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# PROPOSING A NOVEL KINETIC SKIN FOR BUILDING FACADES USING SCISSOR-LIKE-ELEMENT STRUCTURES

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## Keywords

kinetic pattern; transformable unit; scissor-like elements; building skins; kinetic *façade*



## Abstract

*In recent years, kinetic facades have emerged as a suitable alternative for building skins that meet the demands for comfort factors of inside and outside environment and aesthetic criteria. This paper demonstrates a novel transformable geometric pattern inspired by Persian Architecture that provides an environmentally protective yet aesthetically pleasing building skin. This novel skin that is used for building facades is composed of geometric modular units mainly consisting of two kinds of scissor-like element (SLE): simple scissor-like element and modified scissor-like elements which are linked together by movable joints. These units can be connected together to create a transformable system attached to the existing or new building or be used for a particular part of a building. This paper presents a research-based design project using a rarely used SLE system for transformable building facade. In this methodology, in the first stage, a library study was used to find, categorize and evaluate the transformable building skins using SLE systems. In the second stage, an experimental study was carried out to evaluate the best movement strategies for SLE units that employ the most efficient activation and driving system for the proposed geometry. In the final stage through physical and digital model making process, the alternatives derived from the previous stage were analyzed and the best transformation strategies that best suit the selected design was chosen. The result of this paper is a proposal for a transformable grid of SLE systems that can be attached to existing or new building façade and is not only able to control the environmental condition of the building, but it can also change its appearance during a course of a day. The transformation mechanism used in this design is a combination of two types of scissor structure employing pivotal and rotary movement supported on the tracks provided on the building façade.*

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## INTRODUCTION

A building envelope has a significant role in controlling the environmental condition for inside spaces and is a barrier between inside and outside of the building. A facade is an appearance of a building and has a visual effect concerning aesthetic criteria. A static building façade that is in use in most of the building today is not able to fulfill ever-changing architectural design requirement in terms of response to environmental changes and user needs.

A kinetic façade is defined as a configurable system using moveable joints that can change its shape and configuration partially or as a whole according to the responses received. This type of structure may improve the performance of a building either aesthetically or functionally (Sharaidin, 2014). However, the design of the changeable façade system requires a complex and challenging strategy in terms of developing a consistent and compatible design that integrates materials, mechanics, engineering and architecture. On the one hand, architects should synthesize aesthetic and technical design issue of transformable units for the required skins (Asefi, 2010). On the other hand, the proposed design should comply with the functional and environmental requirements of the building. Technical concerns in transformable units relate to the movement mechanism and the way skin's component is transformed. If one element does not do its own task, the whole system will not work, and it may develop a severe failure (Moloney, 2011). Designing a kinetic pattern is in a direct relationship with ways of movement, and there are different kinetic structures and mechanism that utilize these ways of being kinetic.

The present work is to propose a novel kinetic pattern for building facade consisting of different types of scissor-like elements, which can transform according to the building program. The proposed skin is supposed to respond to the building requirements, both functionally and aesthetically as will be explained in details. The theoretical information about kinetic patterns and kind of SLE structures as well as the research methodology that was used in this study are also explained in this paper.

## LITERATURE REVIEW

To have a good understanding about transformable building skins, the main phrases used in this research and the previous studies and projects carried out by other researchers are presented in this section.

### Application of kinetic skin

As explained in the previous section, a building facade provides improvements in the environmental condition within the building and by using kinetic skin; buildings can respond to changing conditions. Application of kinetic skin is not a new concept. Recently, growing investigating around this topic has been seen in publications, and there is an increase in numbers of buildings that are using the kinetic skin for environmental and aesthetic objectives both in the past and in the contemporary research (Sharaidin, 2014). Although kinetic facades look uncomplicated, their development around the world depends on the technology of their implementation and how it can be constructed properly.

Al Bahar Towers in Abu Dhabi (Fig. 1) and Arab World Institute in Paris (Fig. 2) are two samples of buildings that are covered by kinetic skins. In these two building skins, two kinds of dynamic modules are utilized which create a folding and unfolding state in order to adapt to changing environmental conditions and regarding the aesthetical aspect, by expanding and contracting effect of the skin members, creating random patterns and different compositions (Sharaidin, 2014).

Figure 1. Al Bahar Towers and dynamic module (Source: Designboom, 2012).

Figure 2. Arab World Institute and dynamic module (Source: pariste, 2014).

## Kinetic pattern

According to Sharaidin, a kinetic pattern refers to a cluster of individual moving components from various surface configurations (Sharaidin, 2014). Designing these individual moveable elements and their relative movement in space and time is a difficult task. In contrast to static façade, the design of a kinetic system requires an interactive design process through selecting a geometry and analyzing its movement, digital and physical model making to selecting and designing of the required joints and materials by considering the mechanism of movement, and evaluating the functionality of the whole system especially in terms of structure and engineering (Asefi, 2012).

