LEARNING FROM FOLDING FOR DESIGN IN KINETIC STRUCTURES IN ARCHITECTURE

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ABSTRACT

LEARNING FROM FOLDING FOR DESIGN IN KINETIC STRUCTURES IN ARCHITECTURE

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This thesis explores the idea of flat and curved folding with the desire to contribute to the expansion of design in kinetic structures and its practice. It is described how these manifold notions can be used to understand in architectural discourse and its practical implications towards performative and responsive architecture. In this research, it is questioned how it can be learnt from mathematics of folding techniques so that what is learnt can be transformed into real plates and linkages of kinetic systems in a non-deformed way. It is also examined geometric formations of kinetic surfaces in regards with 17 symmetry groups to understand global motion and its enabler mechanisms. The fundamental pursuit of this research is to examine how learning from folding is used as an inquiry method in the field of kinetic structures. Hence, both flat and curved folding schemas are transferred into kinetic structures through by paper folding models, digital simulations, and real prototypes. The methodology served by this research could possibly provide potential methods of investigation for further studies in the field of architectural and structural design strategies.

Keywords: Origami, Flat Folding, Curved Folding, Kinetic Structures, Responsive Architecture

ÖZ

MİMARLIKTAKİ KİNETİK YAPILARIN TASARIMI İÇİN KATLANMADAN ÖĞRENME

Çavuş, Özlem
Yüksek Lisans, Yapı Bilimleri
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Bu tez, kinetik yapıların tasarım ve uygulama alanının genişlemesine doğrudan katkıda bulunma arzusu ile düz ve kavisli katlamaları araştırmaktadır. Bu kavramların mimari söylemde ve uygulamada nasıl kullanılabileceği anlamak için performans odaklı mimariye yönelik pratik sonuçları anlatılmaktadır. Bu araştırmada, katlama tekniklerinin matematiğinden nasıl öğrenilebileceği, ve öğrenilenlerin deforme olmadan kinetik sistemlerin gerçek plakalarına ve bağlantılarına dönüştürülebilmesi sorgulanmaktadır. Ayrıca, tüm yüzey hareketini ve bunu sağlayan mekanizmaları anlamak için 17 simetri grubu baz alınarak kinetik yüzeylerin geometrik oluşumları incelenmiştir. Bu araştırmanın temel amacı, katlamadan öğrenmenin kinetik yapılar alanında nasıl bir sorgulama yöntemi olarak kullanılacağını incelemektir. Bu nedenle, hem düz hem de kavisli katlama şemaları, kağıt katlama modelleri, dijital simülasyonlar ve gerçek prototipler aracılığıyla kinetik yapılara aktarılmıştır. Bu araştırmanın sunduğu metodoloji, mimari ve yapısal tasarım stratejileri alanındaki ileri çalışmalar için potansiyel araştırma yöntemleri sağlayabilir.

Anahtar Kelimeler: Origami, Düz Katlama, Kavisli Katlama, Kinetik Yapılar, Responsif Mimari

To my beloved mom and dad with love…

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LIST OF ABBREVIATIONS

ABBREVIATIONS

2D: Two Dimensional

3D: Three Dimensional

AI: Artificial Intelligence

CAD: Computer Aided Design

CAM: Computer Aided Manufacturing

DOF: Degree of Freedom

SMA: Shape Memory Alloy

CHAPTER 1

INTRODUCTION

Folding paper (origami) is an ancient art of Japanese tradition and today it becomes a new way of inspiration in different disciplines such as architecture, engineering and medicine. It can be seen many examples of contemporary use of origami. These are mainly kinetic structures, many engineering, medical, and robotic applications which are highlighted under this title.

After brief background information about this study, motivation, research questions, aim and objectives, methodology, and disposition of the thesis will be presented respectively.

1.1. Background Information

Kinetic structures, origami, and relationship between origami and kinetic structures are explained briefly under this section to highlight the thesis topic.

1.1.1. Kinetic Structures in Architecture

Architecture is passing through a different dimension with technological developments in the field of information technologies which are one of the most dominant reasons of transformation and change in architectural design and practice. Architects always try to respond users' needs and demands considering changing environmental factors, and today's technology offers architects flexibility in design to provide a new level of responsiveness. Not only in architectural design, but also in building science it is possible to observe the influence of technological developments. For example, advances in technology leads to the emergence of transformable structures which can be controlled automatically according to an assigned function.

This notion has been mostly named as kinetic architecture. Indeed, it indicates integral parts of the building to move with maintaining structural unity.

Involvement of kinetic structures allow architects many potentials in building design. These potentials are mainly flexibility in layout and form, responsiveness, adaptability to environmental conditions, convertibility of the construction, transformability, and automated control. Thanks to these potentials, number of applications is increasing, and examples of the applications can be observed from small scale to larger scale one such as the kinetic facades. Nevertheless, performance of these applications is relatively limited and some of them do not work as expected. This situation causes inefficient use of potentials of kinetic structures. An efficient design is possible with a mechanism working in a flawless way, because kinetic structures are actually controlled mechanisms. Unless the system is designed and operated precisely, it brings about associated design complications. Therefore, more affords are required to develop such structures. In fact, interdisciplinary approaches are necessary, because the design in kinetic structures is a multi-dimensional task including mathematics, material science, engineering, and architecture.

Architects should also cope with many problems faced by mechanical engineers along with satisfying structural stability in order to benefit from potentials of kinetic structures efficiently in their design process, since geometrical form, kinematics, and structural responses are closely linked to each other. In fact, more effective design can be provided if the idea behind the mechanism is understood well, so it needs further afford to design kinetic systems. Therefore, there are always researches concerning new and easier methods for kinetic design supported with different tools such as simulation and physical model. Folding (origami), in that sense, is an excellent analogue medium to study form, force, and motion for various fields as well as for architecture.

1.1.2. Origami

Origami is the ancient art of paper-folding. The word is originated from Japanese and is a combination of oru that means fold and kami that means paper. Starting with a sheet of paper and just by folding it, various shapes that can be obtained, has attracted many people. Although origami is mostly acknowledged as simple 3D models such as a classic origami boat or a crane in the minds of many people, today its potentials are recognized to further develop several complex systems. It does not only connotate folding of a piece of paper anymore. Rather, it is turning into a term which is used to signify folding and bending by many distinct research fields. These fields are mainly the fields concerning kinetic structures, like many engineering, medical, industrial and robotic applications. There are many examples of contemporary use of origami which can be seen in a wide spectrum from a satellite developed by NASA, to a stent designed for heart vessels.

Moreover, today origami turns into a field leading to appear an occupation named origami scientists engineer. The urge behind the recent progress in origami science is closely related with enhanced mathematical understanding of origami and potentials offered by newly arisen computational tools. These advances also result in emergence of new area of researches in origami field such as flat folding which means basically that in the folded state, all lines lie in parallel angels. Including these new research fields, researchers working on origami come together every four years at international meeting of Origami Science, Math, and Education (OSME).

