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A Critical Review and Novel Classification Proposal for Kinetic Roof Structures

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Abstract

Kinetic structures have gained popularity in architecture and structural engineering due to their ability to meet environmental factors and user needs. Among these structures, kinetic roof structures hold an important place, as they are deployable and/or transformable structures that can change their forms between two or more different geometries. Various categorizations of kinetic roofs based on their material, mechanism, and geometry have been offered in the literature. However, in most studies, they are placed under the broader category of kinetic structures. This paper critically reviews existing classifications of kinetic roofs, highlighting their advantages and limitations. Subsequently, a novel detailed classification system for kinetic roof structures is proposed. The superiority, advantages, and shortcomings of this proposed classification are presented. A more comprehensive and tailored classification system for kinetic roofs is provided by this study, contributing to the literature in this area.

Keywords: *Kinetic architecture, kinetic roofs, movable roofs, deployable structures, adaptive architecture.*

Kinetik Çatı Strüktürleri için Eleştirel bir İnceleme ve Yeni Sınıflandırma Önerisi

Öz

Kinetik strüktürler, çevresel faktörleri ve kullanıcı ihtiyaçlarını karşılama yetenekleri nedeniyle, son yıllarda hem mimarlık, hem de inşaat mühendisliği alanlarında oldukça popüler hale gelmiştir. Kinetik çatılar ise, kinetik strüktürlerin bir alt kolu olarak, değişken geometriye sahip olabilmeleri, büyüyüp küçülebilmeleri ve açılıp kapanabilmeleri sebebiyle önemli bir yer tutmaktadır. Literatürde, kinetik çatıları malzeme, mekanizma ve geometrilerine göre ayıran çeşitli sınıflandırmalar bulunmaktadır. Ancak bu sınıflandırmaların çoğunda kinetik çatılar, daha üst bir çerçeve olan kinetik strüktürlerin bir alt kolu olarak ele alınmıştır. Bu çalışmada, öncelikle var olan kinetik çatı sınıflandırmaları eleştirel bir şekilde incelenerek, avantajları ve eksikleri ortaya konmuştur. Ardından, kinetik çatı strüktürleri için literatürde olmayan, yeni ve ayrıntılı bir sınıflandırma sistemi önerilmiştir. Daha sonra, önerilen sınıflandırmanın avantajları ve dezavantajları ortaya konmuştur. Bu çalışma, kinetik çatılar için daha kapsamlı ve özelleştirilmiş bir sınıflandırma sistemi sunarak, literatüre katkıda bulunmaktadır.

Anahtar kelimeler: *Kinetik mimarlık, kinetik çatılar, hareketli çatılar, yayılabilen strüktürler, adaptif mimarlık.*

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1. Introduction

Throughout architectural history, humans have endeavored to design and construct structures that can adapt to changing climatic/ functional conditions and meet visual/ aesthetic demands. In response to these demands, the concept of kinetic architecture has emerged (Megahed, 2016). Although there have been examples of kinetic architecture throughout history, it has become increasingly popular in recent years due to advances in computational design methods, mechanical and construction technologies, and developments in materials science. Additionally, the design and implementation of kinetic architectural structures require interdisciplinary cooperation between architecture, structural design, and mechatronics. This is because the structure must be both static and dynamically stable, and may require electronic control, making it more difficult to incorporate kinetic applications in structures compared to conventional stationary structures (Fouad, 2012; Megahed, 2016). The proliferation of these structures has been accelerated by the increasing diversity of design facilitated by parametric design and the ease of construction utilizing different smart materials and systems. These structures have numerous advantages over conventional stationary structures, including the ability to accommodate changing user demands, adjust lighting and ventilation, diversify the function of the space used, provide architectural aesthetics, and reduce aerodynamic loads (Phocas et al., 2020). In kinetic structures, one or more elements of the structure can be movable. Today, mostly facade and roof systems are used as movable elements while making kinetic designs. For example, kinetic facade systems can be designed to provide conditions such as thermal comfort, energy performance of the building, and user comfort (Yaman & Arpacıoğlu, 2021).

Two fundamental concepts for kinetic architecture research are deployable and transformable structures. While these two concepts have similarities and can be easily confused, there are minor but important differences between them. Deployable structures are structures that can transform from contracted to deployed positions and grow in size. They have two predefined positions and shape changes occur between these two forms. Transformable structures are also changeable and movable, but they are not necessarily deployable (Maden et al., 2019). Kinetic roofs are roof structures that can be deployable and/or transformable, changing between two or more geometries depending on their features. These features may differ depending on the system used. While some examples in the literature can carry loads in motion, others can only support loads in their stationary positions when opened or closed (Ishii, 2000). Kinetic roofs can be traced back to the Roman Colosseum. As technology in mechanisms and materials has advanced, the diversity of kinetic roof designs throughout history has also increased. Kinetic roofs allow the building or the space to be used differently for different purposes. These kinds of kinetic systems are generally designed to protect buildings, spaces, and/or users from external factors such as sun and rain. They also can be used to create indoor or outdoor areas in the building and/or space (Ishii, 2000). In the literature, many examples of kinetic roof structures can be found under the kinetic roof name or else (e. g. movable, convertible, deployable, transformable, retractable). When the examples of kinetic roof structures in the literature are examined, it is noticed that the design of these structures is diversified by considering many different features. These features are the main system/mechanism used, the auxiliary system/ mechanism that plays a role in the operation of the system, the materials used in these mechanisms/ systems, the working principle of the installed system or mechanism, the positions/directions of the designed kinetic roof structure during deployment/transformation.

Considering the studies published by different researchers in the literature, kinetic roof structures are categorized according to their properties. Categorizations were made by looking at different features such as the mechanism, system, material, geometry, and direction used. Although many features are considered, these classifications in the literature do not cover all kinetic roof structures. The aim of this study is to fill this gap in the literature by presenting a novel classification of kinetic roof structures.

2. Materials and Method

In addition to the use of many different methods in this study, the main method is a systematic literature review. Before the presentation of the novel classification of kinetic roof structures, which is the aim of this study, a series of stages were performed. These stages are data collection, data analysis, analyses of the existing classifications, and definition of the gaps in the existing classifications. The methodology of the study is presented in Figure 1.

In the first part of the study, a systematic literature review is presented, these classifications are general classifications of kinetic structures. This literature review was done chronologically and helped to understand the evolution of classifications over time. During this systematic literature review, the keywords 'kinetic', 'adaptive', 'deployable', 'transformable', and 'movable' were used. This literature review has played a major role in understanding the approaches and methods used in the classifications of kinetic structures.

In the next step of the study, the classifications presented chronologically were analyzed sequentially. The methods and categorization methods used in these classifications are examined. As a result of this review and analysis, the deficiencies, limitations and shortcomings of the existing classifications were identified. By examining the examples of kinetic roofs with different materials, mechanisms, systems and geometric principles presented in the literature, the strengths and weaknesses of the current classifications have been gained.

After the examination and analysis of the existing classifications, the next step was to complete the shortcomings of the existing kinetic roof structure classifications. This includes making up for the lack of definition of kinetic roof structures in existing classifications. The variety of kinetic roofs has not been adequately defined in existing classifications. By identifying these gaps in existing studies, the study makes a more comprehensive proposal for understanding and classifying kinetic roofs. For this purpose, it aims to contribute to the relevant field in literature by proposing a more comprehensive and novel innovative classification system.

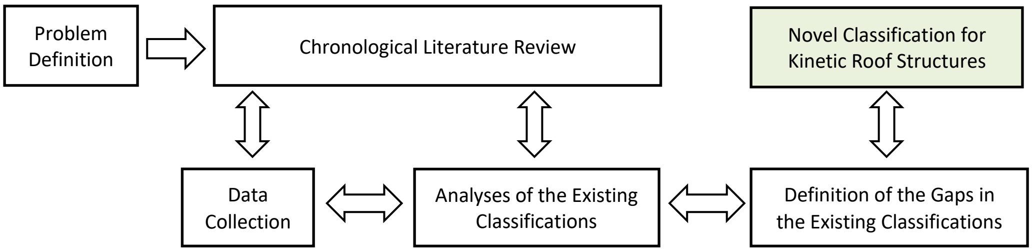

Figure 1. Methodology of the research

3. Findings and Discussion

3.1. Kinetic Structures Classifications in the Literature

In the field of architecture, the design and use of kinetic structures have increased considerably in the last century. With this increase, the interest in categorizing kinetic structures has also increased. In this part of the study, classifications of kinetic structures are given. The classifications are presented chronologically and observations on their classification approaches are presented.