Kinetic pattern, its configuration and an associated transformation mechanism structure play a significant role in the movement process, structural stability and the way the structure respond to environmental challenges. In the recent years, several kinetic patterns were explored and developed for transformable building skins. One of the major systems considered in the transformable structure is called scissor-like-element (SLE) mechanism that due to the use of small-hinged connected elements can provide a creative, dynamic pattern. An SLE structure is an expandable lattice structure that will be explained in detail in the next section of the paper.

An example of kinetic patterns which used this type of structure is a project called Scissornet (Fig. 3). The Scissornet is a modular system with a high degree of transformability. The movement mechanism in the Scissornet is based on SLE structure, and the elements can be connected together in a variety of self-contained configurations. The structure can respond to different lighting conditions by opening and closing (Fig. 4) (Sharaidin, 2014).

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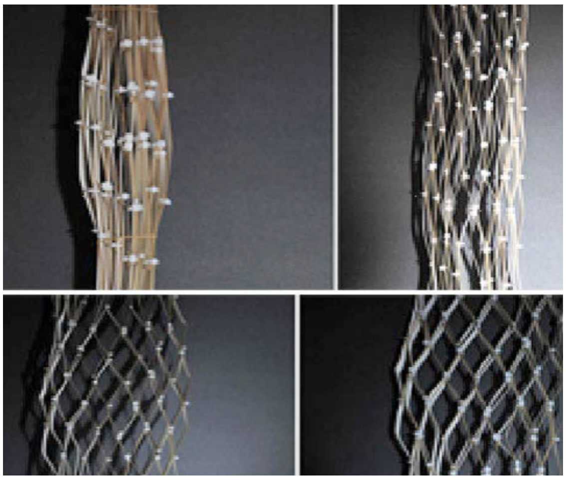

Figure 3. A prototype of the Scissornet illustrating its transformation stages (Source: Sharaidin, 2014).

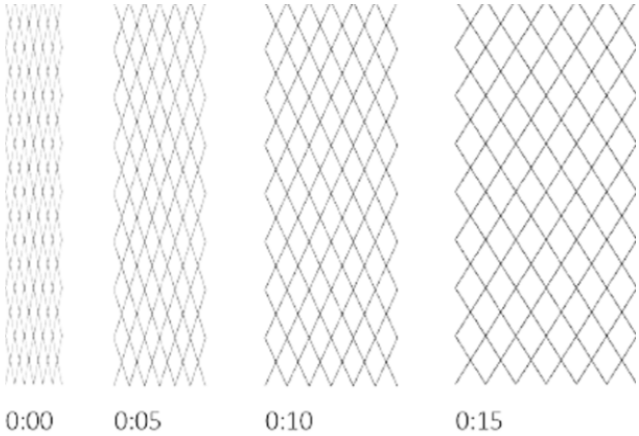


Figure 4. Duration of movement of the kinetic façade demonstrating the contracting and expanding behaviour (Source: Sharaidin, 2014).

## SLE Structures

Kinetic structures have an ability to be transformed and reconfigured in order to respond to changes. They can be classified according to their structural systems and mechanisms. One of these categories is Pantographic (scissor-like-element structure). Pantographic structures are expandable lattice structures consisting of bars that are linked together by scissor hinges that can be folded into a compact bundle. They can provide large span, load-bearing structures and have a potential to be used as decorative structures. Connecting two bars to each other at an intermediate point, with a pivotal connection, can produce a simple structural module (Fig.5). When this module is hinged at its endpoints to the endpoints of other SLEs, it can provide a structure that can be transformed into different configurations (Fig.6) (Asefi, 2010). Another unit that was proposed recently and is the basic unit for the proposed pattern of this research is called modified scissor-like element (Fig.7). In this novel unit, each element of the unit is divided into two different parts. Each element has rotational movement around the pivot and does not affect the other three struts (Haghnazar and Asefi, 2012)

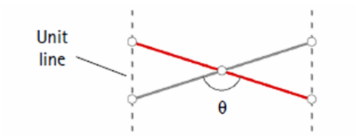


Figure 5. (Left) Scissor structure unit (Source: Temmerman, 2007)

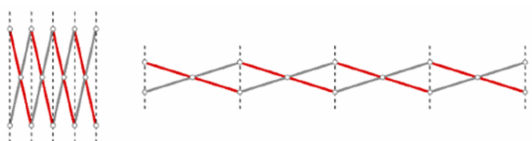

Figure 6. (Right) Scissor linkage (Source: Temmerman, 2007)

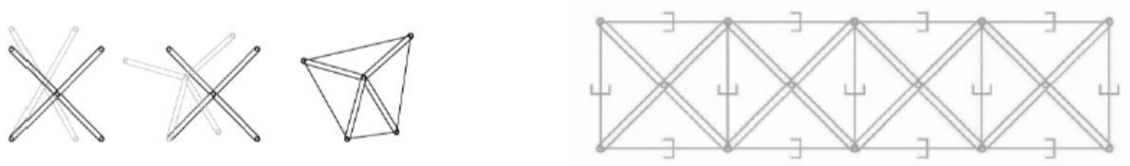

Figure 7. Modified scissor-like element (Source: Haghnazar and Asefi, 2012)

## Research Methodology

The primary objective of this paper is to present a unique transformable skin for building facades. The design of transformable objects is a complex task that incorporates both static and dynamic structure strategies. This paper uses a research-based design strategy that encompasses an interactive process among design sketches, physical and digital model making and transformation mechanisms. A research-based-design method uses a development process whose result is an object, where the thinking and research are embodied in the object and the goal is not primarily communicable knowledge in the sense of verbal communication (Cross, 2001; Roggema, 2016). The design continually weaves between inquiry and proposal and involves values about aesthetics and beauty, which are hard to be assessed through general research indicators or criteria (Roggema, 2016).

