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A Framework for Efficient Environmental Dynamic Façade Design

Kifah Alhazzaa, LEED Green Associate

Lecturer, Faculty of Department of Architecture, College of Architecture and Planning, Qassim University, Buraidah, Alqassim region, Saudi Arabia

Graduate student, Department of Architecture, College of Architecture, Planning and Landscape Architecture, University of Arizona, Tucson, Arizona

Abstract

Dynamic façades have significant impacts on building performance and occupant comfort, but sometimes there is an inaccuracy of the system design due to a lack of considerations. The focus on the structure system and kinetic movement of the system only leads to inefficient systems that do not efficiently serve environmental purposes. The structure system is essential for a successful operative system. However, it is a part of a sustainable environmental system that has many components and considerations. This work presents a framework for environmentally efficient dynamic façades. The framework is built with six main components that drive to a comprehensive perception of the project's challenges and needs. The full understanding of the situation facilitates design decisions.

Keywords: : Dynamic Façade, Kinetic Façade, Environmental Design, Green Buildings, Design Framework, Design Considerations.

1. INTRODUCTION

Adaptable architecture was demonstrated by Frei Otto as the variation of shape, location, and utilization. The main construction principle of adaptable architecture is the lightweight principle, which leans on the idealistic use of materials and fabrication (Möller & Nungesser, 2015) [1]. Werner (2013) characterized adaptable architecture for buildings as structures planned to have the capability to be altered or modified to suit different social functions [2].

Adaptation is the evolutionary process whereby a population becomes better suited to its habitat. This process takes place over many generations and is one of the basic phenomena of biology (Darwin, 1859) [3]. All architecture is adaptive at some level over different time scales (Brand, 1994) [4]. Adaptive architecture is specifically designed to adapt to its environment, inhabitants, culture, and other architecture principles. In architecture, the term adaptation refers to the relation between periodic change and the evolution of architecture needs in terms of social interaction, human experience and health, environmental aspects, and the morphology of architecture.

A good example of adaptation is vernacular architecture, which is based on, among other factors, the typical or average weather of a given region, which, from records covering a period of years, can be assumed to have remained consistent throughout human history. Indigenous people of particular regions respond to the climate by the design of their dwellings. Changing morphologies are the result of shifts in society, the economy, occupancy, and environmental efficiency in various time frames. Long-term change occurs over generations and can result in the particular architectural style of an area. Short-term change occurs in a matter of days, hours, or less and leads to local adaptation. Adaptive architecture can be sub-categorized as interactive, dynamic, kinetic, or responsive.

2. RESEARCH PROBLEM

Designing an environmental dynamic façade that responses to the local climate and users' comfort are a challenging issue, which is a combination of many factors. Currently, many dynamic facades are inefficiently designed to serve one purpose or one more than others due to not having a guideline and framework to assure the design appropriateness to the design aims.

3. RESEARCH OBJECTIVES

This research explores the factors that impact dynamic façade design decisions and performance by creating a framework that contains the main critical components that influence the design. Explaining each component with example will give the project team the knowledge to determine the project's environmental criteria. The main goal of this research is to make a design guideline for designing an environmental dynamic façade.

4. ENVIRONMENTAL DYNAMIC FAÇADE OBJECTIVES

Energy Reduction

The dominance of climate change has created a growing need for new systems that have positive impacts on energy use and human comfort in interior spaces. Buildings, both residential and commercial, are responsible for about one-third of total energy consumption (Figure 1.). The amount of energy usage is reflected in CO2, which represents 81% of greenhouses gases, as shown in Figure 2. Figure 3. presents CO2 by source in the United States and illustrates that the main source of CO2 is the production of electrical energy. Energy conservation is considered the first priority for designers, developers, and planners working in community development since it has a positive impact on reducing consumption (KwH or KBTU/hour), avoiding greenhouse gas emissions (i.e., CO2, NOX, SO2), conserving water, and saving money. The production of one KWh of electricity releases 2.3 pounds of carbon dioxide into the atmosphere.