One of the first attempts at classification was made by Merchan (1987). In his classification, he presented a system that divided kinetic structures into two main categories based on the geometry of their main elements, such as struts and surface structures. He then created subgroups based on the type of movement the structure exhibited, such as sliding, folding, and rotating.

Hinged systems were placed in the rotating category since they can only rotate. However, Merchan's classification did not take into account the function of the kinetic structure, such as whether it serves as a roof, wall, or furniture (Figure 2).

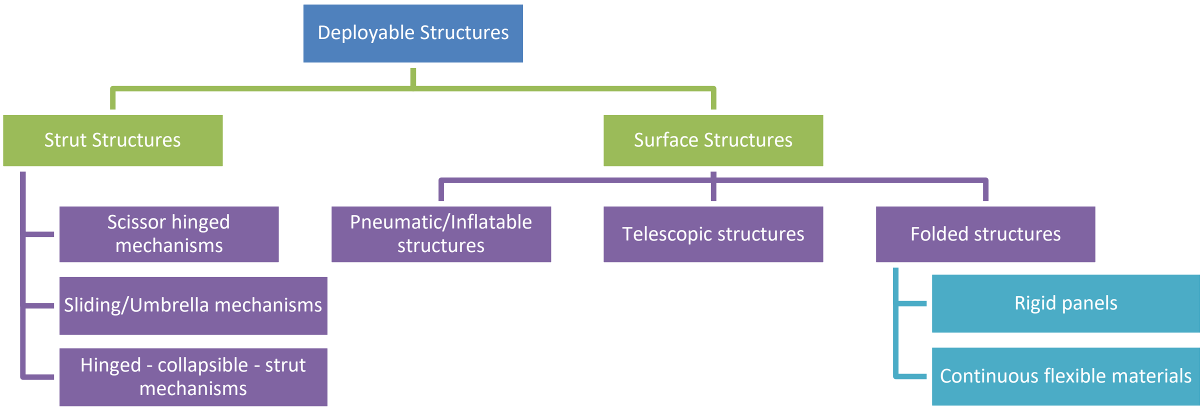

Figure 2. Classification (Merchan, 1987)

Gantes (1991) made another classification attempt, which focused on deployable structures. Gantes divided these structures into subcategories, as illustrated in Figure 3. However, upon a closer examination of the classification system, it becomes apparent that the distinction between the subgroups is not very clear. Gantes' classification system divides deployable structures into two initial subgroups based on their application area: earth-based structures and structures for space applications. Within the earth-based structures subgroup, the structures are further divided into subgroups based on their structural types, with the exception of retractable roofs. On the other hand, there is no corresponding subgroup created for structures designed for space applications.

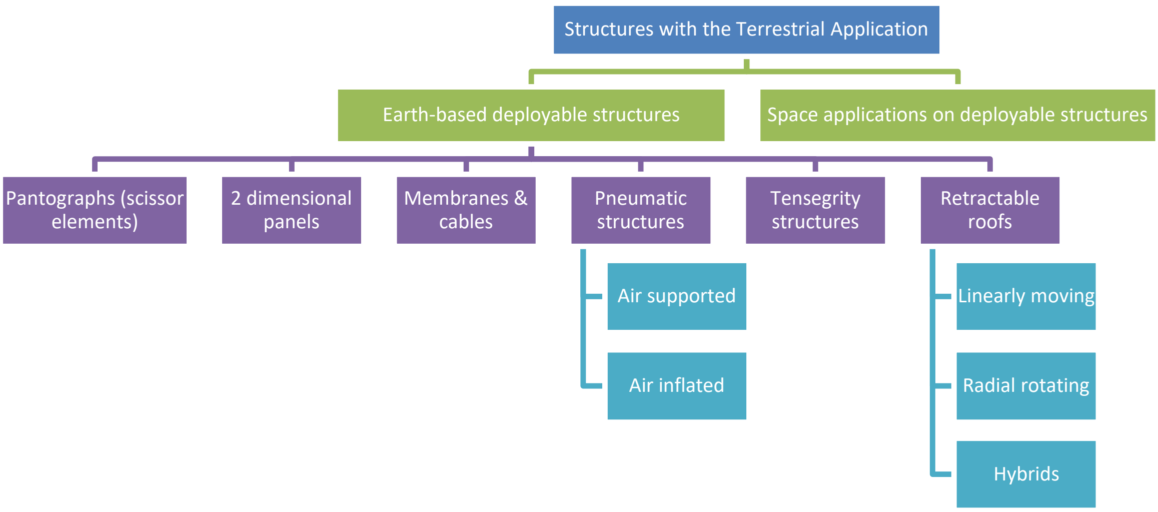

Figure 3. Classification (Gantes, 1991)

Félix Escrig is a notable researcher who has developed classifications for kinetic structures, as documented in his work published in 1996 (Escrig, 1996). However, upon closer examination, it becomes evident that Escrig's classification system has certain shortcomings, including the lack of clear distinction between the concepts of deployable and transformable structures across categories. Escrig's classification system includes eight categories based on the functions of kinetic structures, namely tensile foldable structures, foldable structures, retractable roofs, umbrella structures, mobile structures, tensegrity, and lifting structures, as depicted in Figure 4.

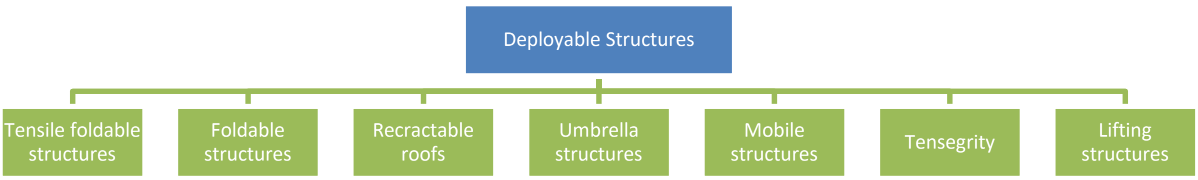

Figure 4. Classification (Escrig, 1996)

In contrast to Gantes, who based his classification on the application area, Pellegrino, a mechanical engineer, categorized deployable structures according to their mechanism and motion typology. In his work, Pellegrino introduced a classification system that divided deployable structures into seven categories based on their kinetic motions and mechanisms (Figure 5) (Pellegrino, 2001). These categories include coiled rods, flexible shells, membrane structures, structural mechanisms, tension truss antennae, rigid panels, and retractable domes. Further, the structural mechanisms category in Pellegrino's classification is divided into three subcategories based on the mechanism types. This classification system offers a more specific and detailed approach to categorizing deployable structures based on their mechanical components and functionality.

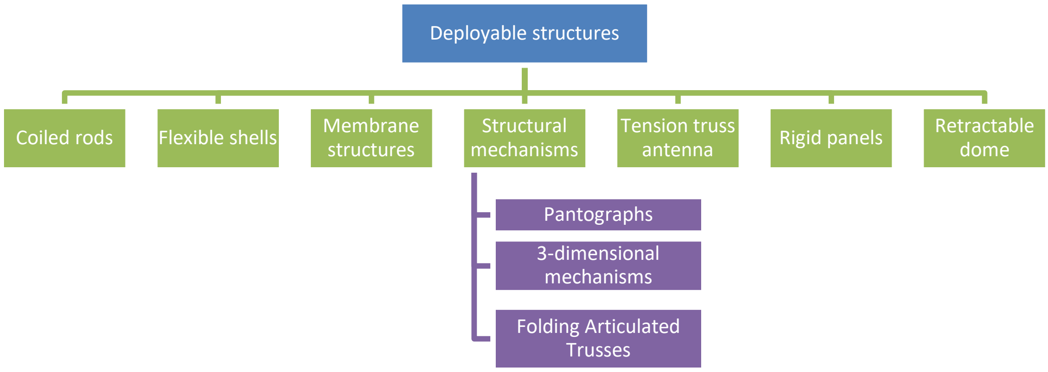

Figure 5. Deployable structures classification (Pellegrino, 2001)

In 2001, Hanaor & Levy (2001) collaborated to produce a new classification of deployable structures (Figure 6). In this classification, Hanaour and Levy mainly dealt with the geometry of the unit elements creating the deployable structures. In the figure, columns represent the morphological aspects and rows represent the kinematic features. Application types are not considered as a criterion for this classification. Both morphological characteristics and kinematic features fall into two main subcategories.

