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Review Paper

Responsive Architecture Solutions to Reduce Energy Consumption of High-Rise Buildings

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Abstract
Today constructing high-rise buildings which consist of a great amount of surface area and also openings is prevalent and is continuing to rise. Therefore, the building's envelope is among the most important elements that has a great effect on energy consumption and wastage. As a result, Responsive Architecture focuses on the design of the external skin of buildings which can change their physical properties in order to respond to various environmental conditions. These facades can play a significant role in reducing energy consumption produced by fossil fuels and maximizing the use of natural energies. This study aims to simply review and categorize the various solutions provided by responsive architecture in order to reduce energy consumption in contemporary high-rise building skins. To achieve this goal there has to be a clear image presented of the impact of these responsive systems on energy consumption and how they actually function. In this regard, comparative studies on some of the most basic studies concentrated on the subject, and also a few case studies well-known in this area of matter were precisely reviewed with a descriptive-analytical approach. Accordingly, a general assortment of responsive architecture solutions and performance in high-rises were attained and gathered which can be classified into two groups; those applicable for vertical facades including "Kinetic Facades", "Double-Skin Facades", "Smart Materials and Windows", and those for horizontal facades including "Kinetic Roof" and a new type of "Ventilation Stacks and Exhaust Ducts". These solutions can be operated in combination with each other or for the better performance of another system, depending on environmental conditions. moreover, they can be applied for either new buildings during their construction or even the old ones by installing them separately from the main facade. They can control the energy consumption of the building and minimize the use of mechanical systems by increasing the amount of received solar energy, reducing internal energy wastage, receiving optimum natural daylight, creating natural ventilation, controlling the amount of excess received heat, regulating temperature through energy storage and generating electricity. Responsive architecture solutions show that they can not only make it possible in getting the maximum advantage of renewable sources, but can also extend the useful life of buildings, and produce a quality of experience that reconnects people to the environment and provides delight in their lives.

Keywords: *Responsive architecture, Responsive facade, Kinetic architecture, High-rise buildings, Energy consumption reduction.*

1. INTRODUCTION

Continuous population growth, increasing migration to large cities, and increased urbanization and price of land, have inevitably led buildings especially houses to give their spot to high-rises. Therefore, vertical growth of the cities and increase in building height have occurred as a result of saving costs, time, and the maximum use of urban lands which has had various consequences, one of which is

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the high energy consumption (Feng & Xingkuan, 2011). Knowing that the high-rise buildings will operate for long periods of time, and the impact of high energy will cost a great number, the issue would be an interesting subject to study. Researchers at UCL's Energy Institute have found that electricity and gas use increase with height by around 40% (Steadman, Hmilton, Godoy-Shimizu, Shayesteh, & Evans, 2017). Heating, ventilation, air-conditioning of high-rise buildings require about 70 % of energy, 20% of lighting, and 10% of maintenance of elevators. The relevance of this direction is determined by the growth of energy consumption of cities in the urbanization process (Zhigulina & Ponomarenko, 2018). As a result, total carbon emissions from gas and electricity in high-rise buildings are more than one and half times greater than in low-rise air-conditioned buildings. Steadman adds that air temperature decreases with height, and average wind speed increases. Taller buildings that stand up above their neighbors are more exposed to these strong winds, as well as to more hours of direct sun. Thus, energy use for heating and cooling would both be increased (Steadman et al., 2017). Other studies have also found a trend of increased energy use with height even in naturally ventilated buildings. Glazing proportion increases systematically with height, as might be expected, suggesting that one cause may be to do with heat loss and heat gain. also, there is a general increase in wind speed and a lowering of average temperature with increasing height above ground, to which taller buildings are more exposed. Buildings that rise above their neighbors are also not as overshadowed and experience greater solar gains (Steadman et al., 2017). high-rise buildings, form one-third of the energy consumption and are responsible for half of greenhouse gas emissions (Friedman, 2009; Toepfer, 2007).

Considering the undeniable key role of the buildings in fuel consumption and energy wastage, the potential of improving the efficiency of the buildings especially high-rises can be considerable. The main principles of energy-efficient construction are maximum use of alternative renewable sources of energy such as thermal energy of the earth, the energy of sun, wind, and reducing the negative impact on the environment (Zhigulina & Ponomarenko, 2018). Researchers predict that the current energy use of the buildings could decrease by 30% to 35% through more efficient energy consumption. A further 25% can be decreased through changing the current basis of the buildings into more energy-efficient buildings (Droege, 2011). Energy efficiency in the buildings is equivalent to using solutions that minimize energy consumption. These solutions make use of appropriate and effective technologies in the whole construction cycle of the buildings such as design, etc. The use of modern technologies for decreasing the consumption of non-renewable energies, and reserving renewable energies are one of the main subjects in sustainable architecture today. Hence, with the growth of high-rises and their high energy consumption, appropriate design solutions should be used to decrease their respective energy consumption. Energy efficiency in buildings can save energy costs and may also make costly power failures less likely and reduce the need for huge investments in power plants and transmission lines.

Design parameters that affect the energy consumption of buildings may include space conditioning, lighting and ventilation, building specifications, embodied energy of building materials, view, interior air quality and wind effect on the building’s design (Naidu & Ramesh, 2015). A large amount of the energy consumption inside the buildings relates to the provision of cooling, warming, air conditioning and lighting, which can be provided in large part through natural energies instead of mechanical systems. For instance, the prevalent use of glass is on the rise in high-rises to achieve a suitable view, internal-external connection and to provide sufficient daylight for all units; this directly affects the energy needs of the building and its level of internal thermal comfort, which means the building’s facade and its components are the most important and influencing elements in its consumed energy (Ghiai & Pour Hajjar, 2014; Planas, Cuerva, & Alavedra, 2018). It can be said that the highest rate of energy consumption in the buildings occurs in their facades, which as the main building skin and the mediator between interior and exterior, influences interior environmental condition, buildings heating performance and the user’s satisfaction (M. M. Ahmed, Abel-Rahman, & Ali, 2015; Dutt & Das, 2012). In this regard, the “Maldegem” institute states that the buildings’ facades and skins are responsible for over 40% of heat wastage in winter and excessive summer warming (Barozzi, Lienhard, Zanelli, & Monticelli, 2016).

