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PROPOSAL OF BIO-INSPIRED KINETIC MECHANISMS UTILIZATION FOR PROVIDING FUNCTIONAL FLEXIBILITY IN ARCHITECTURAL DESIGN

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Abstract

The fact that building design in architecture cannot respond to functional changes over time after the building is built is seen as one of the important problems today. Approaching this problem with kinetic design inputs will bring new possibilities to the design. In this context, biomimetic, which is an approach to use and simulate nature formations, will be a guide in problem solving. The aim of this study is to test the hypothesis of using bio-inspired kinetic mechanisms in order to offer solutions in case of changing capacity and different functional needs. For this purpose, an original design that can respond to such situations is proposed within the scope of the study. The proposed design is inspired by the movement mechanism of a spider's leg. The design has the potential to expand, contract and slide. These abilities make the design suitable for many different functions, from theater to gallery exhibition, from concert to fashion show. The use of bio-inspired kinetic mechanisms in architectural design seems to be an important development in terms of providing functional flexibility in architecture.

1. INTRODUCTION

With the development of technology, the cultures, lifestyles, needs and expectations of societies are changing rapidly. Architecture is also affected by these developments and changes. While permanence and time resistance are the most important design criteria in architecture in old times, the fact that the structure is changeable, and it can meet the changing needs are among the most sought-after features. In order to create spaces that can be adapted to different needs and change and transform according to the changes in the number of users, structures with motion feature are considered as solutions. In this case, approaching the design with kinetic design inputs offers new possibilities for solving problems.

Organisms, plants and animals in nature are constantly in motion to meet their needs such as nutrition, shelter, reproduction and protection throughout their lives. Nature offers a wide range of complex kinetic structures and fascinating mechanisms. In this context, "biomimetic", which is an approach to use and simulate nature formations, will help in the solution of the problems in the design within the concepts of functional flexibility and kinetic architecture.

In the study, the use of bio-inspired kinetic mechanisms, which provide internal and external constructive flexibility, was investigated in order to allow for function and capacity changes within the scope of functional flexibility in design. Examples of natural organisms that could change own form were investigated, and it was demonstrated through a proposed system that functional flexibility could be achieved by adapting the working principles of these examples to the building form and structure system. The designed system shows spaces that could be adapted with mobile building elements instead of fixed spaces as solutions to different functional requirements.

2. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

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2.1. Functional Flexibility

Users try to choose the options that suit their identities and personalities throughout their lives. They expect structures to be adapted to them. In fact, users expect functional and flexible designs where they can spend a comfortable and quality time [1]. Since most structures are designed and built in a way that significant changes are not allowed, it takes great effort to ensure the flexibility of the structure. However lifestyle change is no exception. For this reason, users demand different options. This demand brings up the concept of flexible architecture [2].

There are many discourses about the concept of flexible architecture in the literature. Especially after the 1950s, Gropius' mentioning that architects should design a flexible container for the flow of life, not a monument, was effective in the use of flexibility approaches in architecture. According to Colins (1965), flexibility is a kind of functionalism and allows designs to be customized for different configurations in a scenario determined by the architect. Similarly, Tapan (1972) considered flexibility as functionalism and interpreted the concept of flexibility as the use of the same spaces for different functions [3].

The concept of flexibility has brought along many concepts, inputs and subtitles over time. It was not enough to define flexibility only as the use of the same spaces for more than one function. Norberg-Schulz defines flexibility in two ways; the growth or contraction of the structure by adding or removing elements without losing the integrity of the structure and the ability of elements and relationships to be replaced with movable partitions [4]. Kronenburg (2004) supports these definitions and defines flexible architecture as an architecture that can adapt rather than be recession, respond to change rather than refuse change, and is more mobile rather than static [2].

According to Schneider and Till (2005); flexibility primarily envisages the diversity of units in an architectural arrangement, secondly, it includes the ability of units to be adaptable and changeable over time, and finally it enables buildings to adapt to new functions [5].

Robert Schmidt III and his colleagues at Adaptable Futures Research Group in Loughborough University (2010), interpret the flexibility, as the capacity of a building's context to effectively meet evolving demands and thus maximize its value throughout life [6]. Estaji (2017) also defines flexibility as the potential of a building to respond to expected demands, to adapt itself to this demand and to be rearranged [7].

Considering these comments, flexibility can be defined as structures that can adapt to changing user needs over time, adaptable to different functions, react to effects from external factors. Nowadays flexibility can be provided with such concepts that adaptation, modularity, growth, change, transformation and mobility. In the scope of the study focused on the concept of flexibility in terms of intervention in the building system. Therefore, the concept of flexibility in architectural design; It has been classified as internal constructive flexibility and external constructive flexibility.

Internal Constructive Flexibility (Spatial Combination / Decomposition)

Interior constructive flexibility is the type of flexibility performed with the internal structural elements to meet the changing needs during the use of the structure such as the size, number and space organization. Although there is no change in the outer shell of the structure and the carrier system, there is only interchangeability within the structure [8]. This idea can be seen in the unbuilt Total Theater structure designed by Gropius in 1926. The designer was asked to add transformability and flexibility to the design to remove the scene and increase the artist-audience interaction. In response to this request, Gropius has designed a theater where the game can be staged in the middle of the audience, in frame of the audience and in front of the audience, thanks to the mechanical movements of some areas in the interior. Although not built, this design contributed to the design of modern theater buildings [9,10].