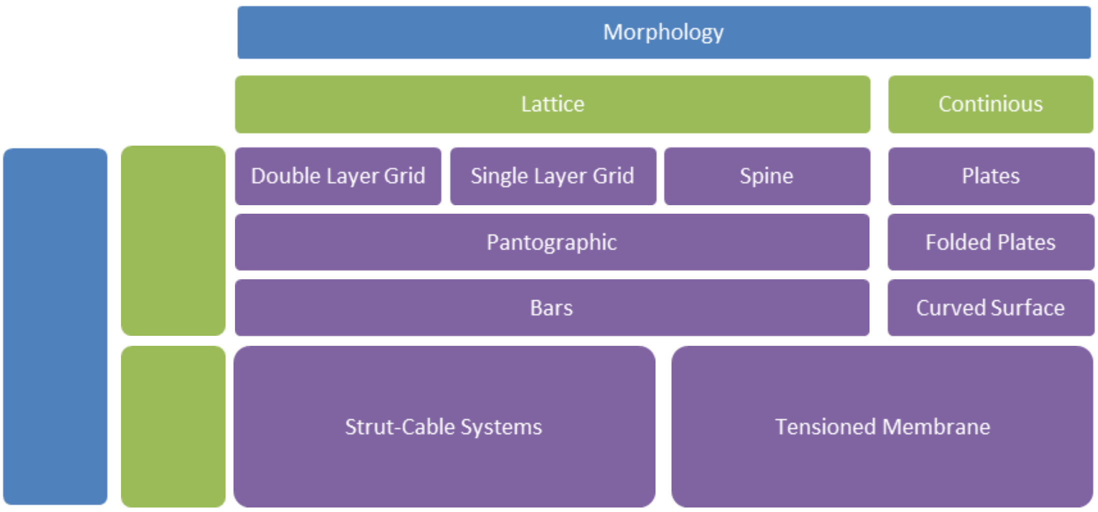

Figure 6. Morphological classification (Hanaour & Levy, 2001)

Koray Korkmaz, a researcher from the Izmir Institute of Technology, developed a classification for kinetic architecture, as seen in Figure 7 (Korkmaz, 2004). This classification system is a comprehensive framework that encompasses all kinds of kinetic architectural products, taking into account various factors such as the variability of geometry and movement, location, form, structure, and material. Korkmaz's classification effectively distinguishes between mobile structures and deployable structures, achieved by dividing the first subgroups into two categories: buildings with variable geometry and movements, and buildings with variable locations or mobilities. Korkmaz's classification is similar to the one proposed by Hanaour & Levy (2001), as they both classify structures based on the distinction between "soft form and rigid form." Korkmaz's classification system also includes a further division of buildings with variable locations or mobilities into three categories based on their functions.

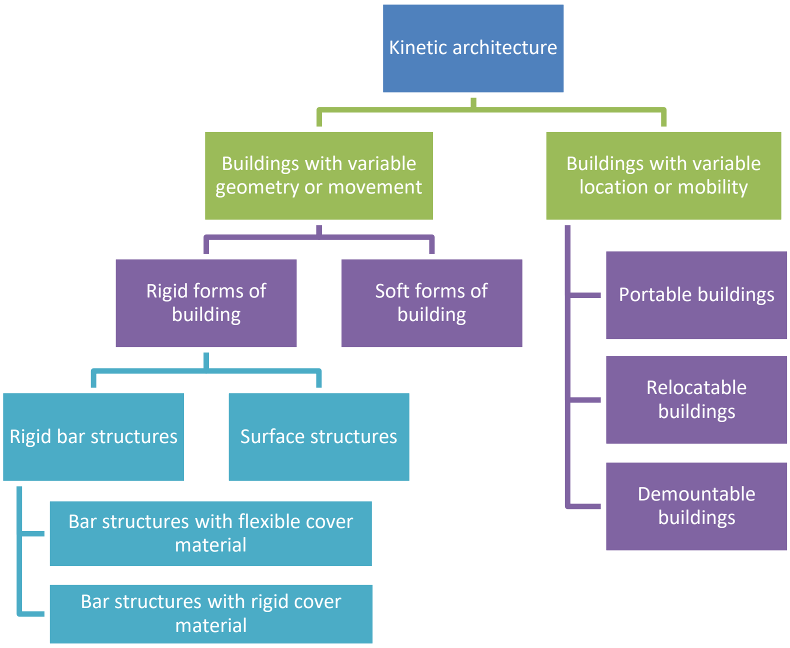

Figure 7. Kinetic architecture classification (Korkmaz, 2004)

In his study, Temmerman (2007) classified deployable structures by considering their structural systems. Temmerman's classification method can be schematized into four groups: spatial bars, foldable plates, membrane structures, and tensegrity systems as seen in Figure 8.

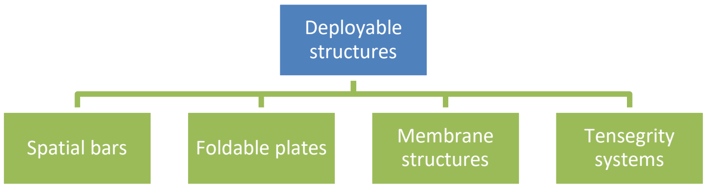

Figure 8. Deployable structures classification (Temmerman, 2007)

In Figure 9, Schumacher et al. (2010) have presented their classification of deployable structures based on the materials they are made of. They have distinguished between two categories: rigid and deformable materials. Rigid materials are further divided based on the type of movement they allow, either rotational, translational, or a combination of both. In contrast, deformable materials are classified based on the properties of the material, either flexible or elastic.

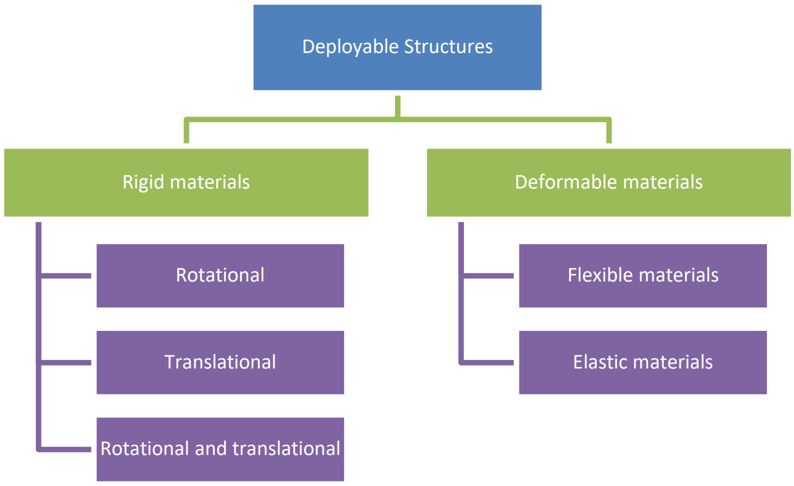

Figure 9. Classification (Schumacher et al., 2010)

In his publication, Asefi (2010) classified transformable structures, one of the subcategories of kinetic architecture. It is seen that more than one classification method is used in this classification. A three-level classification was created by considering material, function, structural type, and geometry as can be seen in Figure 10.

