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Analysis of Origami Applications within the Scope of Kinetic Architecture

Kinetik Mimarlık Kapsamında Origami Uygulamalarının İncelenmesi

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Abstract

In the past three or four decades, scientists working in computer science, physics and mathematics have had significant research studies on origami. Currently, most of the articles and books that can be reached by designers or architects describe and deal with the subject through mathematical expressions. It does not seem possible for a reader who is not related to mathematics to understand what is explained in articles and books. Therefore, folding systems have been basically classified to make the subject more understandable for designers. Examples of kinetic architectural products that act with origami principles were evaluated through folding and building hierarchy concepts. The matrix has been generated to visualize the distribution of the characteristics and to display architectural tendencies. By the visualization of data, it becomes possible to examine the potential outputs of desired folding technique on the existing projects. Thus, the matrix guides designers to select a folding technique that meets the function. It can be mentioned that the proposed method can be attributed as a novel perspective for predesign phase of origami-based elements. Thanks to the matrix, the areas that have not been studied in architectural applications such as flexible foldings are demonstrated. Also, the relationship between building concept levels and movement motivations such as configuration and compactness has been revealed by the study. The findings and the matrix demonstrate that there are still many possibilities that can be studied.

Keywords: Folding, Kinetic Architecture, Origami.

Genişletilmiş Özet

Çalışma kapsamında origami prensipleri ile hareket edebilen kinetik mimarlık ürünleri incelenmiştir. Literatürde ilgili çalışmalar çoğunlukla konuyu katlanma mekanizmaları ve hesaplamaları üzerinden ele almakta ve matematik ile ilgili olmayan birçok okurun anlamakta güçlük çekebileceği ifadeler içermektedir. Konu ile ilgili derleme makaleleri ve retrospektif çalışmalar mevcut olmasına rağmen araştırma makalelerinin genellikle uzmanlık gerektiren konuları olması ve konuyu bütüncül olarak ele alan sınırlı sayıda çalışma olması nedeniyle, okuyucunun zihninde geniş bir bakış açısı oluşturmak zorlaşmaktadır. Dolayısıyla konunun mimar ve tasarımcılar için daha anlaşılır bir şekilde ele alınabilmesi gerekmektedir. Makaledeki metodoloji temel olarak örneklerin seçilmesine ve değerlendirilmesine dayanmaktadır. Literatürden ölçeği, işlevi, katlama yöntemi, yapısal seviyesi, alanı, malzemesi, kat deseni, hareket kabiliyeti, geometrik konfigürasyonu ve kontrol sistemi farklı olan örnekler derlenmiştir. Geniş bir bakış açısı oluşturmak adına farklı özelliklere sahip örnekler seçilmeye özen gösterilmiştir. Seçilen örnekler aşağıda tanımlanan katlanma hareketi ve yapı kavramları gibi temel konular üzerinden incelenmiştir. Çalışmada derlenen bilgiler, konuyu bütüncül olarak algılamaya katkı sağlaması açısından matriste görsel hale getirilmiştir.

Bir eylem olarak katlanma hareketi; bir veya daha fazla etki (serbestlik derecesi) ile yapılandırılabilen, yüzeylerde deformasyon (fiziksel etki) oluşturabilen ve sistemlerin boyutlarını koordinat eksenlerine göre değiştirebilen bir hareket olarak tanımlanabilmektedir. Katlanma hareketi süreç açısından da bir veya daha fazla seferde gerçekleşebilmektedir. Bu sayede katlanma hareketinin özellikleri; fiziksel, kinematik ve süreç odaklı analizlerle incelenmiştir. Katlanma hareketi fiziksel açıdan incelenirken öncelikle yüzeylerin rijit veya esnek olmalarına göre iki başlığa, ardından düzlemsel (2D ⇌ 3D ⇌ 2D) veya hacimsel (2D ⇌ 3D) olmalarına göre de iki alt başlığa ayrılmaktadır. Sistemlerin hareket esnasında boyutlarında yaşanan değişimler kinematik (hareketin geometrisi) açıdan Poisson oranlarına göre incelenmiştir. Poisson oranı bir sistemin hareketi esnasında hareket eksenine (kuvvet yönündeki uzama) dik doğrultudaki uzama miktarının kuvvet yönündeki uzama miktarına oranıdır. Dolayısıyla bir katlanma sisteminin (3 boyutlu olarak düşünüldüğü takdirde) bir yönde uzaması durumunda geri kalan iki eksende uzama(+)/ sabit kalma(0)/ kısalma(-) gözlemlenmektedir. Diğer eksenlerde oluşan bu kombinasyonlar bağlamında negatif (+,+,+), sıfır (+,0,0), pozitif (+,-,-) ve 3 hibrit (+,+,0/ +,+,-/ +,0,-) olmak üzere toplam altı konfigürasyon belirlenmiştir. Katlanma hareketi bir süreç olarak incelendiğinde, sistemlerin istenilen yapılanmaya bir veya birden çok katlanma süreci sonucunda ulaştığı görülmektedir. Birden çok seferde katlanma peş peşe ve bağımsız tek seferde katlanmalardan oluşmaktadır. Bir diğer nokta ise sistemlerin sahip olduğu serbestlik dereceleridir. Bu noktada sistemlerin istenilen yapılanmaya ulaşabilmesi için kaç adet farklı hareket ettiriciye maruz kalması gerektiği üzerinde durulmuştur. Temel olarak bu noktada getirilen ayrım bir ve çok serbestlik dereceli (SDOF/ MDOF) katlanmalar şeklindedir. Literatürde mekanizmaların serbestlik derecelerinin hesaplanması ile ilgili birçok yayın mevcut olmakla birlikte, çalışma kapsamındaki örneklerinin serbestlik dereceleri basit geometrik hesaplamalar veya sistemlerin gerçekte sahip olduğu hareket ettiricilerin sayılması yolu ile anlaşılmıştır. Çalışma kapsamında yapı kavramlarının hiyerarşik seviyeleri (yapı/ yapı alt sistemi/ yapı elemanı) tartışılmış ve açıklanmıştır. Bu sayede örneklerdeki kinetik parçaların yapı ile ilişkisi hiyerarşik olarak incelenmiştir. Bütünden parçaya doğru açıklanan kavramlarda; yapı kategorisi altında, sistemlerin ıslak hacim veya çekirdek içerip/ içermemesine göre iki alt başlığa, yapı elemanında ise elemanların güçlü (duvar, zemin gibi) veya zayıf (kapı, pencere gibi) uzamsal tanımlayıcılar olup/ olmamasına göre ana/ yardımcı yapı elemanı olarak iki alt başlığa ayrılmıştır. Bu sayede kinetik elemanların hiyerarşik konumları net bir şekilde belirlenebilmiştir.