The research methodology in this paper seeks, through the information, implications, and data through model making, a geometrical analysis of the transformable grid in order to achieve a proper building skin. This approach by incorporating engineering, operational, architectural and aesthetic data can contribute to a successful design outcome. In the early design stage, the exploration of the kinetic patterns is carried out through the fabrication of physical models. The main goal of this exploration is to experience different types of kinetic structures and mechanisms for designing and testing a suitable kinetic pattern for building facades. Furthermore, kinetic pattern's morphology and moveable mechanisms were developed through parametric model making and were evaluated and tested utilizing physical model making while aesthetic and operational properties were also considered during the design development process. In the final stage, the best alternatives that has the best possible result in terms of aesthetic, engineering, operation, mechanism and function were selected and developed.

## DESIGN

### Construction of Basic Unit from SLE

The main unit of the proposed skin was realized by considering the possible behavior of kinetic SLE(s) and their combination. The potential of SLE(s) in creating different shapes and configurations in both two-dimensional and three-dimensional geometry were considered in the design of the system. In this research, two kinds of SLE(s) illustrated in section "SLE Structures" are employed. One of them is a simple scissor structure, which transforms in one direction. This scissor is made of two linear elements in which the joint is placed at one-third of the length of each member. The second one is a modified SLE in which the joints allow the unit to move in three dimensions. In these SLEs, each unit is divided into two parts, which can individually rotate around the articulated joint without affecting the other elements (Asefi et al., 2013). In order to limit the degree of movement of this unit and reach the required transformation of the whole systems, two simple scissor units as described earlier are attached to it on both sides (Fig.8). Fig 9 shows a plan view of the resulting unit. The activation of the resulting structures happens by the movement of simple scissor units. When simple scissor units deploy, they move the modified SLE and transform it as planned (Fig.10).

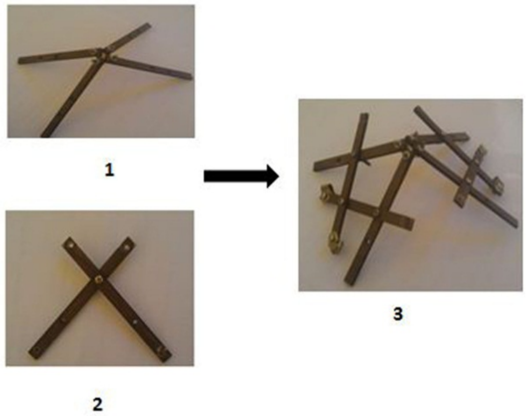


Figure 8. Unit composition (1: modified scissor-like-element, 2: simple scissor-like element, 3: resultant unit)

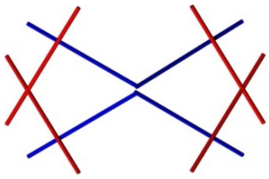

Figure 9. A single unit of the proposed grid

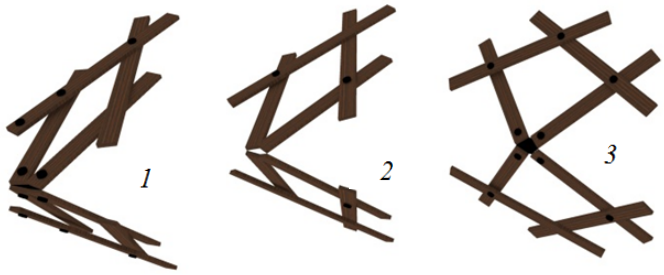


Figure 10. Deployment process of the proposed module

## Transformation Process of Units

Due to the modular capability of SLEs, it is possible to connect several pantographic modules of different types in order to develop a structure that can respond to a specific function. In this paper, a number of designed modules (Fig. 10), as explained in the previous paragraph, were considered to attach together for the development of a transformable building skin (Fig.11). According to parameters (length, width, and height) that are considered for each unit, the resulting skin (Fig. 12) is predicted to have three types of movement mechanism as summarized in table 1:

1- The height and length of the structure changes, but its width does not change.

2- The length and width of the structure change, but its height is fixed.

3- The length and width of the structure change, but its height is fixed, and each unit works independently with no connection to other modules.