Colani Rotor house, which was designed in 2005, can be given as an example of internal constructive flexibility in terms of flexibility. It aimed to provide maximum usage with its flexible solutions in a limited area. Bedroom, kitchen and bathroom spaces were designed in a rotating system (Figure 1). This ensures that the living space and the different spaces are linked in an optional way [11].

Figure 1. Colani Rotor house [12]

External Constructive Flexibility (Spatial Growth / Contraction)

It is a desired type of flexibility in case of changing needs such as number of users, functions during use of the structure. New spaces can be added next to the existing spaces, the external constructive of the building can move, the structure can grow or shrink. Noteworthy in this approach is the change in both the form and the size of the building [8].

This approach is seen in the Shed Bloomberg Building. Designed by Architect Diller Scofidio + Renfro and Rockwell Group, the Shed Bloomberg Building can also be an example of external constructive flexibility in terms of flexibility (Figure 2). Shed is a cultural place where users can do anything at will. The shifting of a part of the building system enables all kinds of different functions from theater to gallery exhibition, from concert to fashion show. The clearly rising movable walls allow the building to have 1250 people sit in the stadium or to be open to an audience of 3000 people [13].


Figure 2. Shed Bloomberg Building [14]

As seen from the examples, movement plays an important role in the concepts of internal and external constructive flexibility. For this reason, kinetic approaches in architectural design will enable functional flexibility.

2.2. Kinetic Architecture

In ancient times, only design criteria such as describe of functions, resistance to external conditions and permanence were considered. Today, these design criteria are insufficient due to the increasing and changing demands of modern society, developing technology and changing environmental factors. To meet these needs, it is necessary to design flexible and responsive structures. Since stationary spaces cannot respond to constantly changing needs, today architects are going to design the structures that can change, be adaptable and dynamic, and adapt to the environment and needs. This understanding is called kinetic architecture in architecture [8].

According to William Zuk and Roger H. Clark (1970), kinetic architecture has been defined as the architecture that can adapt to the changes in the set of forces that affect the structure consisting of many environmental data and the technology of the tool that can interpret and apply this data [15]. Similarly, Charles Eastman (1972) talked about the concept of kinetic architecture and suggested that architecture can be designed as a self-adaptive feedback system to suit user needs in a dynamic determination [16].

According to Fox (2002), structures or building elements with variable motion, position and geometry are defined as kinetic architecture [17]. Expected from kinetic systems is that they are physically variable therefore, instead of large structures with many functions, they can produce structures that can perform all of the functions with the motion of a component.

According to Sean C. Harry (2006), the use of kinetic systems in architecture is highly effective on the perception of space. Changing the perception of space is possible by changing the dimensions of the surfaces that make up the space [18].

According to all these definitions, kinetic architecture can be defined as architecture that can change and transform according to user needs or physical environmental conditions, and can also affect visually.

Michael A. Fox and Bryant Yeh categorized kinetic design into three general research areas; structural innovation and materials advancement, general kinetic typologies in architecture and control mechanisms.

In classification in terms of structural innovations and and materials advancement, it is mentioned that the structure should be handled as an important component of the responsive kinetic system, not singularly, to develop the systems. Structural solution has been considered along with ways and means. Among the ways of performing the kinetic structural solution, folding, sliding, expanding and transforming in both shape and size change can be shown. The means that realize the kinetic structural solution can be pneumatic, chemical, magnetic, natural and mechanical.

General kinetic typologies are examined in three sections according to their scale of motion (Figure 3):
1. Embedded kinetic structures: These are structures in which large components of a whole such as roof and facade have kinetic systems.
2. Deployable Kinetic Structures: These are structures that can be installed in temporary locations and easily transported.
3. Dynamic Kinetic Structures: They are structures that can move independently as a whole. These systems are mobile, convertible or can be modular systems.

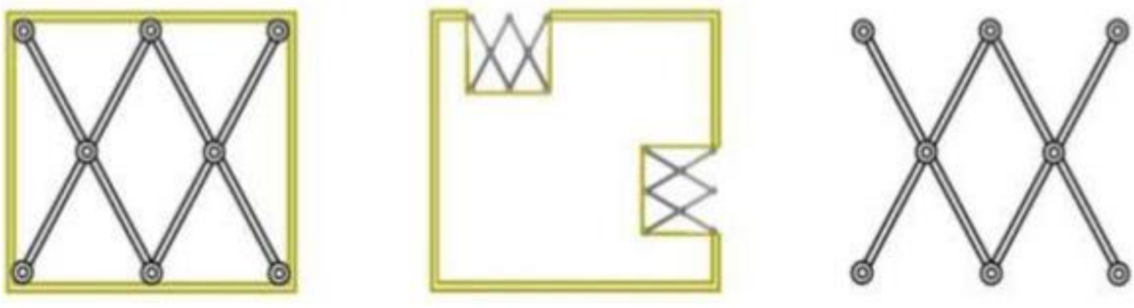

Figure 3. General kinetic typologies (embedded, deployable, dynamic) [19]

According to control mechanisms, they are divided into internal, direct, indirect, sensitive indirect, common sensitive indirect and experimental sensitive indirect systems. Movement can be provided with the help of different inputs and sensors in each system [19].
In line with all this information, in architectural design, the designers should focus on the necessity of building examples that can change over time, change from one function to another, change location or completely eliminate them and kinetic architecture for solution. Approaching the design with kinetic design

inputs offers new possibilities for solving problems. In doing so, it would be correct to see the nature as an inspiration because organisms, plants and animals in nature are constantly in motion to meet their needs such as nutrition, shelter, reproduction and protection throughout their lives. Examination and application of what is in nature will enable the solution of many problems in design.

