Sustainable Interactive Facades through Artificial Intelligence and Advanced Materials

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ABSTRACT

The contemporary buildings play pivotal role in overall energy consumption worldwide. Facades as the separator of external and internal environments of the building have significant impact of the sustainability of the buildings. Designing adaptive, intelligent and multifunctional facades in interactive architecture context is a promising approach to the future of smart buildings. This study aims to identify the pathways to construct interactive facades in order to improve the sustainability of buildings. To achieve this aim, the study reviews the most related literature to the topic in order to identify the main criteria of interactive facades and conceptualize how they should work accordingly. During research process, it is found that developments in artificial intelligence (AI) and advanced materials (AM) facilitates the implementation of interactive systems for facades. Through analyzing purposefully selected case studies based on extracted criteria of interactive facades, this study highlights the strengths and gaps of implementation of interactive facades. Then, this study relates the detected gaps to developments in AI and AM in order to propose pathways for improving interactive architecture in designing facades. These proposals and pathways are presented in terms of architectural implications and recommendations for future studies in final chapter of this study.

Keywords: Interactive facades, Artificial intelligence (AI), Advanced materials (AM), Intelligent buildings.

ÖZ

Çağdaş binalar dünya genelinde toplam enerji tüketiminde çok önemli bir rol oynamaktadır. Binanın dış ve iç ortamlarının ayrıştırıcısı olarak cephelerin, binaların sürdürülebilirliği üzerinde önemli etkisi vardır. Etkileşimli mimari bağlamda uyarlanabilir, akıllı ve çok işlevli cepheler tasarlamak akıllı binaların geleceğine umut verici bir yaklaşımdır. Bu çalışma, binaların sürdürülebilirliğini artırmak için etkileşimli cepheler inşa etme yollarını belirlemeyi amaçlamaktadır. Bu amaca ulaşmak için çalışma, interaktif cephelerin ana kriterlerini belirlemek ve buna göre nasıl çalışması gerektiğini kavramsallaştırmak için konuyla en ilgili literatürü gözden geçirmektedir. Araştırma sürecinde yapay zeka (AI) ve ileri malzemelerdeki (AM) gelişmelerin cepheler için etkileşimli sistemlerin uygulanmasını kolaylaştırdığı bulunmuştur. Bu çalışma, interaktif cephelerin çıkarılan kriterlerine dayalı olarak seçilen vaka çalışmalarını analiz ederek, interaktif cephelerin uygulanmasının güçlü yönlerini ve boşluklarını vurgulamaktadır. Daha sonra bu çalışma, cephelerin tasarımında interaktif mimariyi geliştirmek için yollar önermek amacıyla AI ve AM'deki gelişmelerle tespit edilen boşlukları ilişkilendirmektedir. Bu teklifler ve yollar, bu çalışmanın son bölümünde mimari sonuçlar ve gelecekteki çalışmalar için öneriler açısından sunulmuştur.

Anahtar Kelimeler: Etkileşimli cepheler, Yapay zeka (AI), İleri malzemeler (AM), Akıllı binalar.

TO MY FAMILY

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

Ac	Alternate Current
Ai	Artificial Intelligence
Am	Advanced Materials
BIM	Building Information Modeling
CAD	Computer-Aided Design
CITA	Center for Information Technology and Architecture
COST	European Cooperation in Science and Technology
Dc	Direct Current
DFM	Design for Manufacturing
DHW	Domestic Ho Water
DSSC	Dye-Sensitized Solar Cells
EAP	Electroactive Polymers
El	Electroluminescent
EPIA	European Photovoltaic Industry Association
ETFE	Ethylene Tetra-Fluoro-Ethylene
Eu	European Union
FRAB	Fiber-Reinforced Aerogel Blankets
GDP	Gross Domestic Product
HCI	Human-Computer Interaction
HVAC	Heating, Ventilation and Air Conditioning
Ia	Interactive Architecture
IBMS	Integrated/Intelligent Building Management System
Ie	Intelligent Environments

IEA	International Energy Agency
IEM	Introspective Environment Modeling
IOT	Internet of Things
LEED	Leadership in Energy and Environmental Design
LED	Light Emitting Diode
MEMS	Micro-Electro-Mechanical systems
Ml	Machine Learning
MIT	Massachusetts Institute of Technology
PET	Poly-Ethylene Terephthalate
Pv	Photovoltaics
PLA	Polylactic acid or polylactide
RGB	Red Green Blue
UAE	United Arab Emirates
Un	United Nations
Uv	Ultra-Violet
3d	Three-Dimensional
4d	Four-Dimensional

Chapter 1

INTRODUCTION

1.1 Problem Statement

The sustainability of building in terms of being energy-efficient is the main driver of contemporary developments in architecture. The global environmental concerns including non-renewable energy consumption and emissions are the main motives for architects and scholars to chase improvements in sustainability of buildings' designs. The adverse consequences of buildings' interactions with their external environment can be controlled by interactive buildings designed with the purpose of driving environmental interactions for improving sustainability in buildings through increasing building performance (Fallahi & Henze, 2019; Aksamija, 2013).

Interactive architecture (IA) provides an optimized system with adaptation and learning capability through interacting with the environment and users. This optimized system can bring comfort, safety and higher productivity and efficiency (Jaskiewicz, 2013). On the other hand, facade is the main part of building’s cost, which is about 25 percent of overall required budget regarding construction of a building. Facades are the key part of a building highly related to overall energy consumption and inhabitants' comfort, while with the critical role of providing meaning and aesthetic principles with their appearances (Zemella & Faraguna, 2014). Thus, a system capable of interacting and adaptation is the solution to increase the lifespan and in general, sustainability of the buildings' facades and therefore they can decrease the cost of buildings' operation .

Emerging technologies regarding optimizing the sustainability of buildings, especially advanced materials capable of interacting with their environment and adjusting themselves accordingly are the contemporary solutions for green buildings (Kretzer, 2017). Interactive architecture has the great capacity to embrace technological developments in order to increase the performance of buildings (Fox, 2016). However existing literature covering how recent technologies can contribute to IA are little (Jaskiewicz, 2013).

The literature regarding interactive architecture is more about media surfaces and the other potentials of interaction regarding environmental issues and sustainability of a building have been neglected (Fox & Kemp, 2009). However, the main contributors to interactive architecture believe that IA is a concept beyond media surfaces or facades, which are indeed interactive but are not the only architectures that should be accounted as interactive (Fox & Kemp, 2009; Haque, 2006; Fox, 2016; Oosterhuis, 2012). The holistic approach to the potentials of interactive facades as a complex interface between inside of buildings and the outside will lead to consider their other capabilities besides media-related features as solutions for sustainability.

IA has an interdisciplinary character requiring integration of different fields for multidisciplinary investigation on different aspects of this concept such as intelligence and materials (Jaskiewicz, 2013). Contributors to IA constantly push the boundaries of traditional thinking about architecture in terms of material performance, connectivity and control (Fox, 2016). There is a need to investigate on this evolving concept through reviewing trends and projects from multidisciplinary perspective.

IA is a shift from traditional architecture regarding representation and images towards processes and behaviors (Fox, 2016). IA is not only about a finished product as traditional architecture, but also an evolving process in opposition to finite (Jaskiewicz, 2013). IOT, ubiquitous computing and smart devices are everywhere and full automation similar to driverless cars are now completely feasible in construction industry (Sinopoli, 2016). Designers and architects should update their mentality towards new era of architecture, which is the combination of analog and digital world.

Thus, there is a need to define interactive facades based on fundamentals of interactive architecture described by the prominent scholars of the field. In addition, there is a gap in literature review to connect the recent advancements of Artificial intelligence (AI) and advanced material (AM) to interactive facades in order to propose sustainable solution for future interactive facades.

The stated problems and gaps are led to these research questions specifying the aim of the research and also the nature of the research:

1. What is an interactive facade?

2. How AI and AM can contribute to sustainability of an interactive facade?

1.2 The Aim of the Research

According to stated problems and questions, this study aims to link interactive architecture and sustainability through exploring new technologies in order to optimize the functionality of facades in buildings. Reviewing the literature enables this work to specify the realm of architecture context and define interactive façade accordingly. In addition, the aim of this research is to review the possibilities that recent technological developments in artificial intelligence (AI) and advanced materials (AM) fields have been created in order to develop the performance of facades in an efficient manner.

New technologies regarding facade construction can amend weaknesses or/and improve strong points of an interactive facade through creating more intelligent buildings. Advanced materials can add to flexibility of a facade in order to increase its adaptation with external environment. An optimized system uses the potential of the input in a way that the output will be the most productive as possible. Therefore, this research will review the potential of facades to increase the productivity of them in terms of environmental sustainability. An optimized facade will be defined in the context of interactive architecture and related emerging technologies as the proposed approach for constructing sustainable facades. According to mentioned aims of this study, the objectives of this research are as follows:

1. Discovering the definition for interactive architecture.
2. Defining sustainable interactive facade according to extant literature.
3. Identifying the main properties of a sustainable interactive Facade.
4. Highlighting the recent developments in artificial intelligence (AI) and advanced materials (AM) applicable to interactive facades.
5. Analyzing selected case studies in order to identify the highlights of cases and discover the gaps that can be filled by recent developments in AI and AM in interactive architecture context.

1.3 Methodology

According to the research questions and devised objectives of this study, the chosen methodology is as follows:

The case study research with linear-analytic structure suitable for the exploratory/descriptive nature of this research have been chosen to conduct this study (Yin, 2017). In this structure, the researcher after stating the research problems, reviews the prior literature to extract desired data to analyze the case studies in order to provide results and conclusions (Groat & Wang, 2013).

In order to extract theoretical foundations of this study, a descriptive mapping review of literature has been conducted (Paré & Kitsiou, 2017). Through literature review, a descriptive study provides information about the required definitions, related technologies, features of sustainable interactive architecture and its application in constructing facades. Literature review is used to extract the fundamental aspect, properties, trends and patterns of sustainable interactive facade from previous theories, propositions and findings (Paré et al., 2015).

Further, this study through analysis and exploration of assigned case studies, will assess the extracted properties in real projects to grasp a better understanding towards empirical applications of sustainable interactive architecture in facade design and construction.

Finally, through analysis of case studies based on extracted patterns and trends, this study concludes pathways in terms of architectural implications and recommendations for future studies regarding sustainable interactive facades' design and construction. These pathways are based on available/emerging technologies in order to be feasible to follow.

1.4 Contribution

A sustainable interactive facade within an integrated framework will keep its fundamental characteristics as a facade of a building, while enjoying new capabilities regarding interacting with its environment to be more sustainable. New capabilities can be attained by new emerging technologies in interactive architecture field with the purpose of creating systems to be more beneficial for users and environment .An integrated framework has a core value that all the entities involved within the framework should function together based on that core value. Sustainability as the most crucial topic in modern literature related to building design is the core value of this study's framework. Lack of integration in interactive system can be destructive, since artificial intelligence's interactions without value, strategy and purpose can lead to unknown paths (Jaskiewicz, 2013).

Sustainable interactive facades are expected to bring more comfort for inhabitants while protecting our environment and its non-renewable resources. The proposed combination of properties and adaptivity categorization will function as characterization tool for facade designers to have a holistic approach to sustainability of interactive facades. Comparative studies on cases reveal strengths and gaps in implementation of interactive architecture and linking developments in AI and AM to analyzed implementation can show promising pathways for constructing more sustainable buildings.

1.5 The Limitations of the Study

This research is subject to several limitations:

One limitation is derived from the chosen methodology to reach the aims of the research. Since this research is based on descriptive method, its focus is on linking theoretical foundations to extract criteria concerning the sustainability of facades in interactive architecture context. Thus, this study is devoid of quantitative data regarding technical assessment of proposed pathways. Therefore, this study proposes qualitative pathways, which can be a foundation for further researches having access to facilities to investigate the performance of designed facades based on this study's conclusion. The comparative conclusion of this research is a recommendatory one encouraging further researchers to investigate it with empirical data. However, the feasibility of the recommendations has been considered through using accomplished pathways and already-invented technologies.

The other limitation is derived from the scope of the research. Since this research focuses on interactive façade rather than interactive architecture and there is a gap in the prior literature regarding that, the available time for this research has been spent to conduct an entirely new research upon the desired topic. This research has been exploited the opportunity arisen from lack of previous studies on the topic to present a necessity for further investigations on interactive facades.

It was not possible to for the researcher to investigate the case studies on the spot and access to data was limited. Thus, the collection of data for conducting this research was through available online resources (e.g. websites, books and journal articles).

Chapter 2

INTERACTIVE ARCHITECTURE FACADE

2.1 Theories of Interactive Architecture

Pask (1969) contributes to comprehension of interactive architecture through regulation of a setting and format for this concept as a theory that is namely "conversation theory". This theory was a bedrock for developments in terms of interactive architecture. He encourages an environment, in which flexibility is maintained in a bottom-up manner for users that does not specify a goal and does not interprets desires. In a study conducted by Dreyfus and Dreyfus (1991) it was noted that early theories on this concept faced challenges in terms of establishment. This was mainly due to lack of commerciality as proof-of-concept lacked physical evidence. As computers advanced, artificial intelligences and cybernetics (biological computation, neural nets, evolutionary programs, bionics, and the like) have been funded from the 60s, which can be considered as a catalyst for the aforementioned theory. Thus, early implementations were limited on digital functions and subsequent funds. Brodey (1967) stated a critical point that the environment learns from a complex and self-organized intelligence, which has a consequent evolutionary outcome. A similar statement was provided by founder of Media Lab of MIT, Nicholas Negroponte. This is while his attention was mainly based upon digital media as well as design process, compared to physically built environment (1975).

A model was developed that was referred to as adaptive-conditional architecture, which further moved the abovementioned theories forwards. This theory allowed architects to interpret both spaces and its users as a system of comprehensive feedback (Eastman, 1972). He suggested that this system can be used for meeting the needs of users and increases adjustability of architectures through increased control. Dynamic stability is then referred to the responsiveness of actions of users within the scope of architecture and cybernetics in this context. These dynamics can be used for visualization and visual manipulations (Fox and Kemp, 2009). Notwithstanding that the model, which was proposed by Eastman was a model, which emphasis in the basis of machinery. Another interpretation was established to further increase adaptiveness of architecture and subsequently, add to the lifespan of buildings (Rabeneck, 1969). A hybridized approach was further introduced, in which machine-based approach was merged with cybernetic technologies available to be used within the context of architecture (Sterk, 2006). This model has been growing since and is regarded in other sectors such as, robotics. In this regard, feedback that is automated is merged with processes that are deliberate and function in higher levels (Coste-Maniere & Simmons, 2000).

A concept was developed under the influence of Cedric Price as adoption of theoretical frameworks that have been stretched to architecture through cybernetics that was referred to as anticipatory architecture. Flexibility, responsiveness, and indetermination towards changes within the needs and desires of users was observable in his projects (blueprints). A generator was designed by him that was not directed towards a specific program and entailed artificial intelligence in terms of architecture. However, this project was mainly focused on the outcome (end-effect) (Riley, 2002).

According to Fox and Kemp (2009) intelligent is described in this subject as something that has learning ability from its surroundings and has the capability to build upon the learnings to enhance and improve its interactions. Accordingly, Frazer stated that architecture is to be regarded as a “living, and evolving thing”. This interpretation was derived from extensive research and direct collaboration with Pask. Scientific and biological analogies are dominant in this work alongside chaos and complexities of cybernetics. Frazer emphasizes on various aspects of evolution regarding change as an outcome and the fact that conditions’ affinity is upon information. Environmental aspects are highly regarded in his work, while natural ecosystem replication is not comprehensively advocated. Natural ecosystems are referred to complex structures, in which recycling, change, adaptation, and effective usage of energy is incorporated. Direct analogies are to be derived from natural processes as a fundamental part of being part of natural and environmental ecosystem, which is a key point as architecture has taken a shift in terms of sustainability. A symbiotic behavior that is in persistence and linked with the natural features and properties is the emphasis of what was proposed by Frazer. In addition, he states that this method and perspective is required to move beyond norms and standards with the direction and focus upon organic principles (Frazer, 1995).

As a result, he then reports a number of benefits and advantages that can be achieved through such systems. This becomes more vivid in terms of resource usage (including cost and materials), energy consumption and waste production. In the work of Michael Fox and Miles Kemp (Interactive Architecture, 2009), they have stated that the aforementioned work of Frazer is a vital matter. In addition, they have noted that evolutionary system is to be criticized as genetic algorithms are commonly used for design as equipment, but rather did not expand to establishment of adaptive usage of intelligent spaces. Presence, input, and behavior of users can be adapted in a dynamic manner as descriptions and terminologies are used in a variety of ways in terms of technologies for buildings and construction sites.

Interactive architecture can then be described as a form of architecture, from which autonomous behavior is presented that entails evolution in term of interaction with the environment that it is located in as well as the users. A bilateral linkage among buildings and spaces as well as inhabitants can be thus referred to as interactive that yields in shifts for either side. Hence, it can be said that interaction varies from mutual reaction as interactive incorporates influences upon output as well as the means for achieving it. A mere reaction to wants or needs is henceforth defined as active, which according to what was mentioned, has a clear difference with the term "interactive". In addition, it was noted that the concept of interactive architecture is to be separated from automated architecture, as the latter consists of systems, in which automation has been implemented for construction that is based upon an artificial intelligence on a limited level. Such programs have a planned and predefined behavior (reactive), responsive (linkage and communication between user and building), Trans active (emphasizing on transaction and its emergence) are other forms that are to be distinguished within this context (Jaskiewicz, 2013).

It has been stated by Philip Beesley that architecture is to be regarded as a sector that encourages invention and adaptability, and does not rely on location, time nor technology. Furthermore, it has been reported that in the existing era and with technological advancements, there is a high potential for meeting and solving issues of environment and society. Thus, architecture has a significant power to influence the overall life of inhabitants and also living creatures outside of the building as adaptive systems can be expanded in this regard (Beesley et al., 2014).

Castle (2005) believes that regardless of concerns surrounding the topic of digitalization and high-tech environments, technology can improve social life and it can be implement intelligently in facilities. Digital interactions are widely believed to be the main reason to separate people through virtualizing presence. However, Castle believes that interactive environments at different scales from public media facades to smart phones can eliminate the limitation of distance and provides privacy and publicity simultaneously. Castle stresses the aspects of connection and integration in the concept of interaction in architecture and adds that interactive architecture ultimate goal is only to connect. Castle mentions the Möbius House as the great example of interactive space and structure enabling a family to work and live together without spoiling other members' privacy and need of socialization.

Figure 2.1: The Image of Möbius House Facade (Möbius House, 1993)

Möbius House is built in 1993 by UNStudio in Netherlands and its architects won different awards for their intelligent design. This house benefit from a spatial loop enabling the house to hold workplace and family-space at the same time and connect the family members' lives without sacrificing their need of privacy (Möbius House, 1993). The mentioned house is devoid of sophisticated intelligent devices of interactive system, but it is interactive towards its environment through sophisticated design of space.