Therefore, the use of kinetic elements in architecture has been suggested in order to reduce energy consumption in the buildings due to its adaptation to various environmental conditions. One of these important elements is the Adaptable and Responsive Movable Facade. As the building’s facade is the mediator between the interior and the exterior, it can have the main role in controlling the environmental conditions (Asefi & Ahmadnejad Karimi, 2016). Therefore, the usage of responsive elements in recent years has extensively caught the interest of architects and designers. Responsive Architecture covers various expressions and styles such as "dynamic architecture", "kinetic Architecture", "Adaptable and Flexible Architecture", "Smart Architecture" and "Bio Architecture". It includes aspects of all these design principles and is defined as a response to environmental conditions and user behaviors (Hensel, 2013; Werner, 2013).

2. RESEARCH METHODOLOGY

This research aims to review and present solutions of Responsive Architecture for high-rise building skins, in order to use this technology as a way to reduce energy consumption through increasing the received renewable energies and decreasing the building energy wastage. The study has been guided by the following research questions:

what are the solutions of Responsive Architecture in high-rise building skins to reduce energy consumption? How do they function to reduce energy consumption?

To answer these questions, an analytical-descriptive approach through comparison of existing investigations via reviewing literature resources has been used. In addition, through analysis of some constructed architecture case studies which have employed responsive architecture, a generic categorization of responsive architecture solutions in high-rises and their performance for energy consumption reduction is introduced.

3. LITERATURE REVIEW

Towards the end of the 1960s, architects such as Nicolas Negroponte suggested that advancements in artificial intelligence will soon cause the formation of buildings that could intelligently detect their users' activities and respond to both their needs and changes in interior and exterior (Meagher, 2015). Afterward, in 1970, William Zuk published a book called "Kinetic Architecture" where he introduced kinetic architecture and its role in inspiring a new generation of designers in the process of creating an extensive range of convertible buildings (Zuk & Clark, 1970). Following this, there were limited discussions on how the designers could consider the potential of kinetic architecture with regard to environmental changes.

All the forces that influence the buildings (climate, energy, human factors, etc.) are not constant but are variable and transient. These changes have new consequences for building components especially the façade. It means that the design of these components should have a greater role than solely a protecting cover, separating the interior and exterior (Trubiano, 2013). Building facades have an important role in energy consumption. They provide users' comfort and interaction with external conditions (Wang, Beltrán, & Kim, 2021) and are increasingly growing as a complex collection of compatible elements, resulting from climate changes and energy efficiency. Facades meet and satisfy various building needs such as ventilation, heating, cooling, etc. They are an effective solution for minimizing energy consumption and increasing the interior environment quality (Ahmed et al., 2015). Therefore, the capability and effective functionality of systems used in facades is a key challenge for sustainable buildings (Ahmed, Abdel-Rahman, Bady, Mahrous, & Suzuki, 2016). Based on a recently completed project called "Energy Conservation in Buildings and Community Systems Program" in an international energy agency, the development, operation and implementation of responsive facades as modern global technologies is a necessary step towards improving energy efficiency inside building environments (Asefi, 2012; Loonen, Trčka, Cóstola, & Hensen, 2013). Moloney in his book, "Designing Kinetics for Architectural Facades", details various movements in kinetic elements which are suitable for responsive and convertible facades, and can have a considerable role in protecting the natural environment by reducing energy consumption and benefiting from renewable energy sources (Moloney, 2011). Many other studies also indicate that responsive facades can decrease environmental effects and reduce the dependence on mechanical systems, resulting in less energy consumption (Kensek & Hansanuwat, 2011).

All in all, interest in the context of kinetic architecture has risen continuously in recent years and opportunities for practical functionality of kinetic and responsive architecture have increased rapidly towards the end of the 20th century (Kolarevic & Parlac, 2015; Moloney, 2011). In this regard, kinetic and responsive systems have been employed by architects in order to replace existing systems with adaptable and flexible architectural spaces which are compatible with environmental conditions and the users' needs and known as effective ways to reduce the high consumption of energy usage (Friedman, 2011; Osório, Paio, & Oliveira, 2014).

Many scattered studies have been conducted on the nature of responsive architecture, the history of its emergence, and the effect it can have on reducing energy consumption. These studies have often focused on one of the responsive architectural solutions or have a specific geographical and climatic approach, or have studied the energy efficiency of particular buildings which have applied one or more specific solutions of responsive architecture. Therefore, there hasn't been any general research done to review all the solutions presented by responsive architecture (regardless of a specific geographical or climatic area) and provide a generic classification of responsive solutions and its sub-categories to describe their function in reducing energy consumption. Such review studies appear to be essential for novice architecture students to help them gain general knowledge in recognizing new technologies in architecture and their impact on environmental protection, and also the creation of nature-friendly buildings while meeting the needs of people. Having a general knowledge of various architectural solutions concerning energy efficiency in the world that is confronting exhaustion in reserves of fossil fuel seems crucial. The application of such review studies which deals with the subject holistically can be understood and realized through its ability to promote general knowledge and in accordance with the unique geographical, climatic, cultural, etc. conditions. Moreover, the results of this review research which presents a new and general classification of architectural responsive solutions and their impacts on energy consumption can be used in future studies to practically evaluate the effect of each solution on the functionality of it in building in regard to reducing energy consumption.

Generally, previous studies in responsive architecture can be assorted into two categories: "User Responsiveness" and "Climate Responsiveness". User Responsiveness Architecture concentrates on human-computer interaction for adjustable activities; while Climate Responsiveness Architecture focuses on the external skin of the buildings, which changes their physical properties in order to respond to various climates (Pan & Jeng, 2008). This research, through focusing on responsive architecture solutions in high-rise skins, concentrates on the latter. Buildings need to be in closer relation with the climatic context. As the building skin is the border between the external and internal space, designing facades is becoming a crucial parameter in sustainable and energy-efficient building design.