1.1.3. Relation between Kinetic Structures and Origami

As it is briefly discussed in the previous title, origami has been known as a paper folding for years, but today understanding of origami has been evolved from its first recognized meaning (paper-folding) to a mean for complex design applications. In fact, origami is used as an inspiration tool for many researches including kinetic structures in architecture such as kinetic facades. Many of recent developments are result of increasing mathematical understanding of origami and growing computational design platform. These improvements are significant, as understanding geometrical pattern relations is a necessary part of these studies. The pattern diagram which consists of valley and mountain fold lines can be a source for structural network or a template, since fold-lines can be associated with linkages and vertexes can be associated with joints. That is, these points and lines can be linked to the linkage system of the mechanism. If this mechanism is controlled in a stable and flawless way, the pattern diagram can be turned into a structural network. In addition, origami allows us to see the forces and predict the motion. For instance, focusing on movements of edge points, motion path line can be understood. Origami can teach us folding mechanism.

Moreover, considering geometrical transformations during folding process, it can be observed that any fold-lines remain constant in length. That is, it is an isometric transformation which means shape-preserving transformation. On the other hand, kinetic structures are controlled mechanisms consisting of rigid bodies. Based on this relation between origami and kinetic system, it is possible to claim that understanding spatial organizations of origami patterns which can be associated with rigid bodies can provide improved understanding of mathematical rules behind the folding mechanism. Besides, it helps to create mathematical formalization in computational media. Indeed, underlying mathematical relations of 2D origami patterns resulting with 3D models can offer a new analogue-digital design medium for designers in their works.

Another advantage of origami is that it is used as a form finding tool together with satisfying structural quality at the same time. Starting with a sheet of paper and just by folding it, various structural forms can be obtained. Also, no matter how complex forms are, origami structure can be folded or unfolded without deformation and locking problem which are serious obstacles for deployment. Hence, origami patterns can provide the realization of the network of a mechanism along with facilitating further control of applications. Moreover, curved origami offers potentials to generate shell structures.

Topological configurations of origami forms are defined over points and lines, and they construct diagrams from 2D space to 3D space. Resulting model in computational design environment can provide improved understanding of a constructed structure along with offering also clues for fabrication of these models from simple materials to complex 3D forms. For instance, it gives the idea of descriptive geometries of very complex forms which can be used as a layout drawing for digital fabrication. In addition, it also gives clues about detailing such as where to assign joints and where to overlap structural members or where members should not overlap.

The major advantage of origami-based structures is for the kinetic movements the use of a single type of force such as tension, compression or torsion, which enables the motion in a very simple flawless way. It is 1 DOF, yet complex deployment patterns are possible. A kinetic system should operate precisely. Otherwise, it becomes harder to control especially if a kinetic structure is composed of complex detailing. Regardless of complexity of origami folding diagram, it can be folded with a single type of force such as tension and compression, or torsion together with sustaining stability.

Taking consideration into above-mentioned advantages of origami based kinetic structures for architecture, in particular, origami is examined in two main types as orthogonal and curved folding in the context of this thesis, as both folding types have different potentials for architectural applications. The notion of orthogonal folding contains tessellations and flat folding. While tessellations do not allow any overlap and gap between parts, flat folding does. The term which is named as flat folding means that in the folded state all planes line in parallel planes. Origami which is based on the idea of flat folding can provide not only a single type of force which is adequate to fold or unfold, but also can help to overcome detailing problems which block operating mechanism, since if a kinetic structure is able to reconfigure itself allowing two-way transformations between flat folded state and deployed position, it can be claimed that this kinetic structure has overcome many problems such as detailing. Otherwise, detailing problems can turn into a bottleneck in terms of transmission of motion, overcoming friction, and material deformation. On the other hand, curved origami also offers many potentials for architectural design and practice. It can gain buildings different formal expressions together with the increase in strength and stability for shell structures and curved deployed facades. Instead of using similar patterns on building facades such as accordion folding, for example it can be given more stunning expressions letting architects manipulate forms in response to environmental forces such as sun and wind. If mathematical rules regarding geometric formations of 2D and 3D curved shapes, and their transformations from 2D to 3D are understood well, then it can be understood the language of curved folding in an easier manner. If it does, curved folding can open new areas for architects to explore free-forms and realize what it is wanted to create without material deformation.

1.2. Motivation

The advent of new technologies and changing needs push the limits of architecture allowing built projects to go beyond definitions of static space. Today, conventional definitions are no longer enough to describe flexibility to fulfill responsiveness in the realm of architecture. Design of kinetic structures needs more afford so as to benefit from potentials of technological developments effectively, because the efficient use of kinetic structures provides many advantages that makes them very promising in the realm of architecture. These advantages can be listed mainly as stated as follows;

- Flexibility in layout and form
- Responsiveness
- Adaptability to environmental conditions
- Convertibility of the construction
- Transformability
- Automated control

Due to above-outlined advantages, the use of kinetic structures is increasing in architecture. There are many examples of these structures in architecture and they can be seen from small scale applications to large scale ones such as kinetic facades.

Designing kinetic structures needs interdisciplinary approaches, since geometrical form, kinematics, and structural responses are connected to each other deeply in this sort of systems. In fact, it is significant for a researcher to understand the underlying idea behind the mechanism, because kinetic structures are actually controlled mechanisms and any problem, or any design decision can affect the final outcome. To illustrate, researches have proved that selected geometrical pattern affects the structure's performance. Therefore, architects should learn how to cope with many difficulties in relation with structural stability. Consequently, these challenges and needs draw attention to the importance of having guidelines for architects to design kinetic architectural structures in order to cope with potential problems like:

- Decrease in load bearing capacity
- Friction
- Nonlinear structural behavior
- Managing with a single force
- Maintenance
- Small sizes of components
- Units which are huge in number
- Complicated communication among the components

Above mentioned list can be extended, but majority of these problems are linked to the motion itself. If motion is transmitted in a proper way under simple forces, apparently complexity of the structure is decreased. Besides, if a kinetic structure is capable of working fold or unfold under single force condition, that makes the motion easier and energy consumption is obviously decreased. Therefore, it is crucial to figure out how a kinetic system works and how motion is transmitted in a proper manner. Unless it is understood by architects, these complex structures also limit architects in exploring new form-finding process. Even today, kinetic architectural structures have restricted type of movements such as accordion folding, so new tools are needed to facilitate understanding of kinetic elements. At this point origami can help us to understand kinetic systems as an analogue interface.