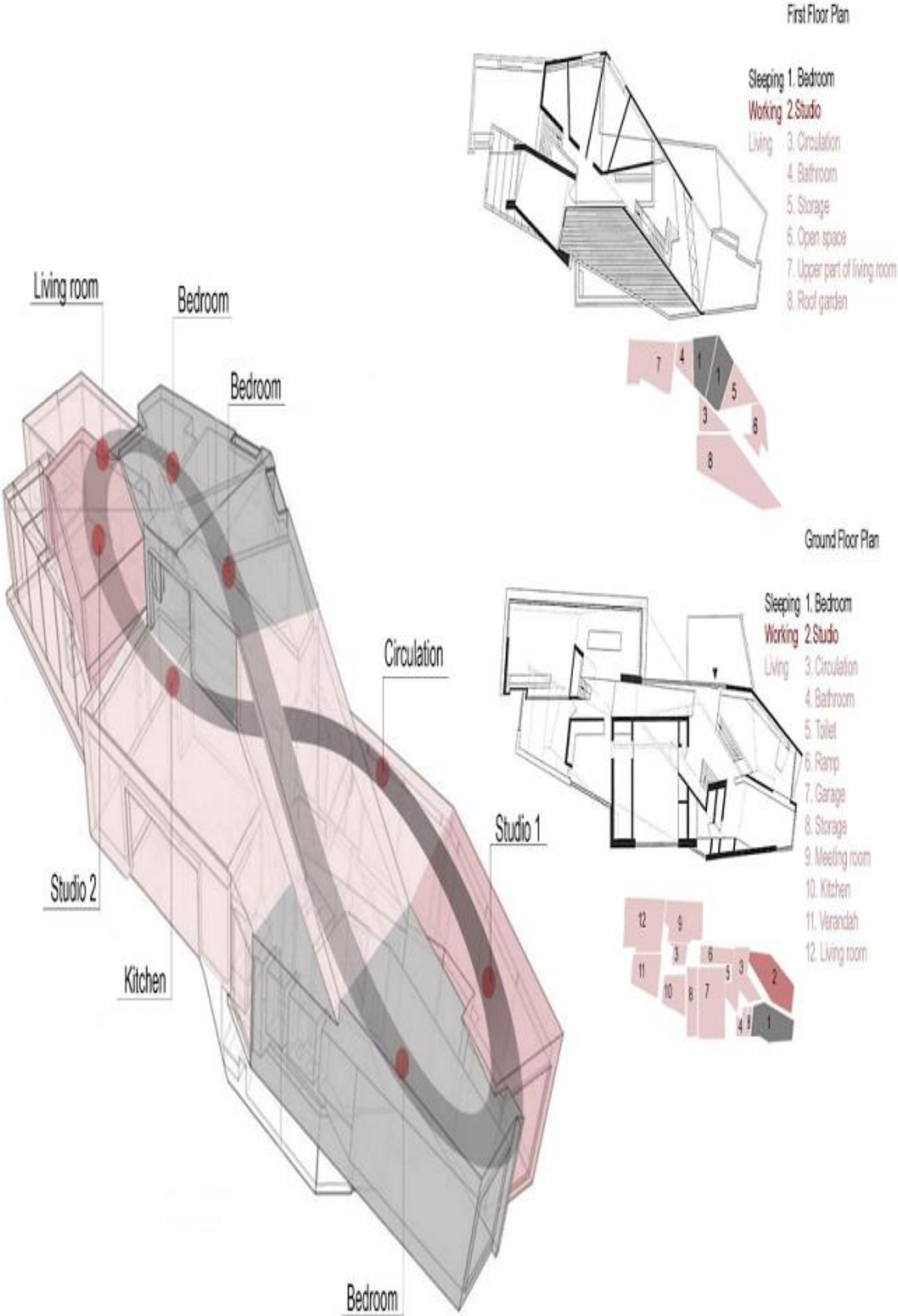

Figure 2.2: The Infinity-Shaped Plan of Möbius House (Möbius House, 1993)

Möbius House example implies that interactive architecture is not only about employing technology such as artificial intelligence and advance materials; it is about employing technology and other means in order to connect different entities, which are not connected without the resulting architecture. In order to have an interactive building, it is not vital to have intelligent systems such as talking elevator envisioned by Usman Haque (2006). This type of artificial intelligence is becoming ubiquitous and we all are experiencing it through our smartphones (e.g. Siri, Alexa and Bixby). The lesson being taught by Möbius House is that the resulting connectivity from interactive architecture should be the main focus rather than pure emphasis on utilization of technological means.

Feifer et al. (2018) explain that user interaction is in first priority among other interactions of building in order to assess the value of the building. They made a slogan in their work saying "people first" to stress this matter. He introduces generations as "indoor generation" that just few years ago understood that should design buildings capable of interacting with its environment in order to improve inhabitants' health. This matter does not belittle the significance of the topic of sustainability and only suggesting that architects should not lose ultimate purpose while designing sustainable buildings and design buildings for human comfort that should be sustainable and green.

Hale (2018) believes that interactive design should be used to make buildings user-centered. Smart buildings are becoming a trend, since they are capable of providing sustainable solutions. However, Hale (2018) believes that, architects have to take well-being into account while designing smart buildings. He envisions that interactive architecture can encourage people to become involved in shaping a better world in terms of sustainability and humans' well-being.

Feifer et al. (2018) introduce the concept of active house as a building with intelligence capable of initiating interactions with its environment. These interactions should be designed in order to achieve three main goals:

- Improving the comfort and health of inhabitants
- Improving the efficiency of energy consumption
- Improving the effect of building on its environment.

Feifer et al. (2018) stress the importance of interactive systems and spaces within buildings for creating entertaining and pleasant environment for inhabitants, while encouraging responsible behavior towards our planet.

Haque (2006) emphasize that interactive and hi-tech do not address the same concept in architecture. He explains that something interactive is not necessarily a high-tech object and vice versa. He asserts that technology is able to facilitate the production of interactive objects and spaces in greater scales. This means that market economy leans on technology to achieve economies of scale in production of interactive buildings as witness in smartphone industry. He explains that interaction concept should be discussed from different perspectives in order to be defined comprehensively. Building exteriors become deteriorated under exposure of wind, rain and sunlight. This single direction transaction between environment and the building is not interaction. He adds that even designed louvers on buildings' facades directing the sunlight into the building are not interacting with sunlight and the right term to use for this relationship is "reaction". The circularity of relationship between two entities is fundamental in interactions. Thus, when building only can responds to its environment and is not able to have an impact on its environment, that building is reactive not interactive. He categorizes interaction into two types: single-loop and multiple-loop. Single-loop interaction is about transaction of some pre-determined and fixed scenarios between two entities such as experienced with teller machines of banks. It is predictable and boring from an artistic point of view. On the other hand, multiple-loop interaction is similar to human interactions and friendships. People in society exchange information with each other and create evolving and on-going relationships. These relationships are becoming constructed through emerged interactions circularly. He believes that multiple-loop interaction is constructive and is dependent on openness and continuation of two-way relationships rather than the complexity of the process of responses. Further, he adds that constructive interactions should have an impact on the goals of each interaction counterparts. He envisions the future holding architectural entities that can interact constructively with humans similar with have experienced among kind. The interactive buildings in Haque's mind is an organization that inhabitants feel that they should be involved in the process of mentioned organization to shape their pleasant environment and they have to feel joy and pleasure from their involvement. The goals and outcomes of this organization will be achieved through unpredictable series of interactions between the building and inhabitants. Thus, buildings should benefit from some sort of intelligence to be able to interact with their inhabitants in multiple loops to create something not pre-determined and creatively new. He explains that devices with reactive and single-loop interactive features can be used in systems for making buildings efficient. This efficiency can be planned in design process of the building and it is limited because users' preferences are not included in the concept of this particular efficiency. On the other hand, interactive buildings capable of creating multiple-loop responses with their inhabitants and acting accordingly enable users to create their perceived efficient environment. Interactive architecture can create user-friendly spaces for users, since the spaces evolve throughout the process of interactions between the architecture and humans and this evolution or transition is based on humans' preferences (Haque, 2006).

Humans are surrounded by products providing interactivity through screens as interfaces. Smartphones, video games and new models of televisions are interactive but they are imprisoned in virtual world. Interactive architecture is a field that aims to merge virtual and physical realm of interactivity in order to encourage people to an active engagement with the created environment. The created environment is capable of rearranging its properties according to its dialogue with humans. In the era of interactive architecture, we should ask what this architecture is capable of instead of asking "what is this architecture?" (Fox & Kemp, 2009).

Oosterhuis (2012) clarifies that interactive architecture is different from responsive and adaptive architecture despite of having some similarities. He explains that interactive architecture needs two active counterparts communicating with each other and becoming influenced by each other. Pure adaptive architecture is about changing according to environmental changes implying that the architecture in this context has a passive role unable of initiating any action in relationship with its environment. An interactive architecture can be adaptive partially in relationship with its environment in order to be sustainable and environment-friendly (Jaskiewicz, 2013; Fox, 2016), but being active towards other system's components and people is fundamental in interactive architecture context (Oosterhuis, 2012; Haque, 2006).

New interactive buildings have been mentioned with different terms in literature such as "smart", "intelligent" and "active" (Böke et al, 2019) addressing same concept but from different perspective. An Interactive facade in a contemporary building is a part of wider interactive system, since integration in all parts of a building is fundamental for creation of an efficient interactive architecture (Fox, 2016).

Actualization of interactive architecture is dependent on the fusion of two main fields. These fields are computation (machine intelligence) as an intangible entity and kinetics (physics of motions) as a tangible entity. The interactions between these entities creates interactive architecture capable of performing beyond responsiveness and adaptiveness (Fox & Kemp, 2009). In further text, this study will analyze a great example of an interactive building to summarize this section.

The Edge has been built in 2015 has won various awards worldwide for its amazing features. It is located in Amsterdam and was built by PLP Architecture as a headquarter for Delloitte Company. This building is famous as the most connected, smart and green building worldwide. Its sustainability rating by Breeam organization is 98.4 % and it was awarded by the same organization in 2016 (Breeam, 2016).

Figure 2.3: The Edge Building in Amsterdam (Build Up, 2017)

All the employees are connected to each other along with the building through a customized app on their smartphones. The building recognizes the employees from their plate number and allow them to enter the building and provide them parking space and car charger (for electric cars). In Edge, there is no specific desktop for any employee. Instead, employees have different spatial options to spend their office hours and work. Employees are free to use Sitting desks, standing desks, balcony desks, work booths, concentration rooms. This concept of workplace design is called "hot desk" by its creators and it brings two advantages: A) increase in connectivity and B) 50% decrease in spatial consumption in comparison with fixed desktop plans (Bloomberg, 2015).

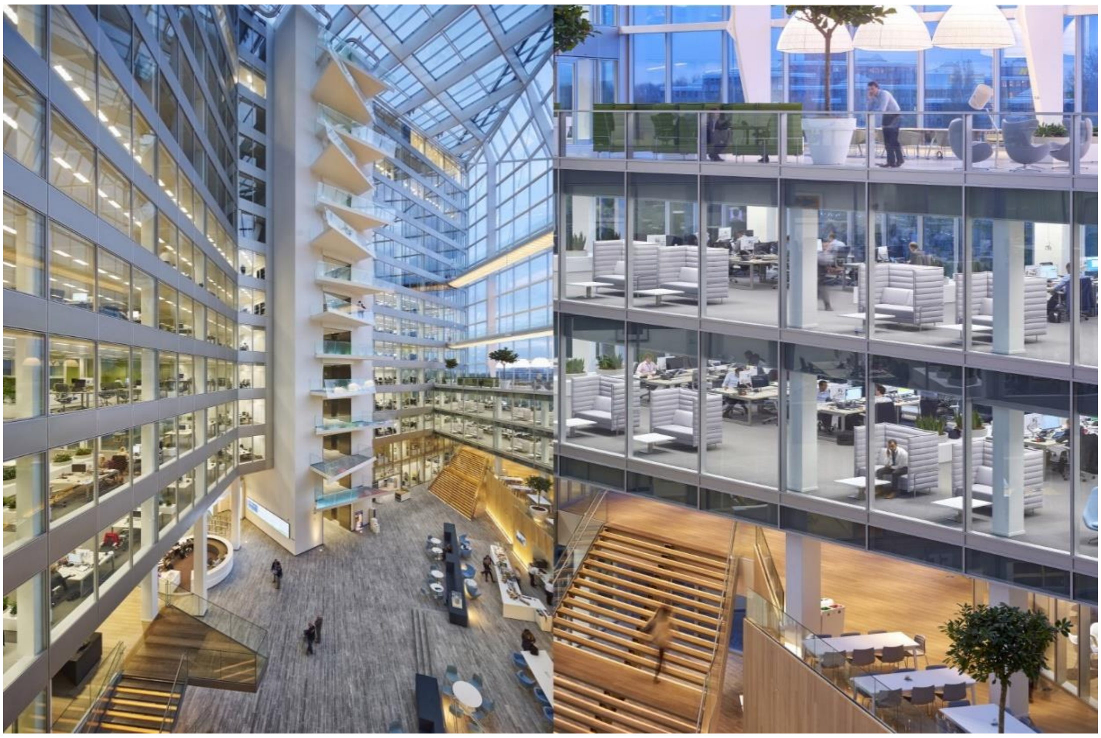

Figure 2.4: The Edge Does not Have Fixed Desktops for Employees
(Bloomberg, 2015)

The building is aware of each employee location and changes the environment according to their saved preferences. In addition, all smartphones can be connected to office media facilities with just touching their smartphones to "connect zone" area. This integrated and ubiquitous connectivity is created by special LED lights manufactured by Philips Company. The LED lights are powered by Ethernet cables enabling these lights to function as internet hub. These lights have been used all around the building transforming the building to a giant internet hub that can use IOT connecting employees with all parts of the building (Build Up, 2017).


Figure 2.5: The LED Lights Powered by Ethernet Cables (Bloomberg, 2015)

The Deloitte chief information officer, Erik Ubels explains that buildings plays a pivotal role in who we are and what we want to become and this factor causes that Edge to be one of the most requested workplaces for applicants in Netherlands (Bloomberg, 2015).

There are wonderful considerations regarding sustainability and eco-friendliness in design of Edge. The orientation of the buildings is based on the movement direction of the sun. This building is equipped with solar panels on the roof and southern facade providing energy for charging all electric devices in the office. These solar panels protect the workplaces against the sunlight as well. The Atrium and north facades are transparent allowing lights in order to regulate the visual comfort of interiors (PLP

Architecture, 2016). The exteriors of Edge is the host of bats and bees and there is a greenspace called "ecological corridor" separating the building from the nearby highway which provides safety for animals and insects against vehicles. The thermal storage for regulation of office temperature has been built underground in 129-meter depth, which is one of the most efficient heating and cooling system in the world. In addition, rainwater is collected for toilet flushes and gardening. The Edge has real-time data regarding employees' presence, exact locations and environmental preferences, thus it regulates the energy consumption accordingly and save significant amount of energy (Breeam, 2016).

Figure 2.6: The Ecological Corridor of The Edge Hosts Different Types of Animals and Insects (Bloomberg, 2015)

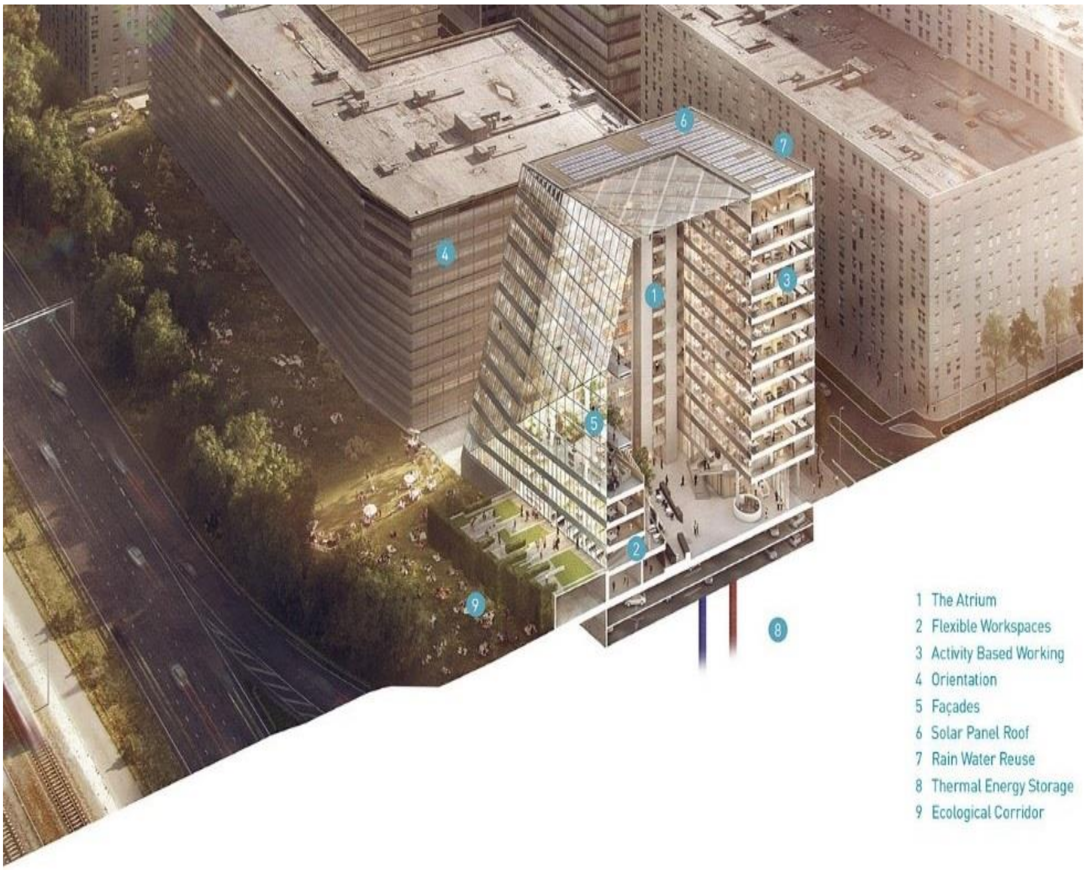

Figure 2.7: Different Part of the Edge Building (Build Up, 2017)

The Edge presents the potential of IOT and artificial intelligence within a building. The building functions as it is alive. It recognizes people, knows their daily schedule, knows where they are located exactly in the building, knows their environmental preferences and even knows how much sugar they want in their coffee. In Edge, employees can order food to the building or the building will inform employees about upcoming meeting in a specific place as it is alive. In addition, there are different types of robots for different tasks such as cleaning and patrolling the building (Bloomberg, 2015).

Figure 2.8: The Cleaner and Security Robots of the Edge Building (Bloomberg, 2015)

The Edge resembles all the words of pioneers in interactive architecture such as Gordon Pask, Helen Castle and Usman Haque. This building connects lot of things in its environment such as environmental forces, wildlife, electric devices, people and spaces similar to the concept of interactivity in architecture explained by Helen Castle (Castle, 2005). Employees are in a conversation with the building being more familiar with each other through time and the new outcomes emerges out of this conversation similar to Gordon Pask vison about interactive systems (Pask, 1976). The building is in multiple-loop interaction with its environment and making impact to the surrounding in purposeful manner. The building creates history with its environment and changes are occurring in the building as well as the environment continuing an evolving relationship. This history-based multiple-loop interaction resembles Usman Haque words regarding an ideal interactive system in architecture context (Haque, 2006). The Edge as the most connected, green and smart building can be the pathway to designing interactive systems and spaces exploiting the potential of interactivity with the existing environment for pleasant present and better future.

2.2 The Convergence of Digital Computation, Human Computer Interaction and Architecture

Theories mentioned above and the work of architects in endeavor to apply interactive and interaction with environment within the context of architecture and its spectrum have been developed as other technologies have grown in line with human interaction (e.g. digital computation). Smart environments incorporate systems of control on a comprehensive level, which is in persistence with the term ‘intelligence’. During the 80s and the 90s, computer science faced a rapid growth, which opened new pathways for integration with other sectors, especially architecture. Intelligent environments (IE) then were introduced as a mean for research and examination upon spaces. This was enabled through integration of computation and communication means and tools. Thereby, computation was linked to physical surrounding. Ordinary activities can be enhanced through computation, which is referred to as intelligent environments. An intelligent house then can be defined as one, where the needs of inhabitants are observed and are predicted to be met over a certain period of time (Mozer, 2005). Adaptive houses can go beyond simply being programed to perform an action and can learn from their surrounding through surveillance, understand actions, follow behavioral patterns and determine future status of the house to further satisfy the needs of the household (Mozer, 1999). Coen (1998) experimented the notion of intelligent room, where any objects touched by humans can take a shift into being smart due to multimodal human-computer interaction (HCI) on a natural manner. These enabled computers to have a participatory role within the conducted actions by humans in a profoundly new manner that was also introduced to people and their interactions with computerized systems.

"Ubiquitous computing" was a term to address HCI in a model that was proposed after desktop era, and was a key determinant in terms of IE and its development (Weiser & Brown, 1996). The term can be interpreted as full and comprehensive integration of computation throughout activities on a routine format. Furthermore, this has been regarded as an equilibrium point, where computer science meets behavioral sciences and design. In this method, users have the ability to access a number of devices and systems at the same time to conduct routine activities regardless of their extent of awareness upon the matter at hand. It was referred to as calm technology era. This can be regarded as the state, where computers function in the background of livelihood of humans. A considerable number of seminal projects were developed based upon the aforementioned intersection of sciences to emerge media, design and environments through computerized mechanisms (Fox and Kemp, 2009).

It is noteworthy and essential to note the fact that drivers that are merely market-related have played a major role in terms of advancements and improvements in the context of interactive architecture. This vitality derives from the direct role of users and their involvement. It is also crucial to note that such were not fully merged and integrated within the scope of architectural theories and conceptual works that were noted earlier in this section. Sensors and remote signals were introduced directly to the building sector and environmental control system implied within them. Remote control played a significant role at the time of its invention as operation was enhanced significantly. Two distinctive diametrical propositions have been noted in this regard that are life controlled by machine, and life defined by pragmatic convenience, leading to a state, where users/humans are highly dependent upon the surrounding environment (Senagala, 2006). However, the fear has been reduced significantly in recent times as technologies are now embraced and/or longed for. In the 70s environmental effectiveness became a notion of interest for architects as justification of usage of technology led to buildings having an improved rate of performance. As a result, this yielded in a lower cost, which was beneficial for the industry. Energy management systems and their rise within the architecture sector were another significant matter, which had their fair share of challenges in terms of application and implementation (Fox and Kemp, 2009).