4. RESPONSIVE ARCHITECTURE AND THEIR CONTROL SYSTEMS

Rudimentary forms of responsive architecture can be seen throughout history starting with the movement of a simple pivoting door to contemporary retractable roofing systems which allow for a complete change in environment and conditions. The first responsive elements in architecture were the creation of operable windows and doors, chimneys and oculi. The word "Responsive" can be defined as a quick and positive reaction. Responsive design is a broad field covering the choreography of functional movement or environmental responsiveness which is referred to as kinetic responsiveness (Asefi & Ahmadnejad Karimi, 2016; Gunderson, 2015). As stated by Negroponte: "Responsive tool is something which has an active role in environmental changes and users' needs and results in simple or complex calculations (Negroponte, 1975). The expression "Responsive" in architecture has been described as the capability of artificial and natural systems to adapt to various environmental conditions (Beesley, Hirosue, & Ruxton, 2006) and points to a reactive system that moves via external control (Barozzi et al., 2016). Responsive architecture relates to elements that are moveable or transformable in terms of their purpose, their composition, their form and their meaning, without reducing the overall structural integrity of the building, and its goal is to make buildings more useful, more energy efficient, and even more aesthetic (Schumacher, Schaeffer, & Vogt, 2012). Sterk who is one of the pioneer describers of responsive buildings, explains Responsive Architecture as a "type of architecture which includes reforms and changes in form in order to have a continuous movement and reaction on the environmental conditions surrounding it" (Asefi & Ahmadnejad Karimi, 2016). Within the building facade, a responsive system is how mechanical structures can be placed next to architecture so that they can apply mutual and smart action on each other (Asefi & Ahmadnejad Karimi, 2016). Surfaces can move to change the appearance or adjust certain properties to play and control lighting, heat gain and even sound (Kirkegaard & Parigi, 2012).

The method of movement must be intended as a deliberate action, rotating, moving, or repositioning itself. It is not necessary for this type of architecture to be of the intelligent type, except if the needed responses require some sort of intelligent processing[2]. Therefore, the building is controlled by a system of sensors or operators and has the ability to respond based on the received information in the form of kinetic architecture (Oosterhuis, 2002). A control system in a responsive architecture is a device or a collection of devices that manages the instructions, and guides and organizes the behavior of devices or other systems. The control system includes two main components:

1. **Inputs:** are appeared through sensors and other methods to provide various information about the surrounding environment. They include five formats namely: a) *Manual Input*, b) *Sensors and Detectors*,

c) *Prior Internal Information*, d) *Manual Programming*, and e) *Internet*.

2. **Controllers:** which are inside the computer and are the factors defining the movements. They receive the information from the input and buffer systems and give them to the operators which cause the movement of the structure. There are three modes of control systems namely: a) *Internal Control*, b) *External Control*, c) *Complex System*

Complex systems are either *Direct Control* which the movement can be controlled by an electric motor or human power, or *Indirect Control* in which the movements result from the feedback of sensors that effect the operator to lead to the desired reaction (Figures 1-2) (Elkhayat, 2014).

5. RESPONSIVE SOLUTIONS

5.1. Kinetic Facade

In recent years, Responsive-Kinetic Facades have caught the attention of architects and designers for their ability to achieve flexible and dynamic architecture. When designing a kinetic facade, the main idea is to design a facade which has a form of physical and automatic transformation in its architectural elements, that provides the best response based on the environmental changes and climatic conditions and results in users' comfort in terms of temperature quality and quantity, lighting, view and energy consumption reduction (Asefi & Ahmadnejad Karimi, 2016). In other words, these facades adapt their components to changes in environmental factors by changing shape through different ways such as folding, expanding, and scaling (Ghaffarian Hoseini, Berardi, Ghaffarian Hoseini, & Makaremi, 2012; Kirkegaard & Foged, 2011). These actions could be done through a combination of various components such as sensors, activators, power supply, signal processors, and communication networks. Components in the kinetic facade can be used in different building parts such as interior, external skin and the roof and can be considered the balance between the impact to and the impact from the environment (Figures 3-4) (Asefi & Ahmadnejad Karimi, 2016).

A responsive building facade includes functional properties similar to a smart building skin, such as precise timing, kinetic elements compatible with the environment, smart materials, automation and the capability to become user-less. In addition, it includes interactive properties like calculative algorithms which allow the building system to organize itself (Trubiano, 2013). These skins which have the ability to learn can respond to the users' needs during the required time based on the processed information received from the internal or external environment through input information detectors (Megahed, 2017; Romano, Aelenei, Aelenei, & Mazzucchelli, 2018). They also give the users the ability to manage and control skin's components for the purpose of controlling environmental conditions (Trubiano, 2013). Responsive facades can change phases based on the various environmental conditions and pave the way for energy consumption reduction in the buildings. Many such examples exist which in addition to reducing consumption, have also assisted in energy generation in the buildings (Asefi & Ahmadnejad Karimi, 2016). These facades are equipped with newly performative materials, sensors, actuators, and computerized intelligence that through their dynamic automated actions and properties such as regulating the building's light, air and sound transmission, heat transfer and interior air quality, affect the energy efficiency inside the building (Trubiano, 2013), and can be considered one of the best options in managing the interaction between outdoor and indoor (M. Ahmed et al., 2016). Responsive facades, even in the absence of users and for short periods, have the capability to intelligently activate the facade components in an automated way for maximum efficiency (Wigginton, 2002). Multi-functional, adaptive and kinetic facades can be considered the future significant breakthrough in facade technology. Adaptive-kinetic building facades can act together with the ecosystem and the user by responding to exterior conditions, insulating merely if needed, generating energy if practicable, shading or ventilating whenever required to enhance indoor comfort and familiarize the behavior and functionality consequently (Yitmen, Al-Musaed, & Yücelgazi, 2021). Considering the systems embedded in kinetic facades, they can organize internal conditions without the user's interference, and even in the absence of users and for short periods, they have the capability to intelligently control the facade components in an automated way for maximum efficiency (Asefi, 2012).

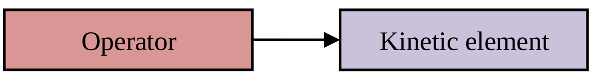


Fig 1. Diagram Describing Direct Control System (Elkhayat, 2014)

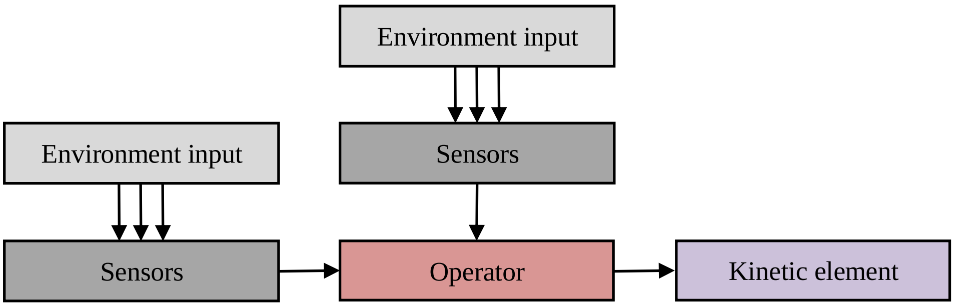


Fig 2. Diagram Describing Indirect Control System (Elkhayat, 2014)

