sun represents August, and the low angle sun represents May, both on the same day and the same time.

For the purpose of this thesis, a simple box model was used for testing as in Figure 4-8. The model dimensions are 4ft × 4ft × 4ft with south-facing window of 26in × 36in. The next step is specifying the features of the materials and the external incident solar flux in details output options in Autodesk Ecotect. Then a precise simulation was run with hourly time steps during the daytime from 10:00 am to 4:00 pm. After the simulation is completed, I was able to determine the solar effect on the indoor temperature in the model and the HVAC energy consumption, as well as obtaining hourly values of the whole incident in KWh.
4.8 Concept of Daylight Deflection

For purpose of the study, the dynamic shading was formulated as motorized daylight deflections. Daylight deflection is a shading device that can be dynamic or static, and it is a technique that works to re-direct sun rays and prevent them from getting into a space in a controlled fashion. It also works to provide the interior environment with an optimum amount of daylighting that meets the comfort level of the occupants. Conventional blinds efficiently block direct light; however, they do not allow daylight to get into the space, which is waste of energy.

Fundamentally, in the aspect of energy efficacy, daylight shading technology have improved and became more than just a daylight deflector and protector against glare; it can control the intensity and direction of light, and its distribution in response of the climate conditions. The advantage of smart shading techniques over solar shading is their
ability to work as a control layer, and to strengthen weak daylighting, specifically at the
darker areas of a space (Koster, 2004).

4.9 Solar Shading Design

The louver shading can be represented by a very simple geometry as shown Figure 4-9.
However, to be able to design the best dynamic shading louver that perform optimally,
we need to calculate the best tilt angle for each time of a day and based on date and
location. In this study, the experiment has been done in two ways: the first way was
through use of simulation tool – in this study used Autodesk Ecotect, and the second way
was by experimental physical models. For both ways I had to calculate the tilt angle
manually to get the best match results. Consequently, to specify the louver geometry, we
need to determine the width of the louver blade \(a\), the distance between louver blades
\(b\), and the louver tilt angle \(\beta\). In addition, the parameter of solar altitude angle \(\alpha\) can
be determined from the ‘Sun path diagram’ that previously described (Jankovic, 2012).

The equation that links parameters in the louver geometry is based on the following
formula:

\[
\frac{a}{\sin(90 - \alpha)} = \frac{b}{\sin(\alpha + \beta)}
\]  

\((1)\)
4.10 Consequences on Building Energy Efficiency

In his book Jankovic represents the thermal mass impact on the efficiency of a building. Figure 4-10 representing buildings without ventilation, the horizontal line indicates to the comfort temperature level in a building, and it can be observed that this level will be crossed in the low thermal mass building over 24 hours, whereas, the with high thermal mass building never reaches this temperature at night-time ventilation in operation. Meaning, to maintain the internal desired temperature level in those buildings with low thermal mass, they will require mechanical cooling/heating air-conditioning; whilst in buildings with high thermal mass it may not be necessary. If the nighttime ventilation operated with high thermal mass, then it will act as a natural comfort cooling system, which results in more energy efficiency in summer time. On the other hand, if no nighttime ventilation is operated or the temperature is not much lower than the
temperature during the daytime, then it will be difficult to control the temperature’s increasing in the high thermal mass buildings (Figure 4-11).

Figure 4-10: Without ventilation.

Figure 4-11: With ventilation.
CHAPTER 5 DESIGN TOOLS AND METHODS

5.1 Overview

As an initial stage and before running simulation on building performance, a CAD model of the building needs to be developed. The purpose of making a model was to define the features of the building as well as to represent its physics and material properties. The simulation, on the other hand, is a numerical experimentation with the model that investigates its response with the environmental changing conditions outside the building.

5.2 Design Components

One of the principles that have been adopted in this thesis is experimentation with Simulation Software. For best building performance, we first need to reduce energy demand by improving building energy efficiency (Jankovic, 2012). Energy efficiency and building performance analysis, economic analysis, and comfort analysis, are significant components for this method, which reflect on the overall success of the design. More details of this simulation study will be presented throughout this thesis.

Jankovic (2012) described the components that are able to impact on the design as follow:

- Response to climate context: climatic conditions for a particular location, taking into account predicted climate change.
- Response to site context: solar radiation, building orientation, prevailing winds, site configuration, overshadowing by the land configuration or existing objects.
- Building geometry.
- Thermal insulation.
- Air tightness.
- Passive solar gain.
• Thermal mass.
• Natural ventilation.
• Natural daylight.
• Electrical lighting.
• Renewable energy systems.
• Internal heat gains.
• Additional heating or cooling.

5.3 Simulation for Kinetic Response

Within the framework of this thesis, the performance of dynamic shading inside office spaces is studied through the use of highly efficient simulation tool. Using such a tool allows for realistic results of shading performance when facade elements actuate. The complexity of this study lies in manually defining angles of the louvers for each designated time, which represents the intelligence of the skin. The model example was developed to see if the performance criteria could be achieved using Ecotect as a modeling tool and performance evaluation.