With growth of personalized computers, users were faced with a significant and drastic change in terms of using technologies. This shift occurred in the 80s and empowerment became a term that was used to change the notion of enslavement (Senagala, 2006). Direct control (digitally), enhanced communication (programmed), and higher integration rates were achievable with the increased rate of PCs and their availability. Various hardware was made available to commune with each other as a standard mean of communication. A considerable number of non-communicative independent frameworks and protocols were introduced into the market as a consequent (Fox and Kemp, 2009). Market-related developments alongside real-world progresses led to a state, where architecture scholars initiated a thorough prototype perspective towards conducting projects. Smart home and workplaces became a topic of interest in the 90s regardless of their high dependency upon parallel technologies that were essential for this development. Wireless networks, embedded computation and sensors turned into justified technologies that made economic benefits on a clear manner due to feasibility. This was in persistence and consensus with prior studies and early theoretical works upon the matter at hand. As computers were made cheap and available for mass, economic terms were justified and integration of computer tools with architecture took a faster pace. It is noteworthy that internet and its versatile functions carried out a major role in the process of integration, information deliverance, and technological advancements (Fox and Kemp, 2009).

It was noted that the architecture sector and its movement towards adaptation and integration with computer tools was prone to optimization through newly introduced processes as a mean of adaptability (Fox, 1996). Thus, traditional perspectives were challenged and innovations were encouraged through conduction of exhibitions and/or conferences. Motion, stasis, and order were the main issues tackled by new technologies and were required to reshape and restructure based upon newly introduced and established opportunities within the market. Technological innovations with specific objectives towards improvement of mobility and transportation were additionally emphasized (Brown, 2003). Patterns of human interaction with the surrounding environment, particularly built, further calls the notion of adaptation in architecture to be improved as technologies progress on a constant manner. Societies and urban conditions face changes on an intense level. This is also influence by other factors such as sustainability concerns, and demand increases, which further lead to a point, where interactive architecture is the mere solution for aforementioned issues (Fox and Kemp, 2009).

New understandings form and emerge as technology opens new gates towards usage of materials and comprehension of natural processes, which in turn leads to optimized manufacturing processes and higher quality in the end-products (kinetic parts), which has entered a variety of production industries such as, fabrics, ceramics, polymers and gels, shape-memory alloy compounds, and composites (Fox and Hu, 2005). In this context, nanocomposite materials have shown a significance in terms of actuation, strength, reliability and performance. Materials as such and robotic science, if merged in a relatively small scale can open pathways towards new interactive architecture technologies that can have a significant influence upon the industry as a whole. Biological functions thus, have a vital role in this regard as nanoscale precision is a key variable for interactive architecture and its development (Fox and Kemp, 2009). As it was noted earlier in this section, integration of technologies from various sectors can be achieved through advancements obtained in terms of technology, which further integrates interactive architecture with other industries. As technologies can be transferred from one industry to another, innovations can find their way into architecture. A vivid example is the derivatives of electronic systems, which find their functions and implementations enhanced in automobile industry (Leen & Heffernan, 2001).

It has been reported by Senagala (2005) that manufacturing and fabrication were the two industries that majority of innovations were conducted and provided for. Traditional form of driving was changed by drive-by-wire technology as a new control system within the scope of HCI. This is a similar advancement with the aircraft industry improvements of fly-by-wire systems. It is noteworthy that these technologies are within the scope of computation and have found their way to be implied and used in other industries, particularly in construction and building sector. It perhaps can be expected to face a technology in this context that can be named “live-by-wire”. Mechanical paradigm can be shifted into biological paradigm through transitions within the concept of interactive architecture. This calls for pragmatic technologies that focus on performance and require comprehension as well as awareness, conceptualization, and philosophical concerns regarding humans, overall well-being and natural environment on an international scale. Designers also take a shift in their roles as technologies merge and thus, evolution occurs in this sector. Thus, the work of designers change and take new formations accordingly. In the light of what was mentioned above, it is crucial to highlight the fact that interactive architecture in its early stage was based upon digital media and IA advancements. Such are intangible forms of interaction. Futuristic visions and perspectives of IA are subsequently designed from interactive architecture. Physical changes and emergence with computation leads to a higher extent of comprehension regarding contextual work in this matter. It has been reported that this field is in its early stages of development, and has a long way for fruition into a thorough state. This is a major driver for conduction of research upon this matter as the experts in the field have suggested additional, comprehensive and comparative analysis and investigations to be conducted in this subject (e.g. Fox and Kemp, 2009). Hence, the proper and adequate question to be asked in terms of architectural functions in this regard is "what are the functionalities of that building" and not "how or what is it made of". This perspective is in persistence with the notions introduced and identified in this research as architecture in its advanced and modern formation brings about new functions and features to buildings.

Embedded computation has been found to be the tool of creating interactive systems capable of interacting with humans. This belief started from conversation theory of Gordon Pask (1976), one of the pioneers of cybernetics, who had remarkable collaborations with architects contributing to the concept of interactive architecture. Architecture and Human Computer Interaction (HCI) have many similarities regardless of architecture being a very old field of design and HCI as a very young field of design (Dalton et al., 2016). HCI after emergence of graphical interface is about creating interactive systems and spaces enabling users to interact and participate in conversations with computers. Augmented and virtual reality are being used by architects to create systems and spaces in order to demonstrate the reality of future for other stakeholders. Bullivant (2005) introduce the digitalization or embedded computation as the fourth dimension of the era connecting time and space in a way that we can travel through time and connect physical and virtual entities together and interact with them.

With the rise of useful technologies in HCI fields, architects became attracted to these tools to design interesting interactions in their projects to engage and entertain their users. Interaction design with the help of technology has become more feasible and the variety of options have been increased (Dalton et al., 2016). In the following text, this study will review some prominent interactive environments created by architects.

In 2008, ART+COM used digital components to create an amazing ambient for showing the history of BMW products. The collection of metal balls present five prominent models of BMW cars in history. The coded Electronic kits control the movements of metal balls in an aesthetic manner that attract visitors of BMW museum in Munich, Germany (Kinetic Sculpture, 2008).

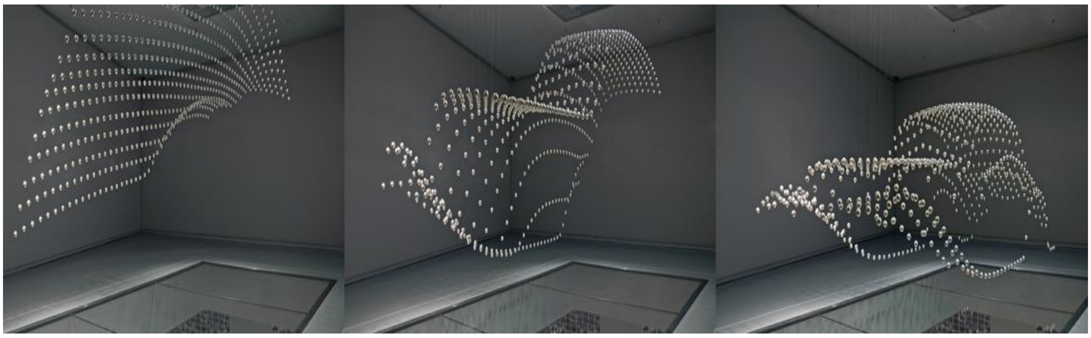

Figure 2.9: The Metal Balls Shape Different Models of BMW in an Aesthertic Manner (Kinetic Sculpture, 2008)

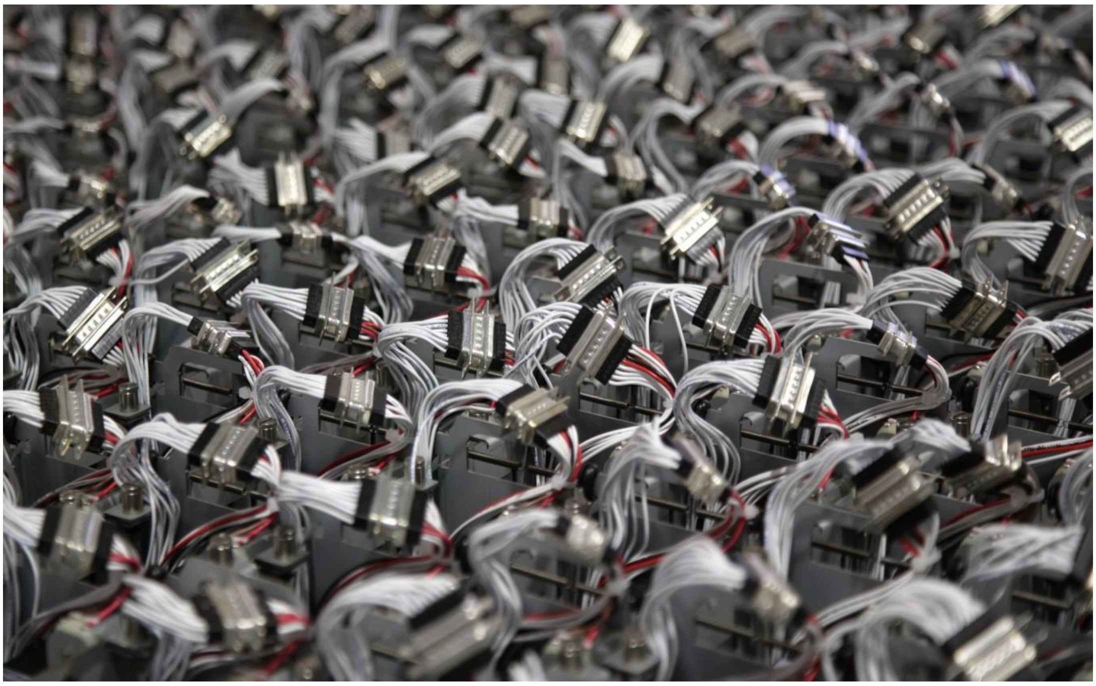

Figure 2.10: The Coded Electronic Kits of Kinetic Sculpture Created by ART+COM (Kinetic Sculpture, 2008)

In 2001, Architects in MIT created an interactive surface called HypoSurface capable of communicating with the visitors through creating aesthetic motions on its surface (Hyposurface, 2001). The combination of sound, light and dynamic change on the surface creates attractive interactions with users that can communicate with this surface through different environmental stimuli including electronic data, sound, climatic conditions and touch (Aegis-hyposurface, 2007). The creators of HypoSurface claim that they have built the first dynamic screen worldwide that can reconfigure its status according to its environment (Goulthorpe et al., 2001).

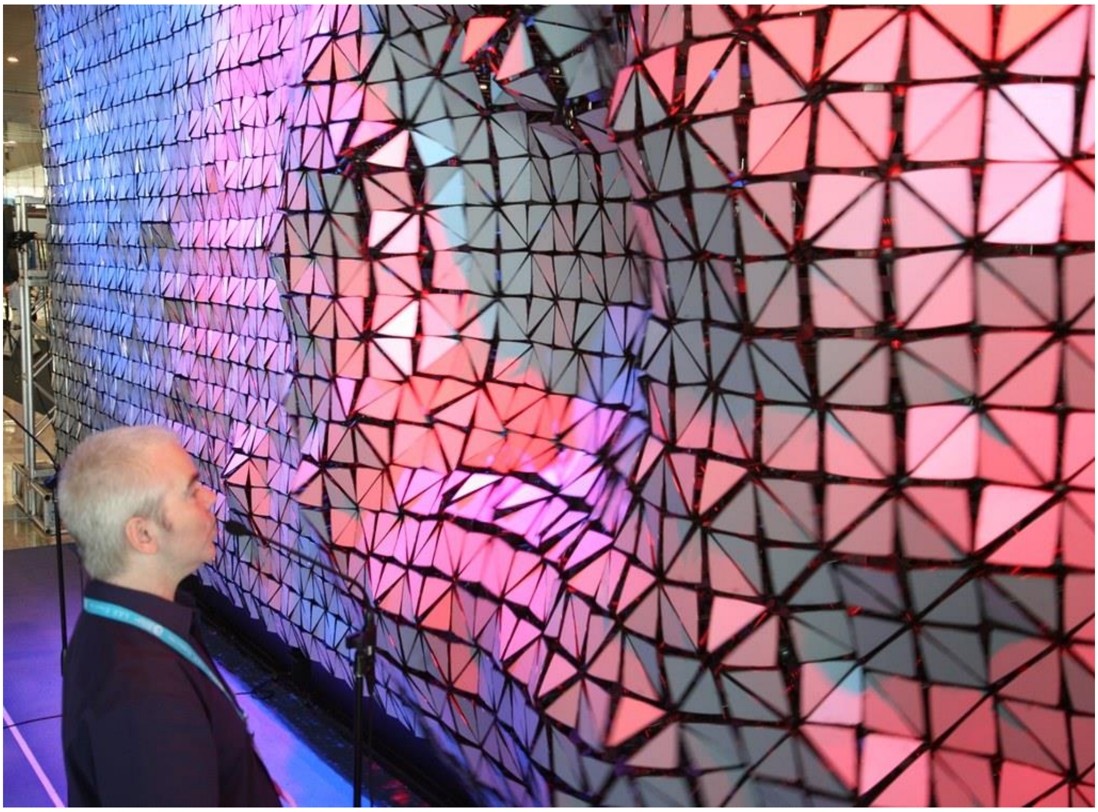
Figure 2.11: HypoSurface Creates Ambient Interactivity (Aegis-hyposurface, 2007)

In 2018, ONL studio has created an inflatable and portable pavilion called "Little Babylon" that can be located in different places. This interactive pavilion can harvest environmental data from its surrounding and present them to audience in an awe-inspiring manner (Little Babylon, 2018). This movable pavilion acts as a "data-parasite" and mixes data from where it is located with specific topics from internet and visitors' requests in forms of hashtags and finally present the resulting data in an artistic way including sound, light and movements (Rezone, 2018).

Figure 2.12: Little Babylon is a Portable Pavilion Harvesting Data from its Environment and Internet to Inform the Visitors in an Artistic Manner (Rezone, 2018)

2.3 Significance of Sustainability

Sustainability, inclusion and smartness are key factors that are regarded in the context of construction sector on an international scale through proper and adequate usage of resources with lowers possible rate of greenhouse emissions (Casini, 2016). This in turn leads to higher profits for the industry as a whole. Within three decades, it is expected that the population of humankind will grow another 2.5 billion, which is not only significant but rather alarming. Living standards, and overall quality of life is threatened by this worldwide growth that is not controlled. Regardless of negative impacts that this notion has upon the earth as in terms of sustainability, energy usage of construction and building sectors are to be increased considerably. According to IEA (2013a) energy efficiency of this industry is predicted to have a 50% growth rate in the next three decades. This gigantic number cannot be neglected, which is another driver for conduction of this research as this is a highly crucial matter for all humans. However, it has been reported that the construction industry can be proven sustainable in terms of energy consumption as innovative products and other interventions can aid the process (IEA, 2015a). Accordingly, construction industry holds the second rank in terms of promising potential for energy consumption reduction and cost-efficiency after energy industry. Buildings can be made and build in a way that emissions are reduced significantly through regulation of new standards parallel to new advancements in architectural technologies considering lifetime of a building and the initiation costs of operations (Saheb et al., 2015).

In accordance with what was mentioned above, existing buildings can be modified and have new sources of energy integrated and implemented within their bodies. It has been reported by EPIA (2011) that all the needed electricity within EU could be generated through photovoltaic (PV) panels, if installed all across the continent and every roof. Unfortunately, still there are areas in Europe that have not embraced the sustainable considerations (such as PV utilization) fully. Environmental impacts of buildings can be reduced significantly through usage of materials that are made with this objective specifically in mind. It is noteworthy that the building sector is held accountable for a third of collective resource consumption on international scale (over 40% solid waste production in developed countries) (Herczeg, 2014). Energy consumption of building is high as the energy is used for various reasons including heating, cooling, interior ventilation, domestic hot water (DHW) production, lighting appliances, electrical equipment, people transport, and cooking, using gas (21%), electricity (30%), and biomass (29%) as main energy sources (IEA, 2015b). The age of building alongside the climate of the area are main determinants of the extent of which a building uses energy (Casini, 2016).

Heating and cooling are regarded as significant aspects that can be aimed to reduce energy consumption through reduction of usage of fossil fuels (IEA, 2013a), which is dominant energy source in a number of countries. Final energy consumption in residential energy use and services energy use have been reported to be above 30% for the US and approximately 40% for the EU (Hun, 2016). Space cooling holds a 5% energy demand. This is while it has been noted that this rate has been increasing in the recent years (43% incline in the last decade). Casini (2016) reported an increasing demand regarding cooling within building industry in 10 years by 72%. This is a significant usage of energy, which through adequate and properly designed technologies can be decreased and optimized to a certain level that is in persistence with international goals regarding sustainability. Home appliances and electric tools are also reported to have an increase in terms of energy consumption. This is in direct relationship with the increasing amount of tools and equipment within houses or offices as well as enhanced performance of these tools. In accordance to this improvement, their usage relatively increases, which supports the aforementioned statement (IEA, 2015a).

According to what was mentioned earlier, shape, orientation, ratio of walls and windows and other features of buildings are main contributors and determinants of energy consumption of a building and its extent. Relatively, if thermal insulations are installed poorly, inertia is low, and thermal bridges exist, can lower the performance regarding energy consumption. Additionally, heating, ventilation and AC (HVAC) is poorly installed and implemented, leads to lower performance. Moreover, lack of using renewable energy sources, lighting systems and other utilities are among the factors that can influence the degree of energy consumption of a building (Casini, 2016). Enhancement in the noted factors leads to higher benefits to the owners as well as inhabitants of the buildings. Maintenance can be done with lower costs, property will have an increased value, durability will be improved, and productivity as well as safety can be positively influenced if systems are implied in this regard. Social health costs can be significantly decreased, air quality can be developed, budget and tax variations can be marginalized and thus, a higher Gross Domestic Product (GDP) can be achieved as energy consumption is optimized (IEA, 2014).

In addition to what was mentioned above, utilities can be enhanced in terms of cost as customers will exhibit a lower rate of turnover (whether intention or actual), and emissions are reduced. Construction sector can be considerably contributed in terms of benefits as performance level increases. This is highly crucial as this sector is a key predictor of GDP due to high rate of employment and vast size of the industry as a whole with its linked sections (i.e. companies and/or individuals). This consequently leads to a state, where the economic state of country can be aided. Only within the borders of EU the construction industry holds 11.5 million jobs that are directly under this sector alongside a rate of approximately 10% of employment in nonfinancial market economy (Saheb et al., 2015). Degree of commitment is a key element regarding buildings and their structure and the extent of which energy consumption is efficient. This required all nations to have a consensus and endeavor to decrease energy consumption for the sake of planet as well as all humanity. This notion also falls within the scope of sustainable development goals defined by the UN. Hence, buildings can be built based on energy efficiency with objective of using alternative energy sources (clean and/or green energies) rather than the traditional and pollutant energy generated by fossil fuels. This is in persistence with the line of progress in terms of architecture and is in line with collective awareness globally to move against global warming and reduce environmental negative impacts from human activity. Buildings that are considered smart have a better shape and incorporate technologies that are directed towards tackling the aforementioned issues. Smart facades (construction) and systems (equipment) can be interacting on an intelligence basis, where safety, accessibility, comfort, and health is encouraged through environmentally-friendly and user-friendly implementations of technologies. This is achievable through usage of natural resources effectively and emergence of technologies within the body of architecture as a whole. In turn, this will yield in an overall improvement of quality of life and well-being of all parties involved from ordinary people to stakeholders (Casini, 2016).

2.4 Interactive Facade

The facade is the intervening component of building between external and internal environment of the construction facing with constant changing situations of mentioned environments. The changes occur in terms of climatic alterations (external environment) and accordant inhabitants' needs and preferences (internal environment) (Knaack et al., 2014). Facades functions fall in categories regarding protective, regulatory and controlling functions (Herzog et al., 2012). In contexts of interactive architecture and modern facades, facades considered as building exterior integrating the desired services of a building (Klein, 2013).

The facades play a crucial role in providing inhabitants' comfort and managing the consumption of energy for buildings. This role including aforementioned tasks has a significant impact of overall performance of the designed buildings. COST (European

Cooperation in Science and Technology) in their recent published book defines modern facades benefiting from adaptability as a multifunctional building (Aelenei et al., 2018).

Facades were originally used as protection against cold and hot weather in shape of walls and as mobile structures in shape of tents. Facades' functions were summarized as the separator of main body of the building and its respective structure. In this context, facades have been considered as "building envelope" and "building shell" throughout the related literature (Böke et al., 2019). In literature, the mentioned terms have been used to focus on expanding the scope of facades' functions through developing new technical concepts. The fruits of this focus are new construction-related ideas regarding multifunctional facades such as "curtain wall" and "double-skin facade" (Knaack et al., 2014).

Designers and architects considered the facade as a shielding component of the building for a long period of time, leading to manufacturing the internal components of the building without considering the existing external environment of the construction (Addington, 2009). In this context, the interpretation of facade's performance is limited to the quality of protection of internal components against the alterations of climatic factors. Adaptive architecture is the modern expansion of this traditional approach to facade's role (Favoino et al., 2014). Adaptive facade is a dynamic solution responding to climatic alterations in order to drive these alterations into various functions providing energy management and inhabitants' comfort. This solution reduces the dependency of a building on non-renewable sources of energy in a dramatic manner. Al Bahr Towers in UAE benefit from an adaptive facade in the responding in a dynamic way to sun movements providing visual and thermal comfort for interiors (Linn, 2014).