As shown in table 1, in the first transformation method the width of units does not change during the transformation. In other words, all elements of the skin move in the same plane so that the skin expands and the total area of the skin increases (according to table 1, type 1). In this type of transformation, a fixed line should be defined in the skin plane in order to be able to control the movement process as required. One of the main weaknesses of this transformation method is that its application is limited to small-scale building facades as the whole skin either hangs from one fixed point or from a fixed line during transformation and it is also quite difficult to control the skin’s movement as is required by the building (Table 1).

In the second method, the width of the structure changes and the structure transforms from a plane to a three-dimensional configuration. This type of transformation can simply be done through predefined parallel track placed on the surface of the building where the skin is attached and defining a suitable control method is more feasible than the first method (Fig.13 and 14).

In this paper, the second method was employed and developed for the proposed kinetic skin. The third movement method is similar to the second method with the difference that each

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module works independently of other modules. This movement mechanism makes it also possible to divide the skin into a number of separately controllable segments that can respond to a building's requirement individually (Table 1, type 3).

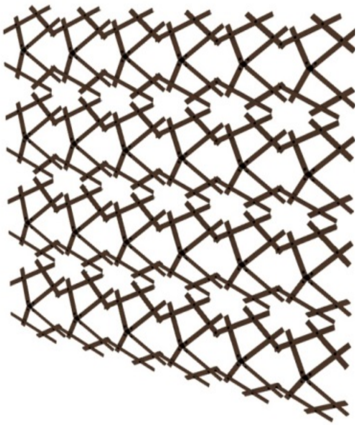


Figure 11. A transformable grid consisting of proposed units

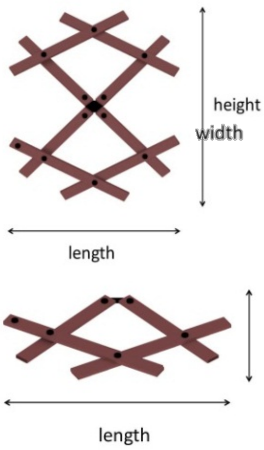



Figure 12. Defined parameters

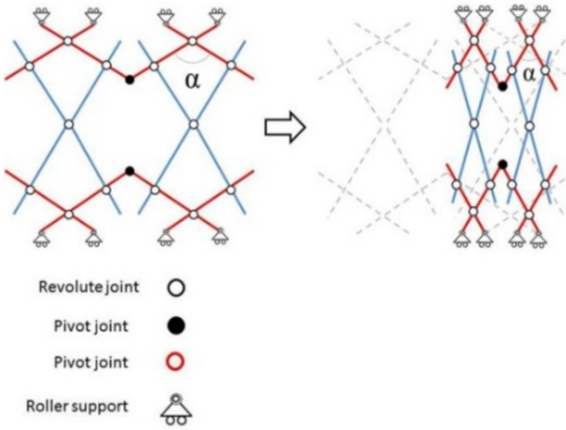



Figure 13. Deployment process of second type of mechanism (type 2)

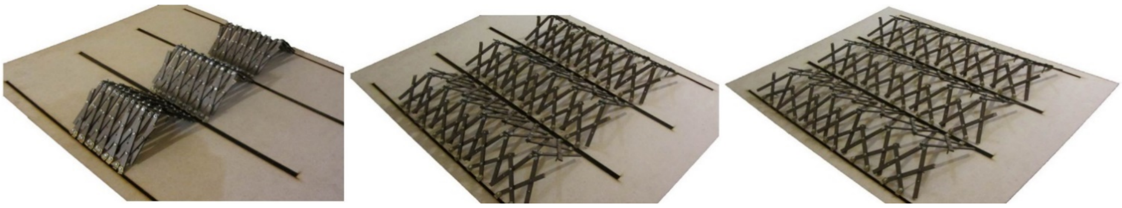
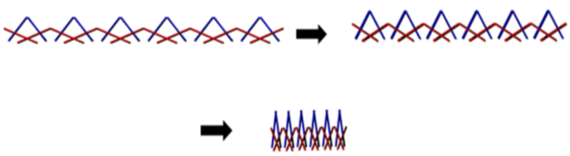
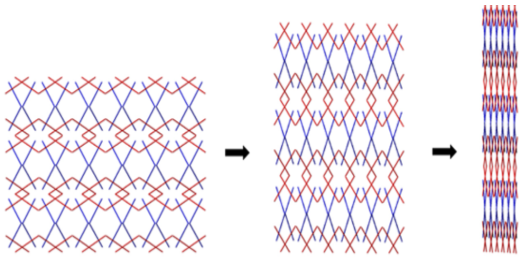
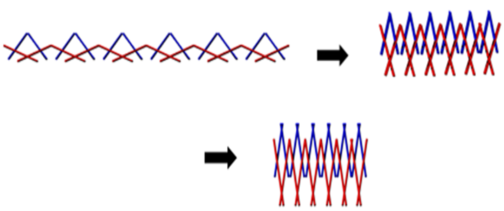
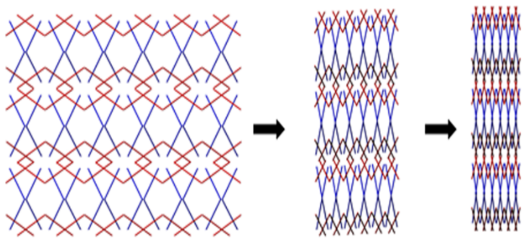
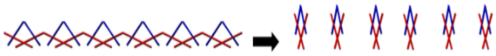
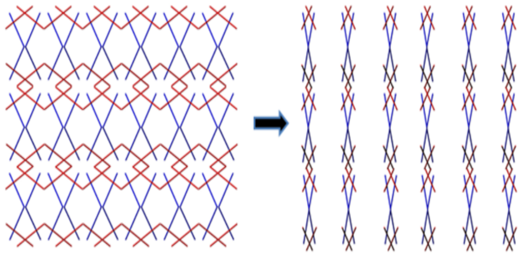