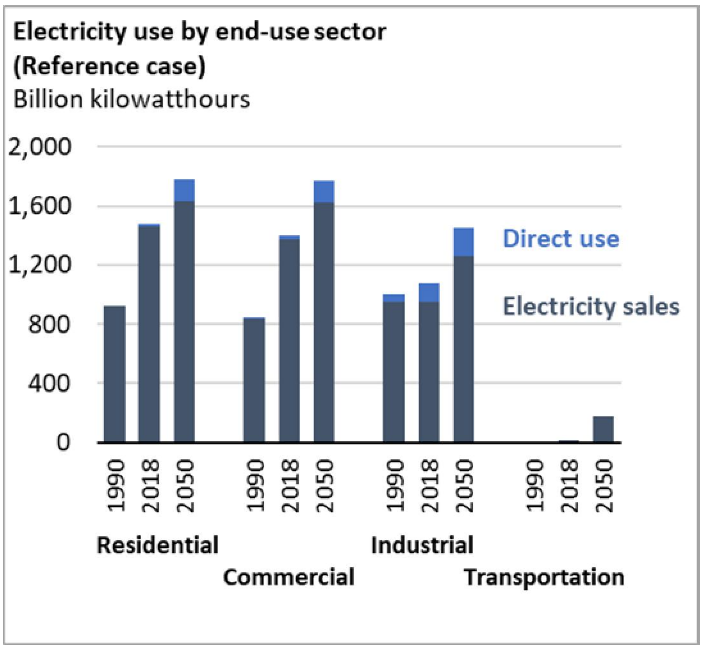

Figure 1. Energy usage by building sector (U.S. Energy Information Administration, EIA)

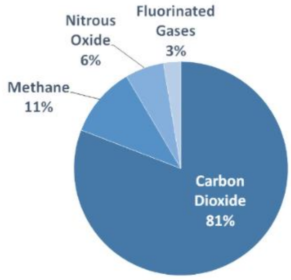

Figure 2. Greenhouse gas emissions percentages (U.S. EIA)

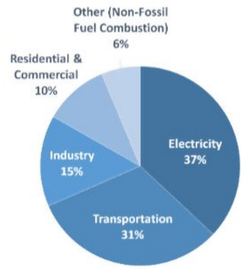

Figure 3. CO_2 sources by sector (U.S. EIA)

Daylight Quality

In 1880, electric light replaced traditional light sources when Thomas Edison introduced the first incandescent lamp. Today, electric lighting consumes up to half of all electricity in commercial buildings, producing a heat load similar to that of HVAC systems, as shown in Figure 4. Designs that integrate daylight with electric lighting have great energy-saving potential in buildings. In addition, daylight enhances human health and psychological wellbeing in many ways. (Humphris, 1924; Kellog,1910; Kovacs, 1924). Luckiesh (1924) stated that there is an advantageous impact of daylight on human health and concluded that "working men are depressed by improper and inadequate lighting" Numerous early 20th-century authors discussed (see e.g., Elton, 1920; Weston, 1921; Weston & Taylor, 1926) the beneficial impact on occupants' productivity associated with illumination level and performance [5]. Successful integration of light in a space hinges on the skillful design of daylight and electric lighting systems, including selection of the type of bulbs, ballasts, and fixtures, but most importantly, the method of control between daylight and electric light.