Çalışma kapsamında toplanan 47 örnek tek veya birden fazla parçadan oluşma durumlarına göre öncelikle ikiye ayrılmıştır. Ardından biçim (konfigürasyon) değiştirme, kompakt duruma gelebilme veya her ikisi olarak tanımlanabilen hareket motivasyonlarına göre üç alt kategoriye ayrılmıştır. Birden fazla parçadan oluşan ürünler ayrıca parçaların bir araya geliş yönleri açısından (radyal, doğrusal, düzlemsel ve simetrik) da incelenmiştir. Matris fiziksel açıdan değerlendirildiğinde, tek parçadan oluşan ürünler altında biçim değiştirme ve kompakt alt başlıklarında yer alan örneklerin neredeyse tamamının rijit, hacimsel katlanma yaptığı gözlemlenmiştir. Örneklerin kinematik, süreç odaklı ve parçaların bir araya geliş yönleri incelemesinde matriste örneklerin homojen dağılıma sahip olduğu görülmektedir. Örneklerin yapısal kavram seviyesine göre farklı gruplaşmalar oluşturduğu gözlemlenmiştir. Tek parçadan oluşan ürünler başlığı altındaki biçim değiştirme alt başlığındaki örneklerin tamamı yapı alt sistemi ve daha alt seviyelerde bulunurken, aynı başlıkta bulunan kompakt alt başlığındaki örneklerin tamamına yakınının, yapı alt sistemi ve daha yüksek seviyelerde olduğu gözlenmiştir. Bu nedenle üst yapısal seviyelerde istifleme ihtiyacının, alt yapısal seviyelerde ise biçim (konfigürasyon) değiştirme ihtiyacının daha fazla olduğu gösterilmiştir.

Verilerin görselleştirilmesi ile istenilen katlanma tekniğinin mevcut projeler üzerindeki olası çıktılarının incelenmesi mümkün hale gelmektedir. Ayrıca matristeki işaretlemelerin dağılımları da mimari yönelimler hakkında fikir vermektedir. Matris sayesinde, esnek katlanmalar gibi mimari uygulamalarda incelenmemiş alanlar gösterilmiştir. Ayrıca, yapı seviyeleri ile konfigürasyon değiştirme ve kompakt duruma gelme gibi hareket motivasyonları arasındaki ilişki de çalışma kapsamında ortaya konulmuştur. Bulgular ve matris, üzerinde çalışılabilecek birçok mimari olasılık olduğunu göstermektedir. Örneğin, tek parça olarak üretilen ve konfigürasyonunu değiştirmeye odaklanan sistemleri yapı seviyesinde incelemek/ tasarlamak mümkün görünmektedir.

Anahtar Kelimeler: *Katlanma, Kinetik Mimari, Origami.*

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1. INTRODUCTION

Nearly all of the built environment consists of conventional buildings. After their structural systems are built, it is almost impossible to change their forms and positions. Therefore, they can not meet today's rapidly changing needs. With the concept of kinetic architecture, a building can be adapted to changing conditions by transformation *(Zuk & Clark, 1970)*. This transformation can be achieved by mechanisms or demountable systems. Though both of them have their own pros and cons, the selection of the system generally depends on context or function, which constantly alters. Therefore they are not designed in their final static shape but in a transition state *(de Temmerman et al., 2012)*. The pioneer designers of kinetic architecture are Yona Friedmann, Cedric Price and Archigram group, who are known for their hypothetical projects and cybernetic approaches *(Maden, 2023)*. They investigated to convey the energy of changing lifestyles with their designs. Thanks to the aforementioned trends, the development of digital systems and technology in the second half of the 20th century, kinetic architecture has become more widespread *(Ramzy & Fayed, 2011)*. Designers focus to find novel ways to reduce the energy consumption of buildings *(cooling, heating, lighting, or ventilation)*, and enhance the performance of users within the scope of sustainability concepts in the 21st century. Therefore, adaptive facades as building envelopes are frequently preferred for high-rise buildings as solar shading systems *(Attia, 2016; Sheikh & Asghar, 2019)*. Nowadays, research projects based on smart materials like shape memory alloys and bio-inspired designs are carried on in terms of kinetic architecture *(Baerlecken et al., 2014; Krieg et al., 2014)*.

The need to classify transformable structures has arisen over time since the number of designs and products has increased dramatically over time. Though there are various categorization techniques in the literature, transformable structures can also be classified according to their different anatomical features. Most studies fundamentally classify products as strut or surface structures and rigid or flexible systems *(del Grosso & Basso, 2012; Hanaor & Levy, 2001; Korkmaz, 2004)*. There are other classifications that focus on the functions of buildings, movement characteristics or typologies *(Fox, 2003; Pellegrino, 2001; Stevenson, 2011)*. Besides, classifications, definitions and typologies are investigated to constitute conceptual frameworks as meta-research studies in the literature *(Fenci & Currie, 2017; Megahed, 2016)*.

Origami can be utilized in a wide range from space exploration to textile, from medicine to industrial design in spite of its traditional roots *(Kuribayashi et al., 2006; Tachi, 2010a; Zirbel et al., 2013)*. Origami designs came to the fore in the world of architecture with Joseph Albers and his courses in Bauhaus *(Lebée, 2015)*. Nowadays, different approaches can be observed in this technique from basic accordion walls to complex folding systems *(Osório et al., 2014)*. Various experimental studies are carried on to explore the potential of origami-based design as a manipulator of space via acoustics and light *(Thün et al., 2012; Imlach, 2011)*. The number of actuators, materials *(plywood, cardboard or polypropylene...)*, crease patterns, etc. are considered in these experiments. In terms of function, origami-based designs are broadly preferred to construct disaster-relief shelters or temporary houses that are used in a short period of time because of their deployability *(Kronenburg, 1995)*. It is also possible to reinterpret functions such as doors and foldable stairs, which are frequently used in architecture *(Torggler, 2013)*. In adaptive facades, origami-based designs that can easily cover surfaces are often used *(Karanouh & Kerber, 2015)*. Thus, there are a lot of folding systems in architecture that have different functions, folding techniques and design principles. Apart from these, there are also origami-inspired static structures, such as the US Air Force Academy Chapel in Colorado *(USA)* and the Church St. Paulus in Neuss *(Germany)* *(Karaveli Kartal, 2017)*.