Figure 14. Deployment process of second type of mechanism (type 2)

Table 1: Three types of movement mechanism and configuration

| Type | Width changing (section) | Length and height changing (plan) |
|---|---|---|
| Type1 |  |  |
| Type2 |  |  |

| | | |
|---|---|---|
| Type3 |  |  |

## Covering Strategies

In general, a kinetic skin system consists of two parts: the main structure and covering components. The covering components play an essential role in controlling the environmental condition and at the same time affect the visual and aesthetic performance of the building. Therefore, an appropriate material with specific features as a proper amount of transparency and an adequate durability should be selected (Ashby, 2005). There are also different movement mechanisms for covering components such as sliding, folding and rotation, etc.

In the proposed structure, according to movability of the whole system, covering material can also add to the stability of the system during and after transformation. Therefore, rigid panels with a folding mechanism were selected (Fig. 15) (Kirkegaard and Nielsen, 2009)

Figure 15. A complete module including the structual and covering elements

Figure 16. Details of connection between the covering elements and SLE’s

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Each panel consists of two segments attached to each other by hinged joints. These joints allow the panel to be folded during the movement and transformation of SLE(s). In order to attach the panels to the structure and at the same time allow the movement of the panels while the structures are under transformation, several physical and digital models were designed and constructed in order to study the best connection points to the structural components. The result of the study shows that it is possible to connect the panels to the structure using two pivotal joints at the intersection of simple scissor and modified-SLE and one hinged line joint at the main connection between the elements of modified SLE. The third joint allows the panels to resist the load of wind and also prevent the lower parts of the panel from falling (Fig.16).

## Actuating and Driving Mechanism

Each system that has the ability of movement and transformation requires an activating and driving system that creates and controls motion. For each movable structure, a specified actuating and driving system is defined according to the designed movement mechanism and the geometry of transformation. The movement of the proposed structure is guided through a number of horizontal tracks (Fig. 17).

These tracks are placed on both endpoints of simple scissor elements as depicted in figure 18. In other words, all the endpoints of simple SLE(s) must be placed on the tracks by small wheels that guarantee their movement during transformation. These wheels in addition to supplying linear movement (Fig.18) provide rotational movements during deployment by the hinge joints installed on them (Fig. 19).

Moving these points towards each other causes the whole pattern to be retracted while moving them in the opposite direction causes the structure to be deployed. The points should be moved simultaneously in order to make a smooth transformation of the whole system. The driving systems include a number of pulleys and cables, which are installed on tracks (Fig. 18 & 19). All the endpoints of simple scissors are connected by cable and are driven by pulleys placed on both sides of the tracks. On each track four pulleys are used: two of them placed in the center allow the structure to move toward the middle during retraction and the others slide the structures towards the sides during deployment (Fig. 20 and 21). A number of these units can be placed in a frame (tracks can be installed into frames) and then these frames are installed on the main structure of the whole facade or only limited parts of the facade that need to control incoming light. These frames together form grids that are shown in figure 22.

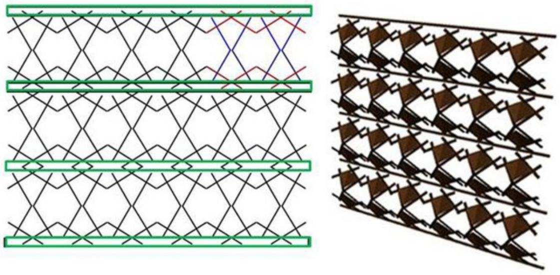

Figure 17. Track and Transformable module in one frame

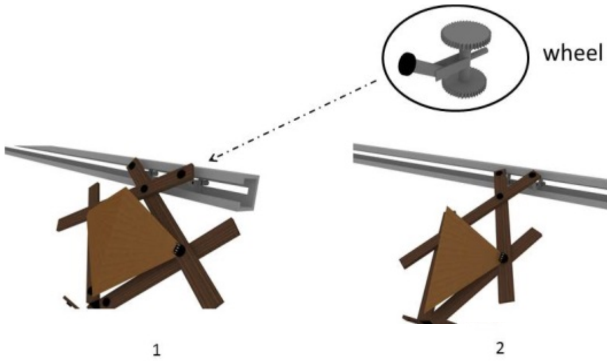


Figure 18. Details of driving and actuating system (linear movement)