2.3. Biomimesis

Biomimesis is the guide in solving problems with nature's biological ideas. In different disciplines, concepts such as bionics, biodesign, biomimicry, biomimesis are encountered. Although these concepts may seem different, they actually contain the same idea. Biomimesis, the nature-inspired design, means the imitation of biological processes, such as protein synthesis and photosynthesis, or biologically produced substances and materials, involved in enzymes and silk, to create solutions to different problems in different disciplines [20, 21].

The earliest example of biomimetic design dates back to the research on flying birds by Abbas İbnFirnas and later Leonardo da Vinci [22]. He applied the movement mechanism existing birds' wings in many flight instruments and roof systems. His works has shown that nature is the best teacher in human inventions [23].

Nature's abilities inspire new mechanisms, devices and robots. An example of this is the woodpecker's ability to blow the tree without harming his brain or the ability of many beings to fly, dig, swim, walk, jump, climb. It is possible to create miniature devices that have great maneuverability like a dragon, adhere to smooth and hard walls like a gecko, adapt to the texture like a chameleon, reconstruct their bodies to pass through narrow tubes like an octopus and reproduce themselves by using the resources in the environment [24].

As in different branches of science and design, biological data will create new paradigms in the field of architecture. It is possible to see the effect of biology on architecture in the produced architectural works since ancient times. As an architectural style, biomimicry remains only the analogy of the natural form, ignoring biological functions and what they learn from these functions. However, Michael Pawlyn wanted to integrate biomimicry into architecture by defining the functional foundations of biological forms, processes and systems in order to produce sustainable solutions [25]. According to Benyus and Koelman, biomimesis has three main application areas in architecture; the first is in the development of self-healing materials; secondly, in the use of natural processes for air conditioning buildings and the environment; the third is in the creation of the environment, which allows the reuse of waste, not by consuming resources, but by producing [26]. Also, the important features of biomimetic mechanisms are that they can function autonomously in complex environments, adapt to change and development, and perform multi-functional tasks.

Pedersen Zari divides the use of biomimicry as a design process into two; design looking to biology and biology influencing design. Design looking to biology; it is a method that investigate how this problem is solved in nature for the definition and solution of a design problem. The fact that the designers identify the problem and mimic the mechanical properties of a form or organism in nature explains this method. Biology influencing design; It is a method of applying the data obtained by examining certain features of an organism in design. In both approaches, there are three levels of mimicry that can be applied to a design problem; organism, behavior and ecosystem. The organism level involves mimicking some or all of the creatures in nature. The behavior level involves mimicking by examining how living beings in nature act in their environment. The ecosystem level is mimicry of the entire ecosystem. Different dimensions of nature are mimicked at each level: form (what the design looks like), material (what the design is made out of), construction (how the design is made), process (how the design works), and function (what the design is able to do) [27].

On the other hand, according to Badarnah, who defines the term biomimetic as reaching a solution by emulating strategies, mechanisms and principles found in nature, the biomimetic design process requires interdisciplinary interaction and it involves of three domains: problem, nature and solution. The design process follows these steps; identify of the problem, explore natural systems, analysis of principles, abstraction, adaptation to a design concept, apply to solve a problem [28].

Nature contains many examples of responsive and kinetic structure. Those structures can be grouped as planar structures compliant tubes, stiff rods and tubes and tensegrity three-dimensional structures [29].

One of the interesting structures made from planar structures is the roof system of the Qizhong Stadium. It is inspired by Peony, the national flower of China (Figure 4). The top cover of the stadium is composed of eight movable metal plates with a leaf appearance. When these plates are closed, the hot air rising upwards is blown back into the stadium. When these metal sheets are opened, the cool air outside is taken inside in a controlled way. This shows that the principle that the flowers move the petals according to the sun and wind is imitated (Figure 5) [30].

Figure 4. Peony – the roof system of Quizhong Stadium

Figure 5. Quizhong Stadium [23]

Other example in this field is the transformable roof system of Starlight Theatre in America. It is inspired from potato's flower structure (Figure 6). The main convertible element is the roof, a hybrid pyramid consisting of six identical triangular panels hinged along the bottom edge [23]. Customers wanted their shows to continue, regardless of the weather. For this reason, the designers have designed a building that allows the college to continue its normal summer performance and activity programs (Figure 7) [2].