The reason to offer origami as a medium of inquiry for architects is that it evolves the form defining its topological relations over points and lines in an easy way. That points and lines have potentials to be used as not only a form finding tool, but also a template or a network for kinetic structures. Besides, based on the transformations of points and lines in association with joints and linkages and understanding motion, it can be learnt the mechanisms of kinetic structures. In addition, it can be figured out how a kinetic surface works as a network rather than working over a single linkage. Hence, learning from origami to understand an entire behavior of a kinetic surface is also significant to develop better control scenarios.

Moreover, the major advantage of origami-based structures for the kinetic movements is the use of a single type of force, which enables the motion in a very simple flawless way. In fact, these structures work with a single type of force such as tension, compression or torsion regardless of folding types and their complexity.

Also, researches on kinetic structures mainly focused on 1DOF structures. Those are associated with flat folding. However, architecture not only concern orthogonal forms, but also curvilinear forms. These forms can be obtained from paper along with thickness considerations. It depends deeply on understanding of its mathematics.

Consequently, this study proposes origami as an inquiry tool for architects to develop kinetic structures.

1.3. Problem Statement and Hypothesis

On the one side, it is not an easy task for architects to design kinetic structures resulting from the improper understanding and transmittance of motion. Therefore, today's kinetic architectural structures have restricted type of alternatives in architectural skins.

Hypothesis of this research corresponding to above-stated problem is that we can obtain kinetic structures that require interdisciplinary approach such as mathematics and mechanical engineering through by learning from folding (origami). In that sense, any sketch which sustains foldability considerations can turn into a real structure

Origami, however, have different modes as flat and curved folding in terms of geometric constructions of lines. In particular, flat folding type of origami can provide elimination of detailing of the mechanism in order to transmit the motion as planned and curved folding can provide a new form generation tool for kinetic structures preserving material from deformation.

1.4. Research Questions

Question 1: How can we transform folding with ideal zero thickness into real kinetic systems?

Question 2: Is there any relation between origami patterns and symmetry groups? If there is, how to integrate this relation to kinetic structures?

Question 3: Is it possible to eliminate detailing of kinetic structures through by learning from flat folding type of origami?

Question 4: Is it possible to benefit from curved folding to create new kinetic forms without deforming material?

1.5. Aim and Objectives

The fundamental pursuit of this research is to propose origami as an analogue medium of inquiry to develop deployable kinetic structures from any sketch which is employed foldability rules. Objectives are to validate that origami is a source to understand kinetic systems, to show how origami patterns are converted into the mechanism, to propose origami as a template for kinetic structures, to prove that flat folding has potentials to eliminate associated design problems, and to validate that curved folding is a tool for new form generations which can be implemented on architectural kinetic skins without deforming material.

1.6. Significance of the Study

In general, experimentations and applied projects concentrate on 1DOF individual kinetic components. In this research, it is tried to contribute to develop kinetic structures working as a network based on the idea of both orthogonal and curved origami through by design research by doing. In this sense, it is also contributed to integrate curved kinetic forms applied in building as an integral part. However, it is hard to develop curvilinear systems due to complexity of its geometry. In fact, they work with at least 2DOF. Still, it is new and open to research.

1.7. Methodology

Two main types of origami which are orthogonal and curved folding are transferred into kinetic structures working as a network by creating simulation and prototyping. First, paper folding is used to understand folding kinematics so that models can be generated in a parametric design environment. After digital model is created in Grasshopper for Rhino, 1/1 scale prototype is developed via Arduino. Then created prototypes are applied to building facade. Accordingly, results will be discussed to test the hypothesis.

1.8. Disposition

The current thesis is composed of five main chapters as introduced as follows respectively; introduction, literature review, research methodology and material, results and discussions, and conclusion.

First chapter is an introduction chapter, presenting the background information followed by motivation, research questions, the aim and objectives, methodology, and thesis disposition respectively.

In chapter 2, literature review is given. It is summarized under two main parts. The first part focuses on kinetic structures' potentials and problems. The second part mentions about origami focusing on contemporary understanding of origami, origami mathematics, and applied origami along with highlighting its benefits for design in kinetic structures.

In chapter 3, theories and postulates regarding mathematics of folding are explained with the aim of drawing framework of the process. It includes relative information about the execution of the computational design procedure and digital fabrication for prototyping. At the end of the chapter, the design process is summarized in a flowchart.

In chapter 4, research materials and case studies are examined through by the discussions on each output.

In the chapter 5, which is the final section of the thesis, topic is taken into account in terms of the importance for the literature by giving a short brief of the outline of the study. The significance of the subject is emphasized regardless of the results which are explained in detail in chapter 4. Finally, possible advices are given for further studies in the field of architectural and structural design strategies.

CHAPTER 2

LITERATURE REVIEW

This chapter intends to sustain relevant information from the literature. The literature survey is summarized under two main sections. The first section highlights kinetic structures in architecture while the second section mentions about origami inspired kinetic structures. In all these studies, form finding and mechanism finding should coexist, because these forms are motion embedded forms and its structure is a controlled mechanism. Nonetheless, they are not occasionally considered together, and this discrepancy is also encountered in the literature.

The first section focuses on kinetic structures in the realm of architectural design and practice. It encapsulates two main parts; general terms and definitions regarding kinetic structures in architecture and their brief historical overview. The first part examines reasons for the preferences of kinetic structures to highlight their significance for architectural applications. The second part mentions about progressive development of kinetic structures to show what is done up to now and what is new in state-of-art kinetic structures.

The second section illustrates the position of origami in literature in terms of its mathematics and applied thick origami. The changing meaning of origami is also discussed under this part, since origami has confirmed as an inquiry tool for further developing new systems in many fields such as kinetic facades. Moreover, today understanding of origami is transformed into several advanced studies like car absorbers, stent for heart vessels, robotic arms, and solar antennas. Its benefits and application fields are presented. The first part focuses on mathematics of origami in regards with geometric transformations from 2D to 3D, simulation of origami, and two folding types: flat folding and curved folding. Mathematics of origami should be understood well, because the underlying mathematical idea of origami facilitates the understanding of a kinetic structure. In fact, it describes geometries and their transformations between 2D and 3D. If geometric relations of origami patterns are well-defined, it remains easier to create computational algorithm, since what is simulated is actually related with geometric transformations in computational design environment. This algorithm can also be used as a template file for digital fabrication of a kinetic structure. The second part engages in applied origami concerning rigid folding, influence of origami patterns, intelligent systems, and materialization and joints.

2.1. Kinetic Structures in Architecture

Under this title, two main sub-categories regarding applications of kinetic structures are examined in the field of architectural practice and design. The first part discusses the importance of kinetic structures in terms of architecture, while the second part gives a brief background information about their progressive development.