In the past three or four decades, scientists working in computer science, physics and mathematics have had significant research studies on origami *(Bern & Hayes, 1996; Bowen et al., 2013; Kanade, 1980)*. Currently, most of the articles and books that can be reached by designers or architects describe and deal with the subject through mathematical expressions. Therefore, the study area is mostly on the side of mathematics and engineering fields. It does not seem possible for a reader who is not related to mathematics to understand what is explained in articles and books. Thus, it should not be expected from them to use the information effectively in the field of design. At this point, there is a gap between research and readers. Since research projects have generally niche topics and there is a limited number of studies dealing with the subject holistically, it becomes difficult to develop a broad perspective in the mind of a reader. Also, existing studies deal with the subject from a review and retrospective framework *(Lebée, 2015)*. For this reason, folding systems have been basically classified to make the subject more understandable for designers. Although there are studies in the literature describing systems on folding techniques and styles *(Dureisseix, 2012; Fei & Sujan, 2013)*, this study interprets the features of existing architectural products to provide a broader perspective on the subject. Gathering many examples related to the subject under a single study and evaluating them according to criteria is important in terms of a holistic approach to the subject. Thus, the study offers designers a new perspective.

The methodology in the paper is basically based on the selection and evaluation of examples. Examples that act with origami principles with different scales, functions, folding methods, building levels, covered areas, material properties, thickness, folding patterns, movement capabilities, geometric configurations and control systems have been compiled. At this point, since the selection of examples with different characteristics creates a broad perspective, it strengthens the consistency of the study. Each selected example is examined according to the defined features of folding movement. Folding systems are studied as physical, kinematic and process-oriented, which can affect both the production stage, usage and visual features. Also, each product can be defined as a part of a building. Therefore, all kinetic examples can be examined according to the hierarchical building concept to understand whole-part relations and their correlations with other features. It is aimed both to present a novel perspective for the analytical evaluation of kinetic architectural products, to guide designers who will work on the subject through existing architectural trends and to clarify possible areas that have not been studied before in architectural applications. By the visualization of data, it becomes possible to examine the potential outputs of desired folding technique on the existing projects before the design stage of a project. Therefore, it can be mentioned that the proposed method can be attributed as a novel perspective for predesign phase of origami-based elements of kinetic architecture.

2. ANALYSIS OF FOLDING

The words fold and bend seem to have close meanings. A surface is manipulated and changed by these activities. Folding can also be perceived as a concentrated bending *(Cambridge Dictionary, n.d.)*. In terms of design, folds do not involve any addition or subtraction. A masonry wall can be obtained by laying many bricks or a sculpture by carving a marble block. However, folding can be described as a transformative action. This feature can enable faster and more economical productions *(Jackson, 2019)*. Based on these properties, foldings can be examined according to the forces that affect their surfaces or the formation of processes. Therefore, folding patterns such as Miura, Resch, Yoshimura, and waterbomb, which are frequently mentioned in the literature *(Peraza Hernandez et al., 2019)* are considered as systems that are examined in the context of these defined features.

2.1. Physical Examination of Folding Surfaces

One of the important features of origami structures is rigid foldability. If all regions remain rigid during the folding, distortions occur only in crease lines; which means that the crease pattern can be folded rigidly *(Evans et al., 2015)*. Besides, to be flat-foldable, all lines in the crease pattern must be folded ±180 degrees *(±π)*. In this way, folded sectors *(assuming surface thickness as zero)* are gathered onto a plane. Thus, if these situations occur at the same time, it means that the folding system can be rigid flat foldable *(Tachi, 2010b)*. During the rigid flat folding process, the configuration of a system changes from a two-dimensional to a three-dimensional phase and transforms two-dimensional state with a different configuration. This feature demonstrates that the initial and final states of a system are gathered onto a plane. Therefore, two-dimensional objects can be effortlessly stacked. Miura-Ori can be given as an example of this folding type *(Miura, 1985)*.

During the folding of a system, bending may occur on surfaces due to loads *(forces)*. In a system, if at least one sector *(region)* bends during folding, it is defined as flexible folding. Therefore, as stated above, if none of the sectors bends during folding, it is defined as rigid folding. Apart from homogeneous bending of the sectors or fold lines in a crease pattern, distortions may be occured at any point on the surface. Any distortion *(deformation)* on surfaces can also be included in flexible folding *(Demaine & O'Rourke, 2007)*.

Some crease patterns can be rigid-foldable but not flat-foldable. These structures can be classified as rigid volumetric folding *(Lynch & Raney, 2020)*. Besides, some rigid volumetric origami designs can be reverted onto a plane. During the folding process of these systems, the configuration is changed from two-dimensional to three-dimensional and again two-dimensional with the same configuration. An example of this folding type is the triangular crease pattern developed by Ron Resch *(Resch Pattern, n.d.)*. After the Resch pattern is folded, it can be returned to a two-dimensional state again. However, some of the patterns can not be reverted to a two-dimensional configuration due to assembled surfaces after being folded. These systems can be defined as rigid volumetric folding that can not return to a flat configuration. An example of this type is reconfigurable metamaterials *(Overvelde et al., 2016)*.

Folds in which bending and distortions occur on sectors can be defined as flexible folding. Since flexible folds are non-rigid by definition, a crumpled paper or fully deformable pneumatic membrane can also be included in this branch, but there is a practical limit that can not be precisely specified. If the number of bends and distortions on a surface increases too much, shape-forming values of fold lines can fall into the background as well. For this reason, it can be mentioned practical importance to achieve a balance between folding, bending and distortions. Flexible folding can also be divided into flat and volumetric likewise rigid folding. Flexible flat-folding processes are similar to rigid flat-folding. However, it can not be said that it is practical to use *(Demaine & O'Rourke, 2007)*. Also, configuration changes in the flexible volumetric folding process are similar to rigid volumetric folding. It can be stated that a typical example of flexible volumetric foldings is curved creases *(Demaine et al., 2011; Mitani, 2019)*. However, flexible volumetric foldings can be obtained by using straight crease patterns *(Jackson, 2011)*. On the other hand, flexible folding that can not return flat configuration has not been found in the literature yet. The aforementioned configurations are visualized in Figure 1, where all the equations that express the characteristic of movements are written.