Autodesk® Ecotect® Analysis is a comprehensive sustainable tool that analyses a building’s design from concept to detail. Ecotect Analysis provides a variety of simulations and analysis of building energy functionality that can improve performance of a given building. It is capable to analyze and communicate/exchange with other tools in order to visualize and receive best outcomes within the context of a certain building environment. Ecotect capabilities are as follow (Autodesk, 2014):

• Whole-building energy analysis—Calculate total energy use and carbon emissions of your building model on an annual, monthly, daily, and hourly basis, using a global database of weather information.
• Thermal performance—Calculate heating and cooling loads for models and analyze effects of occupancy, internal gains, infiltration, and equipment.
• Water usage and cost evaluation—Estimate water use inside and outside the
Solar radiation—Visualize incident solar radiation on windows and surfaces, over any period.
- Daylighting—Calculate daylight factors and illuminance levels at any point in the model.
- Shadows and reflections—Display the sun’s position and path relative to the model at any date, time, and location.

The modeled space in Ecotect has dimensions of 4ft width, 4ft depth, and 4ft height. This model has been scaled to match the physical model as discussed later. A window of 36in height and 26in width has been installed on the south face of the model as seen in Figure 4-8 previously. The interior surfaces have been fully insulated with R-13 Fiberglas insulation. The space has been assigned fully air conditioned, and the opening has been assigned generic single-glazed material with 85% visual transmittance. The secondary skin louvers have reflectance of 85%.

For the relevant of the context, Miami has been chosen to be the initial location of the test because of first; the difficulty of traveling to Riyadh to build a physical model, and secondly, its sunny weather is very similar to the climate conditions that in Saudi Arabia and the sufficiency of daylight.

Initially, the skin system is divided into two louver systems, one horizontal and the other one with vertical louvers as shown in Figure 5-1 and Figure 5-2. Each system is intended to control array of louvers with different tilt angles.
Figure 5-1: Visualization for the horizontal louvers on the suggested model.

Figure 5-2: Visualization for the vertical louvers on the suggested model.
These louvers should have the greatest impact on the sun penetration into the work plan; they will be simulated according to their position at certain time and certain rotation angle. This approach does not however eliminate the flexibility of the definition to independently actuate the louvers except it has to be simulated manually. The variables for the skin alteration are the rotation angle of the louvers, where the distance between them is fixed and set to 4in based on following formula:

\[ b = \frac{a \times \sin(\alpha + \beta)}{\sin(90 - \alpha)} \]  

(2)

The louvers configuration was set on a rotation range between 0° and 90°, which would allow for shading the interior space while allows an adequate amount of daylighting penetration. It has to be pointed out that the focus of the thesis is on the HVAC energy use and not the total operational energy.

5.4 Simulation Method

Simulating louvers configuration manually is useful and powerful for analyzing the results, and compile one scenario for a kinetic louver system on a certain day of the year. The objective of this study is to provide measured HVAC energy consumption based on outdoor climate condition and under clear sky condition.

5.4.1 Simulation Conditions

Ecotect has a user-friendly interface, which allows choosing the type of performance test, sky condition, solar date and time, occupancy, and energy conditions in the space, which is helpful for the context of this study, the "dynamic shading test". The sky condition was
set to sunny clear sky with sun. Solar dates and times used in the study were June 19\textsuperscript{th} - 20\textsuperscript{th} of 2014 at 10:00 am to 4:00 pm. Miami, Florida, was set as the preliminary location for the simulation, based on its high ranking in the list of American cities with most sunny days. Miami has average of 249 sunny days annually; meaning that approximately 70\% of the whole year is sunny. This is very comparable with Riyadh, Saudi Arabia, where the average of sunshine is 267 days, which approximately 74\% of the whole year.

Miami is located at latitude 25.78 ° N (Figure 5-3) and longitude 80.22 ° W. throughout the year, the solar altitude changes rapidly at different times of the day. For this test timeframe, the solar times chosen for the simulation were from 8am to 5pm, all under clear sky, where the solar altitude ranges from 13° to 83° as shown in Figure 5-3.

<table>
<thead>
<tr>
<th>Date</th>
<th>Solar Time*</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM:</td>
<td>6 7 8 9 10 11 Noon</td>
</tr>
<tr>
<td>PM:</td>
<td>6 5 4 3 2 1</td>
</tr>
</tbody>
</table>

| ALTITUDE     | June 21      | 12 24 37 50 63 75 83 |
|--------------|--------------|
| Mar.-Sept. 21| — 13 26 38 49 57 60 |
| Dec. 21      | — 12 21 29 35 37  |

| AZIMUTH | June 21 | 111 104 99 92 84 67 0 |
|---------|---------|
| Mar.-Sept. 21 | — 83 74 64 49 26 0 |
| Dec. 21 | — 54 44 32 17 0    |

Figure 5-3: The dimensions of the space used in the simulation. Source: Schiler, 1992.