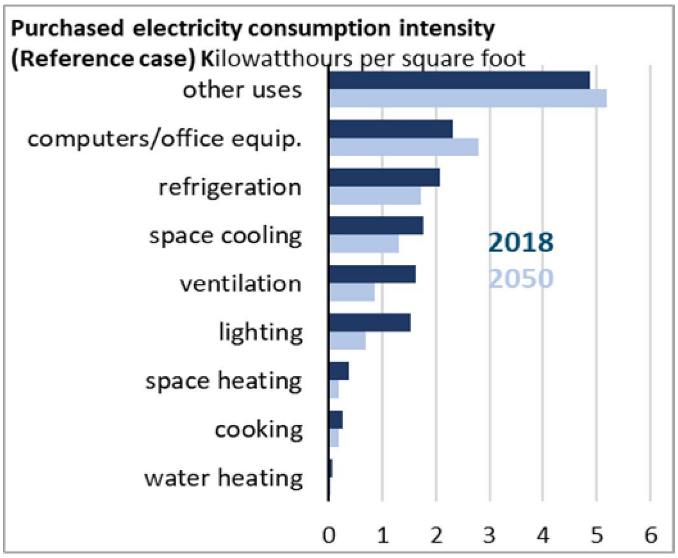

Figure 4. Electricity consumption by building component (U.S. EIA)

Optimizing the View

A view of the outdoors has been proven to have beneficial impacts on health and psychological wellbeing through several studies. Ulrich (1984) found that the view in patients' hospital rooms enhances the healing process. Kaplan, Talbot, and Kaplan (1988) found that in the workplace, access to nature corresponds with a reduction of job stress and higher levels of job satisfaction. Collins (1975) found that a view to any scene is better than not having a view [5].

5. RESEARCH METHODOLOGY

The proposed framework must follow many designs, functions, and operational restrictions to achieve the desired purposes of the dynamic façade. The proper response to restrictions leads to optimized façade functionality and energy performance of the building and human visual and thermal comfort. The proposed framework was developed to contribute to the built environment and achieve a more sustainable, functional dynamic façade. The framework minimizes the inaccuracy of the dynamic facades, which leads to more efficient and sustainable systems. It is designed from six main components; each one of them asks for a comprehensive analysis to understand the project challenges and what is the special considerations for each component. In this research, each component will be explained to illustrate the necessity of these components and their impact on the dynamic façade design.

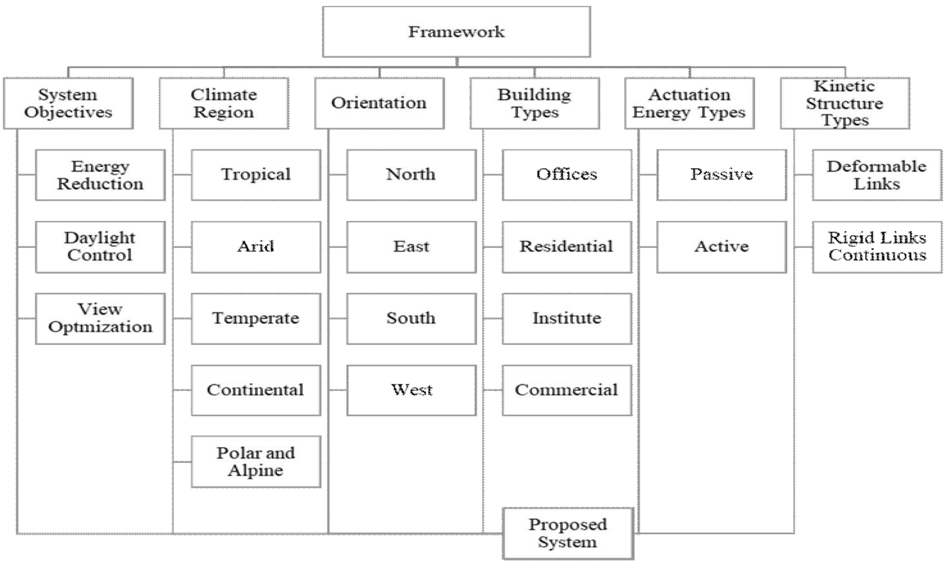

Figure 5. Design Framework (by author).

Climate Region

Weather is the atmospheric condition for a day or portion of a day. Wind speed and direction, precipitation, and temperature are weather factors that determine the climate of a region. Climate is the cumulative weather conditions over a long period. Weather conditions are affected by three main variables. The first is latitude, which determines the placement of a region. The farther from the equator, the less heat is received from the sun. The second is water body proximity, which affects temperature and humidity. The third is elevation above sea level, which affects temperature.