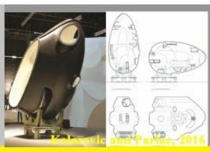
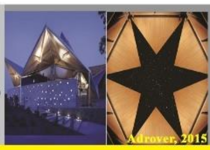
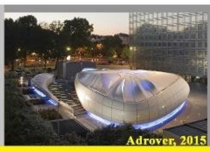
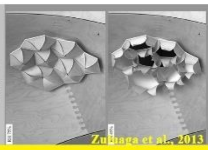
2.1.1. General Terms and Definitions regarding Kinetic Structures in Architecture

The need for the mobility in architecture has existed since ancient times when people moved from place to place with desire to find better pastureland (Gantes, 2001). For centuries, kinetic components have been repeatedly used as architectural components; from traditional hinged windows, sliding doors and shutters to innovative fully portable dwellings, folding bridges and entirely adaptable structures (Stevenson, 2011).

Every age has produced its own architectural language such as ‘functionalism’ in the 1920s and ‘systems’ in the 1960s, but the notion of intelligence which makes architecture a part of a changing environment is one of the most significant language of today’s architecture (Moloney, 2011). In recent years, kinetic structures are used in architecture in many ways, so there are appeared many terms to identify kinetic structures. Commonly used terms and typologies related to kinetic architectural structures are categorized by Megahed (2016) as deployable, transformable / transportable, performance-based, adaptable, responsive, mobile, and intelligent. It is believed that understanding the terminology of kinetic architecture is important, since their features and pros and cons are different. These mentioned definitions focus on different modes of structures in motion. The crucial part in understanding kinetic architecture is understanding its mechanisms. It is possible with the compatibility of these mechanisms with building form and structure. There are three categories of this kinetic tectonic: dynamic, kinematic, and kinetic (Barozzi et al., 2016).

Above stated terms can be summarized as shown in table 2.1. Each term is also exemplified together with their potentials and uses.

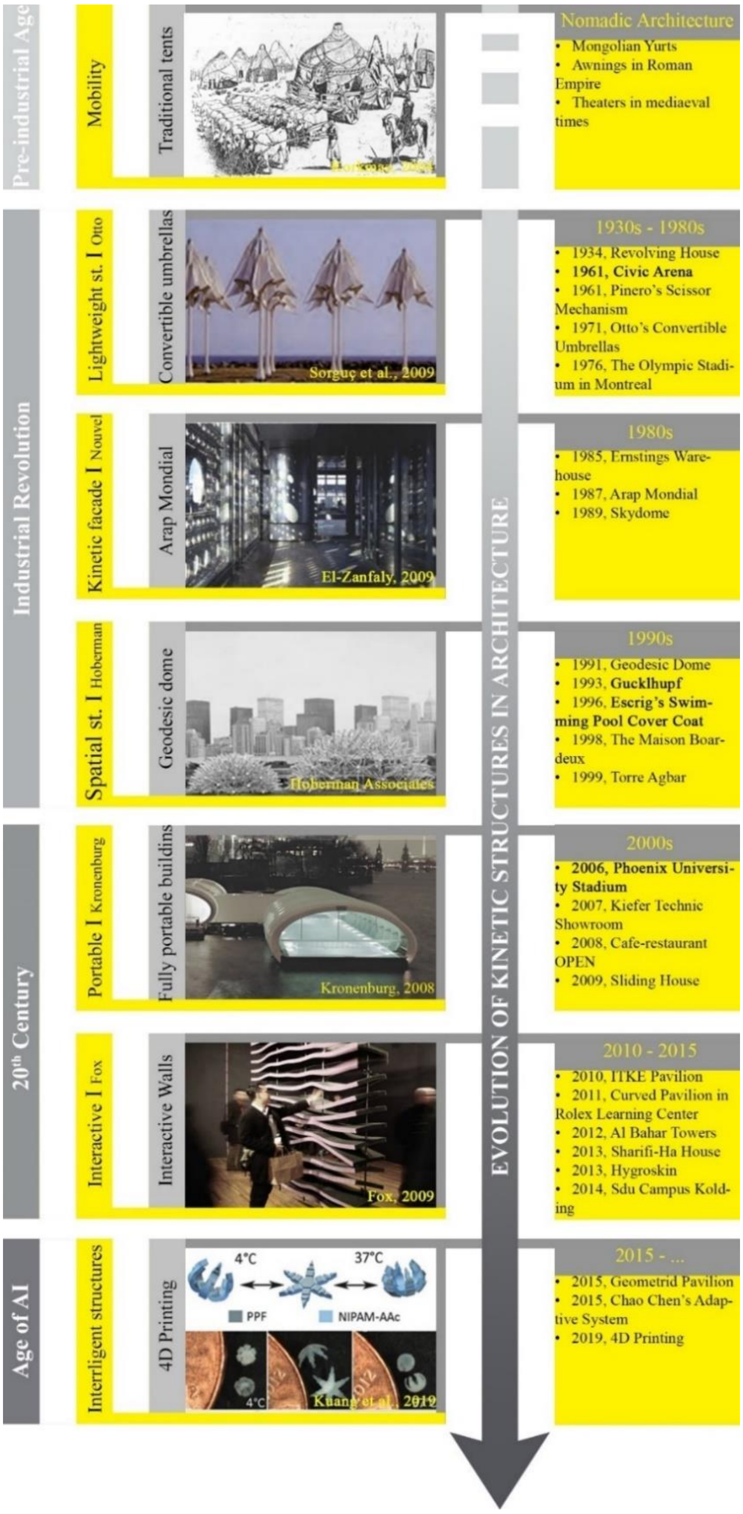
Table 2.1. *Kinetic Structures in Architectural Practice and Experimentations (developed by the author depending on the studies employed by Megahed (2016)).*