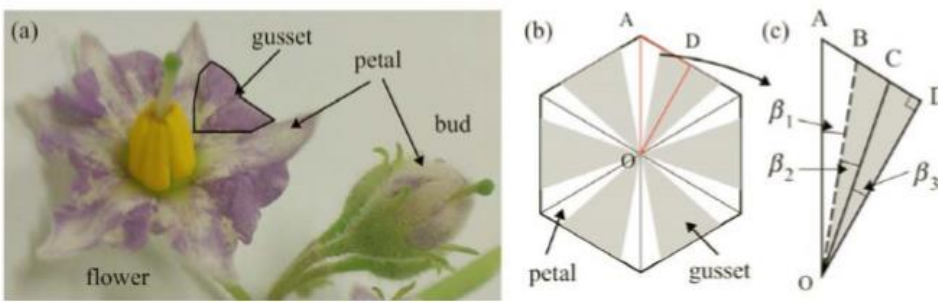

Figure 6. The structure of a Potato's flower [23]

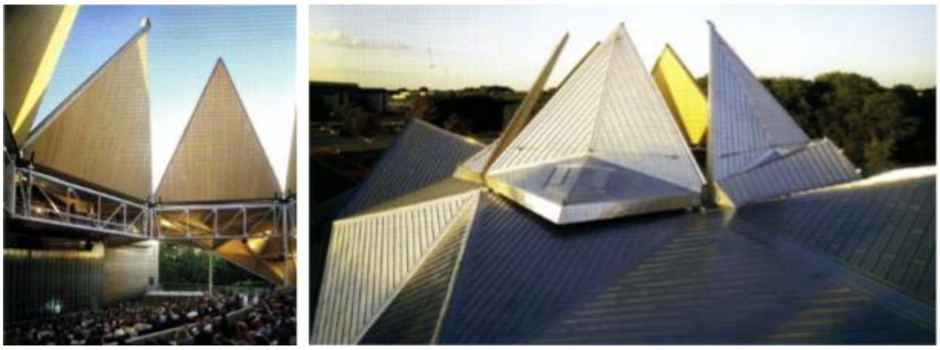

Figure 7. Starlight theatre [23]

One of the examples can be given to stiff rod and tube structure is Renzo Piano's IBM Ladybird Travelling Pavilion (Figure 8). Its structural mechanism was inspired by spider's leg's form and sketlon of bat's wing. Although this project was not constructed, it shows the potential of biological structures to be employed in responsive kinetic building [31].

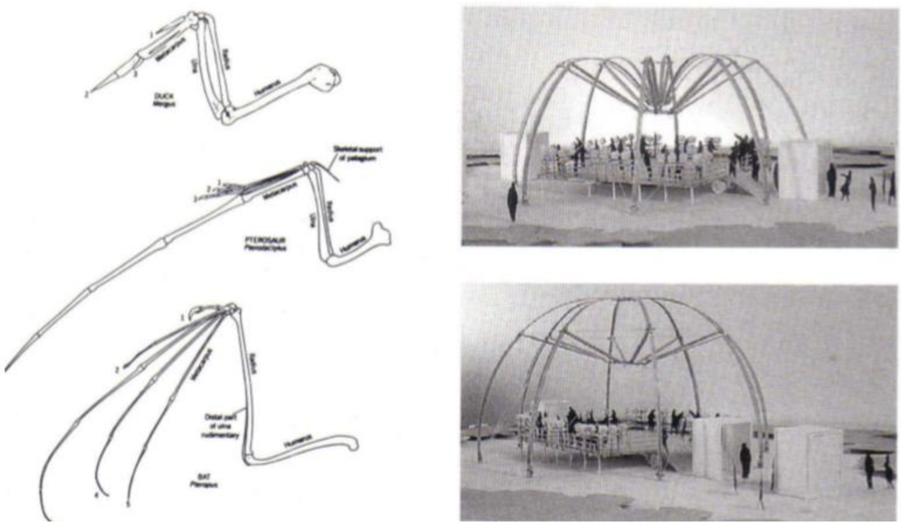

Figure 8. Ladybird Travelling Pavilion [23]

Other example is the Kuwait Pavilion which designed by Calatrava for the 1992 World's Fair in Seville. The design is inspired by the movement of the human hand (Figure 9). The building consists of a closed exhibition area and a square covered with a movable roof. Fingers interlock when they are closed, and when they are opened, their fingertips rise to the sky and the square appears [32].

Figure 9. Kuwait Pavilion

In addition to the Milwaukee Art Museum, Calatrava has designed a structure called BurkeBriseSoleil to prevent the sun on the Quadracci Pavilion. This structure is mobile and draws attention with its bird-like form (Figure 10). It closes a 65-meter span with its wing-skeleton structure and opens and closes like the movement of a bird against the wind. Calatrava developed his design in this form, inspired by the bird form [25]. Thanks to the wings that move according to the opening and closing of the museum, a distant person can understand whether the museum is open or closed. If there is an activity in the museum at night, the wings can be opened and the people around can be informed [33].

Figure 10. Milwaukee Art Museum [34]

All these examples show the potential of nature for design and construction of responsive and kinetic structures. Within the scope of the study, a responsive and flexible design inspired by nature was proposed.

3. METHOD OF THE STUDY

In the study, the "design looking to biology" method by Petersen Zari was used as the design process. The design process was carried out as follows:

1. Description: Description of the problem
2. Discovering: Definition of the role model and movement
3. Abstraction
4. Imitation: Transfer to architecture.

