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A Comparative Study on Responsive Façade Systems

*Res. Assist. **Ecenur Kızılörenli** [1], Assist. Prof. Dr. **Feray Maden** [2]
Faculty of Architecture, Yaşar University, İzmir, Turkey [1, 2]
E-mail [1]: ecenur.kizilorenli@yasar.edu.tr, E-mail [2]: feray.maden@yasar.edu.tr

Abstract
As the interaction between architecture and technology have increased, the technology changed the decisions made on the building designs. The developments in building technology, material sciences, engineering and robotics have opened up a new perspective in architecture leading to kinetic architecture. Among the examples of the kinetic architecture, responsive facades have become more significant in the last decades due the advantages they provide. Compared to the conventional façade systems, the responsive facades are multifunctional since they can reduce the building's heating and cooling loads, control daylight transmission, allow natural ventilation and provide optimal indoor environment for the occupants. In recent years, various responsive facades have been realized in response to the changing environmental, functional or spatial conditions. Although they seem similar in terms of the functionality, their systems are different. This paper aims to propose a comparison matrix to analyse and compare such responsive facades systematically according to their system types, movements, functions, control systems, response time and visibility.
Keywords: Façade Systems; Responsive Facades; Kinetic Architecture; Technology.

1. Introduction

The life has been changing rapidly depending on constantly changing needs, which affects many areas including the architecture. As the activities of the modern society transforms, the concept of movement has become a part of architectural design. Since the existing buildings or building components cannot respond to the changing needs, the design process of the buildings has been started to be questioned. New solutions have been sought even in the façade design in order to adapt to the changes using the concept of movement (Rahbarianyazd & Raswol, 2017).
For centuries, the building facade has been perceived as a static element which acts as a barrier or a separator between exterior and interior spaces. However, it has more than one function since it not only protects the building from external factors but also plays a crucial role in reducing the building's cooling load and in meeting the user needs (Schittich, Krippner and Lang 2012). Despite the aforementioned multi-functionality, the existing static façades neither adapt to the varying climatic conditions nor respond to the needs of users. The main reason is due to the conventional way of façade design. In fact, it requires a new design approach that provides a real-time response to the changing circumstances. Responsive façade design may offer an efficient solution to the problem (Drozdowski 2010).
The responsive facades can adapt to the changing conditions without compromising their overall structural integrity. They can respond to the environmental conditions in real time by changing their geometric configurations or positions whereas the static facades cannot adapt to those conditions due to their limited characteristics (Moloney 2011; Selkowitz, Aschehoug and Lee 2003). The responsive facades ensure the maximum use of daylight and increase the use of natural ventilation. Moreover, these systems can optimize the building's energy consumption and provide optimum indoor comfort for the users (Favoino, Jin, and Overend 2014). Considering that buildings consume more energy than the transportation and industrial sectors (EIA 2013), it can be said that the responsive facades have positive impacts on reducing the energy demands of the buildings (Knaack and Klein 2009).
In the last couple of decades, many responsive facades have been constructed in response to the changing environmental, functional or spatial conditions. When the existing literature on the responsive facades has been investigated, it has been seen that the façade systems are generally reviewed based on their system types or materials. There is a lack of clear definition in element types, movements and control systems. In this study, the aim is to propose a new comparison matrix to review and analyse the existing examples of the responsive facades systematically based on type of system, type of movement, type of control system, control type of elements, façade function, response time and visibility of the system.

2. Proposed Comparison Matrix

A comparison matrix has been created based on the movement of the responsive façade systems since the movement is the main parameter which can be used to identify different façade systems. Five movements have been defined in the comparison matrix such as rotation, deforming, folding, sliding and hybrid. In addition, there are

six other parameters in the matrix which are the type of system (active or passive), the type of control system (hand-operated control or central control), the control type of elements (individually or total movement), the function of the façade (daylight control, thermal control or air flow), the response time of the elements in the system (seconds, minutes or hours) and the visibility of the façade system (low, medium or high) (Table 1).