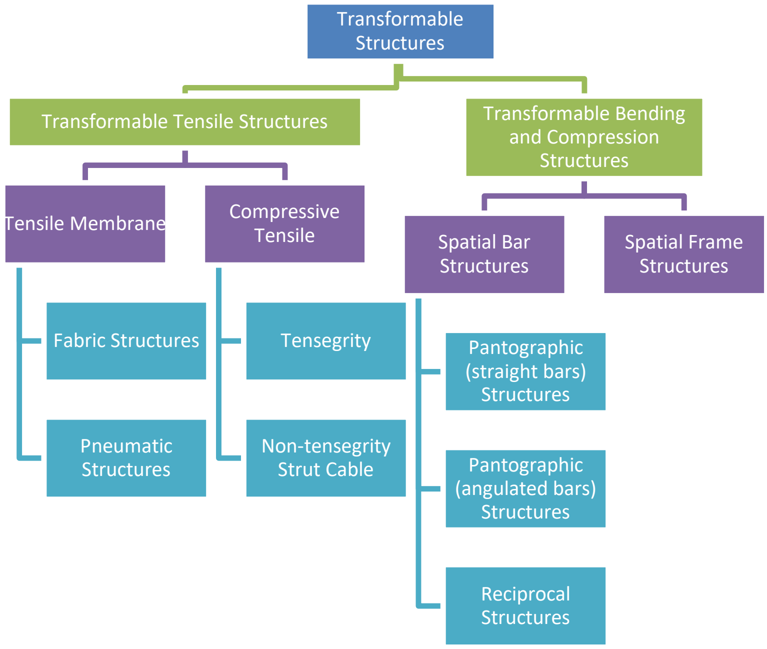

Figure 10. Classification (Asefi, 2010)

Stevenson proposed his classification in 2011, as seen in Figure 11. The physical transformations, which are position, size or shape change, position in space, and direction of transformation, constitute the main factors in Stevenson's classification. The disadvantage of Stevenson's study is that it is difficult for pneumatic mechanisms to find their place in this classification (Stevenson, 2011). The system to be classified in Stevenson's classification can be placed at an intersection in the categories of physical transformation and position in space and direction of transformation. For example, Stevenson listed the movements that provide physical transformation as the change in shape, change in size and change in position. The subcategories of the position in space and direction of transformation category are listed according to both their 2D and 3D properties and whether their patterns are centric or linear. Although shown in the table, a more flexible placement can be made in Stevenson's original classification.

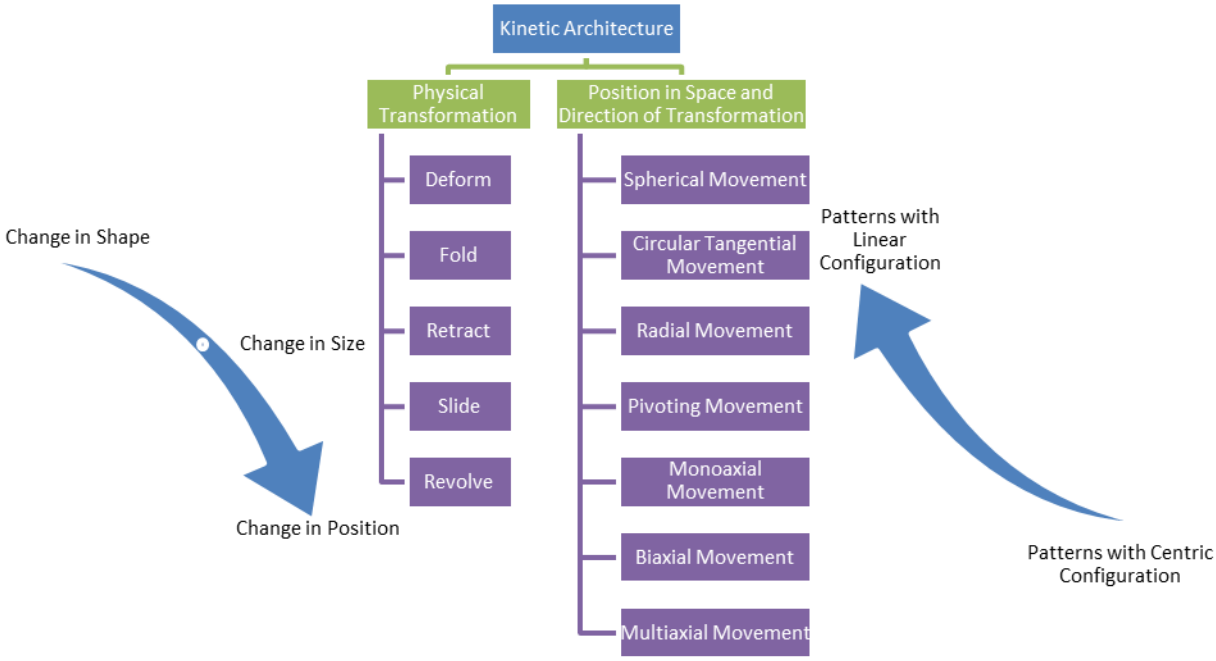

Figure 11. Classification (Stevenson, 2011)

Lee (2012) classified the structures that can change in his thesis. Structures with variable location, geometry, and/or mobility are discussed. In Lee's classification, these structures are divided into four according to their function and structural type. These are adaptable, kinetic, responsive, and transformable below in Figure 12.

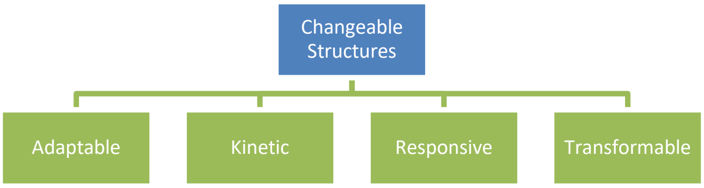

Figure 12. Classification (Lee, 2012)

In their classification, Del Grasso and Basso (2013) created subgroups not mentioned in previous classifications. Del Grasso and Basso used functions as criteria for their classifications. These are compliant mechanisms as a sub-group of deformable structures and morphing trusses as a sub-group of rigid links. The classification is schematized below in Figure 13.

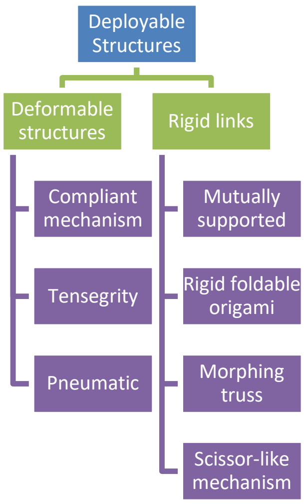

Figure 13. Classification (Del Grosso & Basso, 2013)

Rivas Adrover proposed a rather elaborate classification. At the beginning of the classification published in his book “Deployable Structures,” deployable typologies are divided into two main approaches. The first class is later divided based on their structural properties, and the second class is divided based on the inspiration of the structures. Unlike previously presented classifications, nature-inspired structures were also included. Flexible and combined groups have been added to the distinction between deformable and rigid in previous classifications (Adrover, 2015). This classification is seen below in Figure 14. Adrover mentions two groups named flexible deployable and combined deployable for topologies that do not belong to rigid deployable and deformable deployable components. She created subgroups under these four main groups, considering the inspired structural components. There are a few points that Adrover overlooked. For example, strut-cable systems are more appropriately presented in the subgroup of deformable deployable but presented as a subgroup of combined deployable. Adrover did not keep the examples she gave as belonging to general groups, but by specifying them, causing the classification to become more complicated.