3.1. Description of the problem

This study investigates flexibility expectation in architectural design should be provided with kinetic-biomimetic mechanisms. The aim of the study is to test the hypothesis of "use of kinetic-biomimetic mechanisms to provide solutions and serve different functions if the capacity of the design changes". The problem of functional flexibility in architectural design is approached with kinetic design inputs and nature is taken as reference for the solution. For this purpose, an auditorium was chosen as venues serving different functions such as conference halls, cultural centers, theater and concert areas [21].

3.2. Definition of Role Model and Movement

While scanning for inspiration, a spider's leg opening and closing system, slope and volume setup are noteworthy among the role models. Due to the anatomical structure of the spider, the angle on its legs provides more stable and firm pressing. In addition, as the mechanical working principle, the opening and closing movement of the feet will allow functional flexibility in the auditorium design [21].

Spiders are arthropods, which means articulating. Their bodies, consist of two parts, the abdomen (3) and the cephalothorax (2) to which the legs are attached. Like all arthropods, they do not have bones and internal skeletons, that is, they do not have the muscles that vertebrates have. Instead, they have a hard exoskeleton (Figure 11).

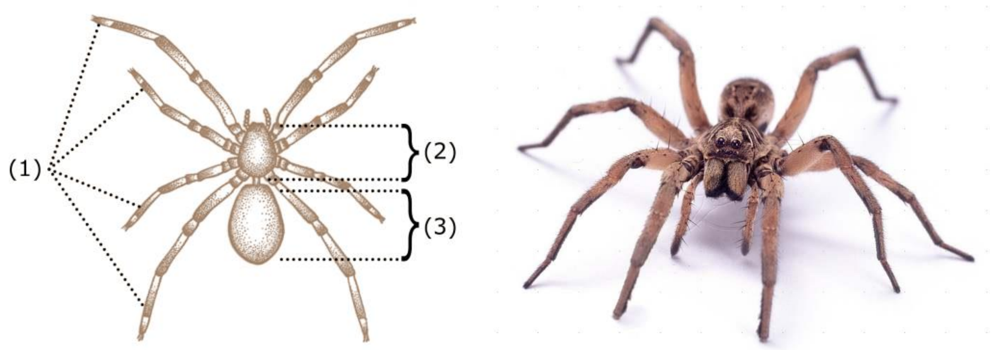

Figure 11. Spider body, fused head and thorax, cephalothorax (2), abdomen (3) and eight legs (1)

There are three types of muscles in the body of the vertebrates: heart muscle, muscle of internal organs and skeletal muscles. Bones are moved by muscles called flexors and extensors. Flexor muscles are bending and extensors are stretching-stretching muscles. Spiders have four pairs of legs and have seven joints for each leg. Due to this structure, there are no extensor muscles. It is the hydraulic pressure that provides the movement of spiders. They can use hydraulics that are very fine-tuned, acting like a fluid-filled bellows for the outward movement of their legs. The outward movement of each leg is regulated by the cephalothorax, which regulates hydraulic pressure. Cephalothorax can push hemolymphia in the spider's body in one second. Spider legs are puckered, but hydraulic pressure enables the legs to move outward and resist this shrinkage movement (Figure 12) [35].

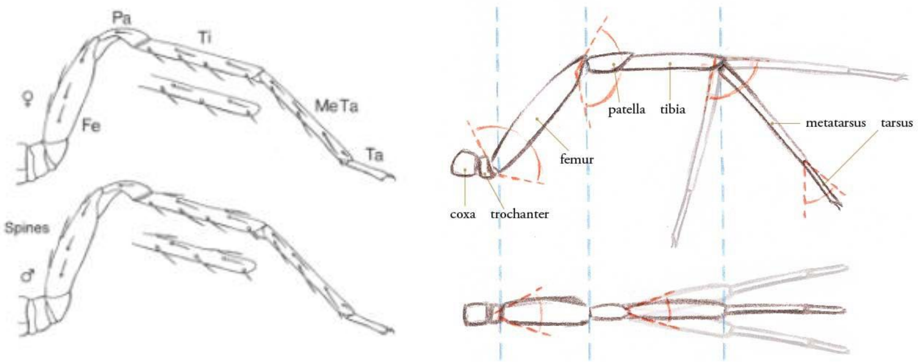

Figure 12. Spider's leg - spider leg motion area [36]

3.3. Abstracted Bio-İnspiration Mechanism

In order to create the inspiration mechanism, how to imitate the spider's movement was thought. In a study with the students at the Smithsonian Environmental Research Center, a mock-up was made by using syringes, water, bars, and an aquarium hose to explain this movement system. The syringe attached to the system was filled with a liquid and operated like a blower, so that the system could move. This system shows how the spider mechanism and the hydraulic system works in a simple way [35].

There are many examples like this for the robotic arm. However, this system does not have an example used in building design. For this reason, a digital model has been created in the study to test the relationship between the form and function of the abstracted biological inspiration mechanism. The obtained model shows the system closed and open. In addition, the model includes the hydraulic system, wheel and rail system which are necessary to achieve this movement (Figure 13). Horizontally and vertically, bar carriers are connected by a shaft. Hydraulic pistons are placed between the carriers to move integratedly and open the system. The closed model is opened by moving on the rails with the activation of the hydraulic system [21].