Climate is never static and always dynamic. The ever-changing climate is a major external force at work on buildings. Designers can manipulate various climatic elements to achieve human thermal comfort. Therefore, it is essential, from an energy-conscious design standpoint, to study and analyze the different climate elements, types, and associated data.

Example: Arid Climate

A region with an arid climate is extremely hot and dry in the summer season and moderately cold in the winter season. Regions with this type of climate have high energy consumption. The diurnal temperature range in the summer is wide and thus summer nights are relatively cool. There is sunshine about 85% of the year, and night skies are mostly clear. The humidity is generally below the human comfort range over the course of a year, and average annual precipitation is about 7 in (18 cm) [6].

Norbert Lechner, in his book Heating, Cooling, Lighting, mentioned a number of climate design priorities, which are:

High priority

- Keep hot temperatures low during the summer.
- Provide protection from the summer sun.
- Use evaporative cooling in the summer.
- Use thermal mass to reduce day-to-night temperature swings during the summer.

Lower priority

- Retain the heat and keep cool air out of buildings during the winter.
- Let the winter sun into buildings.
- Use natural ventilation to cool in the spring and fall.

Façade Orientation

Windows are responsible for 30% of the heating and cooling loads of buildings. The mean radiant temperature (MRT), which contributes to thermal comfort, is influenced by windows [6]. The total heat gain through windows corresponds to a buildings' orientation, as shown in Figure 4.6. Window orientation is an essential factor of building energy consumption. Balcomb's (1987) solar radiation study articulates the amount of solar radiation received by each orientation (Figure 6.). Their study on transmitted solar radiation also shows the amount of solar radiation (Figure 7.) that penetrates to interior spaces through each facade orientation.

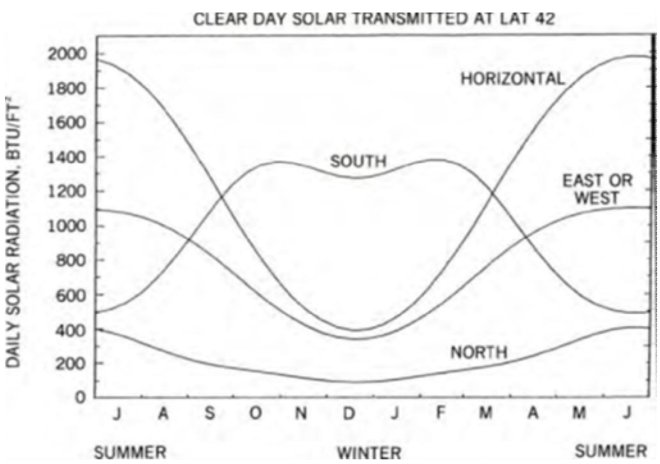

Figure 6. On June 21 South-oriented windows maximize solar radiation in the summer and minimize it in the winter (Balcomb, 1987)

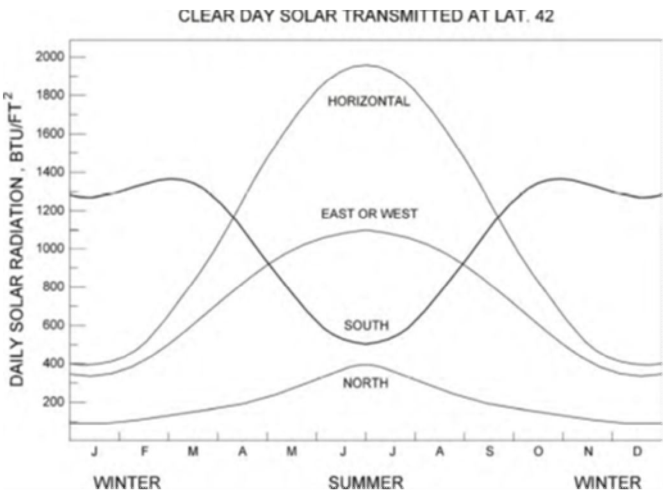

Figure 7. On June 21, windows orientations receive the maximum solar radiation in the summer, except skylights on the south orientation, which receive four times more that south-oriented windows (by Balcomb, 1987)