This simulation model does not account for neighboring buildings, while the proper model should take into consideration the surrounding context. Thus, only indirect climatically condition of the space and the louvers is considered. For these reasons two physical models were developed to take real life situation into account as will be discussed in later chapter.
As previously mentioned, the space was modeled for this study was 4ft wide, 4ft deep, and 4ft high was modeled for this study. The louvers were calculated for 4in deep and, and set 10in from the glazing. The distance between the louvers was set to 4in, which allows partial overlapping in nearly closed shading conditions. Material selection was based on basic generic materials of 2x4in wood studs for the frames, 3/4in plywood for the exterior covering, and 1/2in sheet rocks for the interior covering. Floors, walls, ceiling, and louvers were assigned reflectances of 20%, 50%, 85%, and 85%, respectively.

5.5 Simulation Parameters

The intelligent and kinetic louver system has infinite possibilities and parameters of configuration because the combined skin system depends on independent angle control, which allows each louver to change its own tilt angle based on certain variation. Therefore, the best approach for this experiment is to run simulation manually for each time steps and as many possibilities as the designer desires to achieve the closest accuracy of results. In this study, for each configuration I run seven simulations hourly steps from 10:00 am – 4:00 pm. However, the down side of this method is the extremely time consuming to adjust the louvers in hourly basis.

It is crucial to understand these factors that determine the final configuration of the shading elements. Keith E. Holbert has refined the solar calculation in his paper in 2007. He mentioned that the Earth is tilted on its axis at an angle of 23.45°, and that leads to the angular distance of the sun north or south of the earth's equator, which called declination angle, \( \delta \). The declination angle can be calculated from the following equation:
\[
\delta = 23.45^\circ \sin \left( \frac{N+284}{365} \times 360^\circ \right)
\]  

(3)

Where \( N \) is the day number of the year, with January 1st equals 1. The Earth is divided into latitudes (horizontal divisions) and longitudes (N-S divisions). The equator is at a latitude of \( 0^\circ \); the north and south poles are at \(+90^\circ\) and \(-90^\circ\), respectively; the Tropic of Cancer and Tropic of Capricorn are located at \(+23.45^\circ\) and \(-23.45^\circ\), respectively.

The longitudes are described in terms of how many degrees they lie to the east or west of the prime meridian. A 24-hr day has 1440 mins, which when divided by \(360^\circ\), means that it takes 4 mins to move each degree of longitude. The apparent solar time, AST (or local solar time) in the western longitudes is calculated from:

\[
AST = LST + \left( \frac{4 \text{ min/deg}}{4 \text{ min/deg}} \right)(LSTM - Long) + ET
\]

(4)

Where;

LST = Local standard time or clock time for that time zone (may need to adjust for daylight savings time, DST, that is \( LST = DST - 1 \text{ hr} \)),

Long = local longitude at the position of interest, and

LSTM = local longitude of standard time meridian, (Long and LSTM can be determined directly from the Solar Path Diagram).

The hour angle, \( H \), is the azimuth angle of the sun's rays caused by the earth's rotation, and \( H \) can be computed from

\[
H = \frac{\text{(No. of minutes past midnight, AST)} - 720 \text{mins}}{4 \text{ min/deg}}
\]

(5)
Finally, the louver angle ($\theta$) between the sun and normal to the surface is

$$
\cos(\theta) = \sin(\beta_1)\cos(\beta_2) + \cos(\beta_1)\sin(\beta_2)\cos(\alpha_1 - \alpha_2)
$$

Where $\alpha_2$ is the azimuth angle normal to the collector surface, and $\beta_2$ is the tilt angle from the ground. If $\theta$ is greater than $90^\circ$, then the sun is behind the collector.

Consequently, within the framework of this study, set of horizontal louvers and vertical louvers in a secondary skin layer were placed at a distance of 10in in front of the glazing.
The distance between the louvers is set to 4in, for allowing partial overlap in semi-closed positions. When sunlight hits the lower surface of the upper louver, overlapping allows partial sunlight enters into the space at high-tilt angles. Each tilt angle combination selected for simulation in this study was run for different altitudes and hourly basis from 10:00 am to 4:00 pm under clear sky, for June 19\textsuperscript{th} – 20\textsuperscript{th} 2014. Table 5-1 shows a list of all tilt angle combinations for the simulation runs, and each configuration represents the tilt angle of one-hour frame of the system.