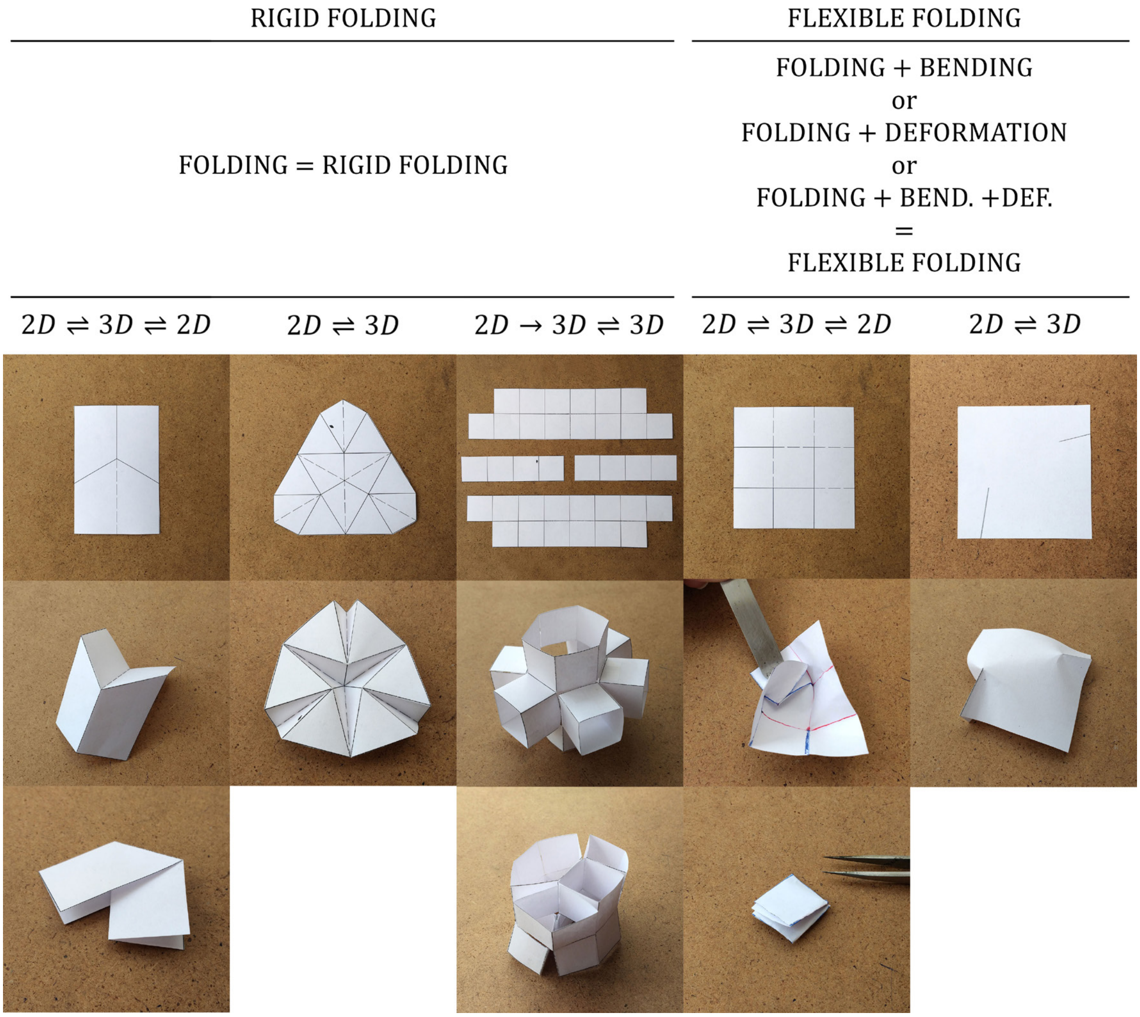


Figure 1. *Folding examples for each branch of the classification.*

2.2. Kinematic Examination of Folding Movement

As an essential consequence of shapeshifting, the dimensions of a system change in all three dimensions. It can be mentioned that there is a ratio between the amount of change of various dimensions due to folding. Therefore, folding systems can be examined according to the Poisson ratio *(), which is perceived visually, can be a guide at design stage of folding systems. This ratio, which was found by the mathematician Simeon Denis Poisson (1781-1840)*, can be defined as the negative ratio of transverse strain to axial strain *(Beer et al., 2009) (1)*.

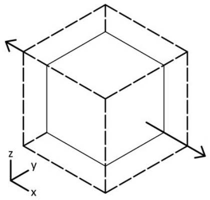
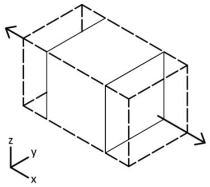
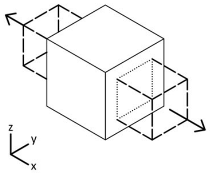
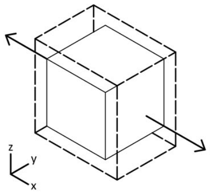
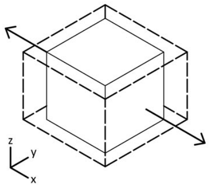
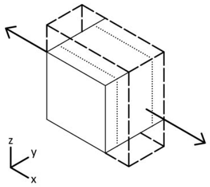
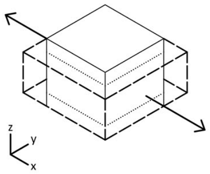
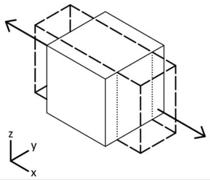
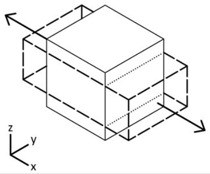
$$\nu = -\frac{\varepsilon_{lateral}}{\varepsilon_{axial}} \qquad (1)$$

If folding systems are classified according to Poisson ratios, their spatial potentials such as covering surfaces or creating spaces can be effortlessly understood *(Arya, 2016)*. Therefore, systems are divided into four Poisson ratio foldings as negative, zero, positive and hybrid *(Table 1)*. Since folding systems are generally produced by using sheets, two dimensions of the surface are more dominant than the other one. However, as with volumetric folding, the third dimension of systems can also become preeminent. In some cases, systems may exhibit different Poisson ratios at the same time, which are defined as hybrid Poisson ratio. Therefore the Poisson ratio of a folding system can be interrogated according to the selected reference plane.

If xz is considered as a reference plane, Poisson ratio of the system is negative

(Table 1, configuration 5, left scheme), when xy is taken as a reference plane, the ratio is positive. Thus, in the kinematic evaluation of folding systems with a hybrid Poisson ratio, there is a need to act from a selected reference plane. If Poisson ratios in all axes are taken into consideration during movements of folding systems, all possible configurations can be determined as in Table 1. The Poisson ratio is accepted as negative, zero and positive, respectively, when the systems extend in the x-direction and expand, remain fixed or shorten on both of the other axes.