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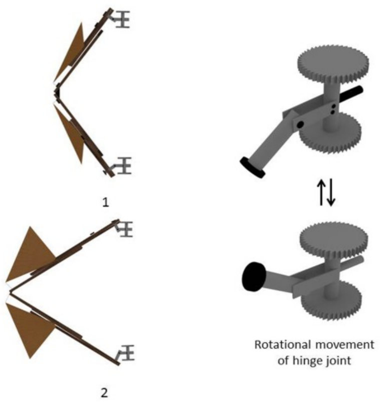


Figure 19. Details of driving and actuating system (rotational movement)

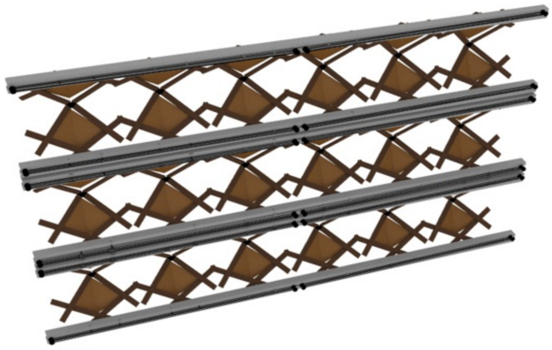

Figure 20. Position of pulleys on horizontal tracks

Figure 21. The driving system including pulleys and cables

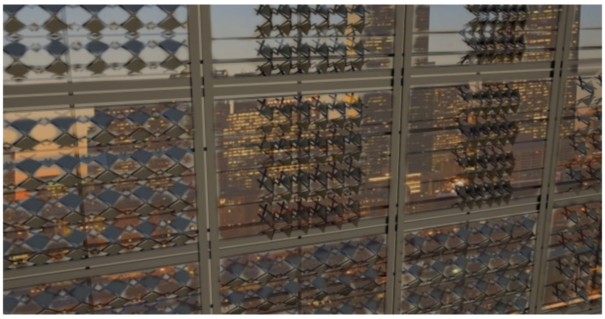

Figure 22. Transformable grids of the proposed kinetic skins in different configuration

## Geometric Transformation Analysis

The geometry in this research has an essential role in the operation of the kinetic facade. This factor controls the behavior of the kinetic system before, during and after movement. In this research, the geometrical configuration of the façade was studied and evaluated through a parametric model making process using Grasshopper software.

This was helpful in extracting information for analyzing the method of movement. As parametric computational design tools, Grasshopper and Rhino dispose facilities for designers in order to evaluate the kinetic structure. These tools prepare visual environment with coding language that provides a parametric design for a designer in order to study structural movement through alteration of parameters.

For exploring the kinetic behavior of the modules in this research, at the first step, the basic geometry of a single module in two states of folded and deployed was studied. For this purpose and according to this point that, joints of elements in scissor-like structure play a great role in the reconfiguration and the stability of the structure, their movement was considered, and they have been numbered for further analysis during motion (Fig.23 and 24). The joint location was marked according to the movement mechanism by considering their

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position from coordinate axes. In coordinate axes, each node or joint has three parameters: x, y, and z. Each joint's position depends on these parameters and alters by changing one, two or all three parameters. For each joint's movement, a vector is defined in which the first point is the position of the joint in the folded state of the module, and its endpoint shows the position of the joint in the deployed configuration. Figure 23 and 24 shows the movement of each joint separately (vectors define the movement of separate joints during transformation). It is used for developing an algorithm for the Grasshopper plug-in (detailed analysis of the joint movement equation and the associated vector are presented in appendix 1). The proposed algorithm can be imported into this plug-in in order to create a parametric model for our proposed kinetic façade. The parametric model illustrates the movement of the grid and allows the evaluation of the kinetic pattern transformation according to the design requirement. By altering the joints position, it is possible to transform the grid from a fully folded to a fully deployed configuration (Fig. 25).

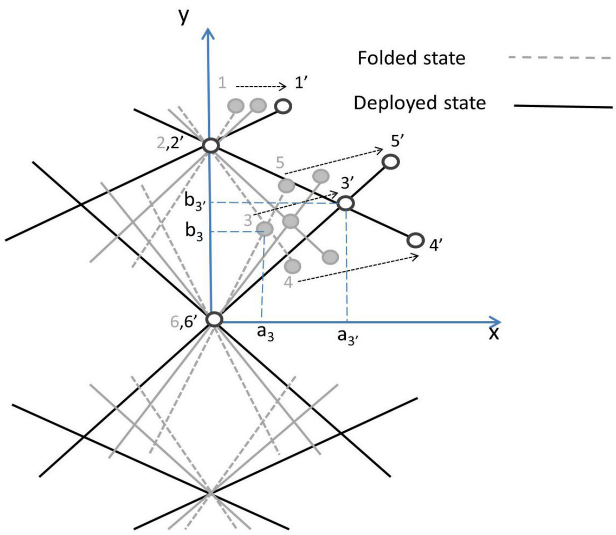


Figure 23. The Movement stages of the joints and their associated movement vector in x-y plane