<table>
<thead>
<tr>
<th>Time</th>
<th>Solar Altitude</th>
<th>Louver Angle for South Façade</th>
<th>Horizontal Louvers</th>
<th>Vertical Louvers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:00</td>
<td>55°</td>
<td>54°</td>
<td>84°</td>
<td></td>
</tr>
<tr>
<td>11:00</td>
<td>67°</td>
<td>39°</td>
<td>80°</td>
<td></td>
</tr>
<tr>
<td>12:00</td>
<td>57°</td>
<td>25°</td>
<td>78°</td>
<td></td>
</tr>
<tr>
<td>13:00</td>
<td>73°</td>
<td>11°</td>
<td>78°</td>
<td></td>
</tr>
<tr>
<td>14:00</td>
<td>63°</td>
<td>8°</td>
<td>81°</td>
<td></td>
</tr>
<tr>
<td>15:00</td>
<td>50°</td>
<td>21°</td>
<td>85°</td>
<td></td>
</tr>
<tr>
<td>16:00</td>
<td>37°</td>
<td>36°</td>
<td>91°</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-1: Tilt angle combinations those used for all simulation runs.
5.6 Visualization of Some Simulated Schemes

Horizontal at 10:00am

Horizontal at 1:00pm

Horizontal at 4:00pm

Vertical at 10:00am

Vertical at 1:00pm
Vertical at 4:00pm

Combined at 10:00am

Combined at 1:00pm

Combined at 4:00pm
CHAPTER 6 DATA ANALYSIS METHOD Diagrams and Charts

6.1 Overview

This chapter will discuss the results of the secondary louver skin layer for energy efficiency performance. These results, as previously mentioned, assess the quality of dynamic shading and its effect on a building performance in terms of HVAC energy consumption. Analyzing and interpreting data method involves quantitative evaluation of the smart shading behavior of the skin and for the model in general. Outcomes are produced using charts to present a comparison between the test cases of combined skin system to the pre-defined performance criteria and two base cases for skin configuration – vertical and horizontal louvers.

6.2 Kinetic Scenario Compilation Method

The main goal of this thesis is to provide an analytical design study for integrating shading device into kinetic facade design. Therefore, it is useful to provide a manual compilation for a proposed kinetic to envision the kinetic process in response to different settings.

Within the context of this study, each shading layer actuates together in certain tilt angle to optimize the performance of shading inside the space. Over the course of a day, the secondary skin experiences different tilt angle combinations to maintain adequate shading performance and light distribution inside the space. It is important to show an actuation pattern for kinetic strategy by combining skin configuration, which will be presented later.
in this chapter, in order to represent the kinetic formation scenario for different solar altitude.

6.3 Dynamic Simulation Analysis

South-facing space with glazing was selected for testing the model. The reason is the south facing does not maintain optimal sunrays under clear sky conditions as well as glare from direct illumination. The case with no-shading will show high illuminance and great value of heat convection; however, it has been presented here for comparative testing purpose. And the useful cases are those with external secondary skin.

In the first case analysis, representations will be shown for non-shaded case for HVAC energy consumption and temperature changing average. One table will show the course of a day – hourly basis – with overall KWh consumption for each hour. Taking into account the model size 4ft x 4ft x 4ft, the results of the KWh consumption will automatically scaled based on the model space. For this case the minimum HVAC consumption is 0.205 KWh at 10:00 in the morning and the highest range is 0.284 KWh at noon (Table 6-1). The purpose of finding this range is to highlight the energy consumption scale of non-shaded case. An accommodating chart is illustrated to show the representation boundaries (Figure 6-1).

<table>
<thead>
<tr>
<th>Time</th>
<th>Non-shaded KWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00</td>
<td>0.205</td>
</tr>
<tr>
<td>11:00</td>
<td>0.266</td>
</tr>
<tr>
<td>12:00</td>
<td>0.284</td>
</tr>
<tr>
<td>13:00</td>
<td>0.223</td>
</tr>
<tr>
<td>14:00</td>
<td>0.276</td>
</tr>
<tr>
<td>15:00</td>
<td>0.245</td>
</tr>
<tr>
<td>16:00</td>
<td>0.266</td>
</tr>
</tbody>
</table>

Table 6-1: The non-shaded KWh consumption for each hour step in the simulation runs.
Figure 6-1: Illustration for the non-shaded KWh consumption within each hour step in the simulation runs.

6.3.1 Horizontal Louvers

Horizontal louver is an arrangement of parallel blades that all compiled in horizontal way. The louvers can be made with different features and variety of materials, such as wood, aluminum, metal, or glass; white color wood was selected for this study model. Moreover, the horizontal shading is mostly effective when sun takes a perpendicular position on the sky and, consequently, to the shading blades. It is expected to block direct sunrays and solar heat gains at the front of the space, which impacts the quality of energy performance and quantity of daylighting in the room.
Correspondingly, a set of horizontal louver was set to the exterior glazing of the model with a range of tilt angles between 36° at 10:00 am and 54° at 4:00 pm (Figure 6-2). The louver starts to close – in response of solar altitude – from the morning time until the peak hour at around 2:00 pm, then they move back to open until the end of the day course (Figure 6-3).
Within this process, a noticeable changes in the behavior of shading inside the space that reflects on the temperature of the indoor environment, and changes in energy consumption as well. The change in the secondary skin configuration comparing to the non-shaded condition results in better energy saving of about 24% of KWh from the different times that fell under the calculated tilt-angle range (Figure 6-4).
6.3.2 Vertical Louvers

The concept of vertical louvers is very similar to the horizontal louvers except fixed vertically. However, they are more efficient with an angular position of the sun, and, accordingly, they are primarily useful for south-east and south-west exposures. Using vertical shading is very important to demonstrate the basic concept of kinetic façade, which will be later, combined with the horizontal louvers to give full configuration of dynamic façade.
Figure 6-5: Visualization for the Vertical louvers configuration from Ecotect.