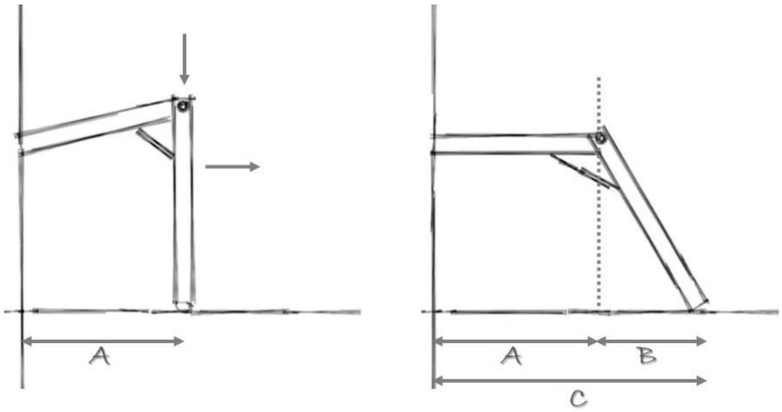

Figure 13. Abstracted movement mechanism (closed - open) [21]

3.4. Transfer to Architecture

In this section, the aim is to test the hypothesis of the use of kinetic-biomimetic mechanisms in the design of the auditorium, in order to provide solutions in case the design changes capacity and to serve different functions. It has been considered whether the abstracted kinetic-biomimetic mechanism may actually have practical use. Alternatives are presented to explain how the model can serve different functions in the auditorium design and how it can adapt to the number of users.

In line with this information, while the abstracted kinetic-biomimetic mechanism is transferred to the architecture, a hexagonal plan scheme is thought to be suitable for the auditorium. This scheme includes 6 bar structures, spreading from a central point, like a spider's foot. With the movement of these feet, it is possible to switch between various needs. The design has a variable scene that can be adjusted with manual and electromechanical systems and kinetic seating areas that can be opened and closed synchronously with the movement of the carrier system on the rails. In this way, the shape, size and relationship of the show area with the audience can be adjusted (Figure 14). In order to open and close the grandstands, the intertwined telescopic systems are used as integrated to the sliding system. Thanks to the sensors following the wall movement, the engine of the stands is activated, and the stands can be opened and closed [21].

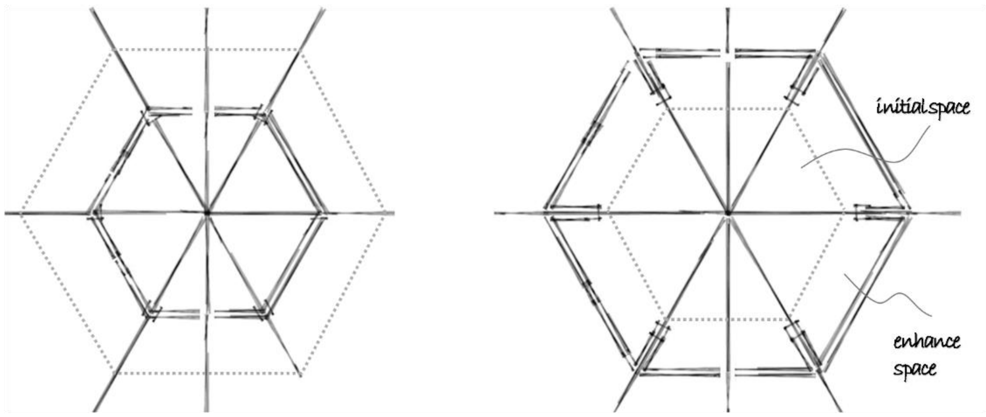

Figure 14. Plan scheme of the suggestion system in the auditorium design (closed - open) [21]

The kinetic system used for the movement mechanism in the proposed system is out of shell; expands-narrows and sliding systems are selected. The reason for this choice is that the spreading system of the spider's feet is similar to the movement structure obtained by the widening-narrowing systems. These systems and movement mechanism serve fewer participants when closed, and more when opened. Thus, the model can adapt to the change of the number of users. In cases where there is no user, unnecessary volumes and areas are not desired to be heated, the cost of heating can be reduced as the system can shrink (Figure 15-16) [21].

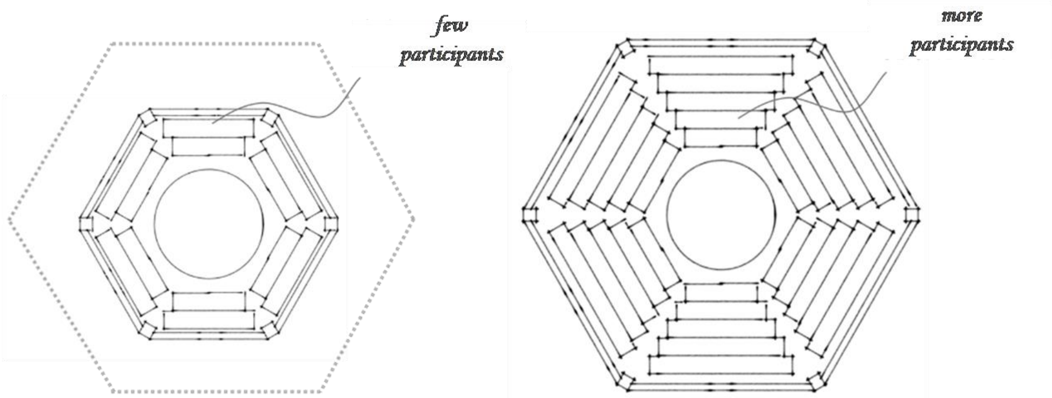

Figure 15. Capacity change plan scheme in auditorium design (closed-open) [21]