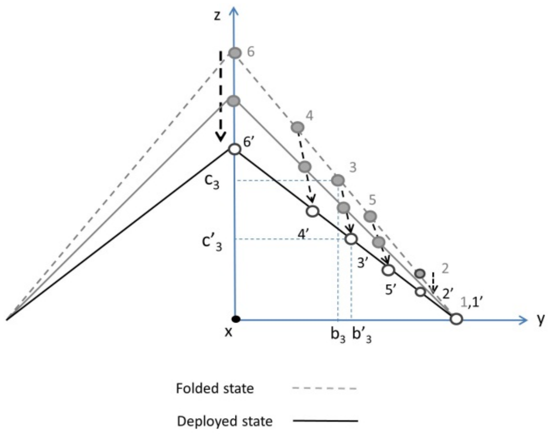


Figure 24. The Movement stages of the joints and their associated movement vector in y-z plane

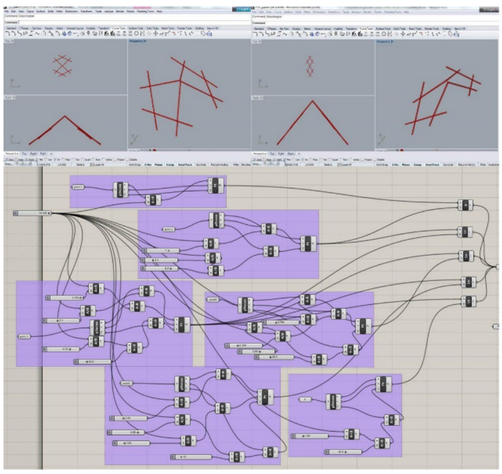

Figure 25. The parametric model (Algorithm) in Grasshopper showing the joint movement

## Material Selection

The selection of materials plays a vital role in the performance, functionality, and aesthetics of kinetic facades. Covering materials in this type of system should not only perform appropriately as an enclosure, but they should also resist repeated movement and environmental changes before, during and after transformation. This issue is especially important because if the selected material fails during operation, it may dramatically increase the whole-life costing of the project and endanger the safety of its users. These issues suggest that the selection of proper materials for transformable skins requires a more complicated process in comparison with that of conventional static architecture. Designers must consider the compatibility and efficiency of materials in different stages of the design process to ensure the safe operation and performance of the structure and consider ease of manufacture, installation, and maintenance of the materials. It is also essential that the proposed material be checked regularly against the design brief in different stages of the design process to ensure it meets the desired performance requirements and provides an aesthetically pleasing environment for users before, during and after transformation.

Beside the features stated, in choosing a suitable material for this type of facade two main subjects must be considered. First, as the material is to be used in the outer shell of the building, it should be able to resist weather conditions and have appropriate aesthetic features. Secondly, as the material moves along with the structural and driving systems, it should have sufficient flexibility, stiffness, and strength in order to prevent any problems during the motion.

In the proposed kinetic facade the materials used in the frames, tracks and SLE units should be able to bear environmental and internal loads and at the same time should resist the dynamic forces imposed through transformation. Therefore, steel is suggested to be used due to suitable density, load-bearing capacity, and durability. Covering panel material should be more flexible, lightweight and have some degree of transparency. By investigation in previous examples of kinetic facades, a number of materials can be considered, including translucent glass-fiber composite material, polycarbonate, polymers, and carbon fibers. In this paper, translucent glass-fiber composite materials were selected as covering materials due to durability, lightness, strength, and having the required degree of transparency.

## Application of Proposed Pattern

The proposed transformable skin can be attached to new or existing buildings and is not only able to control the environmental condition of the building, but it can also change the appearance of the building during a course of a day. This transformable skin can be used as the second layer of a glass building facade, and its ability in being stable in different transformation stages can provide the building with a variety of aesthetically interactive configurations (Fig.26, 27 and 28).

As explained in the previous section, actuating system of the proposed pattern in this paper consists of pulleys that move on the tracks. Due to this point that several modules are positioned along tracks, the number of pulleys that have the task of module movement is considerable so that a computer controlling system is needed to control the movement of all the pulleys simultaneously in order to have a harmonic movement. Each pulley is attached to an actuating motor, which can be addressed individually in the computer system within a determined logic of the movement. The operating computer system requires basic information about the direction of sun movement and other climate factors and can be linked to the internet. This allows uploading information about facade condition and climate change in the computer in order to control the structure.