Figure 2.13: Al Bahar Tower's Adaptive Facade in form of Curtain Wall (Cilento, 2012)

Al Bahar tower was awarded by council of Tall Buildings and Urban Habitat in 2012. Chris Wilkinson the juror of Tall building innovation award explains that awards such as this contribute to generation of awareness among nations regarding the important role of sustainable solutions for designing facades (Cilento, 2012). Sociocultural impact of outstanding buildings is highly significant on present and future generations in order to consider sustainability in designing buildings.

Aelenei et al., (2018) assert that the conceptualization of adaptive facades is in its immature stage and multi-functionality of adaptive architecture is the future of modern facades. Fox (2016) proposes interactive architecture context as the solution to tackle the challenges regarding multi-functionality of adaptive facades. Interactive architecture creates an integration among components of a building through interacting with both internal and external environment of a construction leading to provision of various functions, which would be impossible without employment of interactive systems.

Loonen et al. (2013) explain that adaptive systems are not able to increase the performance of the building when applied solely. In order to be influential, adaptive components should be coordinated through an intelligent system capable of involving components of building services and deciding for the control process of adaptation in facades.

Intelligent building has been interpreted differently in architectural contexts that can be categorized in two groups. Firstly, intelligence in a building constructed by static structures is about employment of intelligent tools in design stage of a building which is not the case in recent developments in facades. Secondly, intelligent building is interpreted as a building benefiting from dynamic structure and intelligent control system capable of decision-making for operational tasks (Wigginton, 2002).

Thus, an interactive facade is intelligent, adaptive and multifunctional component of a building with dynamic structure capable of interacting with external and internal environment of the building in order to provide sustainable services.

2.5 Sustainability through Interactive Facades

Interactive architecture is more than just being adaptive. Interactive architecture is about bilateral relationship and it is different from just being responsive to the counterpart (Oosterhuis, 2012). However, an interactive architecture can adapt to its environment to enhance its sustainability (Jaskiewicz, 2013; Fox & Kemp, 2009; Fox, 2016). Sustainability in facades is a fundamental property, since environmental issues in terms of eco-friendliness and resource conservation is now a global concern

(Aksamija, 2013; Aelenei et al., 2018; Cassini, 2016; Loonen et al., 2015). Thus, adaptiveness is a fundamental property of sustainable interactive facades in present global condition.

One unique ability of interactive systems is that they can affect the behavior of the users through their interaction abilities (Haque, 2006; Fox and Kemp, 2009). They can guide users to a more sustainable behavior, which is the main issue of modern world. Besides the mentioned fact, facades are the face of the building communicating with people conveying messages. The messages can be conveyed through interactive displays (Anshuman & Kumar, 2005) or even the materials that the facade has been made of (e.g. recyclable materials). These messages can be about green practices encouraging people to consider that we are damaging our planet through our careless behavior (Atelier Brueckner, 2000). Socio-cultural impact of interactive facades have been mentioned greatly throughout the related literature as they can encourage people to participate socially with these environments (e.g. Anshuman & Kumar, 2005; Fox and Kemp, 2009; Jaskiewicz, 2013). Advanced facades capable of interacting with inhabitants can have a socio-cultural impact on users leading to more sustainable behavior in them (Feifer et al. 2018; Hale, 2018).

Anshuman & Kumar (2005) assert that real-time responsiveness of interactive facades adds a social dimension to the building through enabling user participation with the designed interactions. They add that Interactive facades create expression and spatial experience that are unique capabilities and other types of facades are unable to be socially engaged with humans. This cultural impact of interactive technologies on society is called "Cultural Computing" and is a very young field derived from Human Computer interaction discipline (Cheok, 2010).

Thus, an ideal and futuristic sustainable interactive facade is an advanced facade capable of adapting with its environment (changing itself according to existing environment when it is needed) and interacting with users and encouraging them to behave more green. In addition, a sustainable interactive facade can interact with it producers or maintenance staff for sustainable and reliable functionality. The mentioned abilities of sustainable interactive facades can be designed through developments in Artificial intelligence (Vattano, 2014) and advanced materials (Jadhav, 2016) that will be elaborated in next chapter.

Considering a sustainable interactive facade as a system facilitates the conceptualization of a model for it leading to an overall explanation for the process of this facade. Oosterhuis (2012) suggests that conceptualizing interactive systems in architecture through input-process-output format will simplify the concept of this complex notion.

An interactive AI interacts with its counterparts through different means. Users can command the system or respond to systems' suggestions through systems' sensor and/or interface, while Interactive software can respond and/or suggest to user through auditory and/or visual interface. In addition, the system can sense the user presence and behavior as input data for providing solutions. Nature and the system interacts through sensors and system gathers data to respond intelligently to nature. Internet of Things (IOT) has made it possible for systems to interact with each other to share necessary data for serving their purposes.

Interactive software of the system can interact with other components of the system through interactive computation algorithms for data gathering or actuating other components. Producers can train and update the interactive AI system through creating simulations and interactive AI can provide operation logs for producers for assessment. Interactive system produces energy efficiency and human comfort, while being environment-friendly and this output is the result of interactions between system's AI and all interactions counterparts.

2.6 Main Properties of Interactive Facades

Through literature review, this study has listed initial properties of a sustainable interactive facade. These properties assist this study to analyze the purposefully selected case studies from different aspects. Interactive architecture context is broad and many pioneers in this context choose to explain this concept through describing the topic from different perspective (e.g. Haque, 2006; Fox, 2016). Thus, this study uses the same approach, as the extracted trends and patterns in form of properties facilitates the elaboration of selected case studies in interactive architecture context. In addition, all the case studies' climate zones are classified based on the Köppen Climate Classification:

- **Sustainability**

According to contemporary buildings agenda, explained in respective section, modern buildings should solve contemporary issues related to people comfort, planet protection and economy development. A multifunctional interactive facade as a part of a smart building should overcome the mentioned issues through interacting with its environment to use nature potentials in order to facilitate the inhabitants comfort in an efficient way without damaging our planet. This criteria is based on the effort of Nadoushani et al.(2017) .

- **Multifunctional**

Facades in smart buildings should be multifunctional in order to be capable of fulfilling all stakeholders' needs in the society. Providing human comfort, while using least possible energy with least possible damaging emission needs multifunctionality. Multifunctional facades can contribute to sustainability from more aspects, which can lead to more healthy civilizations worldwide. Interactive facades in smart buildings should be the representative of a green asset and also they should guide inhabitants and public through sustainable behaviors through interacting with them and making suggestions for betters' use of resources and assets. Thus, sociocultural impact can be one of the function of an interactive façade.

- **Interactive Components**

Smart buildings should have interactive components connected to their facades in order to be capable of interacting with their environments to adapt with them, while intelligently generate human comfort. The best interactive components is interactive artificial, since it brings more opportunities for solving issues through dynamic interaction.

- **Agent of Adaptation**

Adaptation is the key for smart building to use potential of its environments to function in the most proper way in an efficient way. Adaptation align the smart building with the nature and protect the planet against lack of harmony in non-adaptive solutions. The adaptation in interactive façade occurs in response to an external stimuli, which can be environmental forces, people and artificial objects. This criteria is based on the study of Schnädelbach, (2010).

- **System Complexity**

This criteria exhibits how much data and elements have been employed to develop a system that is internally connected and capable of processing the input to the desired output. This criteria is based on Basarir & Altun's (2017) work. The following figure illustrates this classification system in detail:

Level of Complexity	Technical System	Characteristics	Examples
I (Simplest)	Part, Component	Elementary system produced without assembly operations	Bolt, bearing sleeve, spring, washer
II	Group, Mechanism, Sub-assembly	Simple system that can fulfill some higher functions	Gear box, hydraulic drive, spindle head, brake unit, shaft coupling
III	Machine, Apparatus, Device	System that consist of sub-assemblies and parts that perform a closed function	Lathe, motor vehicle, electric motor
IV	Plant, Equipment, Complex machine unit	Complicated system that fulfills a number of functions and that consists of machines, groups and parts that constitute a functional and spatial unity	Hardening plant, machine transfer line, factory equipment

Figure 2.14: The level of Complexity of Facades (Basarir & Altun, 2017)

In addition, in order to analyze the selected case studies, this study has employed the Loonen et al (2015) criteria of characterization. These criteria characterize the adaptivity of facades and has been employed by corporation of science and technology in Europe (Alenei et al., 2018). Thus, the analysis of case studies is executed through combination of extracted properties and the mentioned adaptivity criteria. This combination will characterize the sustainable interactive facades (selected case studies) through adaptivity criteria and the analyze the properties of these facades in context of sustainability and interactivity.

The criteria of characterization provided by Loonen et al (2015) includes:

Goal / Purpose: It is about how the facade can be beneficial for the building. These benefits can be presented through numerical data. However, in this study the goals and purposes will be only mentioned for each cases.

Operation: It is about how the facade parts are being operated or in other words, being controlled in terms of intrinsic or extrinsic. Intrinsic control occurs automatically without processing the stimuli yielding to lower operation and maintenance cost. Extrinsic control enables the processing and intelligence providing feedback for system operation.

Technologies: It reveals the utilized system type in the facade. It does not elaborate the technology. It is introductory criterion.

Response Time: It explains the scale of effective adaptation process in temporal dimension.

Visibility: It reveals that the adaptation process whether changes the appearance of the facade or not.

Degree of Adaptivity: It is about the level of adaptiveness in the facade. On/off type of operation provides low level of adaptivity, because there is no constant and real-time change in facade according to environment and gradual type of operation expresses the higher levels of adaption .

Chapter 3

ARTIFICIAL INTELLIGENCE AND ADVANCED MATERIALS FOR INTERACTIVE FACADES

3.1 Artificial Intelligence

Artificial intelligence (AI) is the simulation of human intelligence processes by machines, especially computer systems. These processes include learning (the acquisition of information and rules for using the information), reasoning (using rules to reach approximate or definite conclusions) and self-correction (Kok et al., 2009).

Although it is relevant to this study to understand technical topics regarding digitalization of interaction design, it is out of the scope of this thesis to elaborate them. Thus, this study only introduces developments in artificial intelligence to suggest some pathways for architects towards contemporary interaction design. This introductory section to artificial intelligence helps architects to understand why they have to collaborate with other scholars from different disciplines and how those scholars can assist them in creating interactive systems.

Autonomous AI systems based on machine learning have been used in various fields recently, however their application rises the concerns regarding their errors under uncertainty (Seshia, 2019). Selman et al (1996) describes the challenges of AI as follows:

1. Through comparing human-made systems with biological systems, we understand that our systems are extremely weak in various aspects;
2. Human-made systems with acceptable performance in some fields are growing as trends hindering the growth of promising and futuristic approaches.

Biological systems are not flawless regarding adaptation to new environment but they are probable to adapt. On the other hand, human-made systems are very fragile lacking the ability of adaptation to new environment. One of the challenges for AI is to be self-configurable and self-optimizing in order to be able to adapt to new architectures (Selman et al., 1996). When robustness and adaptability are the desired features of a system, engineers usually explore the nature to find inspirations, as nature's efficiency and durability are proven throughout the passage of time (Rathore, 2016).

The early theory regarding developing behavior-based systems were based on how to solve large size problems. However, the real challenge is how to make these systems accurate with inevitable uncertainty (Selman et al., 1996). For example, the new generations of Intelligent HVAC control systems are based on behavior-based systems. The mentioned systems analyze the behavior of inhabitants to set a most optimized setting for different places of a building. The main challenge for implementing these types of systems is to develop a complex model capable of analyzing affecting factors to act efficiently (Mirakhorli, & Dong, 2016).

Evolutionary systems have achieved interesting results in solving some particular problems. However, the extraction of success factors from these best cases in order to apply them to other problem cases is an extremely hard task. Thus, the real challenge is to develop AI systems that can be applied in various fields of problem solving

(Selman et al., 1996). One of the application of evolutionary methods in architecture is the provision of comfort for inhabitants based on comfort metrics for thermal, visual and indoor air quality factors. The evolutionary methods are used to create predictive control systems capable of learning to automate the different facilities of a building based on data derived from static and adaptive approaches. The real challenge for mentioned systems is to combine the simulation data with real-time data in an integrated manner to bring efficiency to a building's performance (Lachhab et al., 2017).

The human brain benefits from a fixed structure (synapse) with the ability of learning from its environment. The human-made AI systems imitating human brain have structures that change over time. One of the challenges for AI developers is to be able to design brain-like system that imitate biological learning with fixed structure (Selman et al., 1996). The systems based on neural networks, which imitates the human brain are promising approaches for being implemented in energy management systems of a building. However, the main challenge is the practicability of these systems, since each building should have a unique system to reach optimization and these systems are expensive to be installed (Jain et al., 2020).

The main problems with developed systems are that they are based on approaches that have outperformed the other approaches and now realize that they do not have sufficient potential to grow with the same rate of success that they used to have. We have used our limited sources on the approaches that they were successful for a limited period of time, while neglecting the potential of approaches that their growth were not efficient in comparison with the trend approaches. Moving backward and asking ourselves the primary questions that we have found solutions for takes great amount of courage. However, it seems that it is the only way to develop new methods sufficiently capable to overcome emerged challenges (Selman et al., 1996).

Selman et al. (1996) mentions that specific future challenges of AI are: Development of accurate speech understanding system, competent noise understanding systems and evolutionary systems capable of performing non-trivial tasks. The creation of capability of learning in machines is a complex task leading to complex models and systems. Shafique et al. (2017) explain that one of the most important challenge for these systems is to be energy-efficient as they consume considerable amount of energy to use their memory. Their memory includes a vast amount of data in order to be referred to find the best possible solution for every condition.

AI is flawed regarding to learning and decision-making influenced by inevitable uncertainty. Thus, AI systems in order to be robust in real situations should have an autonomous decision-making system capable of learning from events over time to solve the problems in an efficient way Selman et al (1996). Implementation of intelligent energy-efficient systems in building under high levels of uncertainty is a challenge. One of the recent solution for this challenge is the employment of systems capable of decision-making based on statistical and probabilistic models (Singh, 2019).

Regardless of existing issues surrounding the topic of AI, there are remarkable achievements in this field that has contributed greatly to the feasibility of architectural ideas recently. Machines demonstrates an intelligence enabling tasks for architects that were impossible or economically infeasible. In the following text, the most remarkable AI-related technologies relevant to architecture will be introduced.

3.1.1 Verified Artificial Intelligence (AI)

Seshia et al. (2016) define "verified AI" as a robust system based on AI capable of accurate problem solving through computation and verifying itself. In order to achieve these desired AI systems, they mentioned following existing challenges:

1. Modeling environments, which their all variables are impossible to be defined without uncertainty.
2. Specifying the properties of an AI system to be capable of recognizing and distinguishing the agents and objects in surrounding environment.
3. The use of machine learning for evolution of system based on new data and new situations.
4. Development of AI systems capable of generating training and testing data for facilitating the machine learning and improving the robustness of the AI.
5. Devising verification methods capable of functioning based on both Boolean and quantitative data to test AI systems behavior.
6. Synthesizing a machine-learning model benefiting from correct construction with the ability to generate proper training and test data and update them when it is needed. This machine-learning model would facilitate the process of environment modeling and specification.
7. Designing AI systems including both learning and non-learning algorithms in a way that they can operate together efficiently in real-time situations. Reference data or non-learning components should be updated with run-time data or learning components to increase the accuracy of AI systems under uncertainty.

AI always can be improved and there are significant amount of gaps for improvements. However, the recent developments in AI enable practitioners to create useful systems and devices to actualize their ideas. Further, the solutions for the challenges of verified AI will be introduced:

- **Introspective Environment Modeling**

The Autonomous AI systems should operate with accuracy in complex environments through robust modeling of these environments. The objects and agents in complex environments are hard to be recognized for AI due to huge amount of unknown variables existing in these environments. In simple environments such as interactive interfaces, which the environment is well-defined, traditional algorithms are successful because the environment interacts with the system only through the interface. AI systems in order to overcome the uncertainty caused by the complexity of an environment should employ algorithms which can guarantee the correct operation. Introspective Environment Modeling (IEM) is a method of modeling which analyzes the system's behavior in order to understand how system sense and interact with its environment. Through introspection of a system, it would be possible to devise proper assumptions about how a system understands its environment. These assumptions should be examined during system's operation for their truthfulness in order to be updated or corrected accordingly (Seshia, 2019).

These assumptions can be extracted from simulations with involvements of agents (humans and other AIs) and it is important to continue the data gathering from these simulations to update the primary assumptions and reference data in design time (Seshia et al., 2016). AI systems capable of generating human understandable reports during their operation are aligned with IEM and can be repaired and controlled when error occurs (Seshia, 2019).

- **Specification Mining**

Specifying the behavior of AI systems capable of learning in a formal manner is almost impossible. Hence, AI developers focus on specifying the behavior of the entire AI system from end-to-end perspective. System-level specification can be done easily and can reveal much about an AI system. However, specifying a semi-formal behavior of AI systems with learning capability can be beneficial for increasing its accuracy. To achieve a semi-formal specification, methods of specification mining have been suggested (Seshia et al., 2016).

Specification mining is the process of extracting behavioral patterns of AI systems during operation or after the operation through analyzing operation logs (Reger et al., 2013). Thus, specification mining during simulation sessions can be beneficial to define semi-formal specification. Possible patterns can be compared to emerging patterns in simulations in order to detect successful pattern for defining specification (Dallmeier et al., 2010).

- **Formal Abstraction and Explanation-Based Learning**

Abstraction techniques and explanation generation algorithms can facilitate the development of verified AI systems benefiting from learning ability. Machine learning components are complex in order to be verified with formal methods. Thus, abstraction techniques can decrease the complexity of machine learning components in order to make it possible to apply formal verification methods on these components (Seshia et al., 2016). Probabilistic temporal logic can be used to extract guaranteed situations in ML components under uncertainty in order to increase the accuracy of AI learning simplified by devised formal abstractions (Sadigh & Kapoor, 2016). The AI systems capable of generating explanations for their mechanism of predictions can facilitate the process of modeling AI capable of learning (Seshia et al., 2016). Logical methods are the trend for explaining the output of machine learning (e.g. Vazquez-Chanlatte et al., 2017) and they are aligned with formal methods of verification (Seshia et al., 2016).

3.1.2 BIM

There are controversial opinions regarding what BIM stands for. Some say it is the acronym of "Building Information Modeling" and some say "Building Information Management". However, what really matters are to understand the concept of BIM instead of arguing about the composing words of this acronym (Barnes, 2019).

BIM is the process that all actors in building production involved in design, construction and operation of a building can collaborate with significant efficiency in terms of accuracy, predictability, optimization and schedulability (Autodesk, 2019).

BIM is the process of creating buildings in virtual world in a way that what happens in real world for a building can be simulated in that virtual world for the designed 3D model of the same building. BIM is the simulation of a building's life-cycle including all its important physical and functional characteristics. BIM digitalizes, analyses and saves all the data regarding all the process that a building is involved in it from design to disposal (Barnes, 2019).

With the rise of computer-aided design (CAD) in 1950s, the giants of construction industry started to use CAD to draw 2D plans of their buildings in design stage. The efficiency of this process in terms of time and the decline of cost for having computers encourage other practitioners to embrace the CAD (Kalay, 2004).

In 1990s interactive modeling through constrained-based algorithms opened a new pathway in 3D modeling of buildings. This development enabled designs with connected factors, which means with change in any factor the other factors will change accordingly. These interactive engines had a huge impact on reducing the cost of building modeling in terms of time and money (Barnes, 2019).

In the third millennium, the combination of all developments in machine intelligence and computation related to building modeling brought the capability of adding time to 3D modeling. 4D modeling of building in an interactive environment existing in computers enables practitioners to have a better understanding about the future of buildings in present time. This power of prediction leads us to construct more complex building and systems (Saha, 2018).

Interactive engines of BIM enable a relationship between building and users/producers that was impossible before. Now, buildings in their times of operation, can interact and communicate with humans. These interactions facilitate the controlling the operation of the building. The interactive engines provide an ability similar to imagination of humans but more accurate for buildings to calculate the consequences of their actions. Computers as the brain of intelligent buildings now can learn from users/producers through interactive engines in BIM software such as Revit of Autodesk and improve their behavior towards their environment (Barnes, 2019).