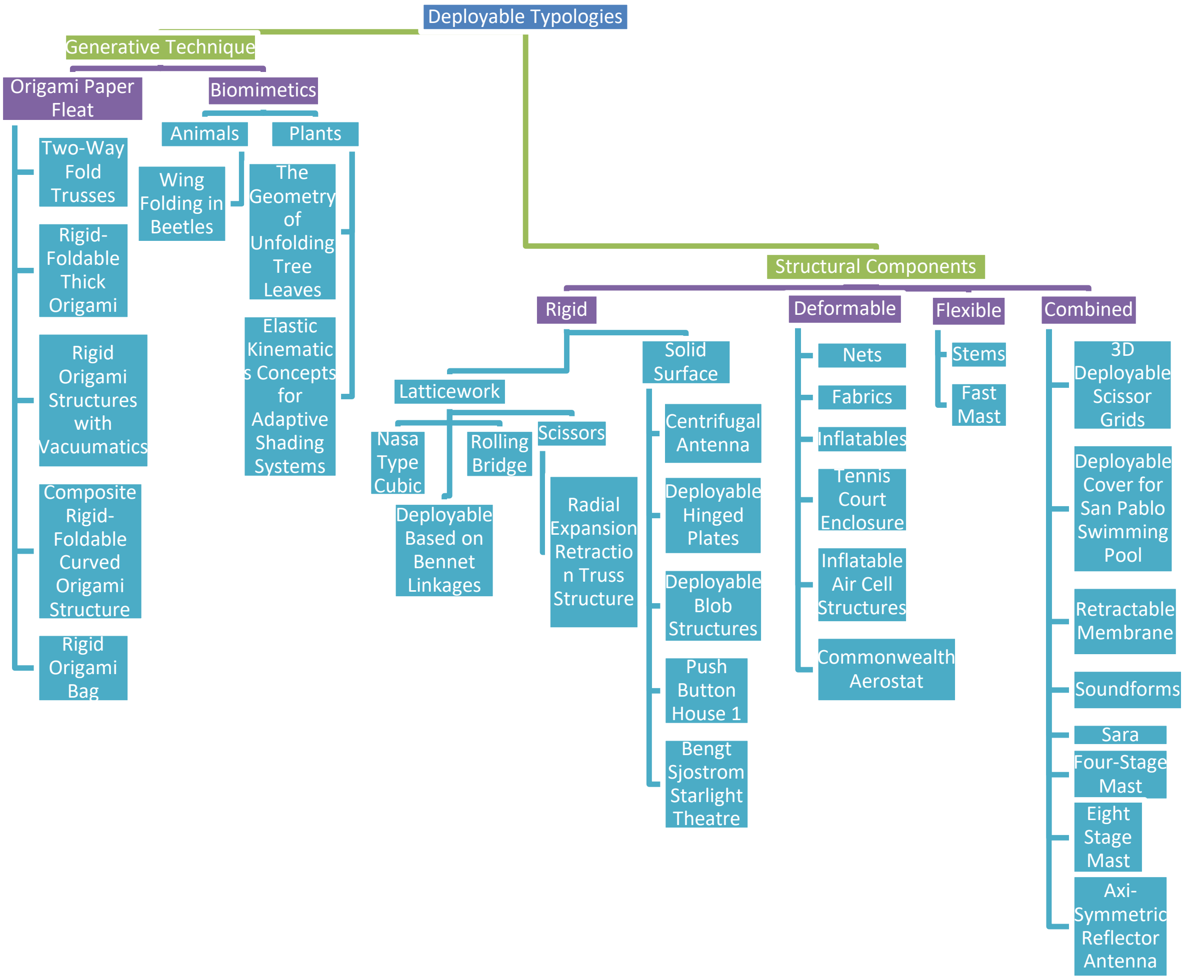

Figure 14. Deployable typologies classification (Adrover, 2015)

Kinetic roofs are a sub-category under the concept of kinetic structure. For this reason, although kinetic roofs are the subject of many studies in literature, they have not been explicitly classified by most researchers. There are several individual classifications proposed for kinetic roof structures. For example, Frei Otto and Berthold Burkhardt made a classification for retractable roofs in their article published in 1972, as seen in Figure 15. This classification has three main categories: "construction systems, types of movement, and directions of movement” (Otto & Burkhardt, 1972).

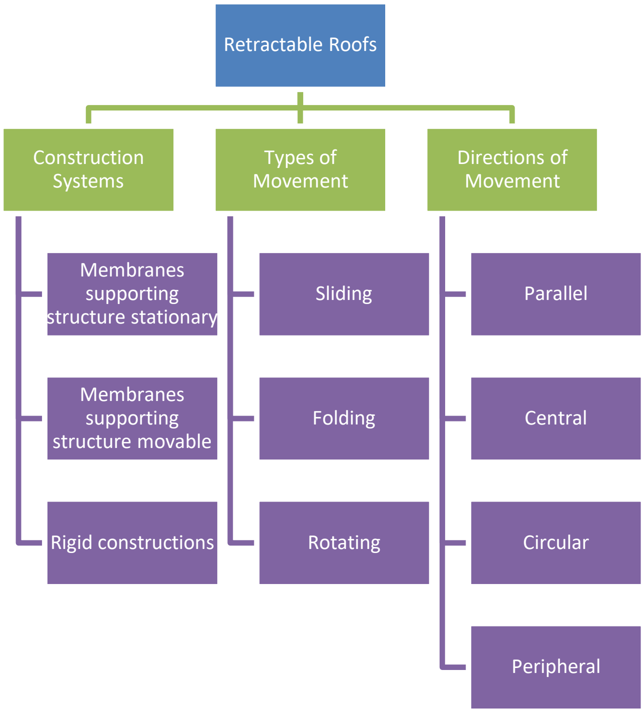

Figure 15. Retractable roofs classification (Otto & Burkhardt, 1972)

Otto and Burkhardt's classification of deployable/transformable structures is based on whether their supporting parts are stationary or movable. The classification system considers the type of roof, movement type, and direction of movement to create subgroups. Stationary supporting structures are classified under the membrane subgroup and further categorized based on their type and direction of movement. Similarly, movable supporting structures are also divided into subcategories using the same approach, as illustrated in Figure 16.

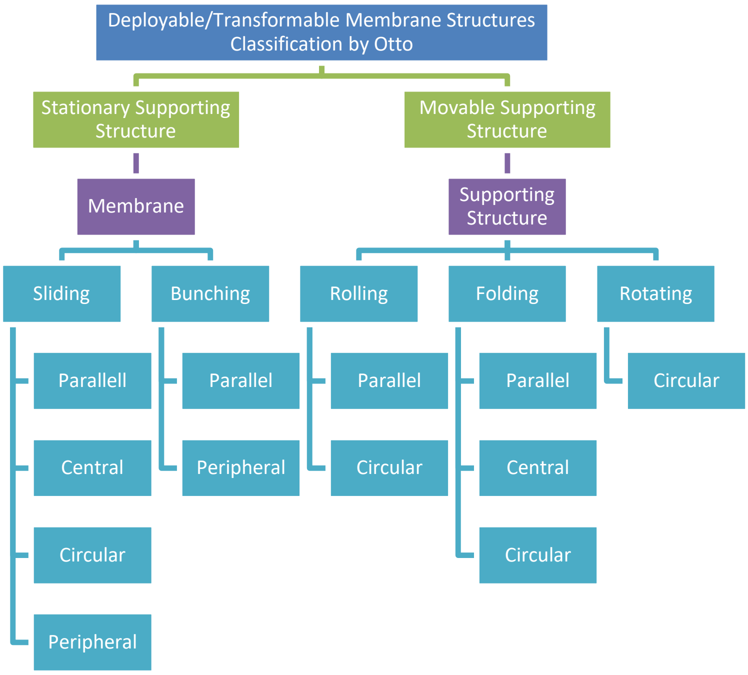

Figure 16. Deployable/transformable membrane structures classification (Otto & Burkhardt, 1972)

There are also classifications explicitly made for membrane kinetic roofs. In the 1950s, a team led by Frei Otto conducted many studies on kinetic membrane roofs and published a classification (Ishii, 2000). Deployable membrane structures were classified in the diagram below in the study by Mollaert (Otto & Burkhardt 1972; Mollaert, 1996). As in Otto & Otto & Burkhardt's calcification, supporting structures are divided into two according to whether they are static or movable. These primary subcategories are then subdivided into secondary subcategories based on movement types (Figure 17).

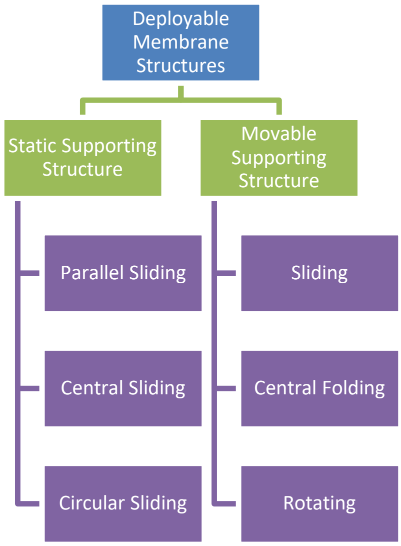

Figure 17. Deployable membrane structures classification (Mollaert, 1996)

3.2. Evaluation of Kinetic Structures Categorization: A Review of Existing Classifications

After examining various classifications of deployable and kinetic structures, it can be observed that most of them focus on kinetic structures in general rather than kinetic roof structures specifically. While there are some classifications that include categories for kinetic roofs, such as retractable roofs or deployable roofs, these can also be grouped into sub-categories based on their mechanisms, movement types, or materials.