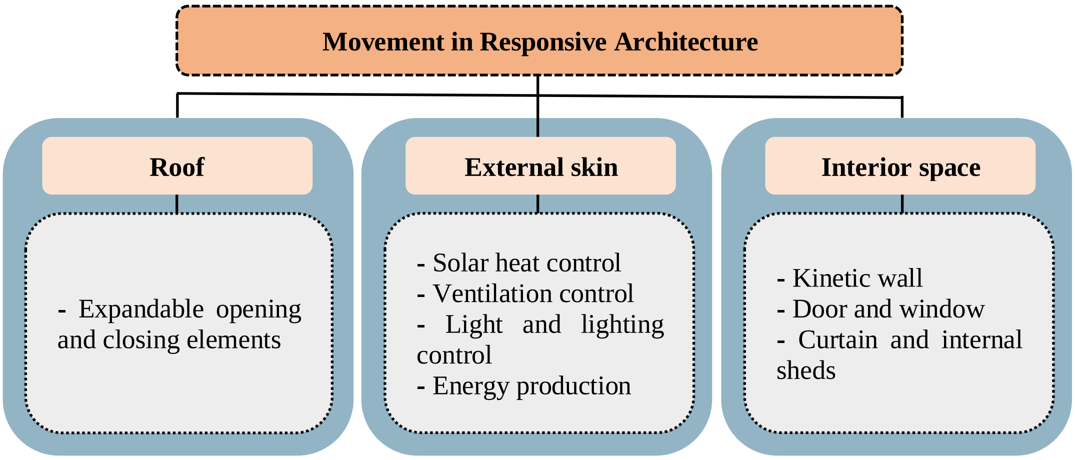


Fig 3. Categorizing Kinetic Components of Responsive Architecture based on their Application Type (Asefi & Ahmadnejad Karimi, 2016)

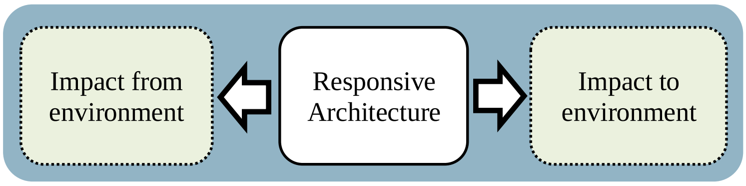


Fig 4. Relationship between Kinetic Components and the Environment in Responsive Architecture (Asefi & Ahmadnejad Karimi, 2016)

The main types of kinetic facades based on their application in buildings can be categorized as follows:

5.1.1. Kinetic Facade and Temperature Control (Solar Heat)

Some kinetic facades are used with the aim of absorbing solar energy during winter and reducing this absorption during summer. Solar heating energy is controlled through various factors including exterior movable shades and adjustable awning systems in kinetic facades. The purpose of using these tools is to control the amount of heat coming inside the building to our preferred amount. Gioni claims that the adjustable external shades permit the full entry of light during winter. Therefore, they are much more efficient than static systems (Asefi & Ahmadnejad Karimi, 2016).

5.1.2. Kinetic Facade and Lighting Control

Controlling the amount of daylight is a key advantage of using responsive facades. As Givoni states, the sun's movement is predictable within daily and yearly movement patterns. Systems such as shades and kinetic awnings can control the amount of daylight in addition to the heating energy. In the facades in order to control the daylight, the positional placement of the kinetic system inside or outside the building has a minor effect on controlling the amount of daylight. Making use of the daylight in the buildings can cause a considerable saving in the amount of consumed electricity for lighting. Building design via dynamic technologies provides a great possibility of designing a higher quality living environment and also solutions for energy consumption reduction (Lorenz, 2001). Lighting control in kinetic facades can be through kinetic shades and awning systems.

5.1.2.1. Kinetic Shades

A very common example of such systems is internal kinetic shades, which are prevalent in the buildings due to their ease of use and cheap price. The drawback of this system is its minimal effect on the building's condition, as the solar heat has already entered the building before it is prevented. Nonetheless, kinetic shades can help reduce the internal temperature of the building by about 4 to 5 degrees centigrade and reduce energy consumption up to around 18-20% compared to shade-less buildings. The use of these shades in buildings especially in warmer regions can reduce both heat transfer and electricity consumption of the air conditioning system (M. Ahmed et al., 2016). Moreover, this system can in two ways cause a reduction in energy use in the buildings. In its closed form, it reduces heating energy requirements during winter and cooling energy requirements during summer (Ahmed et al., 2015; Barozzi et al., 2016). When the kinetic shades are placed outside the building, they have a much greater effect on the solar radiation temperature. Based on this claim if the heating energy is prevented before entering the building, the required cooling energy is reduced to half (Schnittich, Krippner, & Lang, 2006). Up to now, using shades has been the most common solution amongst responsive facades especially within high-rises (Barozzi et al., 2016).

5.1.2.2. Awning System

Another kinetic element in responsive buildings' facades is the awning system. In other words, one of the main ways to control the amount of thermal radiation energy is the use of automatic outer awnings. This efficient and simple system can adjust the amount of sunlight entering the building or generally prevent light from entering the building by adjusting its angle. The major problem with these types of systems is to limit the visual field of view because when they are outside the building, their angle is adjusted regardless of the vision. Another awning system for controlling the amount of sunlight is a fixed horizontal system that adjusts its length with the amount of sunlight. Both systems control a great deal of the sun's radiation energy (Asefi, 2016; Asefi & Ahmadnejad Karimi, 2016).

5.1.3. Kinetic Facade and Natural Ventilation

Natural ventilation of buildings as stated by Givoni focuses on three specific goals which are: "Maintaining the internal air quality through fresh air entry", "providing thermal comfort in warm weather conditions through loss of heat convection" and "Cooling mass of the building" (Givoni, 1969). Natural ventilation in buildings covers a wide range of solutions from the highest technological, to very basic ones. The goal of natural ventilation is the use of natural stimulants such as wind and heat waves for energy consumption reduction and mechanical cooling systems. With the progress of computer technology, sufficient control and prediction of air movement within natural ventilation systems have been made possible. In addition, through a combination of mechanical and natural ventilation systems, known as hybrid systems, it is possible to get rid of obstacles and defects in both systems (Kensek & Hansanuwat, 2011).