Table 1. Proposed Comparison Matrix

Type of System		Type of Movement						Type of Control System		Control Type of Elements		Function of the Facade			Response Time			Visibility		
		Rotation																		
Passive	*Active*	*Full Rotation*	*Oscillatory Motion*	*Deforming*	*Folding*	*Sliding*	*Hybrid*	*Hand-Operated Control*	*Central Control*	*Individually*	*Total Movement*	*Daylight Control*	*Thermal Control*	*Air Flow*	*Seconds*	*Minutes*	*Hours*	*Low*	*Medium*	*High*

- *Type of System:* The responsive facades have been reviewed under two main categories as active and passive systems. The active system has a mechanical system that controls the movement of the façade elements according to environmental data or user needs. On the other hand, the passive system can change its configuration without the need of actuators, sensors or control systems. Rather, it uses the power generated by wind, sun or temperature differences to produce the required movement.
- *Type of Movement:* The type of movement defines the motion of the elements in the responsive façade systems (Figure 1). The movement types have been examined under five main headings: rotation, deforming, folding, sliding and hybrid. Rotation defines the movement of the element that rotates around an axis. The elements can make either a full rotation around the defined axis or an oscillatory motion that allows moving back and forth along an arc. Deforming refers to the shape deformation of the element under applied forces. Folding indicates the folding movement of the system that consists of rigid panels. The elements moving back and forth along a certain axis is defined under the sliding category. Finally, the systems that have more than one movement have been specified as hybrid.

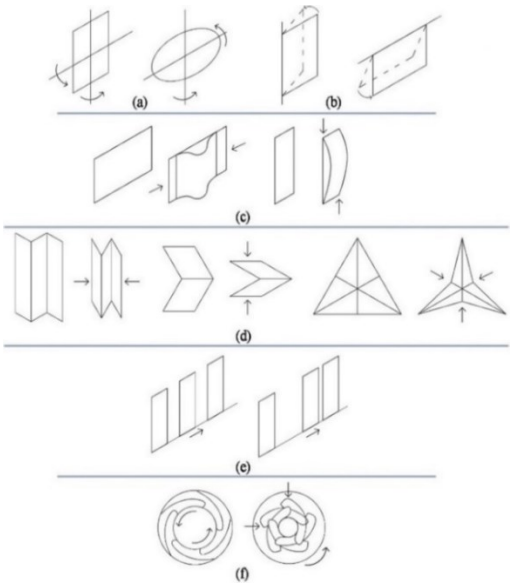


Figure 1. Movement Types: (a) full rotation; (b) oscillatory rotation; (c) deforming; (d) folding; (e) sliding; (f) hybrid

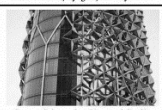
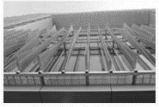
- *Type of Control System:* The factor that provides the movement of the system has been examined under this category. The responsive facades have been classified into two systems as hand-operated control or central control.
- *Control Type of Elements:* Unlike the previous category, the focus is on the control of the elements to investigate whether the elements in the system can move individually or not. If the elements have relative motions depending on each other, then a total movement is obtained since all the elements move together.
- *Function of the Facade:* In this category, the functional purpose of the façade system has been defined such as daylight control, thermal control and air flow.

- *Response Time:* The response time refers to the time required for the elements in the responsive façade system to perform their actions. This time scale ranges from seconds to hours. Although many responsive façade systems generally complete their movements in minutes, there are also some systems that can move in seconds in response to the wind or sun movements.
- *Visibility:* The façade and its elements affect not only the outer appearance of the building but also the interior. Some façade systems do not change the visibility from interior on the condition that the moving elements are either transparent or not blocking the view. However, some of the façade systems prevent visibility to a large extent. In this category, the responsive facades have been designated as low, medium and high visibility. If the structural elements carrying the façade panels block the view partially when the system is folded or opened, the visibility is considered as medium.

3. Comparison of Responsive Facade Systems

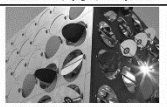
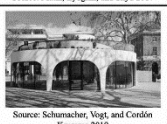
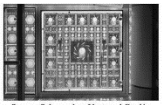
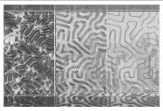
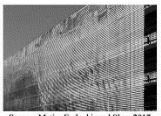
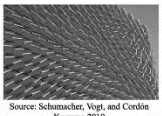
Based on the aforementioned parameters in the comparison matrix, Table 2 has been created to examine the existing applied examples of the responsive façade systems. In total, twenty-three responsive facades have been reviewed in which sixteen of them are active while the remaining four are passive.