Table 1. *Possible configurations of a system that expands along x-axis (The straight line represents the folded state; dashed line represents unfolded state of the system).*

Number of configuration	x axis	y or z axis	z or y axis	Poisson ratio	Schematic representation
1	+	+	+	Negative	
2	+	0	0	Zero	
3	+	-	-	Positive	
4	+	+	0	Hybrid	 
5	+	+	-	Hybrid	 
6	+	0	-	Hybrid	 

Expansion/ Elongation (+), no change (0), contraction/ shorten (-)

During the folding process of systems, Poisson ratio can be changed due to folding geometry. In these cases *(e.g., if expansion at the beginning then contraction is observed along the Y-axis, or if contraction/ expansion rate changes)*, initial and final configurations of the system are taken into account. This situation, which is a result of the microstructure of systems; can be defined as non-linear Poisson's ratio functions *(Schenk, 2011)*.

2.3. Examination of Folding Process

The transition from initial to final configuration takes place by the folding of a system. Therefore, the movement of a system can be considered as a process. The system can be folded in a single phase or multiple phases, depending on its crease pattern, while transitioning to desired configuration. Single phased folding is defined as the ability of a system to transition from initial to final state with an uninterrupted motion *(Figure 2, top)*. Therefore, it can be understood that all sectors in the system fold synchronously. Especially the places *(e.g., spacecraft)* where human interventions are limited, some problems may occur due to the interruption of motion, so being able to be folded in a single phase becomes crucial *(Hanaor & Levy, 2001)*. Multi-phased folding is defined as the inability of a system to change configuration from initial to final state with an uninterrupted motion *(Figure 2, bottom)*. The movement is composed of certain folding stages, one after the other to reach desired configuration. The process can not be carried on until one of the folding steps is finished or a specific configuration is achieved. In systems where fold lines are orthogonal to each other, perpendicular creases can not be folded rigidly and simultaneously therefore, folding sequences must be followed. Also, sectors of some complex crease patterns may collide with each other.

The movement of a system is created by actuators that affect the system by pushing, pulling or rotating. Human intervention can also be considered as a kind of actuator. After a certain number of independent inputs are given to a folding system by each actuator, the system is configurated which can be called output. The number of inputs to obtain desired output is defined as the degree of freedom *(DOF)* of a system. Since multi-phased folding is, by definition, lots of repetitive single phased folding, degrees of freedom of systems are examined over single phased folding.

The predetermined configuration can be achieved in a single degree of freedom *(SDOF)* system with only one input *(actuator)*. SDOF systems can be compared with mechanisms that can only move forward and backwards. Thus, the potential of SDOF system to respond to different needs is low; since only two configurations of a system *(open-closed)* and intermediate phases can be generated during the motion. Therefore, in some cases, this singularity becomes a problem to adapt the structure to various environments. However, configurating system to final state with only one input provides simplicity and technical convenience during the deployment. Besides, malfunctions that may occur where there is no human intervention, can be prevented by this simplification *(del Grosso & Basso, 2012)*.

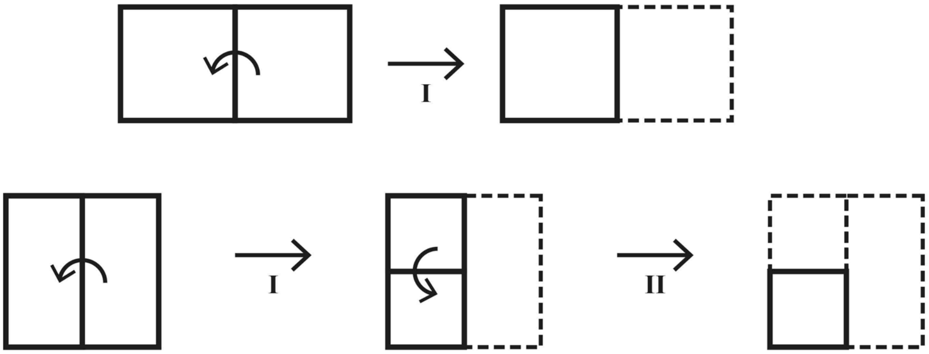


***Figure 2**. Schematic representation of single phased folding (top) and multi-phased folding (bottom).*

Multi-degree of freedom *(MDOF)* system can be configurated to the final state with the effect of more than one actuator. Therefore, possible configurations that can be achieved as a result of movement are much more than SDOF systems. The diversity of configurations makes MDOF folding systems convenient for structures with numerous programs, for this reason MDOF system has the potential to meet more than only one need. On the other hand, undesirable forms may be generated by MDOF systems since it is hard to control the movement of such systems as the DOF increases *(Overvelde et al., 2017)*. SDOF and MDOF systems are shown schematically in Figure 3. System 1 is defined as SDOF since only one input is needed to obtain Output 1. System 2 is defined as MDOF since at least two inputs are needed to obtain Output 2.

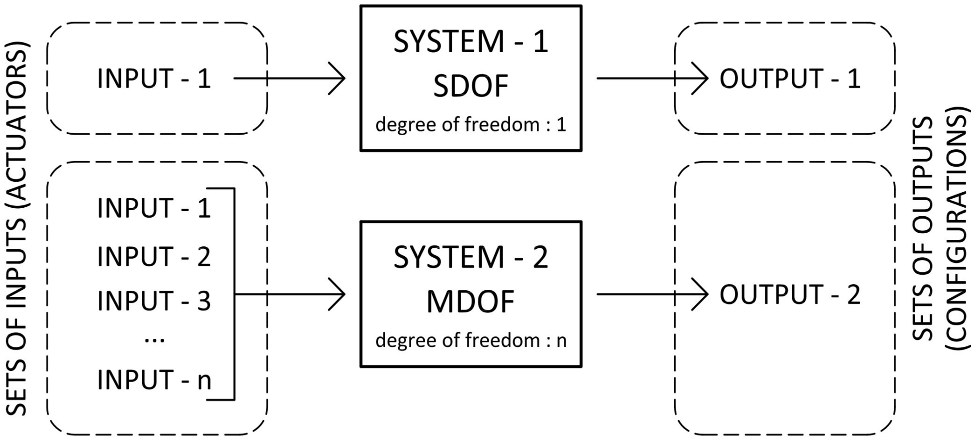


Figure 3. *Schematic representation of the configuration outputs obtained as a result of the motion inputs (actuators) of two possible systems (SDOF and MDOF) that can be folded in a single phase.*

As a result, folding movement is examined as physical, kinematic and process-oriented. Obtained data has been written into a matrix so that architectural designs can be examined and evaluated *(Table 2)*. The bottom part of Table 2 is enumerated for ease of follow-up in Table 5.