Example: West Orientation

West and east oriented windows receive the highest amount of solar radiation in the summer season (Figure 2.7). As shown in Figure 2.8, the solar radiation transmitted through windows on the west and east in the summer season is higher than the amount in the winter. West and east orientation have negative impacts on energy consumption and thermal comfort in buildings. In addition, they affect human visual comfort through the direct sunlight that comes from a lower solar altitude angle. The solar altitude angle in the west and east is extremely low in the late afternoon, making it hard to block with shading devices of reasonable dimensions, or requiring division of the window into small segments (Figure 8.).

Figure 8. West-oriented window in Dinsmore classroom at Collage of Architecture, The University of Arizona outdoor and indoor viewpoints (by the author)

Building Types

Each building type has distinguished code, construction, and function requirements. Air conditioning systems (HVAC) deliver heating, cooling, and air circulation/cleansing; lighting systems deliver illumination; water heating and sanitation systems deliver and dispose of water; electrical and gas systems deliver power and fuel; elevators and escalators provide mobility; and envelope systems (windows, walls, and roofing) seal the conditioned environment from the outside. Moreover, the behavior of a building’s occupants plays an enormous role in the overall energy usage and performance of that building.

Example: Office Buildings

The commercial sector, which includes office buildings, accounts for approximately 35% of all electricity consumption in the United States. Recently, the number of office buildings has increased in response to industry growth. Office buildings are commonly designed with mainly glazed façades in an effort to express luxury, with the unintended consequence of increasing daylight in interior spaces. Thus, this type of façade is a potential source of undesirable glare and daylight and can lead to high energy consumption and thermal discomfort due to high demand for cooling and heating.

Actuation Energy

The first law of thermodynamics states that the total energy of an isolated system is constant; energy can be transformed from one form to another but can be neither created nor destroyed. In physics, energy is the capacity for doing work. Actuation energy is the main energy source for machine or device operation. It represents many forms of energy such as electric current, hydraulic fluid pressure, pneumatic pressure, or human power. The original energy form is transformed into motion and movement.

Actuators

An actuator is an element of a mechanical system that provides a control signal and a source of energy. It converts energy into motion, or is a mechanism control, and is operated by electricity and manual power. Linear and rotary motion are types of actuator movement. A rotating knob or handwheel can be used as a manual source of energy, and rigid chains with linear actuators provide push and pull motions. Valve control is a typical use of actuators, for example, for ball valves or butterfly valves.

Examples of Natural Sources of Energy

There are many types of natural energy that can be harvested to create an active or passive system that uses the original force without conversion to electrical energy. These resources are:

- Solar energy
- Wind
- Material properties
- Biomass
- Hydrogen
- Geothermal
- Ocean
- Hydropower

Example of the Solar Energy Source

Solar energy is dependent upon the sun’s thermonuclear reaction (conversion of hydrogen to helium) at its core (29 million°F), which propagates as radiation to the sun’s apparent surface, called the corona, then travels 93 million miles (149.6 Kilometers) to reach the Earth’s surface [7]. Solar energy can help achieve a more sustainable environment. The total energy received from the sun each day is greater than the total energy used by end-users in a year, placing it at the top of the alternative energy list. Solar energy is among the most efficient sources of energy [8].

Kinetic Structure System

In the literature, there are many definitions of adaptive structures. Adaptable, transformable, and deployable architecture are renowned terms in the sustainable architecture field, but it is difficult to distinguish the differences between them. Adaptive structures involve a combination of materials, structural systems, and operational methods that work sophisticatedly together in response to the environment to enhance human comfort.