5.1.4. Kinetic Facade and Energy Generation

Another key aspect of responsive facades is their energy generation ability. The aim of energy management in buildings is to reduce and optimize energy consumption in an economically feasible way, while not causing any negative effects on the thermal comfort levels. Usage of photovoltaic systems in responsive facades is a way to provide the needed energy for the buildings. In these facades, kinetic panels move with the direction of the sun to provide the building's energy (Asefi, 2016). Panels' performances in any weather condition are accountable and their movement mechanism does not require a computer and is controlled via an electronic board. Smart solar panels could also be used as shades and in addition to electricity generation, provide the required shading for the building.

5.2. Double-skin Facade

A double-skin façade system, has become a major element in the architecture of tall buildings over the last decades. They can reduce energy consumption by 30%, by generating natural ventilation, temperature control and heat convection control (Alotaibi, 2015). High-rise buildings are generally exposed to more sunlight, therefore, heat transfer from the outside to the inside of the building is considerable. This reduces the efficiency of the cooling system and increases energy consumption. The use of double-skin facades in these buildings prevents direct sunlight and heat to the interior facade and has an important role in adjusting the buildings' internal temperature. Also, in high-rise buildings that are exposed to stronger winds, if a double-skin facade is used, the wind will flow in the space between envelopes and will eventually help to cool the main façade and relieve the burden of air conditioning systems to reduce energy consumption and wastage. Therefore, double-skin facades are served as efforts to increase performance and reduce energy consumption for air conditioning and lighting system, especially during the daytime (Budihardjo, Setyabudi, & Hardiman, 2013). Double-skin facades can be considered a natural ventilation system or kinetic facades if combined with mechanical ventilation systems by using thermal sensors. Opening and closing first-skin windows can be controlled by intelligent systems or manually by users (Poirazis, 2004) (Figures 5-6).

5.3. Kinetic Roof

Kinetic architecture elements can be used in roofs as well as facades. They can be applied in various shapes and sizes to create responsive modules in the roofs of buildings that can provide defined natural light and ventilation to the building. The use of sensors allows the ceiling to be automatically controlled and changed throughout the day. A prototype designed by Magnoli and colleagues at "MIT House of the Future" is an example of how interchangeable units can be individually controlled so that the building can enjoy natural light and optimal natural ventilation during the year (Magnoli, Bonanni, & Khalaf, 2002).

Each ceiling panel is coated externally with photovoltaic cells and internally with a capillary heat exchanger (using water as a heat exchange ambiance). Figure 7 shows how this responsive kinetic roof can be modified to adapt to environmental changes. During the summer, kinetic panels prevent sunlight and provide ventilation. By opening in the direction of the sun in winter, it allows the sun to penetrate more light and heat into the building. Configuring the roof on summer nights causes cool night air to enter the building and its closure during the winter nights allows for maintaining the heat inside the building (Asefi, 2012).

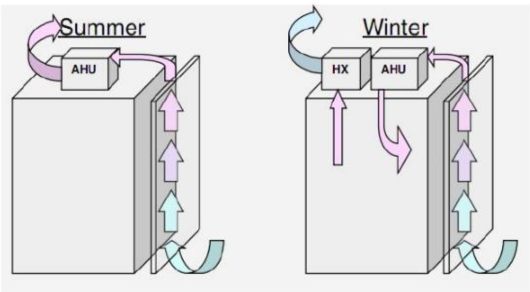


Fig 5. Schematic of a Double-skin Facade with Mechanical Ventilation (Poirazis, 2004)

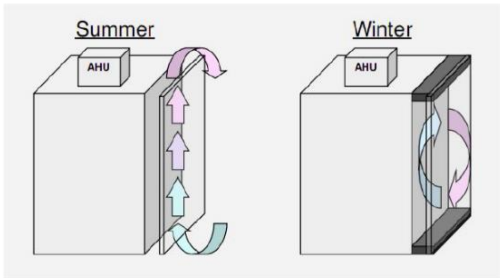


Fig 6. Schematic of a Double-skin Facade with Natural Ventilation (Poirazis, 2004).

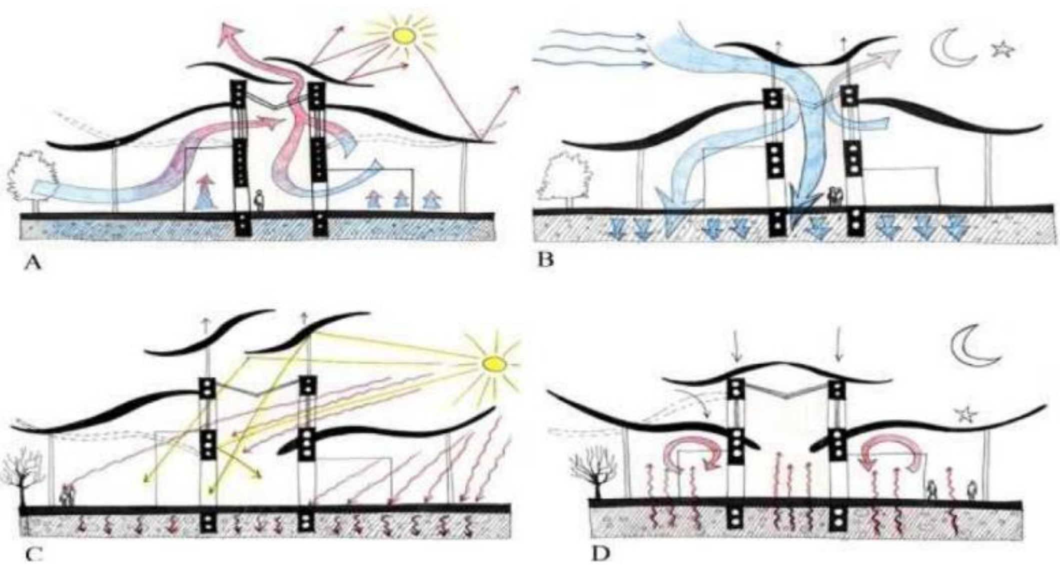


Fig 7. Various Responsive Kinetic Roof Modes during a Year (Asefi, 2012) (A: summer day, B: summer night, C: winter day, D: winter night)