Table 2. Responsive Facade Systems

Project	Project Location/ Year	Image of The Facade	Type of System		Type of Movement						Type of Control System		Control Type of Elements		Function of the Facade			Response Time			Visibility		
			Passive	Active	Rotation		Deforming	Folding	Sliding	Hybrid	Hand-Operated Control	Central Control	Individually	Total Movement	Daylight Control	Thermal Control	Air Flow	Seconds	Minutes	Hours	Low	Medium	High
					Full Rotation	Oscillatory Motion																	
Kiefer Technic Showroom	AT / 2007	 Source: Matin, Eydgahi, and Shyu 2017		x				x				x	x		x	x			x				x
Al-Bahr Towers	UAE / 2012	 Source: Schumacher, Vogt, and Cordón Krumme 2019		x				x				x	x		x	x			x			x	
OPEN Café-Restaurant	NLD / 2008	 Source: Schumacher, Vogt, and Cordón Krumme 2019		x				x				x	x				x		x				x
Mokyeonri Wood Culture Museum	KR / 2017	 Source: Schumacher, Vogt, and Cordón Krumme 2019		x				x				x		x	x				x		x		
ThyssenKrupp Headquarters	DE / 2010	 Source: Spiegelhalter 2017		x		x						x	x		x	x		x				x	
Sebrae Headquarters	BR / 2010	 Source: Singhal 2011		x		x						x	x		x	x		x				x	
Mpavilion 2014	AUS / 2014	 Source: Schumacher, Vogt, and Cordón Krumme 2019		x		x						x	x				x		x				x
Ballet Mecanique	CHE / 2017	 Source: Schumacher, Vogt, and Cordón Krumme 2019		x		x						x	x		x	x			x				x
Council House 2 Building	AU / 2006	 Source: Matin, Eydgahi, and Shyu 2017		x	x							x	x		x	x			x		x		

(Continued on next page)

Table 2. (cont.)

Chicken Point Cabin	USA / 2002	 Source: Matin, Eydgahi, and Shyu 2017		X	X						X			X			X	X					X
Dancing Pavilion	BR / 2016	 Source: Schumacher, Vogt, and Cordón Krumme 2019		X	X							X	X		-	-	-	X			X		
Livraria da Vila	BR / 2007	 Source: Schumacher, Vogt, and Cordón Krumme 2019		X	X						X		X				X		X				X
California Gallery	USA / 2012	 Source: Matin, Eydgahi, and Shyu 2017		X					X		X			X			X	X					X
Duke of York Restaurant	UK / 2019	 Source: Schumacher, Vogt, and Cordón Krumme 2019		X					X			X	X				X		X				X
One Ocean - Thematic Pavilion	KR / 2012	 Source: Schumacher, Vogt, and Cordón Krumme 2019		X			X					X	X			X	X		X		X		
Institute Du Monde Arabe	FR / 1989	 Source: Schumacher, Vogt, and Cordón Krumme 2019		X						X		X	X		X	X			X		X		
Homeostatic Façade System	USA / 2013	 Source: Matin, Eydgahi, and Shyu 2017	X				X					X		X	X	X		X			X		
Pittsburgh Children's Museum	USA / 2004	 Source: Fortmeyer and Linn 2014	X			X					-	-	-	-	-	-	-	X			X		
Wind Arbor	SGP / 2010	 Source: Matin, Eydgahi, and Shyu 2017	X			X					-	-	X		-	-	-	X			X		
Breath Box Waterfront Pavilion	FR / 2014	 Source: Walker 2015	X			X					-	-	X		-	-	-	X			X		
Windswept	USA / 2011	 Source: Schumacher, Vogt, and Cordón Krumme 2019	X		X						-	-	X	-	-	-	-	X			-	-	-
Latvia Pavilion Expo 2010	CN / 2010	 Source: Jordona 2016	X			X					-	-	X	-	-	-	-	X			X		
Wave Wall	USA / 2006	 Source: Schumacher, Vogt, and Cordón Krumme 2019	X		X						-	-	X	-	-	-	-	X			X		

Among those eighteen active systems, the facade systems that have folding movement are the *Kiefer Technic Showroom*, the *Al-Bahr Towers*, the *Open-Café Restaurant* and the *Mokyeonri Wood Culture Museum* (Figure 2). Having 1049 hexagonal panels and 4 linear actuators, the responsive façades of the *Al-Bahr Towers* are controlled by a central building management system (BMS) (Cilento, 2012). The system operates in real time and mainly provides daylight and thermal control. The *Kiefer Technic Showroom* consists of 112 folding panels that are controlled by 56 engines (Ahmad and Alibaba 2019). The façade system serves for the daylight and thermal control (Ahmad & Alibaba, 2019). On the other hand, the *Open-Café Restaurant* has a glazed façade on which each element can move independently by means of a motor. It allows cross-ventilation when the windows are folded. The panels on the facade of the *Mokyeonri Wood Culture Museum* consist of hexagonal leaves connected in pairs on a black metal profile. An engine controls the movement of the leaves that perform a folding movement in minutes. The main function of the façade is the daylight control. While the visibility is high in the *Kiefer Technic Showroom* and the *Open-Café Restaurant*, it is at medium level in the *Al-Bahr Towers* since the frames of the hexagonal modules somehow block the view even in fully opened configuration. It is at low level in the *Mokyeonri Wood Culture Museum*.