In 1970, Zuk and Clark described transformable structures and kinetic architecture as follows: “the architectural form could be inherently displaceable, deformable, expandable or capable of kinetic movement”. The function of transformable structures or adaptable architecture must be specified, such as glare control, control of amount of daylight, or heat gain, in specific conditions such as location, climate condition, or orientation. The transformation mechanism has a huge range of possibilities, from hinging and rolling to inflating. The process works from a compact to an expanded form and vice versa [9].

Time is a significant factor of transformable structures since these structures change over time. The transformable structure is a part of reversible and repeated architecture (Bouten, 2015) [10]. Rivas-Adrover (2015) defined deployable structures as those that “can expand and contract due to their geometrical, material and mechanical properties –

offering the potential to create truly transforming environments" [11]. The difference between a transformable structure and deployable structure, as defined by Werner (2013), is that a deployable structure has connected structural components that need to move together in order to transform. On the other hand, a transformable structure has jointed pieces, but they do not need necessarily to perform together for the form to transform [12].

Classification of Kinetic Structure Systems

There are many classifications of transformable structures. All are based on a central idea that drives the classification. According to Hanaor and Levy (2001), the most useful classification is in terms of the morphology of form, which plays a significant role in kinetic movement, movement mechanisms, movement components, and materiality [13]. The main categories are:

- Rigid links – Bar elements
- Rigid links – Continuous surfaces
- Deformable links – Bar elements
- Deformable links – Continuous surfaces