5.4. Smart Materials

Smart material is a new expression to describe materials and products which have the capability to understand and process environmental circumstances and appropriately react to them. NASA defines smart materials as materials that remember formations and can be compatible with them when given a particular incentive (Taha & Hassan, 2020). In other words, these materials have transformation ability and are able to change their shape, form, color, permeability, texture and internal energy in a reversible way in response to physical effects such as light, temperature, humidity or chemical effects of their surrounding environment. Smart materials are also referred to as "Flexible" and "Adaptable" materials and this is due to their exclusive property of adjusting themselves to the environmental conditions (Coelho, 2008; Parkes, 2009). To create the correct construction, protecting the environment and energy consumption reduction as much as possible, the materials used in the buildings have an important role. Choosing appropriate and sustainable building materials such as smart materials is very effective in this regard. Studies show that by using smart materials in building facades the total energy consumption for one story can only be up to 11%. Hence, the opportunities of low emission glasses in reduction of energy consumption for cooling encourage the architectures of buildings to depend on them (Taha & Hassan, 2020). Smart materials, through their timely response to changes in environmental conditions, can cause a reduction in energy consumption, air pollution and greenhouse gasses, and can result in longer life and stability of the building, simplified repair and preservation of buildings and better protection of the environment. Therefore, the construction of buildings that have more compatibility with their surrounding environment attracts noticeable interest (Abbasi, Sadeghpour, & Entezar Reyhani, 2016). The requirement to achieve buildings compatible with nature is employing technology to produce smart and novel materials which carry the building's ecologic behavior towards intelligent energy management (Addington & Schodek, 2005). Therefore, considering the reduction in energy resources, the use of smart materials which result in a reduction in the buildings' energy consumption is essential in building construction.

Based on their properties, smart materials can be categorized as shown in Table 1:

Table 1. Types of Smart Materials (Arranged by Authors)

Smart Materials	Types	Example	Description
Smart Materials with the capability to change intrinsic properties	Modifying smart material Color changing smart material Synthesis changing smart material	Temperature-responsive smart materials	The group of smart materials which have inner property transformation ability are effective for control and management of energy in buildings. These materials apply reversible reactions towards changes in surrounding environment temperature, and include various types a few of which have a usage in architecture, such as expansion materials that have thermal expansion coefficient and their foremost function in architecture is to control and manage the energy in buildings for thermal thermostat production. In addition, they are used in greenhouses, automatic ventilation systems of rooms and building services as exclusive activators (Abbasi et al., 2016).
Smart Materials with Capability of energy exchange	Light emitting smart material Electricity producing smart material Energy-saving smart material	Phase change material (PCM)	These materials are more applicable to architecture. The most applicable material is known as mode-changing material, referred to as phase-changing material (PCM) that can act as thermal adjusting intermediates. For example, as cold or heat-saving elements, they have features to change their status from liquid to solid by final PCM of room thermal adjusting. It is necessary to say that materials with high heat saving and low heat wasting capacity are not placed in this class of smart materials (Malekizadeh, Nili, & Piri, 2014).
Smart Materials with Capability to change and exchange internal material	Conductive smart material	Self-cleaning materials	These materials have reversible compounds that enclose or release the material in the form of a molecule in the phase of a gas, liquid or solid with various physical or chemical processes. The performance of these materials is that they react with exposure to various types of gas, water vapor, water or even aqueous dilutions. They are mainly used for exterior or interior facades of buildings, and the most famous are self-cleaning materials. They also neutralize and eliminate airborne pollutants by coating them on the building surfaces. Their most important applications in architecture are making facades waterproof and self-cleaning, enhancing indoor air quality, eliminating contamination of the surrounding air, absorbing noise, and creating an aromatic odor in space (Gorji & Hajaboutalebi, 2009).

5.5. *Smart windows*

The unique power transmission properties of many smart materials make them ideal for use in building façades and lighting systems, especially glazing, which is a considered major problem for designers as energy travels in both directions. The architect had to choose the right smart materials to reduce energy, and also, to provide transparency and lighting for the building, so the term smart windows emerged (Taha & Hassan, 2020). Considering that about one-third of a building's energy is wasted through windows, the effort to reduce energy consumption in buildings is very focused on these components. If windows are not properly designed and are not constructed structurally and placed in the proper position, they will be the main cause of thermal and cryogenic loss in the cold and hot seasons of the year (Goharian, 2014). Today, to maximize the use of sunlight and implement some of the new ideas in architecture, wide areas of the buildings are covered by glass, and therefore windows play a key role in controlling the incoming light into the building and the amount of energy required. In these circumstances, the possibility of maintaining adequate environmental heat or cold and energy storage, along with providing the desired amount of light, can be problematic. The use of smart windows is not just limited to reducing energy loss. The application of smart glass which does not necessarily need any curtain to control the intensity of sunlight and heat passing and has energy storage properties, is taken into consideration around the world (Casini, 2014). In fact, the new smart windows, with unique capabilities and with the preservation of indoor climates, prevent sunlight from entering on hot and scorching summer days and allow sunlight to pass through in winter by becoming transparent and storing the heat energy (Goharian, 2014). Studies show that Electrochromic glass in smart windows are the best type to reduce the gain of solar radiation and thus reduce the cooling loads on small window surfaces, and in the case of large window surface, Gas chromic glass achieves better results in reducing the annual cooling load consumption (Nageib, El-Zafarany, Mohamed, & El-Hefnawy, 2020). Smart windows typically have one or more of the following functions noted in Table 2.

6. EXAMPLES OF USING RESPONSIVE ARCHITECTURE IN BUILDINGS

Due to the increased energy consumption and wastage especially in high-rise buildings, nowadays responsive systems have been used in many constructed architectural samples. Examples in this research have been selected according to the multiplicity of repetition in the books and articles related to this topic and the significant impact on reducing energy consumption. Table 3 describes the responsive strategies used in these buildings and how they function in order to reduce energy consumption.