Figure 2. Examples of Folding Category

There are eight façade systems examined in the rotational movement category (Figure 4). Four of them are active systems while the rest are passive. Composed of stainless-steel feather-like elements, the façade of the *Q1 ThyssenKrupp Headquarters* changes its shape according to movement of the sun throughout the day (Loonen et al., 2013). Completing its movement in seconds, this façade system not only provides a regulation of the light entering the interior but also prevents unwanted solar heat gains. Likewise, the façade elements of the *Sebrae Headquarters* are made of metal panels that can be opened independently. Each panel makes a rotational movement around the vertical axis placed on the long edge of the elements. The main purpose of using these elements are to protect the structure from overheating and to reduce cooling load of the building. In both examples, the visibility is at the medium level. On the other hand, there are also other examples in which the visibility level is high. In the *Mpavilion 2014*, the metal panel elements on the façade move independently which can be opened or closed to create different configurations by means of an electric actuator. The panels can be opened in few minutes up to 90 degrees with the help of the hinge located on the short sides. In the *Ballet Mechanique*, the façade elements are multifunctional in such a way that they create new spaces for the users when unfolded and serve as shading roof elements. The façade has been formed by rounded triangular-shaped panels that are placed horizontally and vertically. While the vertical panels can provide privacy, the horizontal panels not only serve for shading purposes but also become balconies. Controlled by hydraulic cylinders, the façade elements provide thermal and daylight controls. The visibility of the façades of the *Mpavilion 2014* and the *Ballet Mechanique* are high since there is no structural element blocking the view.

Four of the façade systems in which the elements make full rotation around a central axis are the *Council House 2*, the *Chicken Point Cabin*, the *Dancing Pavilion* and the *Livraria da Vila* (Figure 3). The west facade of the *Council House 2* building is covered with blinds made of recycled wood. It was built to protect the offices from the sun in the afternoon and to utilize the daylight as much as possible when the sun is in east direction. Composed of a large pivoting window, the façade of the *Chicken Point Cabin* building has a movable system that maximizes the user's

visibility as opening the main living space to the landscape. The movement of the façade is controlled by a hand-cranked mechanism in which a set of gears was used to minimize the load distribution (Kundig 2015). In another example implemented in Brazil, the *Dancing Pavilion*, there are 345 round mirror elements that make full rotation in horizontal direction. There are sensors inside the building which capture the music and the movement of the dancing people. The data collected by the sensors activates the motors, and thereby the mirrors on the façade. Since this building was constructed for a temporary usage, there is no functional objective of the façade like thermal control or daylight control as in the previous systems. The *Livraria da Vila* is a book store in Brazil. Five rotating bookcases are located on the main façade which are attached to the floor and ceiling along the middle axis to create special entrance and to provide air flow.

Figure 3. Examples of Rotation Category

The other type of movement presented in the comparison matrix is the sliding movement (Figure 4). The façade of the *California Gallery* is similar to the design of the *Chicken Point Cabin* building. Gears and pulleys were used to move the glass facade. Opened in seconds, the system allows natural air flow as creating an entrance to the structure without blocking the view. Another example of the category is the *Duke of York Restaurant* in London. The building has a retractable curved glass facade that enables not only to open the main space to the public but also to ventilate that space naturally throughout the year. It uses a simple mechanism like a weighted sash window which allows sliding the glass panels up or down. Guide rails of the structural mechanism are located underground. The engine moves the panels through two deflection rollers and a counterweight with a simple crane drive (Schumacher et al., 2019).

California Gallery

Source: Matin, Eydgahi, and Shyu 2017

Duke of York Restaurant

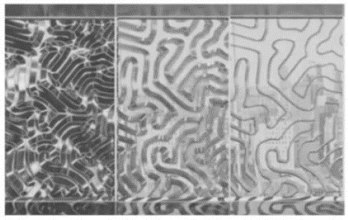
Source: Schumacher, Vogt, and Cordón Krumme 2019

Figure 4. Examples of Sliding Category

Although there are many realized examples of the responsive facades having folding, rotating or sliding movements, the examples of deforming category are limited (Figure 5). The *One Ocean Pavilion Expo 2012* is one of the examples in the deforming category. The façade elements are flexible lamellas that move according to the daylight. As the lamellas move one by one on the surface, they create different patterns on the façade. The other systems in the deforming category are made of smart materials. Unlike the previous example, the *Homeostatic Facade System* is a passive system that regulates itself according to environmental factors such as sunlight and temperature changes, and provides optimum conditions for the users. The system consists of engineered ribbon placed inside the double skin glass façade which are made of dielectric elastomers. These dielectric elastomers are coated by silver layer that reflects the light coming to the surface. The material deforms as it distributes the electric charge through the material.