For instance, in Merchan's (1987) classification (Figure 2), even though there is no specific category for kinetic roof structures, examples of such structures kinetic roof structures can be found in all groups of strut structures and in pneumatic/inflatable and folded structures groups of surface structures. Similarly, in Gantes' (1991) classification (Figure 3), although a special sub-group called retractable roofs is given for kinetic roof structures, kinetic roofs are also classified under other categories such as pantographs, two-dimensional panels, membranes and cables, pneumatic structures, and tensegrity structures.

In the classification organized by Escrig (1996) according to function and structural types, a subgroup called retractable roofs was created for kinetic roof structures, as in Gantes' work (Figure 4), but deployable roofs with folding movement are included in both the retractable roofs and foldable structures categories.

Pellegrino's (2001) classification (Figure 5) offers a more segregated order, with a separate category for the retractable dome subgroup that covers some of the kinetic roof structures and a classification system based on mechanisms and materials but in this classification, kinetic roof structures with different functions and structures are distributed into other subgroups.

Hanaour and Levy's (2001) classification (Figure 6) uses morphological and kinematic aspects to classify kinetic roofs based on mechanisms, materials, the rigidity of the material, and kinetic properties. Kinetic roof structures can find their place in all the overlapping groups.

In Korkmaz's (2004) classification (Figure 7), kinetic roofs can be categorized under the rigid bar and surface structures sub-categories. Temmerman's (2007) classification (Figure 8) divides structures into four categories, with examples of kinetic roof structures present in each category. Schumacher et al.'s (2010) classification (Figure 9) based on material and movement type, kinetic roof structures can be included in all subgroups according to their material and movement. It separates kinetic roofs using rigid materials such as panels from those using deformable materials such as membranes. Asefi's (2010) classification (Figure 10) separates only transformable structures based on forces on the first level of classification and, after that divided into sub-categories based on structural types and functions. There is no special subgroup for kinetic roof structures, as in most of the classifications examined above. They can be included in subgroups according to their material, function, structure type, and geometry.

In Stevenson's (2011) classification (Figure 11) all subgroups were formed according to the movement type, it offers a system that allows for specific categorization of kinetic roofs based on changes in shape, size, position, and direction in space. In Lee's (2012) classification (Figure 12), generally changeable structures are divided into four basic categories depending on their functions and structural types. In Lee's classification kinetic roof structures may belong to one of these groups or to several at the same time.

Del Grasso & Basso's (2013) classification (Figure 13) generally classifies deployable structures, but kinetic roofs can be placed in both the deformable structures and rigid links sub-categories. Finally, Adrover's (2015) classification (Figure 14) is unique in that it is supported by examples and focuses specifically on deployable typologies. In Adrover's classification, only the structure type is considered. In this study with many subgroups, kinetic roof structures may be included in different subgroups.

The common features of all these studies are that they are general classifications and they have not been able to create sufficiently specific subgroups for kinetic roof structures as they try to group large types such as kinetic, deployable, transformable, changeable, etc.

Otto's retractable roof classification divides kinetic roof structures into groups according to important characteristics such as structure type, movement type, and direction. Another work of Otto, the classification of deployable/transformable membrane structures, although not specific to roof structures, is a sufficient classification to be used in terms of the approach of creating subgroups (Otto & Burkhardt, 1972).

As a result of all these findings, it is clearly seen that there is an insufficient number of studies in the literature for the classification of kinetic roof structures only by considering different features. Nowadays, the increase in design and use has increased the diversity of kinetic roof structures. This diversification has led to the need to classify and group these structures.

To summarize, Table 1 provides an overview of the different classifications reviewed, including the author, publication year, what is classified, and the criteria used for classification.

Table 1. Evaluation of existing classifications

			Classification methods					
Author	Year	Classification	Material	Function	Structural type	Movemen t type	Movement direction	Geometry
Merchan	1987	Deployable Structures	✓		✓	✓		✓
Otto & Burkhardt	1972	Deployable/ Transformable Membrane Structures			✓	✓	✓	
Otto & Burkhardt	1972	Retractable Roofs			✓	✓	✓	
Gantes	1991	Structures With the Terrestrial Application		✓	✓	✓		
Escrig	1996	Deployable Structures		✓	✓			
Mollaert	1996	Deployable Membrane Structures			✓	✓	✓	
Pellegrino	2001	Deployable Structures		✓	✓			
Hanaour & Levy	2001	Deployable Structures		✓	✓			✓

Korkmaz	2004	Kinetic Architecture	✓	✓	✓			✓
Temmerman	2007	Deployable Structures			✓			
Schumacher et al.	2010	Deployable Structures	✓		✓	✓		
Asefi	2010	Transformable Structures	✓	✓	✓			✓
Stevenson	2011	Kinetic Architecture				✓		
Lee	2012	Changeable Structures		✓	✓			
Del Grosso & Basso	2013	Deployable Structures		✓	✓			
Adrover	2015	Deployable Typologies			✓			

3.3. Proposed Classification for Kinetic Roof Structures

In the proposed classification seen in Figure 18, kinetic roof structures are divided into three main categories as membrane, rigid bar, and rigid panel, depending on the type of primary system used. Membrane kinetic roof structures are first classified according to movement type and direction. Rigid bar kinetic roof structures are classified according to the movement type. It is difficult to determine the direction of any movement due to the multi-directional nature of the system. Rigid panel kinetic roof structures are also classified according to movement type, direction, and whether there is an overlapping situation. Examples of all subcategories are in section 4.1.

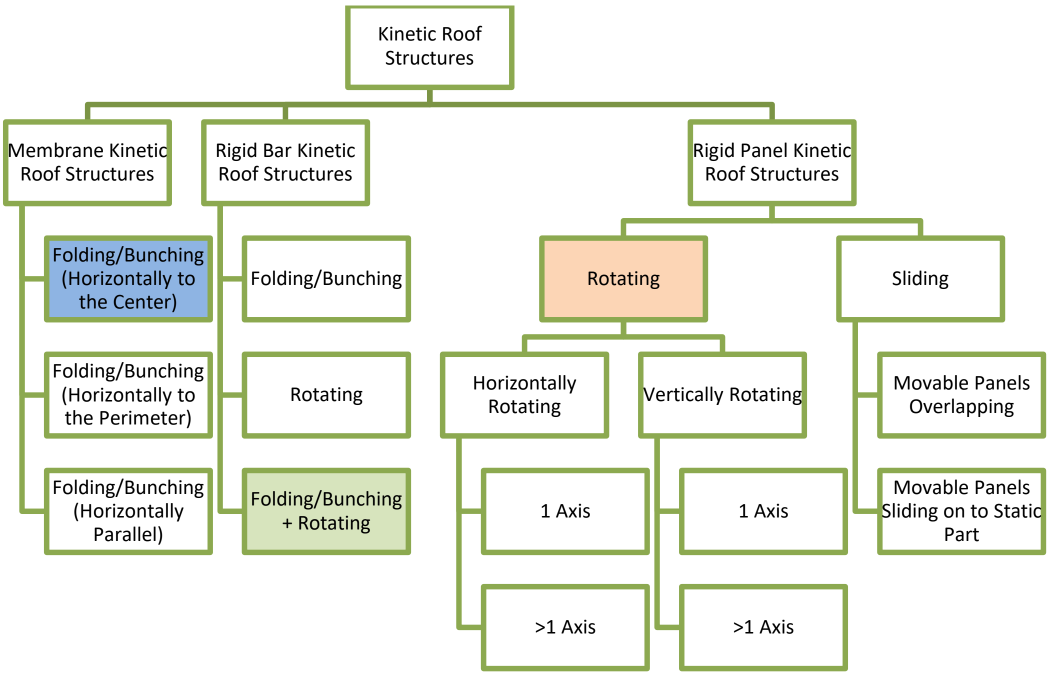

Figure 18. Proposed kinetic roof structures proposed classification

Although the proposed classification covers many of the deployable/ transformable roof structures, some kinetic roof structures can be grouped into more than one subgroup. As an example, umbrella-like kinetic roof structures are structures that serve the same function as a simple umbrella. The proposed classification divides umbrella-like kinetic roofs into three main categories: membrane kinetic structures, rigid bar kinetic structures, and rigid panel kinetic structures, as can be seen in Figure 19. There are also examples where these systems are used together (for instance, membrane+rigid bar used together for the same structure), so the classification is based primarily on which system is used. Since umbrella-like systems are highly popular and are the first examples of kinetic roof structure although umbrella kinetic roof structures belong to the marked categories of the proposed classification given in Figure 18, it is given separately.