		Example		Example			Potentials & Use	Definition
AIM	performative	Algae House		Solar Wings		Potentials & Use	• Enhancing the environmental quality of building • Providing better control for temperature and glare along with reducing air-conditioning expenses • Making solar energy systems more efficient (Ramzy and Fayed, 2011)	"ability to mediate between the comfort required by the users and the surrounding environments" (Turrin et al., 2012)
AIM	responsive	Torre Agbar		Thyssenkrupp		Potentials & Use	• Providing varying vistas • Allowing different orientations of space to cope with whether conditions in different seasons such as active envelopes to obtain desired thermal comfort (Ramzy and Fayed, 2011)	"ability to adapt and change in response to the environment or to accommodate the contingencies of daily life" (Meagher, 2016)
COMMON FEATURES	adaptable	MJE-House		by Chao Chen		Potentials & Use	• Flexibility in layout and form such as interior partitions • Adaptability to site conditions (Chu, 2012)	"changing functions, features or behaviour in response to transient performance requirements and boundary conditions" (Loonen et al., 2015).
COMMON FEATURES	transformable	Room Vehicle		Rolling Bridge		Potentials & Use	• Convertibility of the construction such as bridges and scaffolding for permanent structures (Korkmaz, 2004)	"altertion of their configurations into new arrangements intended to meet changing requirements" (Temmerman et al., 2012)
MODES	deployable	Starlight Theatre		Umbrella		Potentials & Use	• Speed of erection, which is very significant in emergency situations and bad weather conditions • Ease of transportation and storage due to the compact shape in the undeployed form • Reusability such as exhibition structures • Minimum skill requirements for erection, dismantling, and relocation (Gantes, 2001)	"alteration in geometry through the process of deployment" (Calladine, 2001)
MODES	mobile	Channel Pavilion		Mobile Caravans		Potentials & Use	• Reusability such as hot / inclement shelters adjacent to permanent buildings (Gantes, 2001) • Adaptability to site conditions such as travelling theatres and temporary buildings (Chu, 2012)	"Prefabricated structures which can be transported to the site." (Megahed, 2016)
MODES	portable	Caravans		Button House		Potentials & Use	• Convertibility of the construction such as temporary partitions, screens, arches, and beams (Korkmaz, 2004)	"alterations in the structure, skin, and/or internal surfaces allowing new shapes, forms, functions, or characteristics" (Megahed, 2016)
MODES	intelligent	4D Printing		Hygroskin		Potentials & Use	• Reduction of operational costs through efficiency in energy management (Silva et al. 2012) • The capability of being user- oriented encompassing improved safety, health, and well-being (Cempel and Mikulik, 2013)	"Structures that have the ability to learn." (Megahed, 2016)

2.1.2. Brief Historical Overview regarding Architectural Kinetic Structures

Notions defining kinetic architecture such as performative and responsive have appeared in different ways throughout the history. These examples increase and vary day by day, yet each example also brings associated problems as exemplified in table 2.2.

Table 2.2. *Progression of Kinetic Structures in Architecture (developed by the author based on the studies of Ramzy & Fayed (2011)).*



Early examples of kinetic structures dated back to ancient times when nomadic tribes moved from place to place with desire to find better pastureland (Gantes, 2001). Foldable and portable nomadic shelters was not built to physically last, it often had to be repaired and replaced. However, the skills and techniques for their construction were passed, advanced and refined from generation to generation (Stevenson, 2011). For instance, Sorguç et al. (2009) state that principles of the structure of Frei Otto's Convertible Umbrellas is inspired by traditional tents and realized as a prototype for lightweight adaptable buildings in 1950s. Then, in 1960s, Pinero contributes to the development of deployable structures with the use of scissor mechanisms which can enlarge in two directions. Thereafter, Hoberman examines new spatial organizations in regards with the idea of motion by following Pinero's work. In his structures, it is explicitly seen the idea of mechanism. Sorguç et al. (2009) criticize that those structures are mainly installations instead of being a part of building structure.

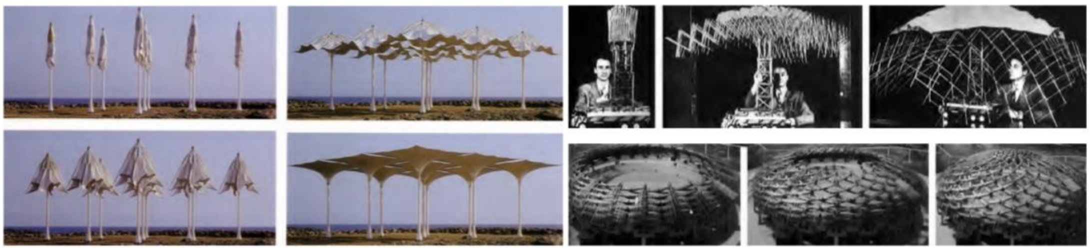


Figure 2.1. Convertible Umbrellas by Frei Otto; Right: Scissor Mechanisms by Pinero on the top; Hoberman's Iris Dome on the bottom (Sorguç et al., 2009)

In the end of the 1970s, buildings such as The Olympic Stadium in Montreal showed that materialization and detailing of kinetic structures could turn into a serious problem, unless the construction material is durable enough to allow deployment and resist against the weather conditions. For example, it is planned to cover the central arena which is 20.000 square meters in area with the use of a retractable membrane, hung from a tower. However, retractable membrane material had serious deformations from hanging points and connections (Korkmaz, 2004).

Figure 2.2. Montreal Sports Facilities. (Korkmaz, 2004)

In 1980s, building facades started to be kinetic like Arab World Institute, one of the pioneer examples of kinetic architecture. Metal kinetic surfaces rotate according to the sunlight in order to mediate the comfort zone (Kolarevic & Parlac, 2015). However, the mechanisms and controls were exposed, even though the system is sandwiched between two glass sheets. This situation causes mechanical problems due to constant need of maintenance (Meagher, 2015).

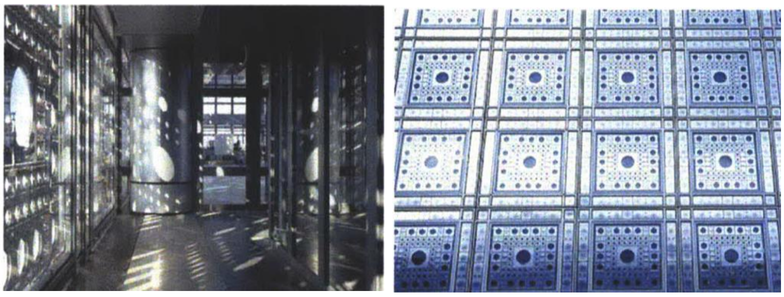


Figure 2.3. Arab World Institute designed by Jean Nouvel, Paris (El-Zanfaly, 2009)

Expandable Dome designed by Chuck Hoberman in 1990s is a deployable kinetic structure (Figure 2.4) which is prefabricated space frames which can expand from a compact bundle of components into a larger span (Mira et al., 2012). In fact, Hoberman evaluates the pantographs to create spherical skin structures such as Hoberman Arch by re-arranging topological relations using the same link in scissors mechanisms (Sorguç et al., 2009).

Figure 2.4. Expanding Geodesic Dome by Hoberman Associates Inc. (Source: http://www.hoberman.com. Retrieved at: 19.08.2019)

In 2000s, scope and application fields of motion has changed. For instance, it is constructed many large span stadium structures such as Mercedes Benz Stadium. The scale of the application where deployability is implemented reached very large scales.

Figure 2.5. Left: Mercedes Benz Stadium. Right: Starlight Theatre (El-Zanfaly, 2009)

Moreover, complexity of such structures like kinetic façade of Al Bahar Tower increases. The facade tries to sustain ideal level of solar and light conditions, yet its shading screen composed of 1049 mashrabiya units which make the system complex and harder to control (Attia, 2016).