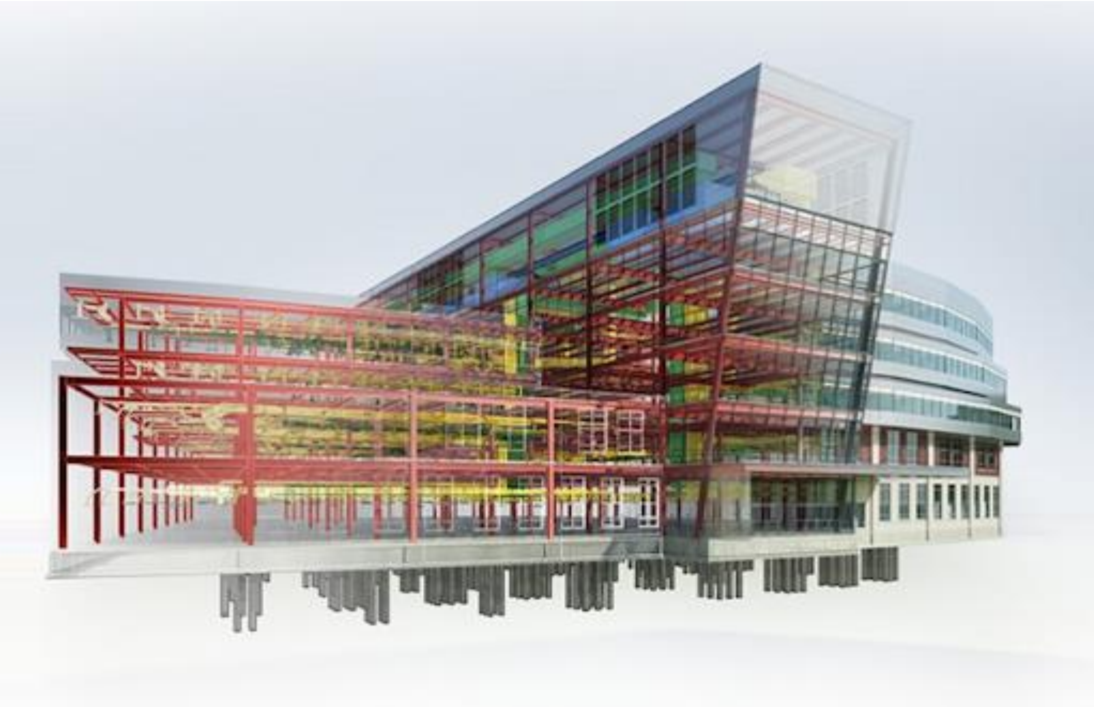

Figure 3.1: BIM Assists Us to Visualize and Plan Very Complex Designs in Architecture (T advisor, 2020)

The BIM provides the ability for designers to visualize what they will build according to the concept design. Visualization of future buildings is an interesting marketing tool for construction companies. Companies can optimize their construction plans through BIM, while harmonizing the contributions of more than one designer to the plan. In BIM, producers can define scenarios of operation for interactive engine in order to increase the reliability of controlling system in decision-making. BIM facilitates the inspections by legislators through providing accurate and comprehensive plans of construction project (Kunz & Fischer, 2020).

Sync-BIM is a prototype integrating the BIM-based intelligence, interactive control interface, variable based engine, environment sensors and actuators. The management system in this prototype functions in Autodesk Revit as the selected BIM software.

There are different software programs enabling BIM for projects such as SketchUp and Revit. This prototype is the combination of a kinetic facade and an interactive engine which operates in BIM software environment (Shen & Wu, 2016). This prototype is in line with the conceptualized and concluded model in chapter 2 of this study benefiting from an interactive engine, which enables the integration among other components of the system to provide services.

The foldable structure of implemented panels in kinetic facade are designed to be cost-efficient for mass production and interactive engine of the prototype benefit from consistency in different climatic conditions. These features of this facade enables it to have potential for mass-production and easy-assemble. The kinetic part of the facade can adjust itself according to climatic factors to regulate interior light, humidity, ventilation and interior temperature. These adjustments can happen according to both climatic conditions and user's preferences. The kinetic part of the facade is augmented by environment sensors monitoring climatic factors and generates required parameters for BIM-based interactive engine to process these parametric data. Interactive engine functions as the brain of the system and decides for optimized adjustments according to its data references in terms of defined scenarios and user's preferences. The procedures of decision-making by interactive engine can be classified in 3-steps (INPUT, PROCESS AND OUTPUT) creating a loop for control system. Interactive engine for this prototype is called Dynamo a plugin in Revit (BIM software) (Shen & Lu, 2016).

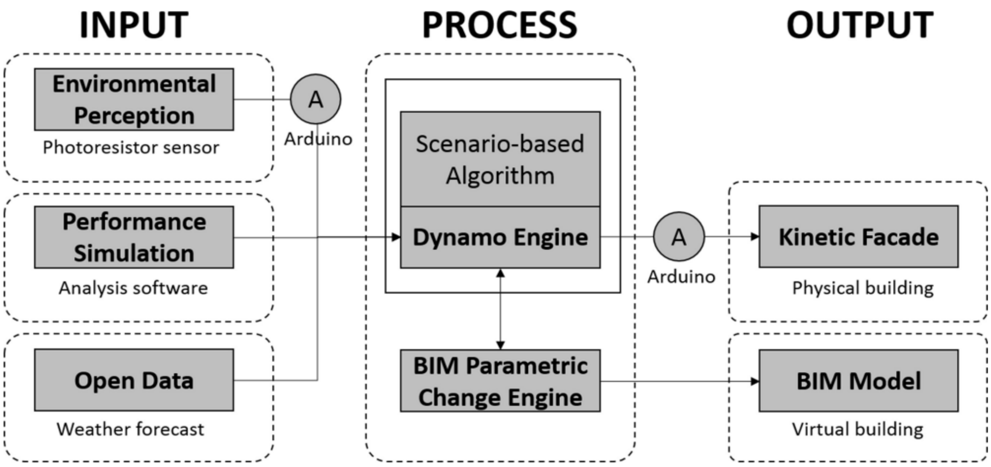

Figure 3.2: Framework of Sync-BIM (Shen & Wu, 2016)

The mechanism of adaptation by interactive facade to external environment (climatic changes) can be described as a 3-step loop with instant feedback. First step is provision of INPUT data for interactive engine. This provision occurs by data gathering through IOT from other devices (weather forecast) and real-time data from environment sensors. Environment sensors are photoresistors called Arduino. These data transferred in parametric format to interactive engine in order to be compared with library of scenarios defined in control system. The interactive engine processes all the parametric data and commands to visualize the optimized solution in BIM environment and actuate the kinetic facade accordingly (Shen & Lu, 2016).

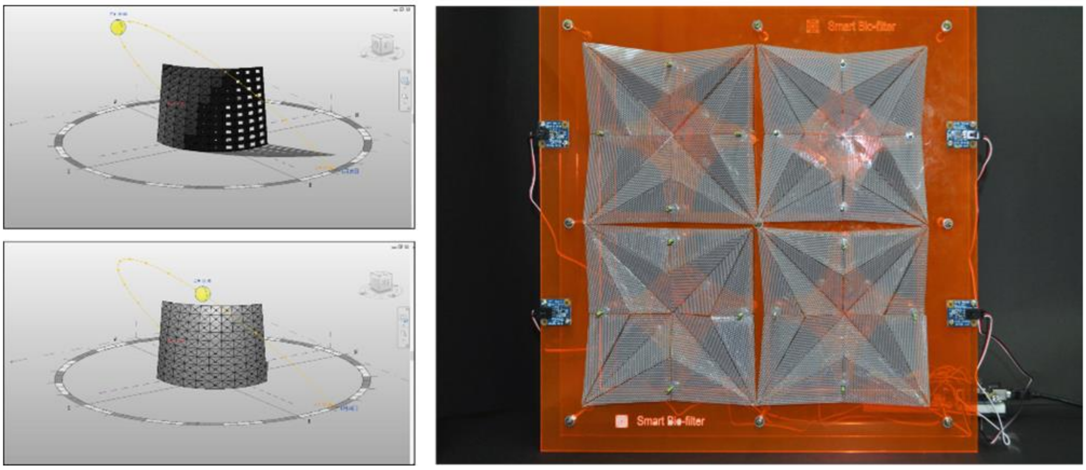

Figure 3.3: The Sync-BIM Prototype (Shen & Lu, 2016)

3.1.3 IBMS

Intelligence demonstrated by machines provides the possibility to integrate the information systems within a building. The automated and integrated management of building systems is similar to the nervous system of human being. The logic behind the Intelligent (or integrated) Building Management system (IBMS) is to imitate the nervous system in our body. Our body has a very complex control system including different information systems (Nerves) interacting with each other and controlled by an interactive engine (the brain). The ideal IBMS is capable of what our nervous system can do (Clements-Croome, 2013).

An ideal IBMS performs is autonomous and works in way that we do not feel its presence. It alerts us when something is not right and it works with least possible sessions of maintenance. It adapts itself with its ever-changing environment and it has the ability to detect malfunctions and suggest us how to fix them. It senses its environment and acts accordingly and reliably without perceivable delay (Davies, 2013).

One of the good example of IBMS in real life is Radison Blue Frankfurt Hotel. Each room has an interface installed on the wall that guests can adjust their pleasant settings through it. There is supervisor platform called "963" in the hotel that every authorized person can monitor and adjust settings of electrical systems, rooms and fire dampers through any web browser of any device. The machine intelligence provides an integrated monitoring system for the entire facilities of the hotel within a platform controllable from anywhere through IOT (Johnstone, 2013).

Figure 3.4: Radison Blue Frankfurt Hotel with Integrated Management System (Radison Hotels, 2019)

Artificial intelligence provides buildings abilities regarding understanding user behavior, managing energy consumption and sensing space occupancy with higher accuracy. Intelligent buildings can learn to sense, process, forecast and act with continuing improvement. In other words, buildings benefiting from artificial intelligence can evolve through interacting with their environment and improve their management systems of facilities (Serrano, 2019).

3.1.4 Adaptive Sensory

Adaptive sensory is about designing environmental sensors capable of interacting and adapting with their environment. They should sense temperature, humidity, luminosity, users' presence, users' behavior, users' health condition, users' emotional status and other buildings to collect data for the process of interactive engine in order to provide comfort for users, while being sustainable and eco-friendly (Lehman, 2013). Adaptive sensory can sense the needs and demands of patients, disable people and children and collect real-time data for interactive engine of intelligent building to act accordingly. Adaptive sensory not only can provide physical comfort for users, but also is able to bring psychological and mental benefits for inhabitants through acting like a guardian who is always aware about vital safety issues, users' needs. This guardian can inform the brain of the building to initiate for the welfare of inhabitants (Lehman, 2016).

In designing sensors for different environments, architects should consider the possible scenarios that will happen in that environment for the users. For example, in designing sensors for hospital rooms, architects should consider what will happen for the patient during the time of recovery that he or she will spend in that room and then they can design what sensors should sense in that environment in order to convey proper data to the interactive engine (Lehman, 2013).

Ideal and futuristic Sensors in context of interactive architecture should be able to observe, learn and adapt (Fox & Kemp, 2009). These abilities in sensors can only be created through artificial intelligence. Sensors without intelligence are not able to learn from their environment in order to correct themselves and evolve accordingly (Qela & Moutfah, 2012).

Advanced facades should have adaptive sensors to perform autonomously in regular basic. The sensors will provide the input data for control unit (engine) to be processed and then the system will actuate the proper components and procedures. These facades can interact with their users in times of need, for example when they want to suggest an action or when something is wrong and user/producer should act for that. Advanced facades are connected with their producers for software update and maintenance and they are able to be sustained without bothering the inhabitants (Attia, 2018).

There are wearable sensors that we can use to share our health and emotional status with our environment in order to receive services accordingly (Hu et al, 2018). An interactive engine of the building similar to an alive being can interact with humans according to health and emotional status suggesting songs, lightning themes or entertaining activities. These things may seem fictional but they have been produced and they are in the market and architects can use them to design environments. A company called My Feel has produced wristbands that are emotion. This sensor is connected to an app (interactive engine) and can provide services according to human's emotional status. One of the services of this product is to provide therapy from a licensed therapist according to the extracted data from our daily life (myfeel.co). The other wearable product is called Empathic a developed by MIT laboratory capable of measuring our emotions and provided services accordingly through its AI engine (Wearable, 2019). Architects with the collaboration of experts from different disciplines are able to create interactive environments that are integrated with other devices such as our smart-watches and smartphones.

Figure 3.5: Empathica is an Emotion Sensor that Works with a Companion App (Wearable, 2019)

3.2 Advanced Materials

The term advance material is used for materials that are made particularly for having modern features that can be structural or functional (technical) and/or environmental. These materials are for enhancement of existing functions through modification processes (Pacheco-Torgal and Labrincha, 2013). Efficiency in terms of energy consumption and environmentally friendliness can be improved significantly through introduction of advanced materials within the construction industry. Life cycle of buildings can be increased, which can have a vivid impact on all processes of construction (i.e. design, and implementation). These materials profoundly smoothen the path for technology to be expanded to other forms of technologies. Socioeconomic aspect, which includes global warming and allocation of resources effectively can be fostered through advanced materials being manufactured that are in persistence with overall well-being and improvement of social quality. In addition, implementation of advanced materials has economic advantages that are beneficial for manufacturers as well as other individuals. Development of new products and goods can drastically change through advanced materials and their usage, which can have specific settings (e.g. low carbon footprint). As a significant player in terms of technology enabling, advanced materials have been recognized as an advancement element by the UK government and the EU (Casini, 2016).

There are different material categorizations addressing recent developments in production of materials such as active materials (e.g. Lopez et al, 2015), smart materials (e.g. Addington & Schodek, 2005), information materials (e.g. Kretzer 2017). However, they are not broad enough to categorize all the new developments as each of this terms addresses particular field of advancements in materiality. Thus, advanced materials as the widest category for recent developments in materiality, has been chosen to introduce a broad variety of new and emerging materials having the potential to contribute to designing sustainable interactive facades.

New features and thus, functions can be introduced alongside new components that can have other benefits such as, added value and increased sustainability. This in turn leads to decline in usage of resources, and creation of materials that have no or lesser harm to the planet through enhanced production processes, optimized distribution methods, green-oriented usage and recycling, disassembly and low-impact disposal. Within the context of this study and as interactive architecture requires new methods and critical perspectives, building sector can significantly be influenced by introduction and implementation of advance materials. Resource usage can greatly be decreased and optimized in a manner that yields in lesser waste and higher impact control from human activity upon the surrounding environment (Casini, 2016). Extent of which architecture can perform and have a better dynamic, can be stimulated through characteristics of advanced materials (Casini, 2016).

The abovementioned improvements in terms of features are among the outcomes of advanced engineering, which can consist nanoscale and/or largescale levels of processes. The latter scale refers to micro-materials or macro-materials, while the former identifies as nanomaterials. It has been noted that there is a higher potential for development of materials that are innovative and have higher performance levels, when compared to current ones, when nano-metric scales are used (Schodek et al, 2009). Bulk state of materials and/or goods differs with nanoscale of the same material on a significant level as a plain concept of matter and its properties. Such variations in property and features lead to a state, where the material can be merged within micro or macro scale levels. As a consequent, this will increase the degree of which bulk material were to perform, with visible and tangible applications. Following what was mentioned earlier, nanomaterials can be used and applied in an array of means. Within the context of thermal energy, nanomaterials have been reported to have a significant potential in terms of improving the current materials. This is due to the specific property of these materials that surface-to-volume ratio is high and thus, physical property of thermal functioning (thermodynamics) for bulk materials can be relatively increased. This can be regarded as an overall improvement in terms of performance (Yildiz, 2009).

It is important to note that advanced materials can also be regarded as end-products. Furthermore, they can be merged and/or integrated within other aspects of production whether throughout the manufacturing process or as a finish-line product before entering the specific predefined market. Within the scope of current research, nanocomposites and coatings can be noted as highly relevant materials that are regarded as advanced and are used for construction. These are significant materials that have an extreme level of impact upon this industry and have acquired the attention of businesses in the field as well as scholarly experts (Casini, 2016). Thin films, nano-coatings, and nano-paints can be vivid examples of the aforementioned notion. Surface quality as well as appearance can be significantly improved through the usage of these materials.

Another key element in terms of advanced materials that can be related to the context of this study and construction and/or architecture sector is the rise of 3D printing and its functionality. Components of buildings can be designed in an optimized manner of processing, transportation as well as installation. Cost and time consumption of the said aspects can be greatly reduced through the usage of 3D printing and prototyping techniques. A single, tailored and specifically designed object can be produced with the relatively low price of mass manufacturing through 3D printing, which can shake the foundation of scale economics. Industrial sector can significantly be improved with this technology as it has been with the case of printing machines in the 15th century, steam motor in 18th century and invention of transistor in the 20th century. All these events had a significant impact on industry as a whole and international scale and have extended these effects to the construction and building sector subsequently (Rifkin, 2011).

3.2.1 Aerogels

Thermal insulators in their traditional form have taken a new shift through introduction of innovative products such as, panels, rolls, granulates (loose) to the market. Low thickness structures have a high thermal protection that is provided by nanotechnology and new scientific materials, which as a conclusion have increased the overall quality of architecture through proper usage of energy as well as optimization of energy consumption (Casini, 2016). Air and gel (hereafter, aerogel) products are nanotechnology products, with low density properties due to the processes, in which gaseous component replaces liquid by dehydration of colloidal gel (Cuce et al., 2014). This product was invented in the 30s by Kistler at California, which led to significant changes in terms of manufacturing processes after three decades. Aerospace, chemical and pharmaceutical industries had a great usage of the product, which now has extended its usefulness within other sectors such as, sports, and construction and/or building sector (Aegerter et al., 2011). Graphene aerogels are now can be produced with 3D printers leading to better economies of scale for this nano product (Zhang et al., 2016).

Aerogel is processed through inorganic as well as organic materials that become gels and can applied in insulation, sensors, actuators, electrodes, and thermoelectric appliances (Acharya et al., 2013). It has been reported that dubbed silica aerogels are more common for various applications in thermal insulation. This is due the fact that silica based aerogels have features that are persistence with the objective and their installation and/or preparation methods are relatively easy (Dorcheh & Abbasi, 2008). This product can be appeared as a solid foam that has a tactile feeling close to rubber and is also referred to with other terms such as, frozen, solid, or blue smoke. This reference to silica aerogels is due to is transparency. The weight per volume and its unique low degree as a solid substance has made aerogels a point of interest that they are in nowadays as more than 90% of these materials is simply air (Sun and et al, 2013). Monolithic blocks or slabs, loose granular form, mats, rolls, and reinforced fiber panels are the means that silica aerogels are available within the market (Buratti and Moretti, 2011). Aerogel is usually integrated in a polyethylene terephthalate (PET) fibrous support structure to give fiber-reinforced aerogel blankets (FRABs) (Casini, 2016).

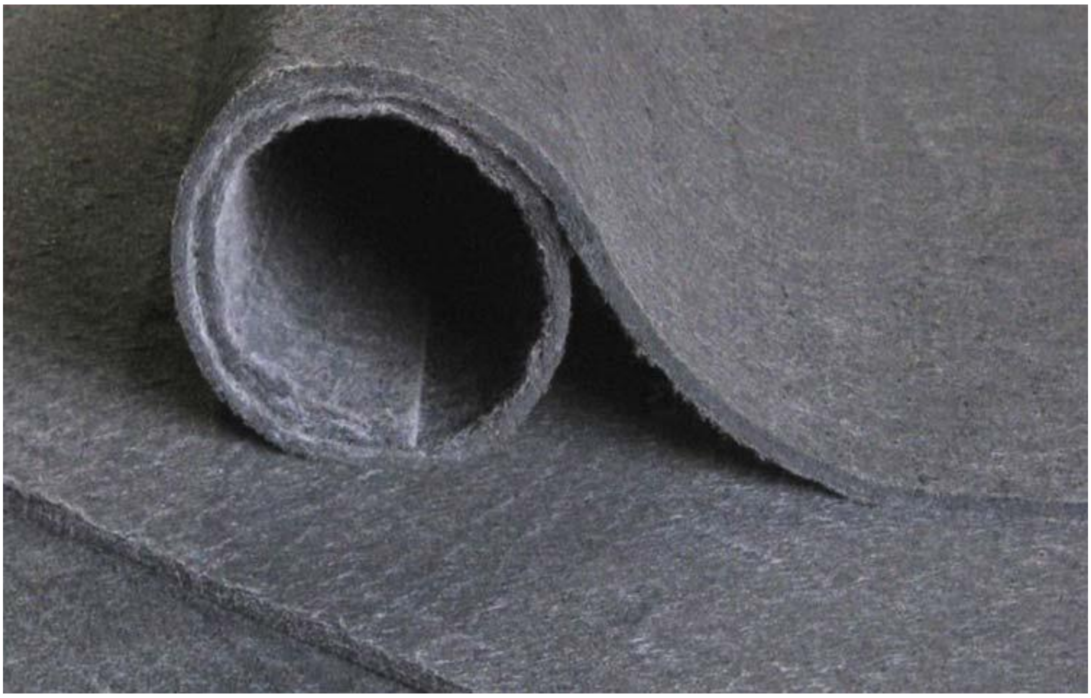

Figure 3.6: Aerogel Blankets (ProctorGroup,2019)

Within the context of this study and relevant to the architectural aspect of using aerogels, silica aerogels contribute significantly to super materials for insulation, especially for windows' materials. Double-glazed windows that are used as a standardized product, possess a value of 1.0 W/m2 k. This is while aerogels that can be applied between panes reach a value lesser than .5 W/m2 K. This is three times lesser than the existing level of triple glazing methods (Kretzer, 2017). As it was mentioned earlier in this section, advanced materials are to improve current status of products and can be applied within other products whether as finishing or throughout the process. The aforementioned feature regarding insulation is a vivid example of how advanced materials can greatly impact processes of construction and building sector. As an alternative to monolithic elements, other advantages can be obtained through usage of granulates throughout the production process as ambient or subcritical drying techniques can be implied. In addition, conductivity (thermal) feature of granular beads have been reported to be slightly more than of those monolithic ones. These can be merged in beds, and/or blankets, which leads to a higher degree of flexibility as well as geometric functionality. Furthermore, they can be used in a form of powder, which enhances the handling process, when compared to fragile forms (Kretzer, 2017).