The same process that has been used on the horizontal louvers has been applied on the vertical louvers. Series of parallel vertical louvers have been set to the exterior glazing of the model with a range of tilt angles between 85° at 10:00am and 90° at 4:00pm (Figure 6-5). The louvers start to close – in response of sun – from the morning time until they reach the peak hour at around 12:00pm and tilt angle of 117°, then they back to open until the end of the day course (Figure 6-6).
Within this process, very slight change undergone in the behavior of shading and solar heat gain inside the space, as well as little improvement in the matter of energy consumption. The change in the secondary skin configuration results in better energy saving for about 6% of KWh comparing to the non-shaded condition, and from the different times that fell under the calculated tilt-angle range (Figure 6-7).
6.3.3 COMBINED CONFIGURATION Horizontal and Vertical

In another simulation, horizontal and vertical louvers are combined to one layer of grid configuration in order to demonstrate the attribution of intelligent façades and dynamic shading systems (Figure 6-8). Since louvers work in response to sun conditions, each layer in the secondary skin moves independently based on its designated tilt angle within different altitudes.

Figure 6-7: Comparison between the Vertical configuration KWh consumption and the Non-Shaded case within each hour step.
The simulation run shows that approximately 36% KWh of HVAC energy saving (Figure 6-9). If we compare this scheme against the vertical and horizontal louvers, it reveals that the combined configuration has better performance and less solar gain in the envelope, with approximately 12% more than the horizontal and 30% than the vertical system. This interesting behavior proves the potential success of this configuration during other day times.

The observed conclusion about this configuration is that dynamic façade contribute in reduction in the energy use and solar heat gain. This functioning fits the attributes of intelligence in kinetic façades. For instant, this configuration may be used with the space sensors to detect if only certain numbers of spaces are occupied in a building.
6.4 Kinetic Scenario for Actuation Pattern

Given the main goal of this thesis, it would be helpful to provide an operational idea about how the kinetic system works. However, because of the limited number of simulation runs, the scheme of this scenario may not be successful at this point. A graph was developed to show a comparison between all conditions in term of KWh consumption (Figure 6-10). Also for an additional comparison results, a static grid configuration was developed and simulated in Ecotect. The results revealed that the non-shaded configuration contribute in higher energy consumption comparing to the other shading settings.
Figure 6-10: Comparison between all conditions KWh consumption within each hour step.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Horizontal Louvers</th>
<th>Vertical Louvers</th>
<th>Combined Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>8%</td>
<td>-22%</td>
<td>16%</td>
</tr>
</tbody>
</table>

Table 6-2: The performance of all dynamic configurations in comparison with the static-combined louvers.

From the simulation runs for this study, a better scenario was proposed in Table 6-2 in order to show the kinetic skin performance. It represents the best available selection from
the manual simulation; however it is not necessarily shows the optimal solution of this compilation. As shown in the scheme, a “performance” values represent the percentage of the energy savings for each setting in the study, however, this time comparing to a static-combined configuration. For the static scheme, the tilt angles have been chosen based on the ultimate performance position from the combined configuration, which is at 2:00 pm, and angles of 45° horizontal and 90° vertical. A better result should have been done automatically by defining the algorithm of the secondary skin, which allows generating numerous configuration parameters that provide the designer with optimal options.

6.5 Validity of Simulation Results for Design Decision Making

Simulation tools have been made to ease the prediction probability of buildings performance; however, they cannot give absolute answers until the model is experimentally validated. Accordingly, the results of the simulation runs can be completely wrong, and that leads to an important question, why doing simulation then? The answer is because simulation is a great analysis tool that gives the opportunity to choose which design option is better when comparing with other options from the same simulation conditions (Jankovic, 2012). However, the absolute answer is still difficult to tell how good these options are. Therefore, physical scale model is highly recommended to determine the best results that suit a building’s requirement, and that gives the ability to the team to be advised and make decisions based on the design parameters along with the simulation results.
6.6 Physical Scale Models Versus Dynamic Simulation Models

Investigating physical models (Figure 6-11) is a powerful method for testing certain aspects of a building performance, such as energy consumption and average of temperature variation. The physical model had been built using real materials that are identical to the prospective building, and requires advanced measuring tools to monitor the building behavior. However, because of some restriction in building actual size model, the scale of the model has been reduced to match the policy of the city of Miami; also, in this case it is difficult to put people inside the model to test the occupants behavior parameters. Accordingly, this tells us another benefit of doing simulation using software tools; the simulation runs overcome these drawbacks and have ability to investigate multiple aspects of behavior simultaneously with much wider application scope than physical scale models (Jankovic, 2012).