3. CORRELATION OF ORIGAMI ARCHITECTURE WITH BUILDING CONCEPTS

Buildings can be examined according to various approaches such as function, material, production method, scale, etc. Within the scope of the study, structures are considered as technical systems and examined in accordance with whole-part relations. Since buildings are systems, there are hierarchical relationships between system levels and the environment. An important feature attributed to this hierarchical relationship is that a decision or factor that affects the upper level becomes a necessity to be considered for the lower levels *(Toydemir et al., 2004)*. Hierarchical levels such as building elements, building components and building

Table 2. *Tree diagram of folding notions.*

<table>
<tr><th colspan="14">Folding Analysis</th></tr>
<tr><th colspan="5">Physical analysis</th><th colspan="6">Kinematic analysis</th><th colspan="3">Process analysis</th></tr>
<tr><td colspan="3">Rigid folding</td><td colspan="2">Flexible folding</td><td colspan="6">Poisson ratio according to Table 1</td><td colspan="2" rowspan="2">Single phased folding</td><td rowspan="3">Multi-phased folding</td></tr>
<tr><td rowspan="2">Flat folding</td><td colspan="2">Volumetric folding</td><td rowspan="2">Flat folding</td><td rowspan="2">Volumetric folding</td><td>Negative</td><td>Zero</td><td>Positive</td><td colspan="3">Hybrid</td></tr>
<tr><td>Folding that can return to a flat configuration</td><td>Folding that can not return to a flat configuration</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>SDOF</td><td>MDOF</td></tr>
<tr><td>F1</td><td>F2</td><td>F3</td><td>F4</td><td>F5</td><td>K1</td><td>K2</td><td>K3</td><td>K4</td><td>K5</td><td>K6</td><td>P1</td><td>P2</td><td>P3</td></tr>
</table>

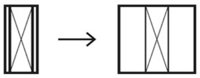
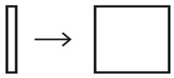
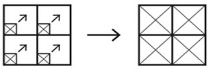
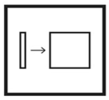
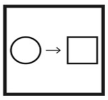
materials are defined as parts of a building *(Türkçü, 2015)*. Besides, a hierarchical level, as a building subsystem, can be considered between building and element levels *(Ching et al., 2013)*. Folding systems are examined based on which level the system responds to the function in terms of architecture. According to this method, it is also possible to understand the degree of kinetic properties of a structure.

At the building level entire structure is a folding system in which almost all parts are kinetic. The system has the potential to transform itself into the form of stowed plates. However, examples at building level, the potential of deployability may also vary depending on whether the system contains a core or not. The fact is that elements such as sanitary, elevators or stairs in buildings generally have permanent features that restrain kinetic features. Therefore, it is possible to consider them as different typologies. Structure with core can be defined as where folding panels are gathered around a core such as sanitary or stairs. These systems are inherently heavier than structures without core typically preferred in mobile units like temporary houses or caravans. Structures without core can be defined as just the sum of folding panels. Thus, they do not have space due to contraction. However, examples that only switch between different forms, it is obvious that all configurations define places to live in. Folding of the entire structure is usually possible on a small scale and lightweight construction such as emergency shelter, is also easily transported to the supply area and can be deployed rapidly since they generally do not contain cores.

Considering a folding system as a building subsystem is only possible if it fulfils a dominant function in building. Although functions of architectural examples have been found in the literature are generally solar control systems, it is also possible to diversify functions such as building shells. Subsystems are generally composed of repetitive combinations of smaller parts that can also be defined as building elements. Coordination or choreography of these pieces should be considered to meet a function due to lots of them. For the 21st century, software is preferred to coordinate such systems *(Schumacher et al., 2010)*.

A building element is composed of multiple building components that fulfil certain functions. These systems have the potential to be incorporated into buildings after construction due to their scales. Building elements can be divided into main and auxiliary elements. Main elements that are influential descriptors, manipulate places horizontally or vertically as walls, floors or roofs. The folding systems as main elements can be used to cover surfaces to create control layers or walls to organize spaces. Auxiliary elements are inherently weaker descriptors than main elements. Parts to connect adjacent spaces such as doors, windows and stairs that are utilised in daily life are included and evaluated in this concept *(Türkçü, 2015)*. Unlike other parts, auxiliary elements are positioned in a grey area that the intersection of architecture and industrial design in terms of scale. Small-scale advantage ensures that they can be produced in a factory thus, it makes them

Table 3. *Tree diagram of building concepts.*

Building Concept				
Building		Building subsystem	Building element	
With core	Without core		Main element	Auxilary element
				
B1	B2	B3	B4	B5

more affordable.

The data has been written into a matrix in order to examine and evaluate architectural designs. The schematics of building concept levels are in Table 3 to clarify the notions. The bottom part of Table 3 is enumerated as Table 2 for ease of follow-up in Table 5.

4. EVALUATION

Examples of structures and components with different scales, functions, folding methods, building levels, covered areas, material properties, thickness, folding patterns, movement capabilities, geometric configurations and control systems have been compiled from various countries. 47 examples are examined in the context of the paper, and also detailed presentation can be found in the thesis *(Süalp, 2021)*. Examples are selected among the kinetic products that perform their movements with folding processes *(origami principles)*. The list of examples is conveyed by number, name, year of construction/design and function of kinetic structure or building part and evaluated in terms of criteria *(Table 4)*.

Examples can be simply divided into two as single and multi-piece products. Single-piece products *(1-38 in Table 4)* are structures that consist of folding system. Therefore, they are not assumed to disassemble under normal circumstances. Single-piece products are designed to change configuration *(1-8)*, become compact *(9-33)* and both *(34-38)*. Multi-piece products consist of more than one part *(39-47)* are designed as systems that can be put together and reconfigured in an orderly manner *(39-40)*. Also, they can be disassembled or compacted for transportation and storage *(41-47)*. Besides, the compositions of parts in multi-piece products have also been examined. Radial, linear, planar and symmetrical arrangements are observed in the examples *(indicated as R, L, P and S on the top row of Table 5)*. Although multi-piece designs are examined according to physical, kinematic and process-oriented based on a single part of the system, they are examined according to building concept level based on the whole of the system.