Table 2. Functions of Smart Windows to Reduce Energy Consumption (Arranged by Authors)

Function	Description
Light Passing Control	Transparency variation (optical intensity) can be used to control solar radiation. This is particularly useful in controlling visible wavelengths and UV. Glasses can be varied, from a high compression mode (opaque or semi-transparent) to prevent direct sunlight and the glare associated with it, to a low compression mode to reduce light radiation intensity (Goharian, 2014).
Heat Transfer Control	Its function is similar to light passing control but with the exception that the wavelengths in the light spectrum extend to near-infrared. At the right time (summer), heat transfer through radiation can be reduced or increased in other conditions (Ibid).
Heat Absorption Control	Transparency and thermal conductivity are similar but operate relatively independent of radiations. When the internal temperature exceeds the outside temperature, a two-way heat flow is created. Radiant energy is transferred inward while thermal energy is transferred outward. Changing the glass absorption rate will ultimately affect the overall thermal conductivity, thereby can disrupt the balance in one of two ways (Abbasi et al., 2016).
Vision Control	The use of variable materials for vision control is currently the fastest growing application of smart materials in the building. For instance, Separators and blades can change from transparent to semi-transparent and allow light to enter, but can also reduce visibility by changing the material's transparency. A transparent material transmits images correctly while a reflective material blurs the image (Addington & Schodek, 2005). This eliminates the need for curtains of windows, and as well as having privacy, receiving proper solar energy is provided.

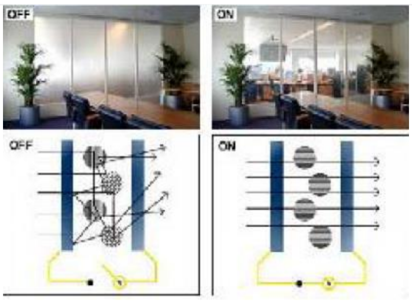


Fig 8. Smart Window Function for Vision Control (Goharian, 2014)

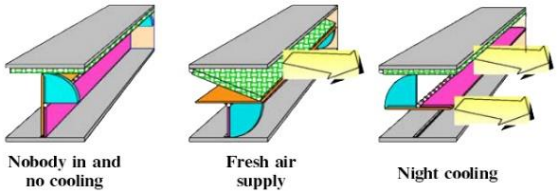
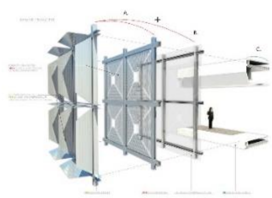
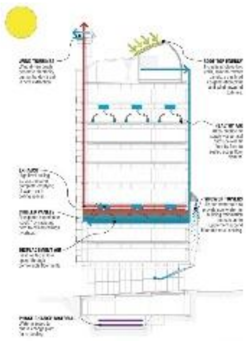
Function	Description
Energy Saving	These materials store energy in the form of light, heat, hydrogen, or electricity. The smart heat-saving materials in this group are of particular interest. These materials have an intrinsic property that enables them to store energy as heat or cold as latent energy (Abbasi et al., 2016). Liquid crystal windows, for example, composed of a multilayer structure that in addition to the energy-saving property, are able to instantly change the glass state from completely transparent to completely opaque (Casini, 2014).
Natural Ventilation Control	Windows create constant airflow that can be adjusted intelligently to control how much they can be opened in response to pressure changes (Niu, 2004).  **Fig 9.** Example of Natural Ventilation Control by Smart Windows (Niu, 2004)

Table 3. Conveying Responsive Solutions in Case Studies (Arranged by Authors)

Project	Description
 Al Bahar Towers	The 29-story Twin Towers Al-Bahar was completed in 2012 in Abu Dhabi, the UAE's capital. A prominent feature of these towers is a kinetic skin consisting of 2000 umbrella-like elements that open and close in response to sunlight intensity (Abbasi et al., 2016). Linear actuators, adjusted by a pre-programmed sequence, send different inputs throughout the day, enabling elements to activate five different settings from fully open to fully closed. According to design estimates, the system should reduce the cooling load by up to 25% (Kolarevic & Parlac, 2015) In summary, this kinetic facade, inspired by the form of Mashrabia, results in the reduction of received solar radiation, improved indoor light, increased occupant thermal comfort, reduction of energy consumption by up to 50% and reduction of greenhouse gas emissions by 1750 tonnes per year (Alotaibi, 2015).
 Instiut Monde Arabe	One of the most famous examples of a responsive kinetic system between two layers of glass is the Arab Institute building, designed by Jean Nouvel in the early 1990s. This pioneering project is an example of a change-based architecture (Meagher, 2014). The southwest facade of the building is formed by a series of metal holes that are automatically opened and closed like the iris to control the daylight and heat of the sun. Each square metal section acts like a camera shutter system, organized in a 10x24 grid (Moloney, 2011). Each square section is individually controlled by motors connected to a central computer system, allowing for different operations (Barozzi et al., 2016).
 Helio Trace Centre	In the Helio Trace project, Chuck Hoberman uses a combination of horizontal and vertical shades and sliding kinetic panels to control the amount of heat entering the building. This responsive facade prevents 81% of the sun's thermal energy from entering (Asefi & Ahmadnejad Karimi, 2016). The system uses two mechanisms, the first is opaque panels that are perpendicular to the frame and the second mechanism is four 50% perforated panels that extend parallel to the building facade and can be programmed to respond to the solar motion. The system can observe the sun throughout the year and prove a unique shade for that day and environmental conditions. This system is estimated to improve energy efficiency by up to 63% compared to normal performance in New York City and can also proportionally be used in other climates (Asefi, 2016).
 Media-TIC Building	The Media-TIC building is an example of a responsive skin built in 2011 in Barcelona. The envelope features a pillow cladding system made of polymer ETFE with encased lamella fins whose pneumatic mechanisms are automatically activated by light sensors that respond to the presence of solar energy (Trubiano, 2013). The building uses ETFE materials to create an elastic kinetic facade designed to improve thermal insulation as well as to act as a shading device using a pneumatic system. The first layer of the facade is transparent while the second and third layers have a reverse pattern design (Sharaidin, 2014). When these layers are inflated, they form shadows, or in other words an opaque area, by connecting the components together. The exterior facade uses three air chambers, where air movement leads to full-face control. The ultimate idea is to create a cloud that protects the interior of the building using a combination of nitrogen and ETFE particles (Chilton, 2013).