When considering umbrella-like kinetic roof structures as an example, it becomes evident that a single system can belong to multiple categories. For instance, umbrella-like kinetic roof structures can be classified into three categories: membrane, rigid bar, and rigid panel. An example of a membrane umbrella-like structure is Mush Balloons, designed by Osaka (Otto & Burkhardt, 1972). Rigid bars are the most employed material for the mechanisms in umbrella-like structures. Frei Otto and Bodo Rasch not only provided design examples but also practical applications. The umbrella-like canopies at the Bundesgartenschau, the umbrella-like canopy structure for Pink Floyd's concert, the Schirm Prototype, the umbrella canopies at Medina Prophet Mosque, the three umbrella canopies at Al-Hussein Mosque, the umbrella canopies at Madinah Piazza, the Prototype U53, the four octagonal umbrella canopies at Schlossplatz, the umbrella canopies at Jeddah airport, and the umbrella canopies designed for Fort Worth Texas are all instances of rigid bar umbrella canopies (Otto & Burkhardt, 1972; Otto & Rasch, 1996; Nerdinger, 2005; Fournier et al., 2008; Michalski et al., 2011; Wikipedia contributors, 2022a; U53-Prototyp. SL Rasch, n.d.). Koray Korkmaz's architectural umbrella and Jaksch and Sedlak's foldable umbrella canopy serve as examples of rigid panel umbrella canopies (Korkmaz, 2005; Jaksch & Sedlak, 2011). When examining these examples, it becomes apparent that they may fall into different sub-categories as shown in the table presented in Figure 18. Similar to this example, various kinetic roof structure systems can be categorized into one or more specific categories.

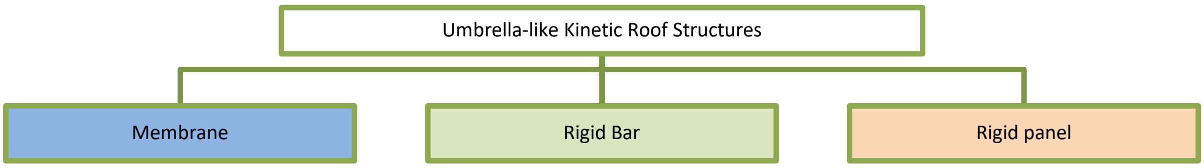

Figure 19. Proposed classification of the umbrella-like kinetic roof structures

3.4. Examples for Categories of the Proposed Classification

3.4.1. Membrane kinetic roof structures

Membrane kinetic roof structures are the first of the three systemic subcategories of the proposed classification. The membrane is a material suitable for kinetic roof design as it is light in structure and flexible enough due to the material (Mollaert, 1996). In addition, another advantage of the membrane material is its compactness, which provides ease of storage. In membrane kinetic roof structures, auxiliary elements are used to stretch the opening and closing of the membrane (Ishii, 2000). The membrane, which acts as a roof with the folding/bunching movement, can perform this movement in different directions according to the design.

3.4.1.1. Folding/bunching (horizontally to the center)

The Stureplan pavilion in Stockholm is an example of this subgroup (Figure 20). The membrane is supported by steel cables fixed on a circular steel beam. The structure is demountable and can be reassembled in 24 hours (Stureplan Pavilion, n.d.).

Figure 20. Stureplan Pavillion's membrane roof (Stureplan Pavilion, n.d.)

3.4.1.2. Folding/bunching (horizontally to the perimeter)

In 2000, Ozawa and Kawaguchi designed a membrane roof system for retractable roof systems. In the initial state, the membrane on a cylindrical geometry is twisted by rotating the rings in opposite directions (Figure 21). When folded, the membranes overlap and close, and the area formed by the membranes can be tensioned by applying internal air pressure. Another way to implement this process is the air-supported system. A single-layer system is created by replacing the cylinder rings with cables, and the internal air pressure is increased. The advantage of both methods is that they are easy to apply and have a simple structure, but the problem is the deformations that may occur in the membrane (Ozawa & Kawaguchi, 2000). Considering a round roof, it did not make sense for the membrane to fold out from the middle because the circumference of the round membrane would change at each point.

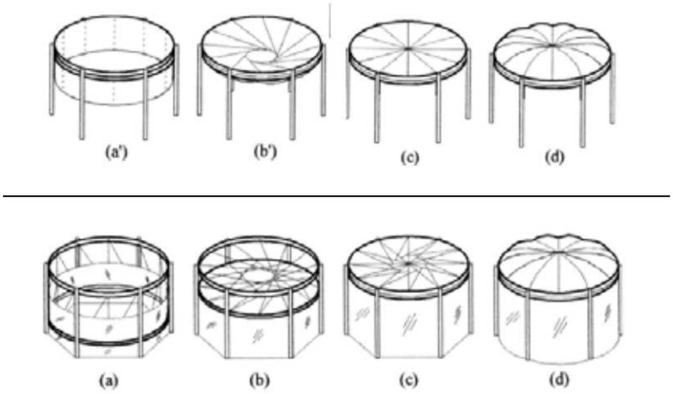

Figure 21. Cylinder membrane (Ozawa & Kawaguchi, 2000)

3.4.1.3. Folding/bunching (horizontally parallel)

The roof of Primorski Park's summer theater is another example of a horizontally parallel folding membrane kinetic roof See Figure 22). The system, which can be opened in about 20 minutes, consists of a PVC-coated polyester membrane and secondary element cables. The cables are fixed to the two-belt truss system (Wikimapia, n.d.).

Figure 22. Primorski Park Summer Theatre (Wikimapia, n.d.)

3.4.2. Rigid bar kinetic roof structures

Rigid bar kinetic roof structures are the second systemic subcategory of the proposed classification. Systems using rigid bars have started to be used and developed frequently in architectural applications. They can create kinetic arches, domes, and roof systems by combining them with auxiliary elements such as membranes and cables. These structures consist of tension and compression elements and are easy to transition from a flat configuration to different geometries. Movement can be achieved using actuators, motors, or compression elements. Rigid bar kinetic roofs, which can be classified according to the type of movement, are divided into three as folding/bunching, rotating, and folding/bunching + rotating.

3.4.2.1. Folding/bunching

The roof structure designed by Félix Escrig for a swimming pool in Seville, Spain, is a remarkable example of rigid bar kinetic roof structures with the movement of folding/bunching (Figure 23). He used two identical side-by-side structures with spherical curvature to cover the entire pool. The structure's skeleton is covered with a fabric that can fold/bunch together with the main structure (Valcárcel, 2022).

Figure 23. Roof structure for swimming pool (Valcárcel, 2022)

3.4.2.2. Rotating

The roof of the Emergency Call Center in St. Gallen, Switzerland, is an example from Santiago Calatrava (Figure 24). The roof system consisting of aluminum elements opens and closes with the rotating movement of these sequential elements. The structure consists of four-bar linkages, and they can move together thanks to the input link that connects these four-bar linkages (Korkmaz, 2004; Akgün et al., 2013).

Figure 24. Emergency call center deployable roof (Santiago Calatrava Architects & Engineers, n.d.)

3.4.2.3. Folding/bunching + rotating

Natalia Torres proposed a deployable arch design in her Ph.D. work. She used articulated bars, folding panels, and a membrane in her deployable arch design (See Figure 25). The design has an opening system that prevents the rupture of the membrane. The system folds/ bunches while deploying and rotating on the horizontal axis (Torres, 2017).