In addition to what was mentioned above, FRAB products have been noted to have a satisfactory fit level in terms of usage for building or renovating. However, they show a high degree of convenience for external/internal interventions as well as refurbishing buildings. This has been more vivid in historic buildings and have exhibited generalized consensus regarding increasing efficiency in terms of energy consumption and increased comfort level in a small space (Casini, 2016). Within cities, thickness of insulation is a main concern as renovation of current buildings is a priority such as in France. Silica aerogels have been reported to have a great usage in terms of insulation rendering in buildings that are currently in existence. It was reported in a study conducted by Ibrahim et al. (2015) that optimum level of thickness rendering is 1.7 to 4.4 cm with a resulting effect of 1.4 to 2.7 years that is under the influence of climate. As heating set-point and current worth factor increase, optimum thickness is bound to increase relatively. It is also important to note that optimum thickness can be decreased if rendering cost were to be increased (Ibrahim et al., 2015).

One of the most interesting construction material for facades are the aerogel infilled glasses that a company called Advanced Glazings LTD has been produced and various of new projects such as Toronto Zoo, Berkeley Art Museum and Kellogg School of Management have been utilized. These glasses can be installed on any standard frames and curtain walls without further machining. High levels of light diffusion, high levels of light distribution and shadow elimination are the remarkable abilities of these glasses enhanced by aerogel panels (Advanced Glazing, 2019).

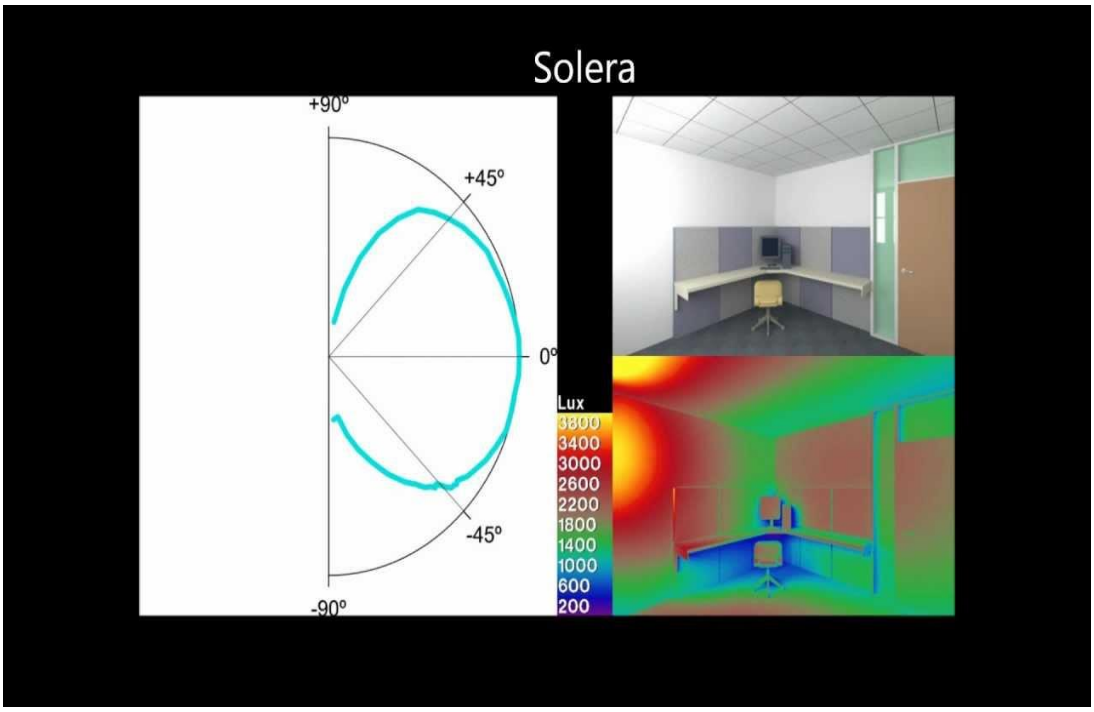

Figure 3.7: Aerogel Infilled Glasses Eliminated the Disadvantages of Daylighting (Advanced Glazing, 2019)

Kellogg School of Management is the holder of LEED platinum certificate for implementations related to sustainability and also the winner of design competition in 2011 (Gonzalez, 2018). The officials of this school believes that aerogel infilled glasses have been a great solution for them to provide a sustainable environment for their inhabitants (Advanced Glazing. 2019).

Figure 3.8: Kellogg School of Management Glasses are Enhanced with Aerogel Panels (Gonzalez, 2018)

3.2.2 Bioplastic

Bioplastic challenges that are organic compounds and have a significant impact as they are alternative to fossil fuel plastic. In this regard, two main aspects are to be highlighted that are, packaging or single-use items that have a low lifetime before obsolescence and are to be produced in a manner, from which degradation can be easily applied (or are composed industrially in air or water); and permanent items with high durability that have properties that are similar to their oil-based counterparts with the difference of recyclability (Kretzer, 2017).

Figure 3.9: A pavilion Made of Bioplastic in Stuttgart (Griffiths, 2013)

Although bioplastics offer valuable advantages (i.e. reduced carbon dioxide emissions, less dependency on fossil fuel, and lower toxicity production), they face an extreme challenge to compete with the petrochemical products that dominate the international market and manufacturing industry. This economic low speed development faces other threats such as fear of losing land and higher production costs. In addition, comprehensive understanding of its effects on water or soil does not exist, which adds to the aforementioned economic development restraint. Plastic is highly used within the building and construction sector, which exhibits the height of potential for reduction of plastic pollution through usage of green alternatives. However, as bioplastics are biodegradable, their usage within this sector is limited to interior and/or temporary designs (Özdamar & Ateş, 2018).

However, the biodegradability of the bioplastics is still a challenge for economies of scale production of bioplastics for exterior applications and their usage within this sector is almost limited to interior and/or temporary designs (Özdamar & Ateş, 2018). The case of ArboSkin pavilion enlighten a promising path for utilization of bioplastic as an exterior material for architectural purposes, which can decrease the plastic pollution of future buildings demanding for materials with similar features of plastic. According to Köhler-Hammer et al. (2016), polylactide (PLA) is the most interesting bioplastic for exterior applications due to its low cost of production, high capacity of machining, endurance against ultra-violet radiations and general availability. Polylactide (PLA) is a bioplastic mainly derived from different sources of starches that has a very low energy requirement for production (Vink et al., 2010). Köhler-Hammer et al. (2016) predict that in a very close future, there will be sufficient production plants for PLA in order to provide this bioplastic for different applications including construction of facades.

3.2.3 Photovoltaics and Dye-sensitized Materials for Solar Cells

The application of semiconductors in order to convert light to electricity is called Photovoltaics (PV). PV panels absorb light of sun to generate direct type of electricity current (Wenham et al., 2013).

Figure 3.10: SwissTech Convention Center Facade with PV Panels Embedded in Glassy Structure (BIPV, 2019)

In this context, dye-sensitized solar cells (DSSC) have shown a significance in terms of emergence with other technologies with high economic promises. DSSC is referred to solar cells that are nanostructured and are photoelectro-chemical, which incorporate films of TiO2 particles. These particles are porous and are coated with layer of dye with sensitivity towards light. This can be regarded as a similar product to chlorophyll within plants that generates chemical energy. Dye absorbs energy (solar) and then, it transforms the absorbed energy into electricity (Junghanel, 2007). These cells are made with materials that are common, available and cheap and with a series of processes that are low-cost and not complicated. Colors and transparency of these cells can vary, they are produced with a low weight, are flexible and conserve power on an efficient level even under unlikely situations (e.g. low light, diffusion of light and/or indirect light) (Kretzer, 2017). Based upon such characteristics, DSSCs open a path for greater usage in terms of architecture (temporary structures, or emergency shelters, and windows or curtains). In addition, indoor usage of these cells is encouraged due to their ability to work under low-light (Kretzer, 2017).

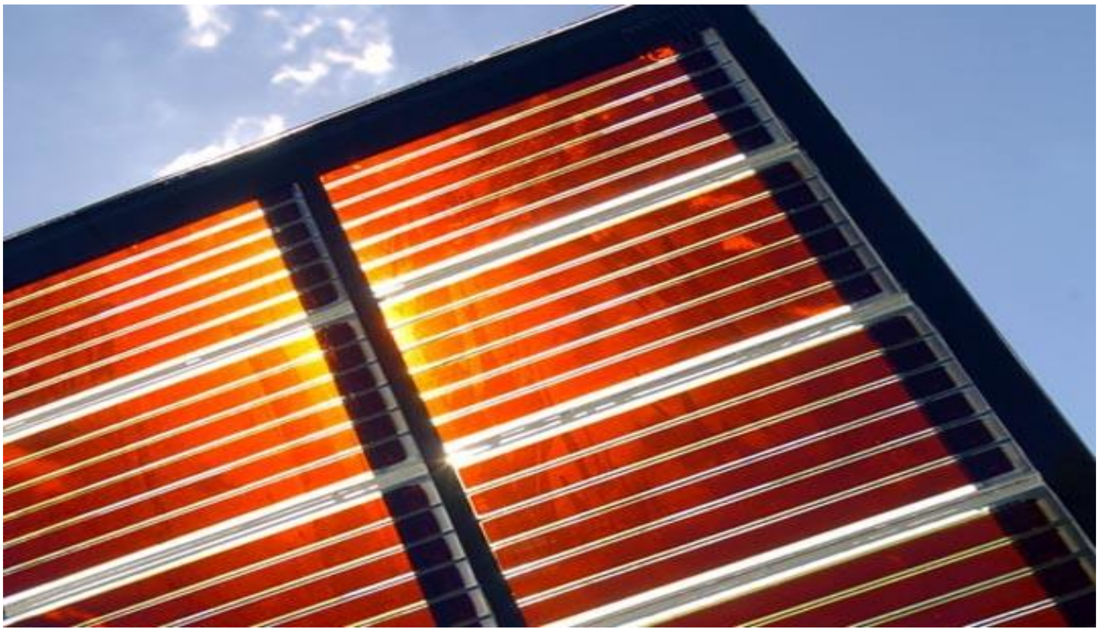
Figure 3.11: Dye-Sensitized Solar Cells (Teletype,2019)

In the light of what was mentioned above and in relation to the usage and challenges that are posed towards DSSCs, these products are required to advance in terms of commercial availability as well as application on a large scale. In this context, photovoltaic technologies have been met in terms of conversion efficiency as DSSCs improve constantly. However, this shortcoming is a major challenge for these products alongside low stability. As the extent of competitive rivalry increases within the market, cells are to maintain a high level of stability regarding changes of temperature, humidity and illumination (both intrinsically and extrinsically). Additionally, this stability is to be maintained in a timespan of two decades with less than 20% loss. Additionally, usage of cells in architecture faces another issue that is low scalability. This is due to liquid electrolyte. It is noticeable that improvements have been initiated and experts have noted that these issues are solvable in a short time as new technologies and innovations are in line with lowering such issues (Freitag et al., 2017).

3.2.4 Electroluminescent Materials for Displays

Light can be produced in two broad manners that are namely, incandescence and luminescence. The former is defined as electric current that is generated from a conductor and leads to heating resistance applied to the current. As a result, this creates light. This is while the latter refers to any formation of visible light that is not generated by temperature. Electroluminescent (EL) however, is referred to generation of light in a manner that is non-thermal and is the fruit of electrical field applied to a substance (Kretzer, 2017). Accordingly, there are two distinctive types of EL according to Mauch (1996) that are namely, injection and high-field. The former type of EL is described as a common principle for emitting light (diodes) that can be generated from a semiconductor p-n junction that is directed towards a direction and is due from a source of DC. Excess holes are then injected to ‘n’ or excess electrons to ‘p’. As holes and electrons within the two regions combine, luminescence takes place. The latter (high-field) however, can be described as a principle emphasizing on function that is used for electroluminescent displays that is generated from “impact excitation” through highly energized electrons (Ono, 1995).

Figure 3.12: Lighting System Made from Electroluminescent Displays
(Lighttape,2019)

Electroluminescent displays can be thus described as a form of panel display that is flat and is produced by a light-emitting substance being placed in between two conductors. It has been noted that they have high rates of ruggedness, are not overly sensitive to ambient temperature, have a rapid display response, do not need much current, and have a soft and homogeneous light emitting feature. This light is visible and can be seen from great distances regardless of the angle of view. In terms of production, these products are lightweight, cheap and compact, and can be produced in a variety of colors. Generated light by these displays have high extent of reliability

(10% loss on average/10k hour work) with a relatively high life cycle of over 100,000 hours of work (Stauffer & Tybrandt, 2016). Walls or floors as well as format displays placed within public spaces that are luminescent, fall within the vast applications of electroluminescent displays. Similarly, they have been used in arts as experimentations of EL for having not complex animations or patterns to be displayed Such as the work of Jonas Samson (Lucept, 2009).

Based on the great extent of usability of these products, the aforementioned artist has been able to allow customers to design their own pattern illuminated in the store. These individualized designs then will be used as wallpapers or wall coatings for the respective customers. This is a great exhibition of the extent of which advanced materials as a whole and particularly, electroluminescent displays can be applied in various manners and disciplines. As advanced materials expand throughout industries and can be integrated to one another, phones and tablets are now able to control the illumination processes of decorations in The Electroluminescent store. In 2004 sliding panels allowed a designing studio located in London to display their wallpapers in an electronic format. Small size and ability to be disassembled and reassembled in a short time enabled the illumination to follow complex patterns. This integration was further added by sensors and textiles that were sensitive to the environment and the changed occurring in it (Loop.pH). Subsequently, electroluminescent displays exhibit a high extent of usage and applicability, which in line with the current study expands to interior and exterior architecture. However, it is important to note that according to Kretzer (2017), these products are to be in small-sized and in number to be used in architectural surfaces regardless of their mass production and growing scales.

3.2.5 Electroactive Polymers (EAP)

These polymers vary in size, shape and volume as a reaction to electrical field and based on its strength. The electrical charge generates a force, which is applied to particles. EAPs have a high degree of flexibility regarding deformation and reshape in a short manner with low density and enhanced resiliency, which allows them to possess such feature (e.g. piezoelectrics, thermo-elastic polymers, shape-memory alloys/polymers, and magnetostrictive materials). In addition, these products offer a range of benefits that can be namely, lightweight, cheap, high applicability (e.g. stretch sensors), and compliant. It has been noted that these products can be categorized in two distinctive groups that are namely, ionic and electronic electroactive polymers.

When ions are displaced throughout an electrical stimulation, Ionic EAPs exhibit transformation (whether shape or volume). This group of EAPs offer a low voltage for actuation (1-2V). It is key to note that this group requires a degree of wetness for diffusion of ions within the electrolyte. Ionic EAPs possess a high bending ability, but due to high accuracy level that is required for their production, commerciality is low and production cost is high, which consequently leads to lesser usage of these products. On the other hand, Electronic EAPs require relatively stronger electric fields that through electrostatic power yields in transformation of the polymer in an electromechanical manner. Planar actuators are the main place of their application as the deformations and transformations are in-plane and large in scale. This is contradictory to Ionic EAPs as the function of Electronic ones is placed in a rather dry environment. However, as it was mentioned earlier, this group requires a relatively higher voltage for activation (several kilovolts). In addition, this group of EAPs have lower response delay, large activation stress, and the ability to hold displacement that is induced in DC activation (Bar-Cohen, 2002).

In the light of what was mentioned above, it can be seen that EAPs have a high range of flexibility in terms of reformation and deformation, which is considered as a unique feature that allows these materials to be versatile in their production. In this regard, these products have shown functionality within exoskeletons, microelectromechanical systems (MEMS), medical equipment, braille displays, speakers, prosthetic means, artificial muscles and gaming interfaces (Runyana & Blazie, 2010; Evangelho, 2014). To mimic cephalopod chomatophores and active camouflaging, due to their organic behavior and response, these products have been a point of interest for research (Rossiter et al., 2012). Furthermore, they can be used as sensors due to contraction and stretch, which leads to changes within electrodes as resistance becomes episodic. Moreover, their usability expands to mechanical force and its conversion into electrical force, which can be put to use in terms of harvesting natural energies such as, sea waves by dielectric elastomer generators. Ferroelectric, electrostrictive graft, electrostrictive paper, piezoelectric, and liquid crystal elastomers are other forms of EAPs that can be noted within this scope (Bar-Cohen, 2002).

In addition to what was mentioned above and in relation to functionality of EAPs there are other elements that can be noted. Heat loss and heat gain can be regulated through homeostatic facade systems made of EAPs through autonomous close and opening of the system based on changes that occur in the surrounding environment (DeckerYeadon, 2013- New York architectural office). Another architectural development was conducted by Hickok Cole in Washington through usage of EAPs as shading layers that can be activated by solar energy (Architizer, 2019). Aurélie Mossé at the Center for Information Technology and Architecture (CITA), located in Copenhagen focused on energy structures as interior perspective for reciprocation in terms of the link with nature and environment. Accordingly, wind intensity and direction were used to respond in terms of electroactive modules used in ceilings (Mossé et al., 2011).


Figure 3.13: Dynamic Shading Layers Made from EAP (Architizer, 2019)

It has been noted in the literature of the subject that regardless of the above noted statements, EAPs yet face challenges regarding performance and durability that requires both research and industrial development (Kretzer, 2017). This has led to the state, where commerciality is low for available products and is restrained significantly regardless of the advancements made in terms of successful demonstration of materials and their usage. In the context of architecture, EAPs show a high potential in terms of features that are in persistence with quality of surface, transparency, deformation in active manner, and visual appeal. This is while scalability remains a major issue as manual fabrication is prone to error, which can limit the desired size. Similarly, durability as it was noted earlier is a key challenge that lacks meeting standards of architecture. This becomes more vivid, when materials are exposed to the environment that is changing and severe climatic conditions. Accessibility and location of materials that are needed is another element that requires emphasis, especially in open spaces. This is due to the fact that component require high voltages and may pose danger.

In 2010, Manuel Kretzer supervised a project called "ShapeShift" of architectural application of electroactive polymers (EAP) as a dynamic surface material. It can change its size, shape and volume in contact with high voltage of electricity. ShapeShift is composed of several thin layer of EAP attached to electrodes (Materiability, 2010). Each layer of EAP is framed and connected to the other layers creating a structure that forms different spaces with the help of high voltage electricity (Fox, 2016).

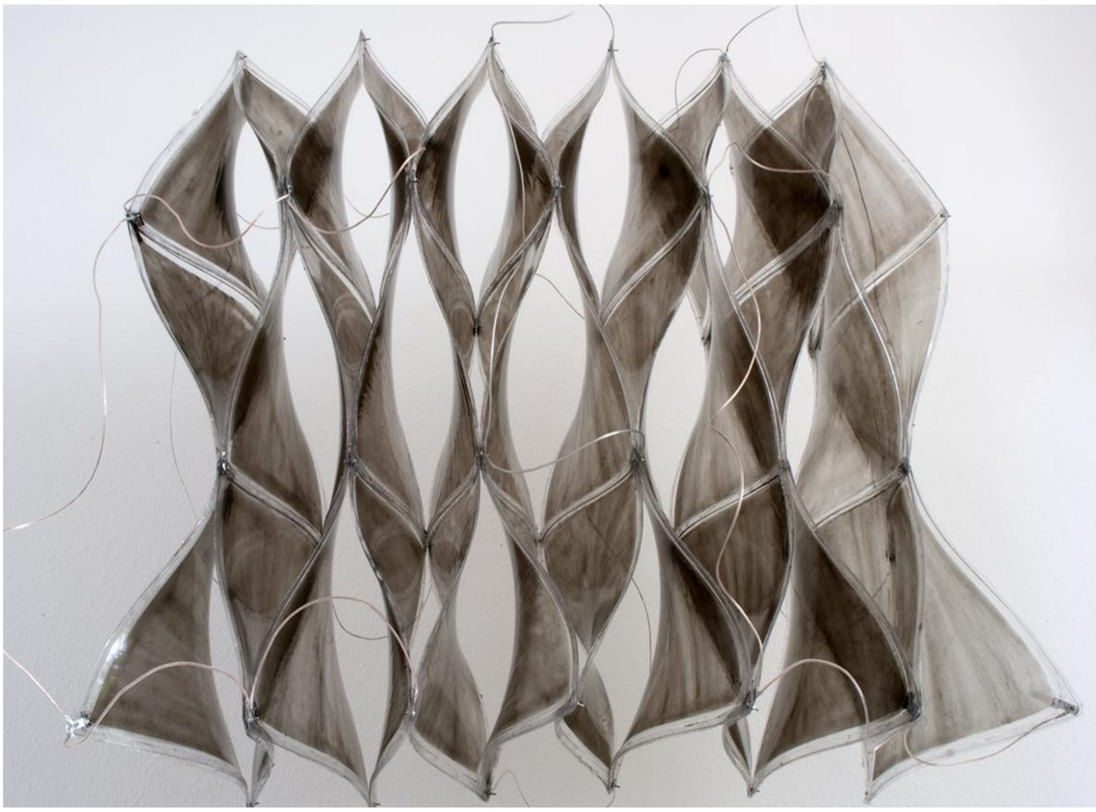
Figure 3.14: ShapShift can be Compressed and Stretched out Forming Different Shape of Spaces (Materiability, 2010)

The main application of electronic EAP used in ShapeShift is in production of artificial muscles due to its high flexibility. In this project, architects explore the potential of this material in creation of layers that can interact with each other and their environment (Fox, 2016). ShapeShift introduces the kinetics in material scale instead of system scale and reveals a horizon for scalability. The ShapeShift can be compressed and stretched out with different level of electricity. The movement of ShapeShift components are similar with the sun shadings of Al Bahar tower mentioned earlier.