The paper demonstrates how buildings are examined in this section. Two examples from Table 4 are selected to show how the defined classification is applied. One

Table 4. *List of examined buildings and parts.*

No.	Name	Date	Function of kinetic structure or building part	No.	Name	Date	Function of kinetic structure or building part
1	Tessel	2010	Installation	25	Habitaflex		Accomodation
2	Evolution door	2013	Door	26	Ha-ori shelter		Experimental
3	Resonant chamber	2013	Acoustic	27	Foldable container		Multipurpose
4	Appended space	2014	Experimental	28	Klapster		Staircase
5	Canary wharf kiosk	2014	Building shell	29	NOHA folding house		Accomodation
6	Kinematic sculpture	2018	Installation	30	RD shelter		Shelter
7	Bloomframe		Balcony	31	TF-64		Multipurpose
8	Kaleidocycle		Experimental	32	Tri-tainer		Multipurpose
9	Acorn house	1945	Accomodation	33	TSB shelter		Shelter
10	Markies	1995	Accomodation	34	Recover shelter	2008	Shelter
11	Rolling bridge	2004	Bridge	35	Cardboard banquet	2009	Experimental
12	Origami shelter	2011	Installation	36	Apartamento JAP	2016	Seperation wall
13	Auto-lock box dome	2013	Experimental	37	Archi folds	2018	Installation
14	Cardboard pop-up dome	2013	Experimental	38	HuSH2		Shelter
15	Origami zip	2013	Shelter	39	Kiefer technic showroom	2007	Solar control
16	Foldable half dome	2016	Experimental	40	Al Bahar towers	2012	Solar control
17	Rigid origami shelter	2017	Experimental	41	Plydome	1966	Building shell
18	Lunark	2020	Building Shell	42	Xile	2006	Tunnel
19	Boxabl		Accomodation	43	Packaged	2008	Installation
20	Cardborigami		Shelter	44	Foldable dome	2015	Experimental
21	Compact shelter		Shelter	45	SURI shelter	2015	Shelter
22	EBS block		Accomodation	46	M.A.DI. M60		Accomodation
23	Fold & Float		Shelter	47	Origami shelter (KSL)		Shelter
24	Exp. shipping container		Multipurpose				

of them is selected from a single-piece and the other from multi-piece products. Cardboard pop-up dome was designed by Dwayne van Halewijn and Leon Zondervan in 2013 at Delft University. It is made of 5 sheets of corrugated cardboard, 7 mm in each layer, connected to each other by translucent tapes *(Latka, 2017)*. It can be classified as rigid volumetric folding that can return to a flat configuration *(F2 in Table 5)*. Poisson's ratio is negative because the system expands in all three directions *(K1)*. It can be seen in Figure 4 that it can be deployed in a single phase by four people therefore, it is MDOF system *(P2)*. Also, it can be defined as a building without a core *(B2)*.

M.A.DI. M60, which was designed by Italian architect Renato Vidal, can be defined as a prefabricated modular frame that can be attached side by side in the form of the letter 'A' *(M.A.DI. M60, n.d.)*. It can be classified as rigid volumetric folding that can not return to a flat configuration *(F3)*. Poisson's ratio is zero since the system expands in only one direction *(K2)*. It can be defined as multi-phased folding since at first, the roof must be deployed then, the floor can be attached to the roof *(P3)*. Also, it can be defined as a building with a core since sanitary is included *(B1)*. Besides, modules can be attached linearly to each other *(L) (Figure 4)*.

Since a plane is a two-dimensional mathematical concept, one of the columns of the matrix, rigid volumetric folding that can return to a flat configuration *(F2 in Table 5)*, are considered structures that leave tiny air space inside when folded. In the matrix, only one option can be selected for each example in the groups of physical examination *(F1-F5)*, folding process *(P1-P3)*, building concept level *(B1-B5)* and composition of parts *(R, L, P, S)*. It is not possible to mark more than one for these four sections at the same time. Since systems can be examined with different reference planes, the aforementioned situation may not be valid for kinematic evaluation. Therefore, more than one or none of them can be marked for a few of the examples due to complex geometry of folding system *(K1-K6)*. Configuration, compactness or both options under the single or multi-piece products are included in the rows of evaluation matrix. Subheadings 'Configuration' and 'Compactness' under multi-piece products are briefly referred to as 'Conf.' and 'Comp.'. Besides, options that can not be evaluated are left blank *(Table 5)*.

When evaluating from a physical point of view *(F1-F5 in Table 5)*, it is detected that almost all of the examples of configuration and compactness under single-piece products exhibit rigid, volumetric folding *(F2-F3)*. It is observed that almost all of the remaining examples are rigid, flat folding *(F1)* and rigid, volumetric folding that can return to flat configuration *(F2)*. These groups are indicated in Table 5 with

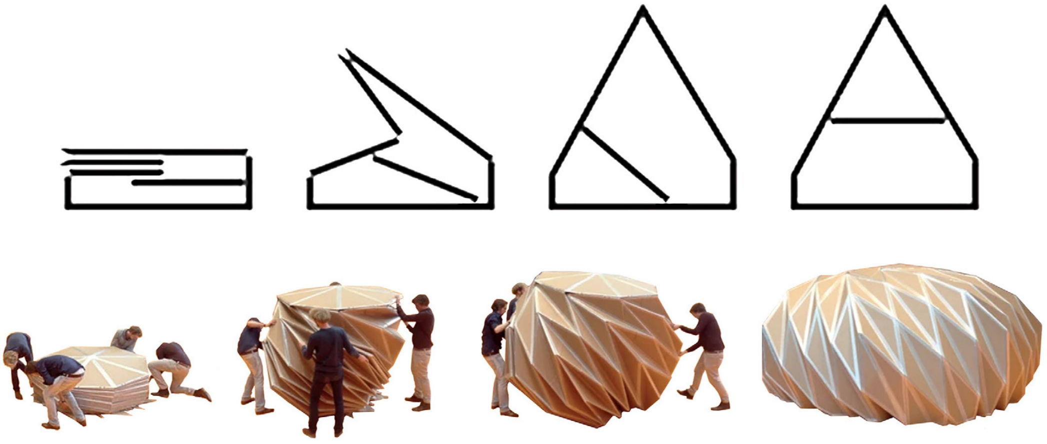


***Figure 4**. Deployment of M.A.DI. M60 (row 46 in Table 4) (top) (We fold, n.d.), and Cardboard pop-up dome (r. 14) (bottom) (Latka, 2017).*