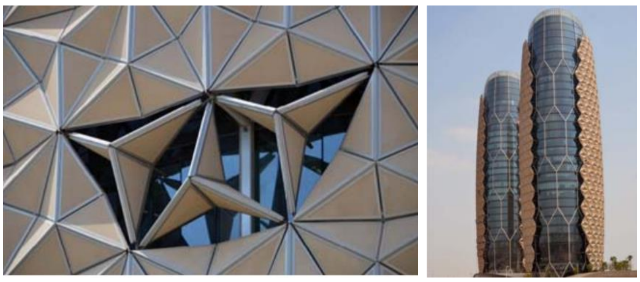


Figure 2.6. Shading Device and Entire Facade of Al Bahar Tower (Attia, 2016)

These complex structures are tried to be understood especially in terms of their motion types by many researchers. For instance, Fox & Kemp, (2009) collected under 3 main categories as embedded, deployable, and dynamic kinetic structures. Sorguç et al. (2009) claim that these improvements make architectural design process so complex that it becomes harder to design and evaluate kinetic systems which are integral part of the building. Hence, architects are forced to develop new approaches through inter-disciplinary studies, as designing such systems requiring the certain degree of knowledge in many disciplines like material science, mathematics, and mechanical engineering. Therefore, authors suggest that researchers should search new ways to cope with design problems of these structures so as to efficiently integrate them in design process as well as exploring new forms.

Grobman & Yekutiel (2013) argues that technology and cost constraints restrict designers with only certain types of motion sustained by façade cladding. One of the main limitations is based on designing and controlling motion scenarios that architects face in kinetic facades.

Especially with the idea of performance, Sharaidin (2014) states that incorporating performance of kinetic facades in pre-design stages offer many advantages for the construction process. These facades aim to improve building performance, however current applications have problems to sustain desired level after they were implemented. As designing kinetic elements is complicated due to moving components, author suggests new methodologies and alternative tools to grasp challenges before the actual facades are built.

In recent years, the language of kinetic systems has been evolved deeply, since lines between physical and digital are blurred and built projects move beyond borders of thinking in regards with material performance, connectivity, and control (Fox, 2016). Barozzi et al. (2016) mention that operation of adaptive facades consumes a lot of energy due to activation of mechanical system. This required energy should be less than energy saving in the optimum level. Maintaining this level is necessary for sustainability of the system yet increase in complexity increases energy consumption reducing performance.

Kinetic structures are used in larger scale applications as well. For example, encasement of Sliding House in Suffolk can slide along the rails set into the ground in order to offer the sense of enclosure, open-air living and different vistas. (Stevenson, 2011).

Furthermore, kinetic structures are used as demountable and relocatable structures with different forms. Eversmann, et al. (2017) create a curved folded pavilion as a composition of computational design and digital fabrication technology to structurally connect single and double-layer curved-folded aluminum panels. Authors state that structural joining techniques are challenging due to the complexity of the geometry and assembly trajectories between multiple curved-folded panels.

Figure 2.7. Left: Assembled wall detail, Right: Exhibition at Rolex Learning Center (Eversmann, et al., 2017).

In recent years, intelligent kinetic structures which move based on material property are also searched by many researchers. For example, the HygroSkin pavilion whose inherent behavior of material becomes an issue in kinetic architecture. The skin opens and closes in response to changes in moisture (Krieg et al., 2017).

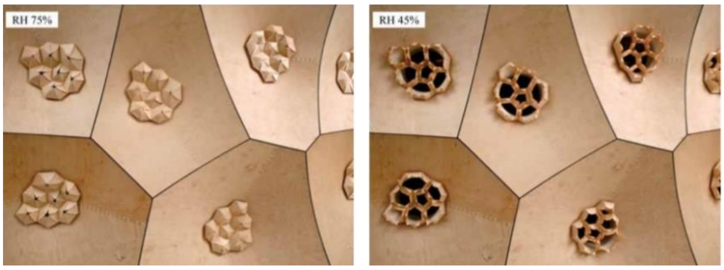


Figure 2.8. Exterior Faces of Hygroskin Pavilion. (Krieg et al., 2017)

In addition to hygroscopic materials, folding mechanisms can also move autonomously based on their material property. Also, form is assigned in accordance with its mechanism. For example, in 4D printing technology, the shape, property, and functionality of a 3D printed structure change when it is exposed to a preassigned stimulus, like heat and water (Kuang et al., 2019). Therefore, 4D printing is a new challenge for architects which can be new target for kinetic architecture.

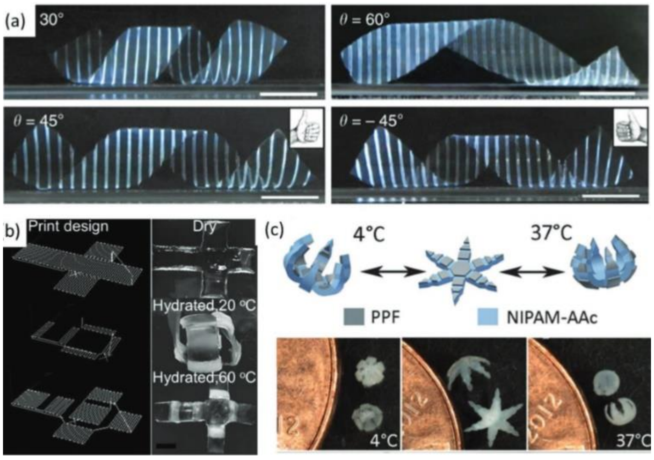


Figure 2.9. Temperature-responsive hydrogel composites based on PNIPAm. (Kuang et al., 2019).

Consequently, looking through the evolution of kinetic architectural structures, changing factors in their development throughout the process can be summarized as shown in figure 2.10.

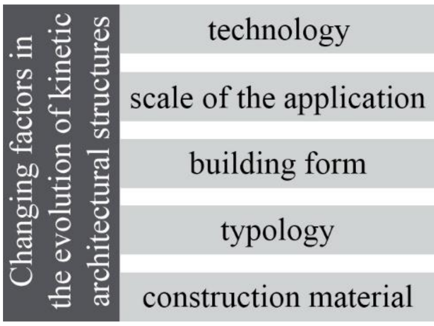


Figure 2.10. Changing Factors in the Evolution of Kinetic Architectural Structures (developed by the author).

Besides, problems stated in literature can be collected under two main categories (figure 2.11). First, how to design a kinetic system? Second, how to operate mechanisms of kinetic structures in a flawless way?