Figure 3.15: ShapeShift can Changes its Size, Shape and Volume Through High Voltage of Electricity (Fox, 2016)

One challenge ahead of EAP is the increase the durability of this material exposed to natural forces such as wind, rain and heavy sunlight (Kretzer, 2017). However, the ShapeShift envisions a bright future for EAP application in architectural and interactive spaces. If experts find a solution for durability of EAP in exteriors application, we will witness the dynamic sun shadings in facades made from EAP interacting with their environment in material scale decreasing the cost of construction, operation and maintenance of sun shadings in comparison with project similar to AL Bahar tower.

3.2.6 Thermochromics

These materials fall within the category of chromogenics that are regarded as possess reversibly adjustment regarding their color. This is influenced by some external stimuli that induces the process. The term chromogenics refers to the products that incorporate electrical switchable technologies. In addition, photochromic materials are used in this context due to the ability to change color (hue) under ultraviolet radiations. Furthermore, piezochrmics, and mechanochromic materials are referred to as materials that have the ability to adjust colors based on the stress or pressure posed to them. Moreover, halochromic materials can be described as those, which react to the level of acids in the environment and its changes. Another form of these materials are thermochromic ones that have the capability to change and adjust color, when exposed to changes within the temperature of the surrounding environment (Lampert, 2004). Thermochromic materials have a high usability in terms of home appliances when accurate response to the temperature is not deemed as absolute necessity. For instance, toothbrushes have such materials that shift colors after a certain time is past while being used, a number of infant items, kitchen items that shift based on temperature applied (spoons, cups, plates and kettles), packaging of food and consumables (cans, or bottles), battery testers, and hypercolor t-shirts can be among the various products that have been made with thermochromics. However, due to usage of chemicals for washing, and UV sensitivity, these products have been limited in terms of applications within textile sector (Kretzer, 2017). Modern coatings "smart coating" have the capability to respond to environment, which has turned them into a point of interest and importance in terms of production. Paints with energy consumption reduction ability can be used as exterior architecture applies thermochromic materials. These paints can shift the color to white as the temperature increases. Subsequently, this feature leads to a state, where usage of AC would deem unnecessary (Miodownik, 2008). As previously noted, sensitivity towards UV is the key issue in this context, which diminishes this ability in time and as exposure to changing environment remains constant. Light absorption of windows can be greatly enhanced through usage of thermochromics as solar energy fluxes visible light, thus leading to higher control over transmissions. This can lead to a significantly lower level of heat gain as the smart window has the ability to reflect the infrared, in situations where temperature exceeds a certain level (Parkin et al., 2008).

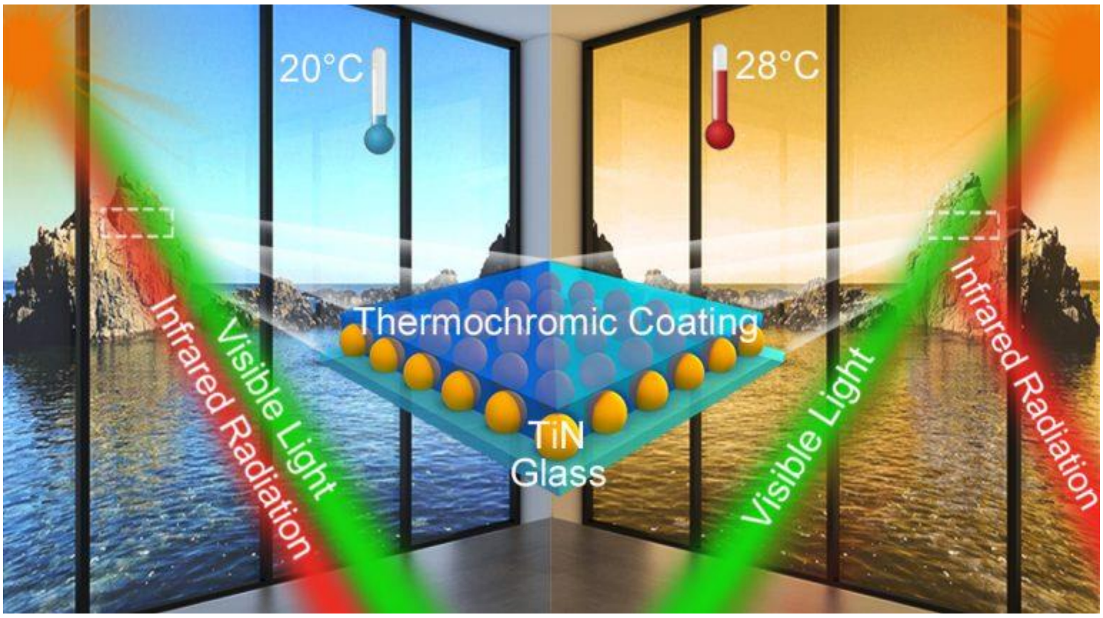

Figure 3.16: Thermochromic Window's Color Change According to Different Temperature (Advanced Science News, 2019)

3.2.7 ETFE

Ethylene tetrafluoroethylene (ETFE) is a plastic material that has been reported to be able to replace glass due to its transparency (LeCuyer, 2008). It was made by DuPont in 40s and was later developed in the 70s to be used within the aviation sector. This was further expanded to construction sector due to high extent of usability of this product and its technical components. Designers were able to increase their innovation and tackle problems with new solutions that was made available through technology and exhibited a satisfactory degree of sustainability (Monticelli et al., 2009). National Aquatics Center (2008) built in Cornwall, Munich, and Beijing respectively, had this polymer embedded in the process of construction. Other examples of these materials having been used in construction sector can be King's Cross Station located in London, Canary Wharf Cross-Rail Station, Manchester Victoria Station, Anaheim Transportation Intermodal Center located in California, Olympic Stadium constructed in Baku, Azerbaijan, and Tottenham Hale bus station. The aforementioned projects have been undertaken in recent years and as it can be seen the usage have been increased since the year of 2012. Transparency of these products is relatively higher regarding solar radiation, when compared to glass, they have a higher degree of lightness, enhanced resistance to mechanical forces in high temperatures (200 Celsius degrees), UV resistance, Air pollution resistance, acoustic features (sound-absorption), low cost in terms of installation, and can be cleaned by a mere rain without extra efforts in terms of cleaning. The last feature is due to the fact that these materials have a low coefficient in terms of friction that is supported by antiadhesive feature. This yields in a lower cost in terms of maintenance. In addition, these materials have a ranking of B1 with regard to fire resistance standards (DIN, 4102). Furthermore, in unlikely situation of combustion, these materials shrink upon themselves, which significantly decreases danger posed in terms of fire and as a consequent, evacuation processes will be easier to be conducted (Casini, 2016).

Figure 3.17: Allianz Arena Facade Made from ETFE (Seele, 2016)

Chapter 4

CASE STUDIES

4.1 Case Study Selection

The selection of multiple cases for this qualitative study have been conducted. This selection follows purposeful sampling method in order to select information-rich cases. Thus, the selective sampling and theoretical sampling as the strategies derived from purposeful sampling have been implemented. In this research, case studies have been chosen (selective sampling) from buildings that their facades are recognized as "interactive" in European Cooperation in Science and Technology (COST) (Aelenei et al., 2018). Through literature review, three additional studies have been selected based on reviewed data regarding interactive architecture and facades (Theoretical sampling). The procedures of purposeful selection of cases have been conducted based on the guidance of related literature (Mills et al, 2009; Yin, 2017).

4.1.1 GreenPix (China)

GreenPix is an enormous LED display with RGB colors providing dynamic visual contents. The selection of low-resolution technology for a large scale application provides an artistic and abstract form of visualization, which is unique in comparison with ubiquitous employment of high resolution displays as media facades (Aelenei et al, 2018).

The collaboration of German and Chinese manufacturers has led to development of new technology regarding embedding PV cells in curtain wall with glassy structure.

The glassy curtain wall augmented by polycrystalline PV solar cells has covered the entire facade of the building enabling the facade to harvest and store energy in daytime for tasks of the assembled large display. The glassy curtain wall has distinctive pattern of density in order to facilitate the visual and thermal comfort. This pattern allows daylight to enter the building and this process is controlled by an intelligent system. In addition, the intelligently designed density improves the performance of harvesting energy by PV cells. The harvested energy during daytime is used for the function of display in night time (Simone Giostra & Partners, 2019).

GreenPix benefit from a bespoke software capable of interacting with regulatory staff, artists and public audience. This intelligent software enables the facade to be used as an entertainment medium for public visitors. The customized software is developed by a multinational company called Arup who are experts in lighting and façade engineering (MAI, 2008).

Figure 4.1: Image of GreenPix Interactive Façade at Night (Basulto, 2008)

Figure 4.2: Image of GreenPix Interactive Facade in Daytime (Basulto, 2008)

4.1.2 CycleBowl (Germany)

CycleBowl is a pavilion with interactive facade built by a German company called "Duales System" active in recycling practices. The facade is made from ETFE developed by "Vector Foiltec", which is marketed with Texlon brand. This interactive facade controls the incoming daylight into interiors of the building and consists of three layers functioning with the aid of pneumatic energy. The two outer layers have printed patterns shaping leaves through the combination of positive and negative themes. Pneumatic energy triggers the middle layer to combine with outer layer pattern to form opaque barrier or with inner layer to create transparent separator (Atelier Brueckner, 2000).

Figure 4.3: Image of CycleBowl Interactive Facade (Cycle Bowl Expo, 2002)

Optical energy transforms to pneumatic energy by pressure chambers and resulting energy moves the layers made from ETFE cushions. The movement of layers with leave patterns creates an awe-inspiring ambient, while providing thermal and visual comfort for visitors inside the pavilion. The facade is responsive towards the amount of sunlight and creates appropriate transparency for inside the building through the movement of ETFE made middle layer (Cycle Bowl Expo, 2002).

Vector Foiltec products provide quality shading textures for facades, while being sufficiently sustainable. The production of these products requires very low energy consumption and they are partly recycled and all of them can be recycled after demolition of the project. The weight of these products are low in comparison with other alternatives, thus the designing of supportive structures is easier (Aelenei et al., 2018).

Figure 4.4: Image of CycleBowl Interactive Facade from Inside the Building (Cycle Bowl Expo, 2002)

4.1.3 Kolding Campus (Denmark)

Kolding Campus is a learning center in a Danish university providing courses in various fields such as art and languages. The facade of this campus is made from perforated steel creating a solar shading system providing thermal and visual comfort (Archdaily, 2015).

Implemented sensors monitor the amount of light and temperature and control system actuates the solar shading system consists of triangular panels to adjust themselves for optimization of user comfort in terms of thermal and visual convenience (Aelenei et al., 2018).

The intelligent design of this building enables it to practice variety of sustainable operations:

- Employed PV cells harvest energy for buildings' services.
- Cooling system utilizes the water of nearby river to function.
- Ventilation system benefit from mechanical structure consuming significantly low energy (Aelenei et al., 2018).

The constructed shutters made from perforated steel adjust themselves according to amount of light and temperature. The shutters create a flat surface when they are fully closed and when they are fully open to allow light inside, they create an awe-inspiring figure for public view. The actuation of these shutters is the role of a small mechanical motor and the sensors are embedded in the shutters to constantly monitor the amount of light and temperature (Dezeen, 2015).

Figure 4.5: Image of Kolding Campus Interactive Facade (RMIG, 2015)

The patterns of shading panels are perforated in the shape of round holes providing a unique appearance for external environment, while optimizing the thermal and visual comfort for the inside. The intelligent design of the facade through calculation of perforations' size and shape and the respective angles of shutters facilitates the process of user comfort provision. The control system has an interface to be controlled by regulatory staff (Henning Larsen, 2015).

Figure 4.6: Image of Kolding Campus Shading Panel Made of Perforated Steel (RMIG, 2015)

4.1.4 Duke Energy Center (USA)

This skyscraper has 51 floors and is located in New York, Charlotte district (iOffice Corporation, 2018). It is the first and tallest skyscraper that was able to obtain platinum level certification of LEED Council in United States (Duke Energy Center, 2020).

Figure 4.7: Duke Energy Center Interactive Facade with 45,000 LED Lights (S & ME, 2020)

There were numerous sustainable efforts in construction of this building. It has water-harvesting facilities saving 30 million gallons of water per year from different resources including rainwater, ground water and domestic water. This saved water is enough for cooling the building and gardening of building's greenspaces (Planet Technology, 2019).

Energy efficiency has been implemented in this building. Custom blinds of exteriors reflect the sunlight into the building in a way that natural light provides visual comfort for interiors. These blinds' coatings are made of Flouropolymer coatings made them sufficiently durable. There is a roof garden designed for shielding the building against excessive heat. Glazing exteriors and lighting sensors regulates the amount of light inside the building. In addition, HVAC system in this building is highly efficient (Duke Energy Center, 2020).

Figure 4.8: Duke Energy Center Daylight Harvesting Blinds
(Duke Energy Center, 2020)

There are 45,000 LED lights installed on the exteriors illuminating at night. Every hour there is a light performance to announce different events and causes. These events and causes are mainly about non-profit acts that are being held in local area. These light shows have created a community for supporting non-profit foundations, which have attracted more than 13,000 followers on Twitter (iOffice Corporation, 2018).

4.1.5 The Arab World Institute (France)

Located in Paris, France, The Arab World Institute has a special position in cultural architecture. It has a hybrid identity showcasing western and eastern culture designed by Jean Nouvel. The northern façade is the representative of western culture is made of glass facing Seine River mirroring the river and cityscape in a beautiful manner. The Southern façade consists of panels sensitive to light. These panels operate like the diaphragm in cameras responding to light intensity altering their sizes accordingly. These panels create themes consist of layers of images through lights and shadows (Nouvel, 2006).

The building is the winner of Aga Khan award for architecture in 1989. Although jury of award criticized the excessive complexity of mechanisms in the building in order to be used and maintained, they admired the role of this building as the connector of France and Arab worlds (AKDN, 2012).


Figure 4.9: The Southern Façade of the Arab World Institute (Winstanley, 2011)

The main feature of this building that is also related to this study is its complex and beautiful brise soleil. The brise soleil is an architectural term, which means sun-breaker in English providing visual and thermal comfort for an architectural structure through controlling the incoming sunlight (Hodges, 1988). 30,000 motorized diaphragms have been laminated between two glass layers, which each diaphragm is controlled by the central control system of the building (Hraska, 2018). Photovoltaic sensors control the adjustable diaphragms controlling the penetrating lights inside the building and creating patterns that are aligned with the theme of the whole building (McKiernan, 2013).

Figure 4.10: The Panels of Façade Function Similar to Camera Diaphragm Controlling the Lights (Winstanley, 2011)

The southern façade of the Arab World Institute is a motorized sun-breaker, which its architectural patterns are inspired by Arabic oriel windows called Mashrabiya. These traditional patterns are widely used in Middle East for thermal and visual comfort as well as privacy. The motorized panels of southern façade have layers of lens that alter the patterns of created shapes through incoming sunlight. These shifting geometric shapes formed by lights and shadows through motorized diaphragms decorate the interior and exterior spaces in an astonishing manner. In addition to aesthetics, the southern façade provides thermal and visual comfort for inhabitants via controlling solar gain (Winstanley, 2011).

Figure 4.11: Interiors are Decorated by the Mixture of Lights and Shadows Provided by Panels of Façade (Nouvel, 2006)

4.1.6 Allianz Arena

Allianz Arena is the stadium of FC Bayern Munich soccer club in Munich, Germany. This stadium has the largest membrane structure as the façade with height of 35 meters and 29,000 square meters of external surface area (Allianz-Arena, 2015). This façade is made of inflatable panels of EFTE enabling various functions for this stadium. Regulation of interior climate, light management, loading support, enabling various shape designs and aesthetics are the functions that these EFTE panels have provided for this stadium. In spite of being lightweight, ETFE panels have the ability to tolerate great amount of loadings. Allianz Arena façade benefits from transparent façade enabling versatile lighting designs for this stadium. This façade announces different soccer matches through different color settings (Seele, 2016).

The EFTE panels in Allianz Arena façade is adaptable to different climate conditions. It is highly durable against solar radiation and due to its non-stick quality, there is no need for cleaning the façade. Regarding safety concerns, the EFTE panels are fire resistant and they will not produce smoke in exposure to fire accidents (Juaristi, & Monge-Barrio, 2016).

Figure 4.12: Allianz-Arena Interactive Facade (Allianz-Arena, 2015)

In order to illuminate the façade, Philips Company has installed more than 300,000 LED lights capable of generating 16 million colors beneath the outer layer of inflatable EFTE panels. The utilization of LED lights instead of fluorescent lamps has decreased the energy consumption rate more than 60 percent. In addition, LED utilization decrease almost 400 tons of CO_2 emission in comparison with fluorescent solutions within a year (Lighting Philips, 2016).

Figure 4.13: The Installed LED Lights for Allianz Arena (Lighting Philips, 2016)

Philips has provided a cloud-based software for Allianz Arena called ActiveSite in order to facilitate the management of lighting operations. This software enables the remote monitoring, management and maintenance of lighting systems in a speedy and effortless manner. The staff including managers, designers, and field workers are connected through different levels of access to this software to accomplish their tasks in an optimized way (ActiveSite, 2016).

Figure 4.14: AcitiveSite Software Utilized for Lighting-Related Operations in Allianz Arena Stadium (ActiveSite, 2016)

4.1.7 Al Bahr Towers (UAE)

Al Bahr consists of two 25-storey towers, was designed to be landmark as well as a contemporary representative of Arabic architectural heritage. The façade of this building is a curtain wall, which is covered by an advanced responsive solar screen, was constructed through inspirations of nature, Mashrabiya and hi-tech solutions (Arch2o, 2014). The curtain wall frames are made of aluminum and the employed glasses are double glazed (Karanouh & Kerber, 2015). The Mashrabiya units of the façade, which are installed on the curtain wall and fixed to the main structure behind the curtain wall, acts as a living flower responding to sun movements (Fox, 2016).

Figure 4.15: The Facade of Al Bahr Towers Consists of a Curtain Wall (Cilento, 2012)

The major challenge of designer in Al Bahr project was to create a balance between environmental regulations and the practicality and efficiency of solutions for inhabitants' comfort (Fox, 2016). The comprehensive BIM process assisted the creators to plan and implement tasks in order to accomplish the mentioned challenge (Attia, 2017).

The main objective of Al Bahr's creators was to build a tower to be extremely astonishing to become the landmark of the region. Thus, they planned a building with a contemporary design benefiting from hi-tech facilities, which should be sustainable, prestigious and capable of contribution to architectural and cultural heritage of Arabs of Emirates (Oborn, 2014).

The Al Bahr Towers developed the traditional Islamic architecture, Mashrabiya in particular through employment of hi-tech methods and materials. In order to accomplish this, the creators of Al Bahr utilized digital methods to automate the process of design and implementation, which are common in advanced industries such as Aerospace and Automotive. A customized software for computational tasks and simulation of automated operations was developed exclusively for this project (Karanouh & Kerber, 2015).

Figure 4.16: The Al Bahr Towers’ Façade at Night (Cilento, 2012)

The dynamic solar screen employed in Al Bahr Towers’ façade act as a dynamic Mashrabiya. The other inspiration for the design of this solar screen is origami (Japanese paper folding) enabling the triangular parts of the screen to unfold with high levels of flexibility in response to the real-time sun location. These dynamic features overcome the limitations of traditional and static Mashrabiya, which are not suitable solution for buildings with complex design (Karanouh & Kerber, 2015). This advanced solar screen improves visual comfort for interiors, while maintaining the views of surroundings for inhabitants through dynamic protection against sun instead of employment of static solutions such as dark glass claddings (Fox, 2016). In addition, the well-designed geometry of contemporary Mashrabiya eliminates the high wind-loads for the building (Attia, 2017).