Figure 26. The application of the proposed structures for interactive building skins

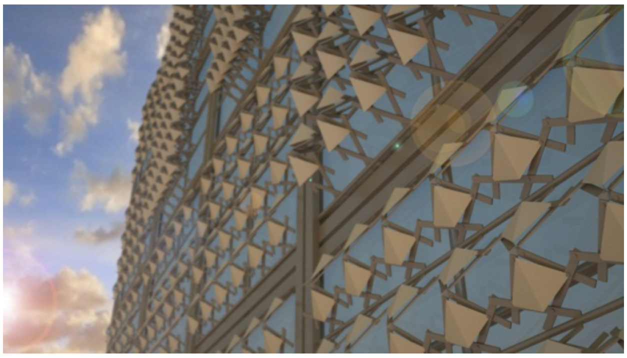

Figure 27. The application of the proposed structures for interactive building skins

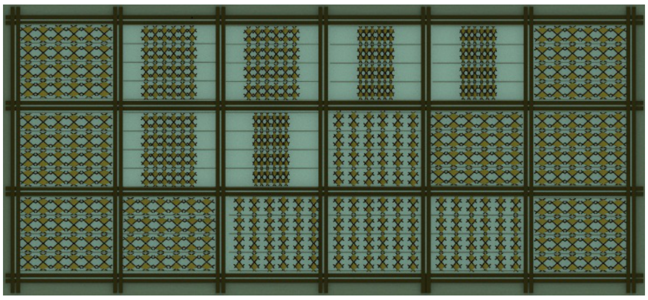

Figure 28. The application of the proposed structure for interactive building skins

## CONCLUSION

Building facades are considered as an important part of architecture as they play an essential role in buildings' appearance and protect buildings from the environmental changes. Also, a building facade provides a boundary between architecture and urban spaces and it has an essential influence on people's reaction and understanding of the built environment. One of the important roles of a building skin is controlling the amount of light penetrated into the building. Historically, this is done by use of curtains or horizontal and vertical sunshades, which are able to filter light and heat penetration partially and may have an undesired influence on building appearance. In recent years, the use of transformable structures in building skins has brought a new language into architecture which integrates art, architecture, science, and engineering (Fortmeyer and Linn, 2014). This paper proposes an innovative proposal for building facades by the implementation of transformable SLE. The structure consists of two types of SLE(s). One of them is a simple scissor structure, which transforms in one direction. This scissor is made of two linear elements in which the joint is placed in one-third of the length of each member. The second one is a modified SLE in which the joints allow the unit to move in three dimensions. In this SLE, each of the scissor elements is divided into two parts, which can individually rotate around the articulated joint without affecting the other elements. The rigid covering panels of the structure allow the structure to be folded during movement and transformation while covering the unit in fully deployed configuration. The panels are connected to the structure using two pivotal joints at the intersection of simple scissor and modified SLE and one hinged line joint at the main connection between the components of modified scissor-like element. The third joint allows the panels to resist the load of wind and prevent the lower parts of the panel from falling down. At the end, materials for components of the structure and covering were investigated and selected. The proposed transformable skin can be attached to a new or existing building and is not only able to control the environmental condition of the building, but it can also change the appearance of the building during a course of a day. The movements of the structure are controlled by a computer controlling system in which actuating motors are defined for the movement of the modules in a logic manner. This transformable skin can be used as the second layer of a glass building facade and its ability in being stable in different transformation stages can provide the building with a variety of aesthetically interactive configurations.

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## APPENDIX A

For presenting equations for the movement vector of each joint the following parameters are designed as follows (refer to section " Geometric Transformation Analysis"):

a: numerical value of each joint in folded position in x-axis.

a': numerical value of each joint in deployed position in x-axis.

b: numerical value of each joint in folded position in y-axis.

b': numerical value of each joint in deployed position in y-axis.

c: numerical value of each joint in folded position in z-axis.

c': numerical value of each joint in deployed position in z-axis (these parameters for joint number 3 are shown in fig 21&22).

t: numerical variable. $0 \le t \le 1$

Note: numerical value of a, b and c for each joint is different.

joint 1:Vector coordinate: (a'-a, 0 ,0) (1)

Vector equation: t=(x-a)/(a'-a)=(y-b)/0=(z-0)/0 , x=ta'-ta+a , y=b , z=0

Example: if t = 0, point position in coordinate axes: (a, b, 0)

If it = 1, point position in coordinating axes: (a', b, 0)

Joint 2: Vector coordinate: (0,0,c'-c) (2)

Vector equation: t=(x-0)/0=(y-b)/0=(z-c)/(c'-c) , x=0 , y=b , z=tc'-tc+c

Example: if t = 0 , point position in coordinate axes:(0 ,b , c)

if t = 1 , point position in coordinate axes:(0 ,b ,c')

Joint 3,4,5: Vector coordinate: (a'-a, b'-b, c'-c) (3)

Vector equation: t=(x-a)/(a'-a)=(y-b)/(b'-b)=(z-c)/(c'-c) , x=ta'-ta+a , y=tb'-tb+b ,

z=tc'-tc+c

Example: if t = 0, point position in coordinate axes: (a, b, c)

if t = 1 , point position in coordinate axes:(a' ,b',c')

Joint 6: Vector coordinate: (0,0,c'-c) (The center of the coordinate axis is considered at this joint )

Vector equation: t=(x-0)/0=(y-0)/0=(z-c)/(c'-c) , x=0 , y=0 , z=tc'-tc+c (4)

Example: if t = 0, point position in coordinate axes: (0 ,0, c)

if t = 1 , point position in coordinate axes:(0 ,0, c')