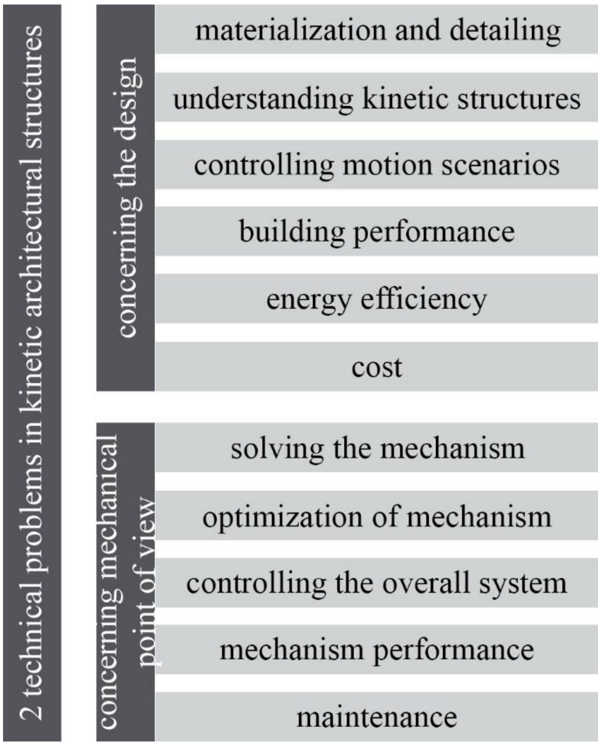


Figure 2.11. Technical Problems of Kinetic Structures (developed by the author).

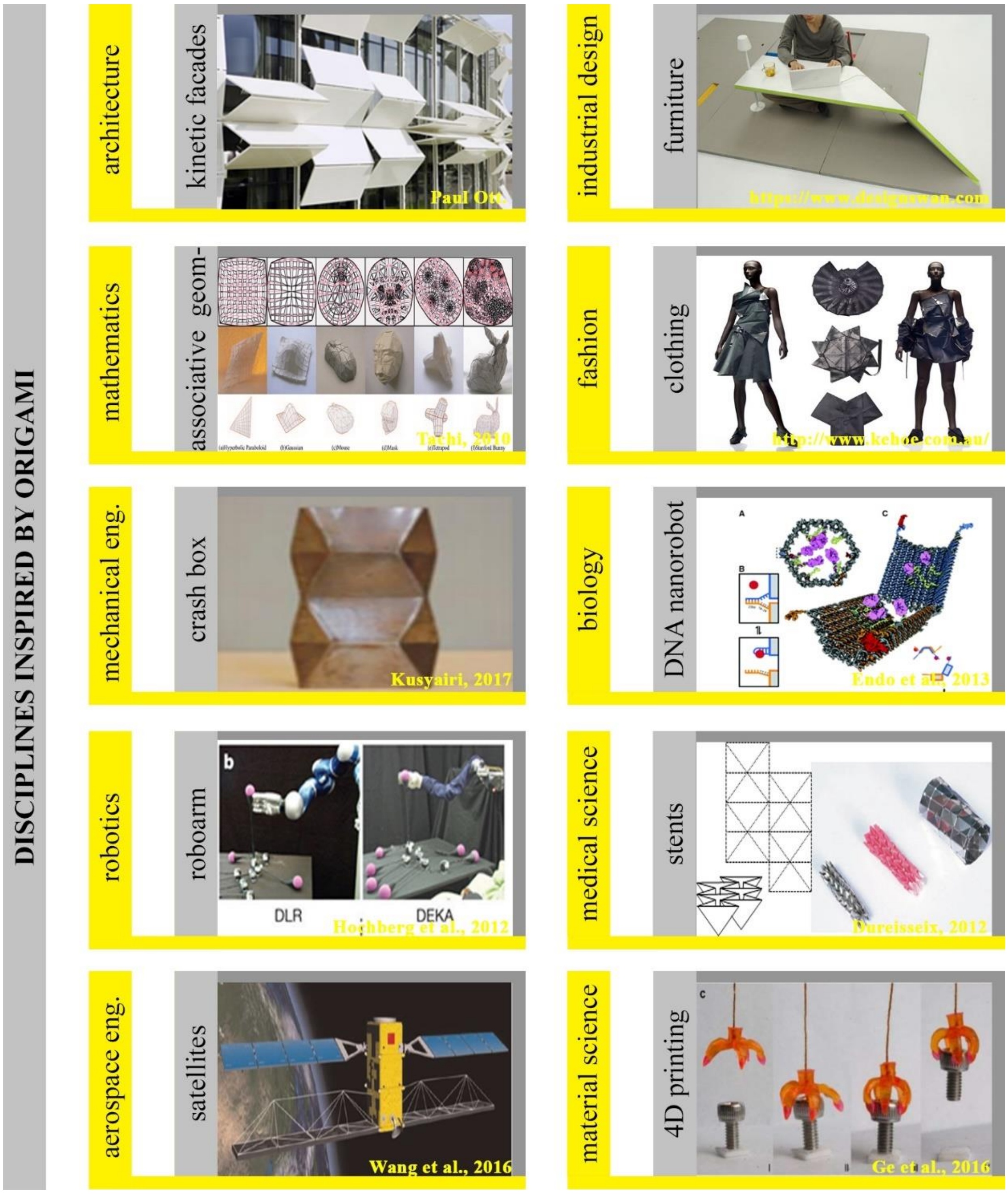
As a result, complexity increases in recent years, so it causes new complex problems with which designers face. These problematic fields should be studied, and new tools should be developed for architects to cope with associated problems with the aim of facilitating the design. It is indeed necessary for understanding of interdisciplinary perspectives which are required for the design in order to overcome limitations.

2.2. Origami

Origami is originated from the Japanese art of paper folding, and the word is a composition of ‘oru' and ‘kami’, referring to ‘fold’ and `paper' respectively. Nonetheless, modern use of origami is a design research medium to develop discrete and complex design applications and its mathematics becomes a tool to understand transformations of kinetic systems (Sorguç et al., 2009). That is, even though many people regard origami as simple models such as the classic origami crane, today origami tessellations like Miura-ori, which is the classic technical folding pattern, is used from light-weight cores for sandwich panels to deployable solar panels (Schenk, 2012). In fact, origami has turned into a discipline where researchers are named as origami scientists and researchers come together every four years at the international meeting of Origami Science, Math and Education (Lebee, 2015).

There are many studies on origami in which several different branches are involved such as engineering and biology, so it becomes a very powerful mean of motion embedded form (Pesenti et al., 2015; Lebee, 2015). Hence, origami is conceived as a very useful tool for design research of kinetic structures (Gilewski et al., 2014). In this sense, main application fields of origami can be briefly exemplified in table 2.3.

Table 2.3. *Disciplines inspired by Origami (developed by the author).*



The position of origami in literature is explained under two main categories: mathematics of origami and applied thick origami. These categories and their related topics to be discussed are illustrated in figure 2.12.