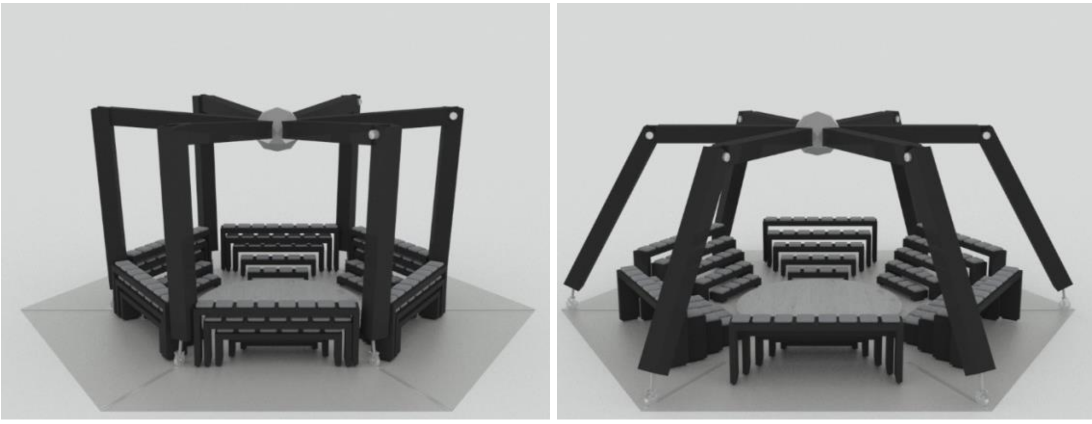

Figure 16. Capacity change in auditorium design [21]

This system allows a building used as a rehearsal room when it is closed to be a structure used for all kinds of different functions, from theater to gallery exhibition, from concert to fashion show, this enables functional flexibility (Figure 17-18) [21].

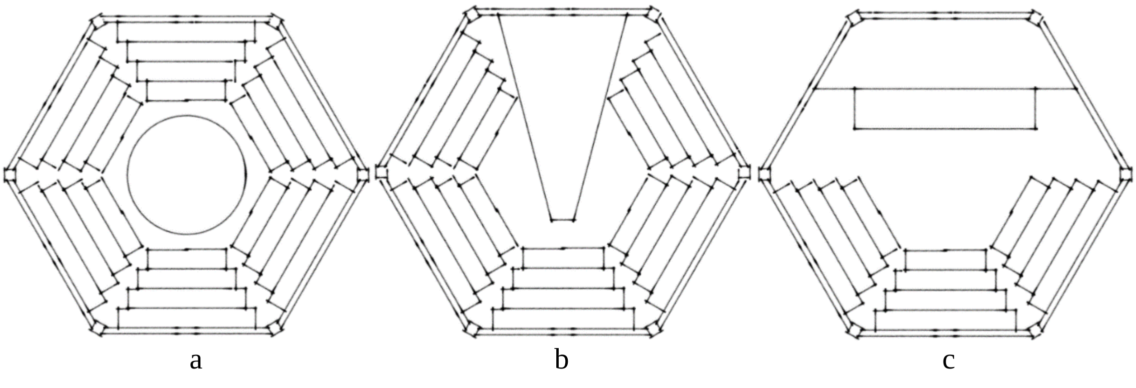

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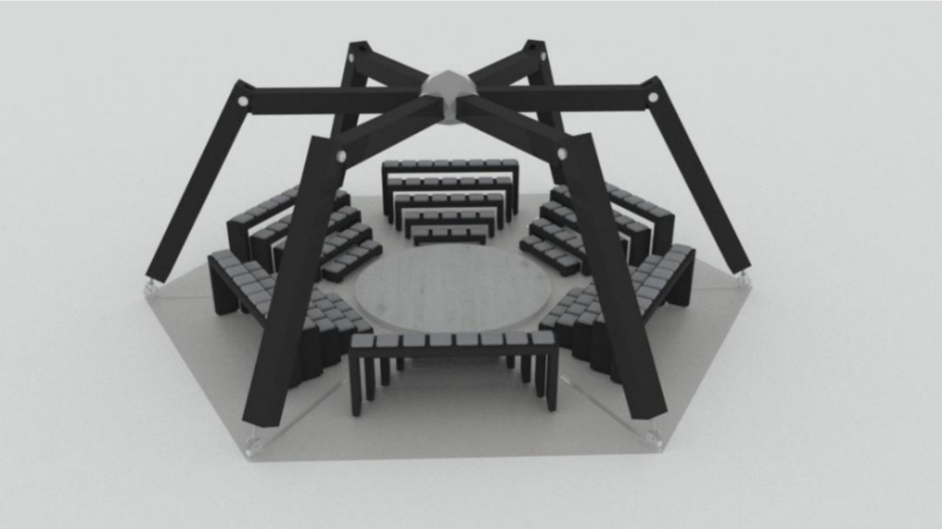
Figure 17. Plan schemes for the formation of different functions in the auditorium design a. theater area b. fashion show c. auditorium [21]