One Ocean - Thematic Pavilion

Source: Schumacher, Vogt, and Cordón Krumme 2019

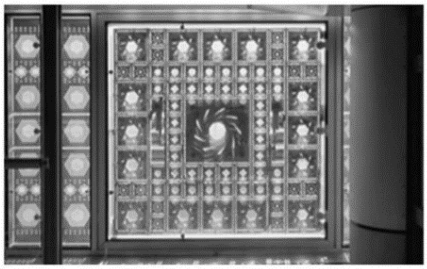


Homeostatic Façade System

Source: Matin, Eydgahi, and Shyu 2017

Figure 5. Examples of Deforming Category

Apart from the previous examples, there is also a façade system that has hybrid movements such as rotation and translation (Figure 6). Inspired from the Islamic pattern, Mashrabiya, the *Institute Du Monde Arabe*'s south façade consists of camera-like diaphragms. The diaphragms open at low altitude levels while they close in opposite direction when the sun shines brighter. The expansion and contraction mechanism of these diaphragms are regulated by the sliders to automatically control the amount of light entering the building (Schumacher et al., 2019).



Institute Du Monde Arabe

Source: Schumacher, Vogt, and Cordón Krumme 2019

Figure 6. Example of Hybrid Category

Apart from the active systems, there are also passive façade systems which can move without requiring any actuator, motor or sensor. Six samples have been examined in the passive responsive system category which are the *Pittsburgh Children's Museum*, the *Wind Arbor*, the *Breath Box Waterfront Pavilion*, the *Windswept*, the *Latvia Pavilion Expo 2010* and the *Wave Wall* projects (Figure 7). Designed as a second façade skin in the *Pittsburgh Children's Museum*, the façade elements move slightly with wind pressure without the need of energy or additional

support. These elements, which create a light and bright effect on the facade, are located on the aluminium space frame structure (Fortmayer & Linn, 2014). Likewise, the façade of the *Wind Arbor* has same design principles and goals as in the first example, but the elements are positioned on a thin cable net. Consisting of 260.000 aluminium metal fins in total, the system covering the glass façade of the hotel lobby shades the interior, blocks the sunlight and heat entering the building. On the other hand, the panels positioned in the *Breath Box Waterfront Pavilion* are reflective modules that strengthen the wave effect as reflecting the sea based on the light during the day. Having similar movement behaviours in the elements, the *Latvia Pavilion* is composed of 100.000 coloured and transparent plastic elements that are positioned to represent the nature (Jordona 2010). Designed on the south facade of the *Windswept Museum*, the responsive façade consists of 612 wind indicators and 25 brown panels that are free to move independently according to the wind, and remain at their initial configurations when there is no wind (Schumacher et al., 2019). All the aforementioned façade elements sway in the wind and move independently. Various configurations can be seen on the facades in a short time.

Figure 7. Examples of Passive Rotation Category

4. Conclusion

In this paper, a systematic review has been conducted for the responsive façade systems using the proposed comparison matrix. Including both active and passive systems, the responsive façades have been discussed based on their main characteristics, movement capabilities and other features. Based on the comparison matrix, it can be said that most of the applied examples of the responsive facades have active system in which actuators, motors or sensors are used to provide a real-time response to the changing environmental conditions. Passive ones are usually used for pavilion or exhibition structures since the aim is not to provide thermal or daylight control. Among the reviewed twenty-three examples of the responsive facades, only three of them are based on hand-operation whereas the rest of them are controlled centrally. Twelve of the systems complete their movements in seconds and eleven of them in minutes. Since the responsive facades systems are generally composed of modules that have capability of moving individually, the elements in such systems are free to move. That means each can be controlled separately. The elements in the reviewed eighteen examples have this capability. When the types of movement are examined, it is seen that fourteen of the responsive facades have rotational movement while four systems have folding movement, two systems have deforming movement, the other two systems have sliding movement and one has hybrid movement. On the other hand, the rates of the low, medium and high visibility categories are almost equal.

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Conflict of Interests
The Authors declare no conflict of interest.

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