Figure 6-11: The experimental models in the campus of University of Miami.
6.7 Physical Model Experiments Analysis

Physical models experiments with horizontal and vertical louvers were conducted as part of this study to validate the outcomes from the simulation runs. The models have been created with dimensions of 4ft x 4ft x 4ft and built with 2x4in wood frames and ¾ plywood and ½ sheet rocks for the covering. A window of 36in height and 26in width has been installed on the south face of the model, as well as an air conditioning unit has been installed in the opposite wall to the window. The interior surfaces have been fully insulated with R-13 Fiberglas insulation. Ultimately, the total R-value for each model is 8.17 ft²F/BTU. In the experiment step, a temperature probe was placed inside and outside the boxes to record the temperature change. The Portable Environmental logger from (CO2 Meter Company) measures carbon dioxide (CO2) 0-1% (0-10,000ppm), temperature, and relative humidity in remote locations. Also a Kill A Watt device was plugged on the electricity outlet to read the energy consumption out from the air conditioning (Figure 6-12). As a result, energy consumption along with internal and external temperatures are recorded in one-hour time step from 10:00 am and over a period of seven hours based on calculated tilt angles that according to solar altitudes.
As a result, the same settings and respects that have been done on the dynamic simulation have been applied on the physical experiment. Therefore, the results from monitoring each configuration are presented below.

6.7.1 Horizontal Louvers

Within this process, a noticeable changes in the behavior of shading inside the space that reflect on the temperature of the indoor environment; also, a more improvement in the matter of energy consumption. The change in the secondary skin configuration comparing to the non-shaded condition results in better energy saving of about 34% of KWh from the different times that fell under the calculated tilt-angle range (Figure 6-13).
6.7.2 Vertical Louvers

Within this process, very slight change undergone in the behavior of shading and solar heat gain inside the space, as well as little improvement in the matter of energy consumption. The change in the secondary skin configuration results in better energy saving for about 9% of KWh comparing to the non-shaded condition, and from the different times that fell under the calculated tilt-angle range (Figure 6-14).
6.3.3 COMBINED CONFIGURATION Horizontal and Vertical

The combined configuration in the physical experiment shows that approximately 40% saving in KWh of HVAC energy consumption (Figure 6-15). If we compare this scheme against the vertical and horizontal louvers, we see that the combined configuration has better performance and less solar heat convection, with approximately 6% more than the horizontal and 21% than the vertical system. This interesting behavior proves the potential success of this configuration during other day times.
The observed conclusion about this configuration is the good performance of the dynamic façade regarding the energy saving and solar heat gain. This functioning fits the attributes of intelligence in kinetic façades. For instant, this configuration may be used if the space sensors detect that only certain numbers of spaces are occupied in a building.

6.8 Kinetic Scenario for Actuation Pattern

From those results, we can see again that the model with secondary skin has better energy performance and temperature average than the non-shaded condition, and a better scenario was proposed in Figure 6-16 in order to show the kinetic skin performance. It represents the best available selection from the manual test; however it is not necessarily show the optimal solution of this compilation. As shown in the graph, the KWh values represent the amount of the energy consumed for each setting in the study, however, as
the same taken in the simulation runs, this time comparing to a static-combined configuration. For the static scheme, the tilt angles have been chosen based on the ultimate performance position from the combined configuration, which is at 2:00 pm, and angles of 45° horizontal and 90° vertical.

![ALL CONDITIONS - KWh CONSUMPTION](image)

Figure 6-16: Comparison between all conditions KWh consumption within each hour step.

Also, better results should have been done automatically by implementing advanced equipment of sensors and actuators on the secondary skin, which allow generating numerous configuration parameters that provide the designer with optimal options.

6.9 Experiments Conclusion

In this experiment, the results show better performance for the combined configuration rather than the only horizontal, vertical, or static modes. The horizontal configuration however has shown good energy performance and lower temperature fluctuation
comparing to the others. The reason for this behavior because the horizontal louvers perform better when placed on the south facing since the sun altitude is perpendicular to the blades, whilst the vertical louvers perform better when placed on the south-east and the south-west facades due to angle position of the sun. These results justify why the combined configuration is better in energy performance and less extreme in interior temperature. Table 6-3 represents the best available selection from the manual test and its performance percentage; however it is not necessarily show the optimal solution of this compilation.

<table>
<thead>
<tr>
<th>Performance of Physical Model Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 19th – 20th</td>
</tr>
<tr>
<td>Static-Combined Configuration 45° - 90°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Horizontal Louvers</th>
<th>Vertical Louvers</th>
<th>Combined Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>8%</td>
<td>-21%</td>
<td>17%</td>
</tr>
</tbody>
</table>

Table 6-3: The performance of all dynamic configurations in comparison with the static-combined louvers.