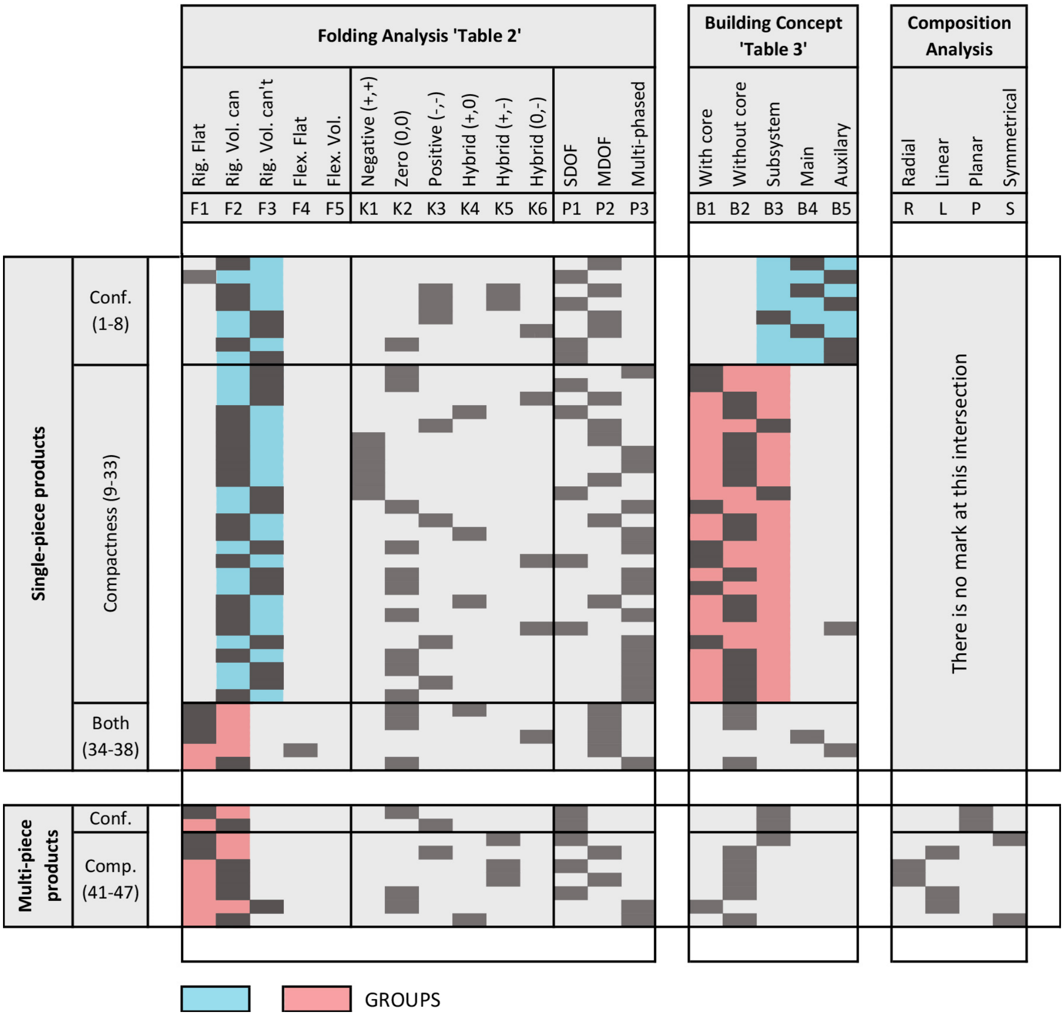


Table 5. *Evaluation matrix (groups are emphasized).*

two different colors. Also, no example is detected that met the criteria of flexible, volumetric folding *(F5)* that is also currently an exploration area for researchers.

In kinematic evaluation *(K1-K6)*, products that have Poisson ratio of zero *(K2)* are the most frequent with 17 examples and positive Poisson ratio is the second with 9 of them *(K3)*. There are 5 examples in each of the remaining ratios. While evaluating the kinematics, some systems are not marked since there is no distinct configuration change for Tessel *(row 1)* and Archi folds *(r. 37)*, and the systems return to the same configuration for Evolution door *(r. 2)* and Kaleidocycle *(r. 8)*. Also, more than one ratio has been marked since examples of Resonant chamber, Appended space and Recover shelter *(r. 3/4/34)* can be examined with various reference planes.

In the examination of folding processes *(P1-P3)*, it is observed that markings have been almost evenly distributed. It can even be stated that it is the most homogeneously distributed section in the matrix. This situation can indicate the diversity in architectural needs and preferences. There is no marking in the intersection of multi-phased folding *(P3)* and configuration under single-piece products and also, the intersection of SDOF *(P1)* and both. It seems correct by definition that there is no marking in the intersection of SDOF and both sub-heading. Since as mentioned above, a qualified response to various needs can not be provided by SDOF systems that can only swing between two configurations.

In terms of building concept level *(B1-B5)*, two main groups are observed and indicated in Table 5 with two different colors. All of the examples in the configuration section under the single-piece products are defined as building subsystems and lower levels *(B3-B5)*. On the contrary, almost all of the examples in the compactness are defined as building subsystems and higher levels *(B1-B3)*. Thus, it may be stated that the capability of contraction and transportation for higher hierarchical levels and transformation for lower levels are crucial factors. The only exception for this situation is Klapster *(r. 28)*. In the case of multi-piece products, no example is detected at the level of building element *(B4-B5)*. This can be interpreted as a logical result that such a product at the scale of a building element is not constructed by using more than one piece. Also, it has been observed that almost all buildings with core *(B1)* exhibit rigid, volumetric folding that can not return to a plane *(F3)*. The only exception is Fold & Float *(r. 23)*.

In terms of the composition *(R, L, P, S)*, two examples under the configuration section are arranged in a planar manner. On the contrary, only the planar column is not marked under compactness. The matrix contains more single-piece products than multi-piece products also, compactness is dominant in the subheadings of both. No multi-piece product that is convenient for both sections, is detected. In the paper, the three most frequent functions of kinetic structures are shelter, experimental, and accommodation.

5. CONCLUSION

In the paper, folding systems have been basically classified to make the subject more understandable for designers. Thus, examples of kinetic architectural products that act with origami principles were evaluated through folding and building hierarchy concepts. The matrix has been generated to visualize the distribution of the characteristics and to display architectural tendencies.

By the visualization of data, it becomes possible to examine the potential outputs of desired folding technique on the existing projects. Therefore, the matrix guides designers to select a folding technique that meets the function. It can be mentioned that the proposed method can be attributed as a novel perspective for predesign phase of origami-based elements. Thanks to the matrix, the areas that have not been studied in architectural applications such as curved creases are demonstrated. Also, the relationship between building concept levels and movement motivations such as configuration and compactness has been revealed by the study.

The findings and the matrix demonstrate that there are still many possibilities that can be studied. For example, it seems possible to study systems at the building level, which are produced as single piece and focus on changing its configuration. Besides, it is foreseen by the paper that architectural products with flexible folding capability can also be designed to increase the diversity.

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