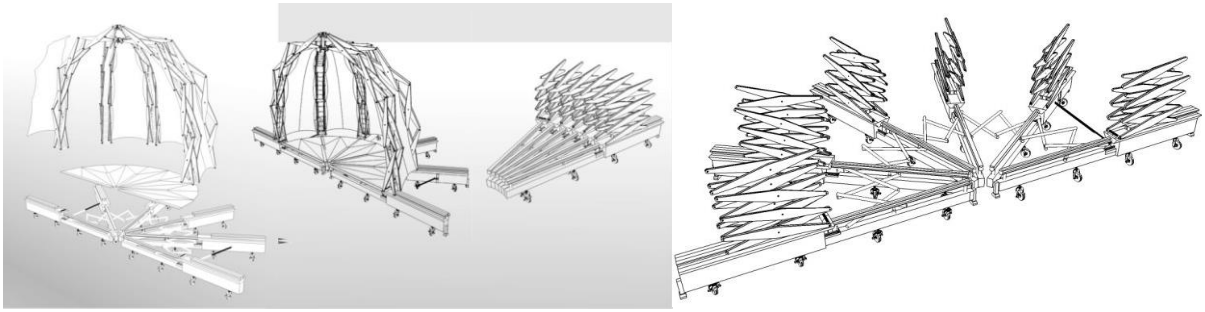

Figure 25. Deployable arch design (Torres, 2017)

3.4.3. Rigid panel kinetic roof structures

The last of the three systemic sub-categories of the proposed classification belongs to rigid panel kinetic roof structures. The number of kinetic roof structures composed of rigid panels has increased gradually since the middle of the 20th century. While the first examples were generally stadium roofs, the variety of uses has increased. Its use is quite common from past to present. Again, as in rigid bar kinetic roof structures, it is categorized according to the type of movement. It is also divided in itself again towards the direction of movement.

3.4.3.1. Rotating

a. Horizontally Rotating

Fukuoka Dome is an example of a kinetic roof with a horizontally rotating movement (Figure 26). It is opened by rotation on a single axis vertically. The roof can be completely open in about 20 minutes, spans 213 meters, and height is 84 meters. It consists of three panels, and when opened, it exposes 2/3 of the stadium (Tanno et al., 1994; Zaizen et al., 2000).

Figure 26. Fukuoka dome (Klook Singapore, n. d.)

Although the Fukuoka Dome rotates on a single axis, there are also examples that rotate on more than one axis. For example, Sapporo Media Park Spica.

b. Vertically Rotating

Merck Serono Headquarters is an example of a kinetic roof that rotates horizontally on the same axis (Figure 27). It has a 60-meter-long roof made entirely of glass (Werner Sobek, n.d.). Qi Zhong Stadium is an example of the kinetic roof with a vertically rotating movement, but on more than one axis despite the Merck Serono Headquarters.

Figure 27. Merck Serono headquarters (Werner Sobek, n.d.)

3.4.3.2. Sliding

a. Movable Panels Overlapping

The Rogers Center (formerly Skydome) is an example of a kinetic roof structure that moves horizontally (Figure 28). The kinetic roof, with a span width of 180 meters and a height of 86 meters, consists of one fixed and three movable panels. The roof, which can be opened in about 25 minutes, makes an overlapping sliding movement (Mohamed & Abu Elfadle, 2013).

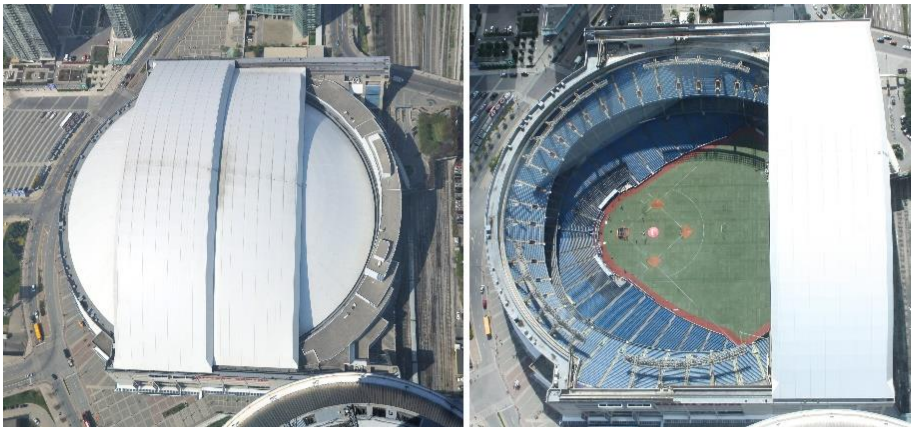

Figure 28. Skydome (Renamed Rogers Centre) (Urban Toronto, n.d.)

b. Movable Panels Sliding onto Stationary Part

Johan Cruyff Arena, formerly known as Amsterdam Arena, is an example of a kinetic roof that moves horizontally, where movable rigid panels do not overlap; instead, movable rigid panels slide over one or more of the fixed parts in the roof system (Figure 29). The roof comprises two main panels that can be opened in 30 minutes (Mans & Rodenburg, 2000).

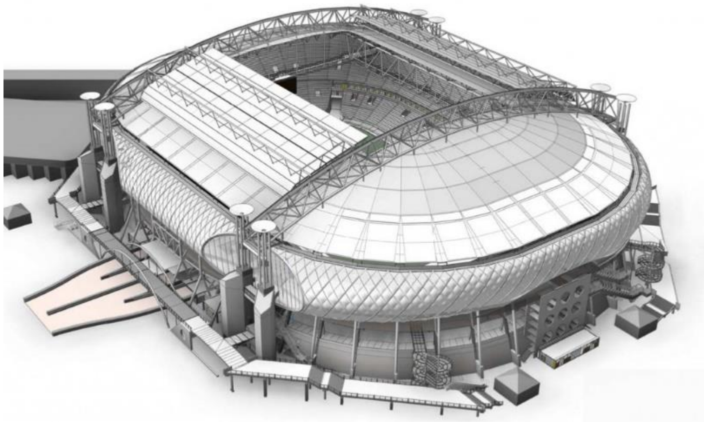

Figure 29. Johan Cruyff Arena (Stadiumdb.com Stadium Database, n.d.)

4. Conclusion and Suggestions

There exist several classifications of kinetic structures in the literature of architecture, each of which offers unique perspectives and categorizations. While some of these classifications demonstrate similarities, they are still distinct from one another. Notably, few classifications specifically categorize kinetic roof structures, which suggests a need for a more comprehensive and dedicated classification system for this architectural element. This paper examines and interprets various classifications of kinetic structures and kinetic roof structures, including studies by Merchan, Gantes, Escrig, Pellegrino, Hanaour and Levy, Korkmaz, Temmerman, Asefi, Schaffer and Vogt, Stevenson, Lee, Del Grosso and Basso, and Adrover (Merchan, 1987; Gantes, 1991; Escrig, 1996; Pellegrino, 2001; Hanaor & Levy, 2001; Korkmaz, 2004; Temmerman, 2007; Asefi, 2010; Schaffer & Vogt, 2010; Stevenson, 2011; Lee, 2012; Del Grasso & Basso, 2013; Adrover, 2015). Furthermore, it also looks into Otto's retractable roof classification, the Institute for Lightweight Structures' deployable/transformable membrane structures classification, and Mollaert's deployable membrane structures classification (Mollaert, 1996). While all of these classifications include kinetic roof structures, they differ in how they categorize them. For instance, some classifications specifically distinguish kinetic roof structures as a subcategory or main category, such as Retractable Roofs, Kinetic Roofs, and Movable Roofs. However, other classifications do not have a specific category for kinetic roof structures and instead, place them under other categories such as material connected to the mechanism. Therefore, kinetic roof structures are often located under multiple categories in some studies. Overall, the lack of a dedicated and extensive classification system for kinetic roof structures, despite their widespread use in architecture, is apparent.

A novel classification system for kinetic roof structures is proposed, which aims to categorize them based on the system used for movement. The classification comprises three main groups: Membrane Kinetic Roof Structures, Rigid Bar Kinetic Roof Structures, and Rigid Panel Kinetic Roof Structures. Once the type of system is determined, further subcategories are established based on characteristics such as movement type, direction, and the number of axes where movement occurs. Each main category has several subcategories that help to differentiate between types of kinetic roof structures. For instance, the subcategories for membrane kinetic roof structures consider types of folding/bunching movements. Meanwhile, the subcategories for rigid bar kinetic roof structures take into account either folding/bunching or rotating movements. Rigid panel kinetic roof structures are primarily divided into two categories: rotating and sliding movements. The rotating movement subcategory is further divided into two according to the first horizontal or vertical, and these subcategories are then differentiated based on the number of axes involved. The sliding movement subcategory is divided into two based on the overlap of moving or still panels.

Overall, this classification system aims to provide a comprehensive framework for organizing kinetic roof structures based on their characteristics and movement systems. By doing so, it will help architects and engineers to better understand and communicate the design and construction of these complex architectural elements.

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Author Contribution and Conflict of Interest Declaration Information

All authors contributed equally to the article. There is no conflict of interest.

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