### 6.10 Analysis Conclusion

To sum up, a table has been developed to conclude the whole configurations results by means of their actuation range and the cooling consumption during their performance. The dynamic secondary skin has infinite probabilities of configurations with different tilt angles. Therefore, simulating the model manually is less efficient to define the possibilities than doing it via parametric software, such as Grasshopper from Rhino. As a
result, Table 6-4 represents the selected configuration for both simulation runs and physical models study. In addition, because of the wide range of possibilities and time limitations, these results are just showing limited results, which means that only limited actuation is refined within this case for the kinetic skin.

<table>
<thead>
<tr>
<th>Secondary Skin Configurations</th>
<th>Watt Hours Consumption of all Skin Performance</th>
<th>June 19th - 20th</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dynamic Simulation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10:00am 11:00am 12:00pm 1:00pm 2:00pm 3:00pm 4:00pm</td>
<td></td>
</tr>
<tr>
<td>Glazing Only</td>
<td>205 266 284 223 276 245 266</td>
<td></td>
</tr>
<tr>
<td>Static 45° - 90°</td>
<td>162 210 224 176 177 194 210</td>
<td></td>
</tr>
<tr>
<td>Horizontal Louvers</td>
<td>157 204 217 171 211 188 204</td>
<td></td>
</tr>
<tr>
<td>Vertical Louvers</td>
<td>193 250 267 210 260 231 251</td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td>132 170 182 143 177 157 171</td>
<td></td>
</tr>
</tbody>
</table>

|                                     | Physical Model Experiment                     |                  |
|                                     | 10:00am 11:00am 12:00pm 1:00pm 2:00pm 3:00pm 4:00pm |
| Glazing Only                        | 295 304 309 284 249 241 247                  |
| Static 45° - 90°                    | 210 221 220 209 161 198 172                  |
| Horizontal Louvers                  | 184 167 157 192 194 183 200                  |
| Vertical Louvers                    | 299 257 229 246 247 238 241                  |
| Combined                            | 171 180 179 170 161 152 140                  |

Table 6-4: The results of all dynamic configurations performance that have been used in the study per Watt Hours.

The possibilities in the table show efficient outcomes during the selected solar altitude. By taking into consideration a static configuration for the experiment, the space will experience inefficient energy performance comparing to the dynamic ones. In addition, because static louvers cannot consider the all day solar condition; therefore, it cannot
enhance the interior space environment. It does show effective results during certain periods and altitudes, but not during the all day course. At 12:00 pm for example, the combined configuration works better than the static one.

Accordingly, kinetic systems are mainly developed to actuate in response to the climatic and environmental conditions, while static configuration is not efficient to interact with those surroundings. Finally, the geometry of the skin is very essential and it should be considered in future studies; designing a mindfulness transformation of the skin should ensure best results on both high and low solar altitudes.
CHAPTER 7 CONCLUSION AND FUTURE WORK

This chapter provides summery and concluding discussion of the work that has been presented in this thesis and according to the simulation runs and the physical model tests. Also, a possible future works will be presented for developing this thesis subject.

7.1 Conclusion

Smart shading is about protecting the interior space from the unfavorable sunlight that results in increase in the heat level in areas that encounter hot weather conditions. The normal shading elements in real life are designed to be closed during the high solar gain. Although this technique shows effective results in the matter of protecting the interior space from the hot solar gains; however, that results in dark interior environment and use of more artificial lighting. This waste of energy consumption can be mitigated by integrating the scheme of shading with intelligent features in one skin configuration that allows the shading device to track the sun movement and work in response to the environmental stimuli. Combining both strategies may result in better energy and daylighting performance in the interior space. In this thesis, the hypothesis is stating that the appropriate energy efficiency can be achieved through the use of advanced building’s envelope strategies involving kinetic façade, which presents potential of success in their results from the manual simulation runs of selected tilt angels together with the physical model tests, and if the dynamic louvers are applied to a building envelope, then there will be a noticeable reduction in energy use in comparison to the non-shaded and static configuration.
The study was conducted on various configurations of the secondary skin and their impact on quality of the interior space and its energy performance. The experiment was divided into two parts: a manual simulation using Autodesk Ecotect with a brief of how the tool is intended to work, and a physical model experiment to provide a relevant for the context of the simulation outcomes. Although not all factors were considered in the tests, the research shows that utilizing intelligent kinetic façade may enhance the quality of the indoor environment and adapt to the different environmental changes and occupants’ demands.