Project	Description
  GSW Building	This office building in Berlin utilizes two intelligent systems for comfort and optimal energy use in the building. One of these is for ventilation and the other for adjusting light and shade (smart windows and sheds) in the building. Both systems operate automatically to respond to natural conditions. The building is naturally ventilated 70% of the year. Ventilation is done by passing air through the inner skin of the western façade to the space between the two skins. This double-skin glass wall prevents temperature reduction in the building and the air flowing in between the two skins is adjusted by the building's control system. Light and shade adjustment is done by the exterior skin of the building, which is made of full-color kinetic solar glass, which is automatically adjusted (Beisi, 2007).
   Council House 2 (CH2)	Project (CH2) is an office building in Melbourne, Australia built in 2006 that incorporates multiple sustainability strategies, including wind turbines on the roof, cold roof, double-skin facades and wooden shades as a kinetic device to protect Residents from direct sunlight, by tracking the direction of the sun in summer and providing complete shadow for indoor. This is the first office building to receive six Australian GBC green stars (Alotaibi, 2015). Fresh air ventilation stacks on the roof automatically open and close depending on environment air conditions, inject fresh cool air through the bottom of the floors, and previously heated air exits through the exhust ducts from the building roof. At its exit is a turbine that also generates energy. Ventilation stacks are situated on the north and south facades of the building. On the north side, which receives more sunlight, the stacks are a dark colour that aids absorption of the sun heat, helping to heat up the air inside the stack which rises and is exhausted out the top. This creates a pressure differential, pulling cool fresh air through the building. The ventilation stacks are angled so that they increase in size up the building, facilitating air movement and allowing for the increased volume of air coming from the building. The building has achieved significant results in environmental performance, reducing electricity consumption by 85% and reducing greenhouse gas emissions by 13%. The kinetic system applied to the west facade has over 95% of daytime shading and provides natural night-time ventilation by automatically opening windows and allowing cool night air to enter the building. The west facade mechanism works on a computer-controlled automatic motion system to track the sun's position and provide shade in the afternoon (Sharaidin, 2014).

7. DATA ANALYSIS

In general, a new classification of architectural responsive solutions and their functions are presented in Table 4. Having knowledge of the impacts of architectural responsive solutions on various mechanical parts of the building, it has been determined that each responsive architecture system can reduce energy consumption via replacing that specific mechanical part with natural energies and controlling environmental conditions.

Table 4. Performance Analysis of Responsive Architecture Solutions to Reduce the Energy Consumption of High-rises (Arranged by Authors)

Location	Responsive solutions	Functions	Positive impact of solutions on the energy consumption of building mechanical systems					Potentials to reduce energy consumption through facades
			Cooling	Heating	Ventilation	Lighting	Energy production	
Building Facade	Kinetic Facade	-Temperature control -Lighting control -Natural ventilation -Energy production	✓	✓	✓	✓	✓	- Increase the amount of received solar energy - Reduce internal energy wastage - Receive optimal natural daylight - Creating natural ventilation - Control the amount of excess received heat - Acting as a heat insulator - Temperature regulation by energy storage (cold and heat) - Reduce the use of mechanical systems - Generation of electricity - Minimizing the undesirable effects of the construction and causing coordination with sustainability
	Double-Skin Facade	-Natural ventilation -Heat control -Lighting control	✓	✓	✓	✓		
	Smart Materials	-Temperature control -Lighting control -Energy production -Energy saving	✓	✓	✓	✓	✓	
	Smart Windows	-Light passing control -Heat transfer control -Heat absorption control -Vision control -Energy saving -Natural ventilation	✓	✓	✓	✓		
Building Roof	Kinetic Roof	-Temperature control -Light passing control -Natural ventilation	✓	✓	✓	✓		
	Ventilation Stacks and Exhaust Ducts	-Ventilation control -Temperature control -Energy production	✓	✓	✓		✓	

8. CONCLUSION

Studied solutions that can be used in high-rise building skins and can play a significant role in the energy consumption of these buildings can be generally classified into two types. Those that can be used in the facade and those that can be used in the roof. Usable solutions for facades include “Kinetic Facades”, “Double-Skin Facades”, “Smart Materials” and “Windows”, while usable solutions for roofs include ‘Kinetic Roof’ and a new type of “Ventilation Stacks and Exhaust Ducts”. These solutions can be operated in combination with each other or for the better performance of another system depending on environmental conditions.

Apart from reducing energy consumption and wastage, the benefits of responsive architecture can also include prolonging the useful life of the building by being more adaptable and accommodating to users, and achieving sustainable development goals. By using responsive systems, natural ventilation and environmental conditions control are made possible and will result in reducing energy consumption in the building. Responsive solutions in high-rise buildings skins with various functions such as temperature control, lighting control, energy storage, energy production, etc. reduce energy consumption, for which their function can be more precisely described as follows:

- Increase the amount of received solar energy
- Reduce internal energy wastage
- Receive optimal natural daylight
- Creating natural ventilation
- Control the amount of excess received heat
- Act as a heat insulator
- Temperature regulation through energy storage (cold and heat)
- Reduce the use of mechanical systems
- Generation of electricity
- Minimizing the undesirable effects of the construction and causing coordination with sustainability

Responsive systems reduce the use of mechanical cooling, heating and lighting by controlling external and internal environmental conditions. They can also hybridize with these mechanical systems and reduce the energy consumption of the building through reducing building energy wastage and maximizing the use of natural energy. Considering that these systems can be installed separately from the main facade, they can be used in both new and old buildings. Evaluating the terms of using these systems in existing buildings and simplifying their mechanism while acquiring a better performance could be the goals of future research in this field.

Advanced technology and new materials in building facades and roofs not only have achieved optimum energy efficiency but also have produced a quality of experience unique to its users and context. Responsive Architecture can generate extraordinary moments or make people more aware of an experience by playing with light and shadows, repetition, balance, and engaging the imagination. Responsive architecture has the ability to reconnect people with their environment, generate a more stimulating and enriching environment and provide delight in occupants' lives. It should be noted that responsive architecture needs to ensure that the ease of maintenance is considered in the design and that the benefit of fixing the system is worth more than abandoning the project and the system becoming obsolete. People need to want to interact with the building in order to make the response successful. If there is little incentive to participate in the action, the system might not work as efficiently as designed.

NOTES

1. Not to forget about the specific factors that countries must take into account in the design process of energy efficiency requirements. These include the type of climate, the cost of energy use, current construction practices, the cost and availability of energy-efficient technologies, and last but not least local authorities' capacity for enforcement.

2. For example, an adobe wall provides cool temperature internally as a response to the warm temperature outside. This action is one of the properties of building material which is obviously not separate from intelligent processing. In fact, adobe wall precisely based on the information provided from the building exterior and processing, cools the interior of the building (Asefi, 2016). Therefore, perhaps one of the most suitable and efficient strategies for giving consideration to the discussion of energy in buildings, is the use of thermal mass and the use of cool air at night time, instead of mechanical air conditional systems (Kroner, 1997). This processing falls under intelligent architecture.

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