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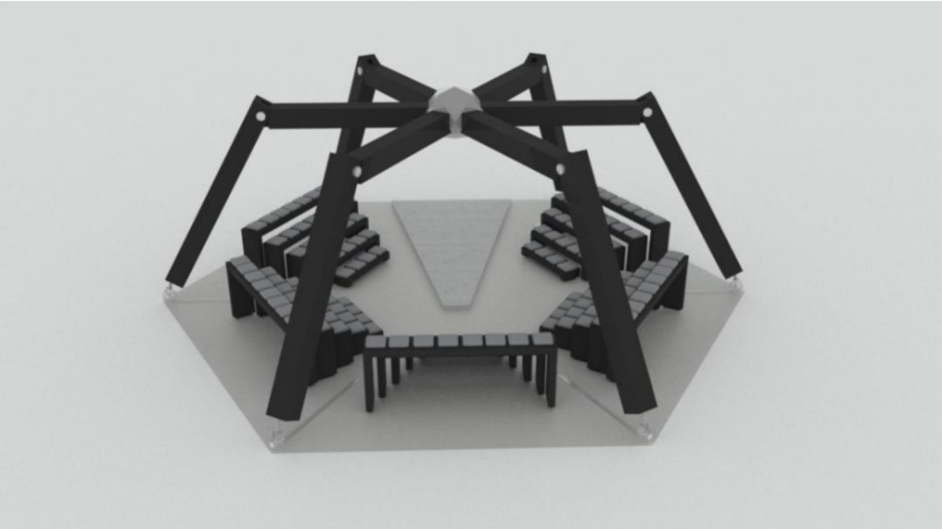

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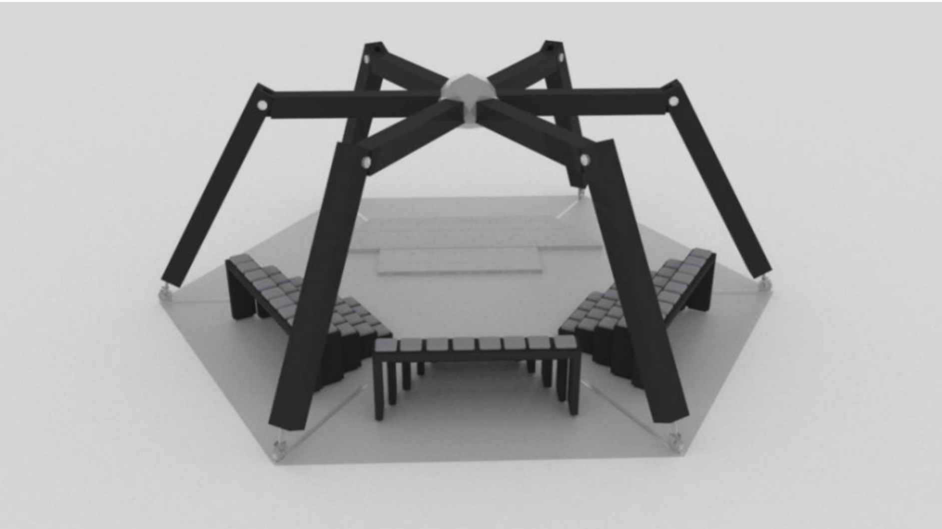

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Figure 18. Formation of functions in auditorium design (a. theater area, b. fashion show, c. conference hall) [21]

4. RESULTS

The aim of the study was to meet the expectation of flexibility in the capacity of the auditoriums. For this purpose, a biomimetic process has been followed. According to Zari's biomimetic design process classification, "design looking at biology" is effective in solving the problem and developing the proposed system. In addition, nature is used at the organism level in the proposed system. The opening and closing of spider feet affected the form, structure and process of design.

From the classification that M.I.T. Kinetic Design Group made in line with its researches, "installable kinetic structures" is effective in transferring the role model to architecture. The working principle of the design is the system called the “direct control system”. In this system, motion is carried out by any of the numerous energy sources, including electric motors that can respond to environmental conditions, human energy and biomechanical changes. In this design, the operation of hydraulic systems is realized by direct motor control thanks to a sliding movement.

In the proposed system, it is possible to create a completely closed structure by using flexible or movable materials between the bars. As the coating material, there are many different alternatives from flexible materials such as fabric, membrane etc. to movable panels. Flexible cover materials can be folded in various ways with the help of cables and rollers. Moving the plane and curved panels by sliding them, is prevent deformation during the movement of the system.

In summary, as the original solution, the opening and closing movement of the spider's feet allowed for "external constructive flexibility". It has been seen that new spaces combinations can be obtained if the carriers slide on rails. In this system, movable building elements enable function and capacity changes with three different spatial variations.

With this study, it is thought that analyzing the motion principles of forms in nature can inspire architects and engineers in the use and implementation of new strategies in the context of functional flexibility in architectural design. It will also combine the basic building blocks between different disciplines such as architecture, engineering and biology. Thus, it will open the door to the design of more complex and more flexible systems.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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