The number of configurations of the secondary skin was limited to one-hour time basis in the simulation and the physical model as well, which means that the initial results is more likely to be correct. However, for more accurate and successful results, it is important that we run hundreds of configurations using advanced algorithm tools. During the early design stages, the algorithm tools allow designers to simulate numerous amount of iterations according to certain criteria to achieve the optimal configuration for the skin. However, due to time limitation and technical difficulties with the algorithm parameters, manual simulation and physical model experiment were implemented for the skin configuration selection based on solar calculation formulas. The simulation tested the performance of the secondary skin on June 19th -20th from 10:00 am to 4:00 pm, and involved running of series of dynamic horizontal and vertical blinds, grid dynamic configuration, one static configuration, and one non-shaded condition. The drawback of this technique is that the selected configurations are not necessarily the optimal solution for the shading system. The algorithm would have selected better configurations that
have not been simulated within the framework of the test, and considering that would be a useful step for future work.

The purpose of this study is to find the best configuration in selected date of the year, which validates the effectiveness of using intelligent skin that brings better building’s performance. However, the simulated configurations didn’t show acceptable results on all times of the day course. The solar calculations took into account the clear sky conditions, which means the simulation showed effectiveness under the clear sky condition but not under the overcast sky periods within a day. The kinetic façade shows a successful potential in enhancing the indoor environment from different aspects; in better indoor luminous, and more efficient performance in term of energy saving. On the other hand, the fixed tilt angle shows a proper result in energy saving, but poor results in daylighting, which eventually would increase the need of artificial lighting.

7.2 Scope and Limitations

The science of intelligent shading and kinetic façades evolves a variety of characteristics that have not even discussed in the previous chapters. The study has considered the HVAC energy consumption along with the temperature average for the space, and was mainly intended to be conducted on the capital city of Saudi Arabia, Riyadh; however, due to time limitation, the assessment has narrowed down to only the city of Miami.

Another major limitation is the absence of modeling the occupants’ behavior. The proposed tool does not take into consideration the direct activities of the users inside the space, while the main feature of the kinetic façade is its ability to react with the occupant’s behavior. Accordingly, the ability of changing the desired configuration based
on certain tasks requires sensors and advanced equipment that detect the behaviors of the users inside the space.

### 7.3 Future Work

The proposed simulation was used to evaluate the performance of the secondary skin in optimizing the indoor environment quality for better HVAC energy and building performance. However, some other important factors have not been taken into account such as skin geometry, the direct activities of the occupant’s behavior, and surrounding urban context.

#### 7.3.1 Occupants' Behavior

The activities of the occupants inside the space are a very crucial and independent research topic. Although the occupants factor has been incorporated in the simulation runs; however, it does not incorporate the more complex behaviors and actions of the users like recognizing their facial reactions and their changes of tasks during their work time. The system should have the ability to change its performance to suit the use demands in accordance of their work time and location, and such attributes are very important step for more successful results for this area of study.

#### 7.3.2 Skin Geometry

In this study, the performance of the shading system was tested through the rotational motion of the louvers; however, this is not the only formation that can be applied on a building façade to enhance the quality of the indoor environment. The geometrical shape of the secondary skin and its actuation pattern can impact on the performance of the
indoor space. Another benefit of the variability of skin geometry is its potential to satisfy the aesthetic aspect for the architecture, which would allow architects to produce countless number of geometrical parameters to find the optimal iteration that combines the desired performance with the aesthetic requirements.

7.4 Summary

In conclusion, achieving innovative efficiency in building’s performance requires a high integration of work and research between architects, engineers, computational and digital fabrication designers, as well as high-qualified consultants. Discussing the design approaches at the early stages of the project life cycle is very important and has a significant impact on decisions that might shift the logic of the architectural project. Incorporating such factors like shading, daylighting, and human behavior into the simulation tools from the beginning of the design phase results in better performance and enhanced indoor environment, which addresses issues of energy efficiency and occupant comfort.

The performance of intelligent system depends on relative evaluation process including occupants’ demands and space functionality, and therefore, assessing such parameters does not follow any absolute standards. Accordingly, it is necessary to involve occupants model in the testing for more reliable results, and that leads to the importance of developing higher performance tools in the architectural field.

In addition, the intelligent skins and kinetic façades may lead to solutions for better energy performance; however, the downside of these systems is the high cost of the installation, operation, the difficulty of the maintenance. These issues make this kind of
solutions very controversial topic, and without taking these issues into account, the intelligent skins would not be feasible in the real architectural world. The architect plays a significant role in the design process and the feasibility of the system; however, working in such a system is a cooperative adventure and requires incorporation of different disciplines beside architecture like mechanical, electronic, material science, physics, and business. All that to ensure more performance effectiveness and shorter payback period.
REFERENCES

Aksamija, A. Sustainable facades design methods for high-performance building envelopes


Fu, T. S. (2009). Smart buildings: Synergy in structural control, structural health monitoring and environmental systems. (Ph.D., University of Southern California). ProQuest Dissertations and Theses,


Kim, J. T., & Todorovic, M. S. (2013). Tuning control of buildings glazing's transmittance dependence on the solar radiation wavelength to optimize daylighting and building's energy efficiency. *Energy and Buildings, 63*(0), 108-118.