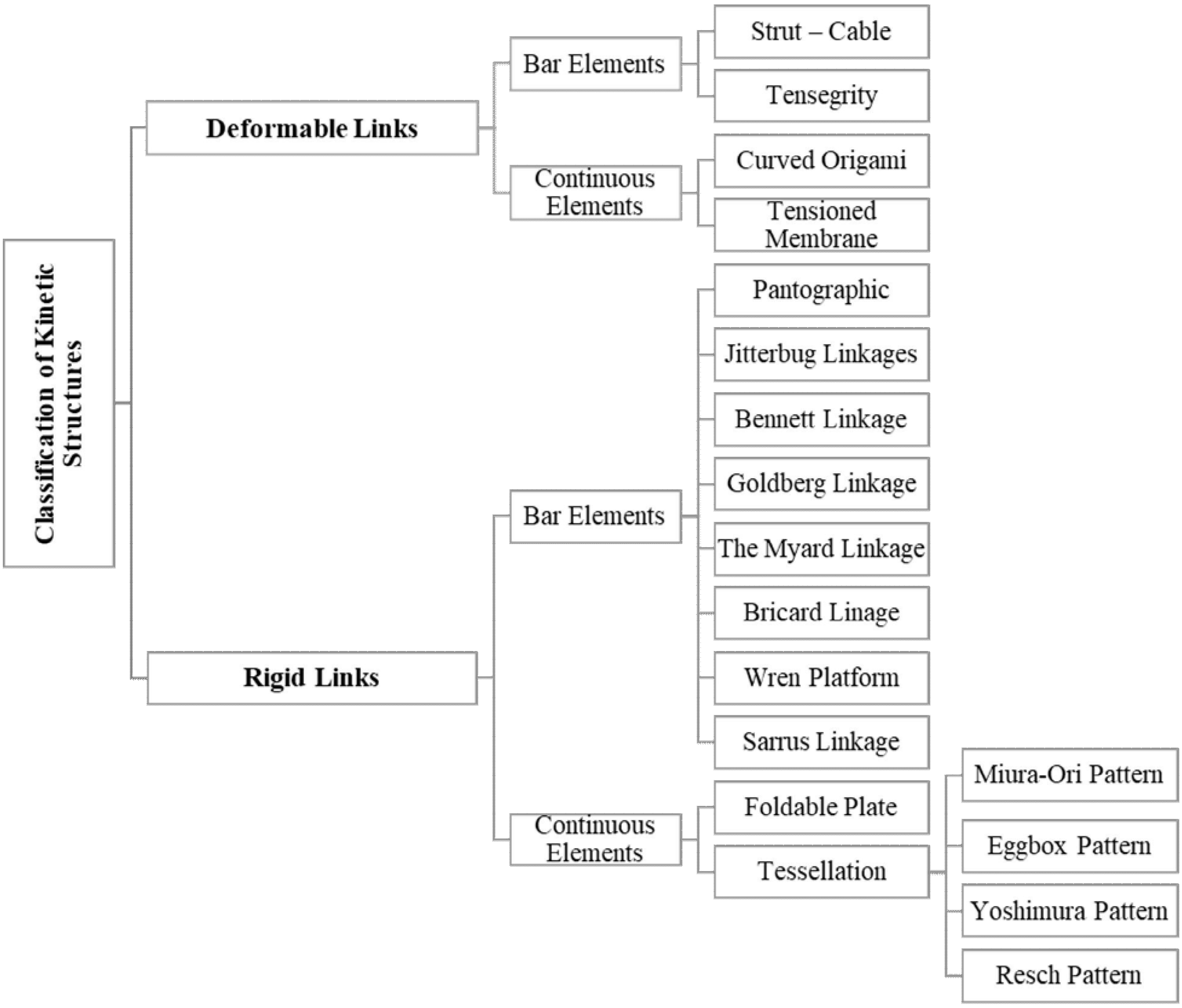

Figure 9. Classification of kinetic structure systems (by the author).

Example: A longitudinal foldable plate structure

A kinetic system has a longitudinal foldable plate structure also known as a hinged plate element. The mechanism is based on planar surfaces that have only one degree of freedom. They mainly use a linear deployment method that results in an efficient system but with relatively heavy weight. The integration of a large structure and foldable connections is complex and challenging as the foldability resulting from connected elements is affected by the thickness of planar surfaces (Hanaor & Levy, 2001) [13]. Changing the relative in-plane angle of the edges of the plate elements results in the kinetic movement of this type of system (Bouten, 2015) [10].Planar surfaces are used for structural support and to cover the system, so less time is required for assembly. In contrast, they are generally lighter compared to scissor structures (Ohsaki et al., 2015) [14].

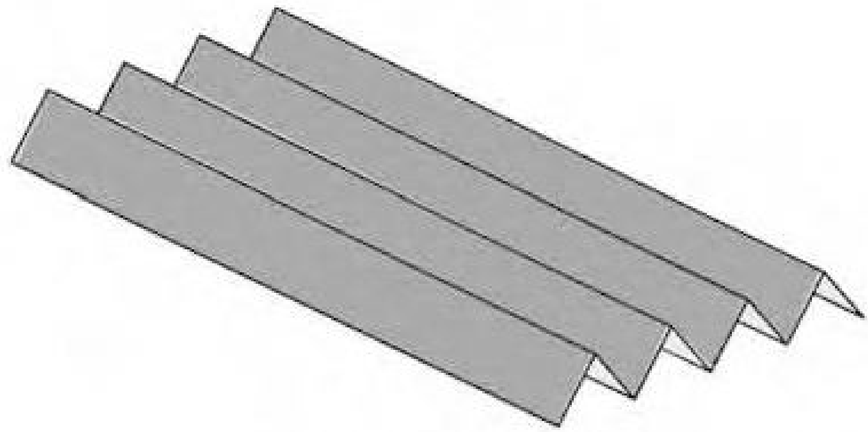

Figure 10. Longitudinal folding surface (by Hanaor & Levy, 2001)

6. CONCLUSION

Architectural environmental treatments must change. Conventional solutions are becoming outdated as the world changes and new environmental challenges need creative solutions that satisfy the social, economic, and health aspects and the environmental and energy performance requirements for buildings. Climate is becoming a critical parameter in sustainable, efficient design. When designing building envelopes, architects must consider the climatic context and space functionality as a primary parameter to frame the design. Creative designs can enhance occupants' satisfaction with a building's aesthetics and indoor environment.

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