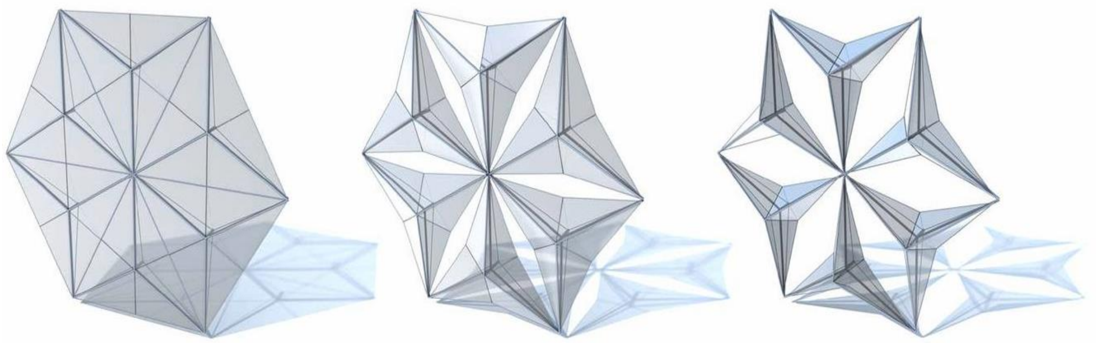

Figure 4.17: The Dynamic Solar Screen of Al Bahr Towers (Cilento, 2012)

The façade of Al Bahr Towers contributes to the sustainability of the building in various manners. It reduces the need for artificial light used in interiors and through controlling solar gain the need for air-cooling is significantly reduced. Therefore, the façade reduces the energy consumption, while providing comfort for inhabitants through interacting with sun and wind, which are the main sources of residential problems in region (Cilentio, 2012). Al Bahar Towers is the first holder of silver LEED certificate in gulf region due to reduction of solar gain to 50 percent in comparison with skyscrapers built before in the same region (Laylin, 2014).

Siemens provided a custom interactive platform for controlling the dynamic Mashrabiya, which every foldable unit of solar screen is recognizable by software and the service staff can track them in the interface of the platform. The software simulates the position of the sun according to reference (pre-programmed) data and command the foldable units to shape the desired formation. In addition, the platform is connected to sensors receiving real-time data regarding speed of wind, humidity and light intensity and providing this data to control staff in order to deal with unusual conditions when programmed instructions do not provide the best solutions (Karanouh & Kerber, 2015).

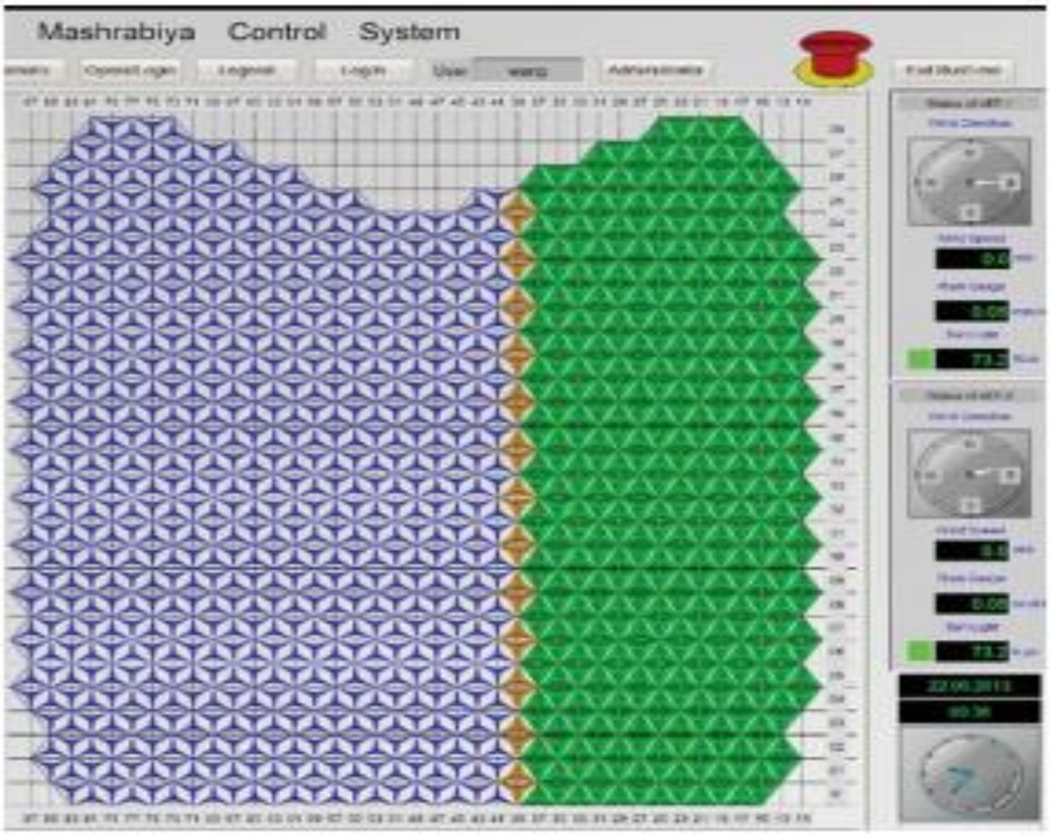

Figure 4.18: Siemens Platform for Controlling Dynamic Solar Screen in Al Bahr Towers (Karanouh & Kerber, 2015)

According to a survey conducted by Attia (2017), almost 50 percent of inhabitants rated their comfort level ranging from neutral to very uncomfortable due to the fact that the movements of Mashrabiya are automated and the inhabitants does not have access to interact with façade for personal configuration.

4.2 The Analysis of Case Studies

Here, this study provides the analysis of case studies based on Loonen et al. (2015) categorization criteria:

Table 4.1: The Analysis of Case Studies

Building	Climate	Goal/Purpose	Sustainability	Multifunctionality	Interactive Component	Agent of Adaptation	Operation	Technologies	Response Time	Visibility	Degree of Adaptability	System Complexity
GreenPix	Hot Summer Continental Climate	1. Visual comfort 2. Thermal comfort 3. Appearance 4. Energy generation 5. Media	1.Environmental impacts 2.Performance 3.Social Benefits	√	1-LED Screen 2-Customized software interface	Solar radiation	Intrinsic	Building-integrated photovoltaics	Minutes	Visible (Smart glazing)	On/off	Level 2
CycleBowl	Marine West Coast Climate	1. Thermal Comfort 2. Visual Comfort 3. Energy Management 4. Mass Transfer Control	1.Environmental impacts 2.Life cycle cost 3.Performance 4.Social Benefits	√	1-Kinetic facade	Solar radiation	Extrinsic	pneumatically controlled shading systems realized with ETFE cushions	Minutes	Visible (surface change)	Gradual	Level 2
Kolding	Temperate oceanic climate	1. Thermal Comfort 2. Visual Comfort 3. Appearance	1.Environmnetal impacts 2.Performance 3.Social Benefits	√	1-Kinetic facade	Solar radiation	Intrinsic/ Extrinsic	1. Building Automation System 2. Shading system with dual-axis tracking	Seconds	Visible (shape change)	Gradual	Level 4
Duke Energy Center	Humid subtropical climate	1. Thermal Comfort 2. Visual Comfort 3. Appearance 4. Media	1.Environmental impacts 2.Performance 3.Social Benefits	√	1-LED Lights	Precipitation	Extrinsic/ Intrinsic	1. Custom Blinds 2. Rain harvesting system 3. LED displays	Minutes	Visible	On/off	Level 2

Al Bahr Towers	Hot desert climate	1. Visual comfort 2. Thermal comfort 3. Energy Management 4. Appearance	1.Environmental impacts 2.Performance 3.Social Benefits	√	1-Kinetic façade 2-BIM software	Solar radiation	Extrinsic	BIM based shading system	Minutes	Visible (Shape Change)	Gradual	Level 4
Allianz Arena	Temperate oceanic climate	1. Energy Management 2. Durability 3. Appearance	1.Environmental impacts 2.Life Cycle Costs 3.Performance 4.Social Benefits	√	1-LED lights	Outdoor temperature	Intrinsic	LED Lights ETFE cushions Cloud-based control system	Seconds	Visible (Color Change)	Gradual (for ETFE) On/off (for LED)	Level 3
The Arab World Institute	Temperate oceanic climate	1. Thermal Comfort 2. Visual comfort 3. Appearance 4. Energy Management	1.Environmental impacts 2.Performance 3.Social Benefits	√	1-Kinetic facade	Solar radiation	Extrinsic	Motorized Diaphragms with individual computational control	Minutes	Visible (Shape Change)	Gradual	Level 4

4.3 Comparative Discussion

Analyzing the selected case studies has revealed the empirical application of interactive architecture concept in designing facades by architects. Exiting buildings with interactive facades (recognized by COST) has different systems and functions showing that involved designers have employed different methods to employ interactions in order to serve different purposes. For example, in Greenpix case, interaction of facade with sun provides required energy for the function of facade through PV technology (Zero energy wall), while in Cyclebowl case, interactive facade harness the incoming light to provide visual comfort and artistic ambient for visitors of exhibition through ETFE cushions. These facts suggesting that the desired functions and purposes drive designers to use possible interactions to provide different solutions. Different solutions require different technologies (e.g. PV for energy storage and ETFE cushions for sun shading).

However, regardless of the employed systems, the exiting building cases show that interactive facades are able to significantly contribute to sustainability through interacting with people and nature and function accordingly. In addition, analyzed cases suggest that adaptation through interactive facades are possible and their functions can be controlled properly. Analyzed cases suggest that adaptation through interactive facades are possible and their functions can be controlled properly.

Intelligent design enables interactive systems to use available resources for improving multifunctionality and sustainability. In the case of Kolding campus, interactive system benefits from various resources (sun, river and solar cells) to sustain its functions.

BIM-based interactive engines are the most relevant and promising development in architectural practices. The resulting AI can increase the autonomy and reliability of control system in interactive facades as reviewed in Sync-BIM case.

This study states that according to reviewed literature regarding AI and Advanced materials recent developments, the performance of interactive systems can be improved in terms of efficiency and multi-functionality.

AI with learning capability is able to interact intelligently with its environment and facilitate the human comfort while being green. Advancements in AI suggest that smart buildings can learn inhabitants' interests and behavioral patterns through interacting with them and provide best environmental condition for them in an efficient way by constant interaction with nature. Adaptive capabilities of advanced AI leads to more functions for a facade through interacting with inhabitants and other environmental factors. Embedded AI capable of learning from simulations and operational logs (feedbacks) increase the reliability of control system in interactive facades.

Advanced materials can improve the performance of facades in various ways. Silica aerogels embedded in glasses can improve the performance of glass structures in terms of thermal insulation. Bioplastics can contribute to sustainability of interactive facades, since they are less pollutant. However, their durability for exterior application is the main challenge for future developments.

The concept of zero-energy wall reviewed in the case of GreenPix, is the proper way to manage energy of facades in a sustainable manner. PV integrated walls can harvest and store energy for interactive facade's functions. The future of zero-energy walls are dependent on affordability of PV integrated structures and other developments in solar cells field (e.g. dye-sensitized solar cells).

The combination of zero-energy walls with other advance materials can increase the performance of interactive facades. Electroluminescent Displays can be added to an interactive system benefiting from zero-energy walls in order to decrease the energy consumption of interfaces. Electroactive polymers can use harvested/stored energy by zero-energy walls to change their properties and can be employed for different functions such as kinetic facades. Thermochromics materials can be used in exterior coatings in order to reduce the energy required for interior air conditioning. The intelligent design (BIM-based design is recommended by this study) of interactive facades enables the capability of exploiting available advanced materials according to situation (external available resources such as sun, water and wind; users' preferences) and eventually can contribute to fulfillment of third millennium buildings' agenda.

The case of Duke Energy Center is a successful case of interactive façade linked to a social media to empower its sociocultural effect. Social media has proved its effectiveness in digital and IOT environments and an interactive system can enhance its interactivity through this media solution.

In order to lower the cost of maintenance, intrinsic solutions can be implemented such as solar panels, since the environmental data should not be processed first for system to behave in an adaptive and sustainable manner accordingly. These solutions, decrease the complexity of the system, but provides less intelligent performance by machines.

The more a façade has ability to interact with its environment, the more it can contribute to sustainability. As this study reviewed in the case of Al Bahr towers, the façade was unable to interact with inhabitants and consequently, the inhabitants were not satisfied with how the façade responds automatically to sun movements. The lack of consideration towards the benefits of provision of interaction between façade and inhabitants has resulted partial dissatisfaction among inhabitants in Al Bahr case. This dissatisfaction damage the overall contribution of a project to sustainability. AI wearables, Adaptive sensors and other AI developments can increase the customizability of facades' functions and increase the human comfort efficiently contributing to sustainability of facades.

The construction of hi-tech facades require utilization of materials with similar properties to plastics such as resistance to fire, chemicals and electricity. Bioplastics present a bright future to be replaced the plastics in order to decrease the pollutions derived from plastics. Thus, façade designers should consider the environmental advantages of bioplastic utilizations especially PLA as the most advantageous kind of bioplastics.

Aerogel infilled glasses and walls can be great sustainable elements in order to construct interactive facades. Aerogel infilled glasses can provide thermal and visual comfort for buildings while having great insulating value for a building. Aerogel infilled walls benefits from great insulating properties as well. Façade designers should consider these amazing properties of Aerogel-based construction materials in order to boost the multi-functionality of an interactive façade.

Chapter 5

CONCLUSION

5.1 Architectural Implications

IOT facilitate the design for sustainability through interactive architecture. Wireless components of an interactive facade such as sensors can increase the sustainability of employed materials. Wireless components can be protected easily against destructive forces such as hygrothermal conditions. From technical perspective, application of wireless components will increase the validity of measured data, since the health of component has been secured through removing physical connectors that should be exposed to destructive forces outside of the building. From ecological point of view, securing materials from destruction will contribute to elimination of waste and removal of physical connectors will eliminate the excessive consumption of materials.

In order to use new technologies for interactive buildings in optimized and energy-efficient manner, these technological components should be tested through simulations in labs by designers. AI, advanced materials, adaptive sensors and other trends should be tested and optimized before implementation into real buildings. Building information modeling (BIM) as an intelligent process can assist architects and engineers in simulating the desired environment to test their designed prototype in similar way mentioned in selected prototype case study.

Technological developments bring the possibilities of enhancing the buildings' capabilities in terms of real-time response to environmental conditions and autonomy. AI and advanced materials facilitates the process of enhancement through increasing the intelligence and efficiency of the building. Intelligent control and decision systems augmented by wireless components have the potential to increase the performance of the buildings dramatically. This fact has encouraged the architects to shift their focus from traditional way of thinking about design to innovative ones. This shift as focusing more about the performance rather than form and more about facade rather than structure.

This shift derived from technological developments should be followed by architects, engineers and policy-makers in order to increase the performance of sustainable third millennium buildings. For instance, In UK, all the governmental projects should be designed and documented through the process of BIM. These kind of policies and shifts will increase the awareness of actors in construction-related industries to employ interactive systems in architecture of buildings.

In order to increase the applicability and feasibility of interactive architecture, developments in 3D printing, design for manufacturing and mass-production of related advanced technologies are vital. Finished products or components, which can be used in interactive architecture, can increase the availability and accessibility of technologies in order to make interactive facades. Programming AI, inventing and manufacturing advanced materials are really hard and time consuming tasks. In addition, the skills, facilities and budget for conducting these tasks are not available for all actors in construction-related industries.

Companies are producing advanced materials for commercial purposes. These companies are selling products such as PV glasses (e.g. Onyx Solar), Aerogel insulations (e.g. Proctor Group) and sustainable and carbon friendly advanced materials (e.g. Lucideon). Actors in construction industry should pay more attention to available sustainable solutions in terms of advanced construction materials in order to fulfill the third millennium buildings' agenda.

AI-related products such as Siri of apple and Alexa of Amazon demonstrate the power of present AI in terms of interaction with their users. These products benefit from natural language generation and learning. They can interact with their user through available interfaces such as smartphones. In case of smart buildings, Microsoft has been developed an AI called Bonsai. This ready-to-use AI makes it possible for architects to add intelligence to a building without dealing with AI development process. These types of artificial intelligence are described thoroughly in their respective section in this study. Having smart buildings with AI similar to what we have now on our smartphones is the possible future of interactive world and architecture according to recent technological developments. Bonsai provides a HVAC system benefiting from AI to implement strategies for optimization of indoor temperature, efficient consumption energy and reliable functionality. Bonsai as an AI similar to *verified-AI* concept reviewed in this study, is constantly being trained through simulations and through its end-to-end platform it will provide efficient algorithms (not a single and fixed algorithm) to increase the reliability of its autonomous system.

BIM as the revolutionary technological concept in digitalization era in architecture context, can facilitate the development of interactive energy management systems for sustainability. BIM support energy management systems of buildings in different phases of implementation. BIM can be used in design stage to plan for energy management. In design stage, BIM is able to predicting energy consumption of desired function of interactive systems. In construction stage, BIM can assess the energy performance of employed construction materials through visualizing the model of building under construction. BIM database of construction material can guide the designers to sustainable employment of available materials for construction. Designers can be assisted by BIM for minimize the waste of construction materials. BIM can monitor the energy performance of building in operation stage and can learn from the feedbacks (operation logs and user preferences) provided by interactive system of the building.

BIM can assist designers in appropriate selection of construction materials in terms of recyclability and gas emissions. In order to build sustainable constructions, interactive systems should be developed by materials that can be reused after the demolition of project. Decreasing the waste of materials through reusing them for new buildings can be a great contribution to sustainability.

The developments in BIM, AI and advanced materials is the future of interactive architecture for sustainability. Thus, the researcher believes that actors in construction-related industries should acquire knowledge about the mentioned fields of technology in order to employ them for optimization of buildings performance.

5.2 Recommendation for Future Studies

This study has been conducted in order to identify the characteristics of interactive facades through reviewing literature and analyzing purposefully selected case studies.

As mentioned before, there is an ocean of options to design based on interactive architecture context. However, the agenda of modern cities is clear and all the actors should seek for sustainable solutions. Future studies can contribute to this agenda through providing empirical data from experimenting innovative ideas regarding interactive facades. The performance of interactive systems in buildings should be compare to traditional systems and also to other interactive systems in order to find optimized solutions regarding sustainability. Future studies can focus on single or few functions of interactive architecture (e.g. energy harvesting) and provide reviews and empirical data in order to conduct more specified researches. Interview-based studies can be conducted and actors of construction industry (e.g. architects, engineers, policy-makers and real estate agents) in specific regions can be asked to extract the regional demands to be fulfilled through interactive systems. Surveys and interviews can be conducted to measure the awareness of people regarding interactive solutions for sustainability. Specific studies on AI and advanced materials can be carried out in order to provide in-depth study of these developments related to interactive architecture (e.g. AI learning regarding inhabitants' behavioral patterns).

Technological developments regarding design for manufacturing (DFM) such as interactive design software programs and 3D printers expands the area of interest for researchers to suggest strategies for increasing performance in terms of sustainability (people, planet, profit) in interactive architecture context. From economic and organizational perspective, future studies can investigate the outcome of development in DFM in terms of reducing on-site operational tasks and costs. From technical perspective, investigation on the reliability of manufactured products through experimental and comparative analyses is one of the recommendation of this study for future researches. Producing prototypes benefiting from offered products available in market (e.g. Bonsai AI for HVAC system, programs for BIM such as Revit and SketchUp) facilitate the researches to analyze and compare different solutions in interactive architecture context.

Adaptivity has been introduced as the solution for a system to optimize its desired output (goals) through interacting with surrounding environment (Fox & Kemp, 2009; Jaskiewicz 2013). The constantly changing environment evoke the need of dynamic structures in buildings capable of adapting with present and future conditions to guarantee the sustainability of solutions (Edupuganti, 2013). The future researches can study the adaptive interactive solutions (products and prototypes) and assess their adaptivity in terms of flexibility, learning capability, agility and reliability.

Application of new technologies in manufacturing industry creates the potential for firms to customize their products in mass scale for equipping buildings with smart systems (Menges, 2015). These products can be improved in terms of being easy-to-assemble, affordability and physical properties such as weight and lifespan. Future studies can focus on the manufacturability of solutions in the realm of interactive architecture.

The creation of solutions based on technological developments for more sustainable buildings have been the main issue to be tackled. Developing interactive systems for buildings benefiting from intelligence is believed to be an effective way to reduce the energy consumption, while providing convenient conditions for users. However, the effectiveness, reliability and feasibility of proposed ideas are the matters that should be investigated by researchers. It is recommended to future studies that focusing on the analysis of already-developed technologies rather than proposing new innovative ideas can be a great contribution to architectural literature. Identifying the strengths and weaknesses of already-developed technologies can reveal the horizon for further developments.

Interactive system enhanced with intelligent energy management system and advanced materials for energy storage and harvesting can function efficiently in terms of energy consumption, while being multifunctional and providing variety of services with harvested energy to inhabitants in terms of thermal and visual comfort, entertainment and suggestion for green behavior. Future studies can analyze existing interactive energy management systems and/or develop innovative prototypes in this context for sustainability.

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