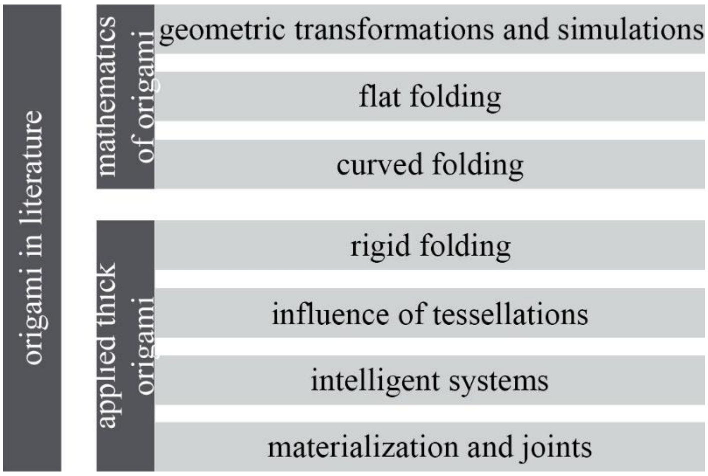


Figure 2.12. Summary of the Literature Review of Origami (developed by the author).

2.2.1. Mathematics of Origami

One of the growing research fields of origami is mathematics and it is mainly discussed under three main categories; geometric transformations and simulations, flat folding, and curved folding.

2.2.1.1. Geometric Transformations and Simulations

One of the most important reasons for origami to become a science has been understanding of folding. In this regard, origami is a transformation of points and lines from 2D to 3D (Sorguç et al., 2009). Studies on origami basically depend on Kawasaki, Maekawa, and Miura-ori theorems. The essence of these theorems is based on mathematical rules concerning how lines and points should come together.

Geometric formations of patterns affect the response to stresses. For instance, triangular patterns can resist stresses with the ratio of acceptable rigidity to avoid deformations. On the other hand, in square patterns, stresses occur across the diagonals of each far vertex and adjacent vertexes which results in deformation of squares allowing bending diagonally across its face into two triangles. Thus, triangular patterns can resist bending in creating curvatures (Yeh, 1998). Moreover, regarding geometric patterns, Sorguç et al. (2009) draw attention to the relations of geometric patterns and mathematics implying that what it is learnt from mathematics is a guideline to understand structure and its computation. Also, authors assert that origami inspired forms can be regarded as mappings of the tessellations into 2D and 3D spaces in the field of mathematics. These tessellations are usually obtained from isometric and/or analogy conversions of lines in 2D space and they have potential to transform into a structural network, because valley and mountain folds can be regarded as a structural grid.

In addition, these transformations of origami patterns contain the idea of associative geometry which is indeed the idea behind meshing. Many folding structures are developed early in order to understand transformation from 2D to 3D, and they play a very important role in development of meshing and associative geometries of today's CAD and CAM systems. The idea of models shown in figure 2.13 is based on associative geometries. For example, 2D triangulation is converted into 3D surface of a rabbit shape (Tachi, 2010).

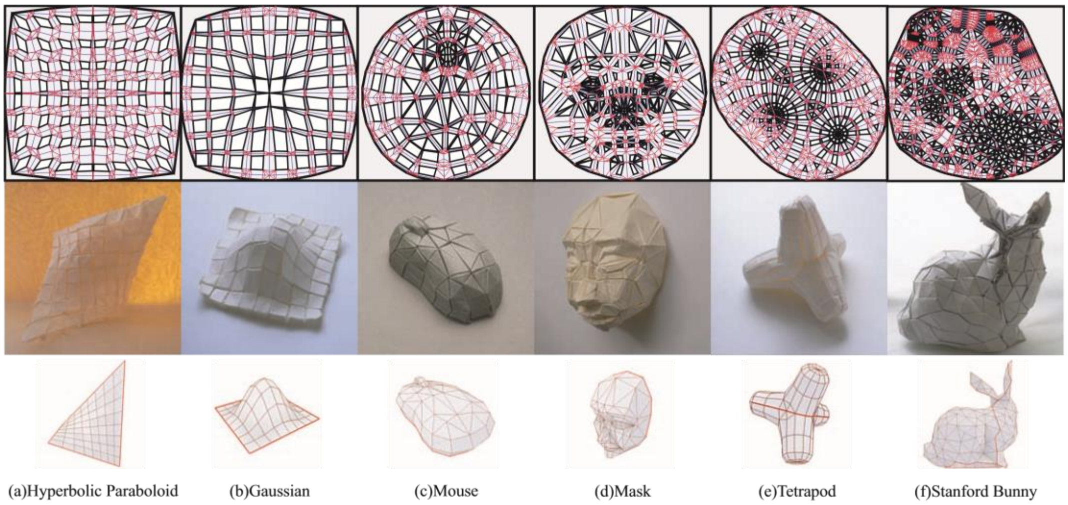


Figure 2.13. Origami Models and their Associative Geometries (Tachi, 2010).

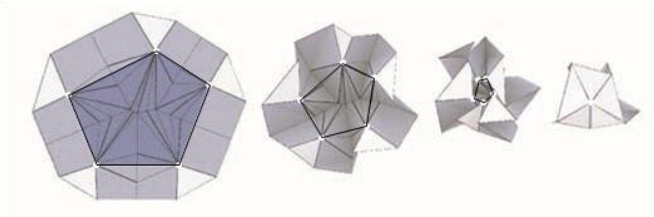


Figure 2.14. Folding Motion of the Crease Pattern (Tachi, 2010)

According to Schenk (2012), in order to understand behavior of structures inspired by origami as well as digital language, it is crucial to understand first whether it is able to fold or not and required conditions for folding. Therefore, there are many researches focused on folding theorems to develop 3D folded shapes or unfolding them into a plain. For instance, Itoh & Nara (2011) question whether every folded state of polyhedral pieces of a paper be reached by continues folding process using Cauchy, Connelly and Sabitov theorems. It is concluded that each platonic polyhedron is flattened on its face by a constant folding process whose crease pattern is two dimensional. Further research has been issued by Horiyama et al. (2016). They use the same methods to complete the previous study, but with different theorems since a problem is detected in the case of dodecahedron. Both researches reveal the fact that folding is directly linked to assigning proper angular conditions.

Lebee, 2015 states that understanding these transformations can lead to comprehend movements of points and lines which helps to understand folding kinematics, since these transformations are actually isometries such as translation and rotation. Material thickness is ignored in simulations, so these transformations is regarded as isometric embedding by mathematicians. Still, it is essential to investigate accessible forms for by folding. (Lebee, 2015).

Brancart et al. (2016) study over deployable bending-active structures based on the interaction between a deployable grid and a restraining membrane: deployable textile hybrid structures. A case study regarding multiple structural transformations is achieved by parametric form finding and structural analysis. The form finding approach illustrates how stress output and the final geometry can be controlled in a digital design environment. The results show an acceptable and well-distributed prestress in the textile membrane, even when using a high-strain fabric without cutting pattern.

Lang (2018) summarizes the terms regarding mathematical models of origami as defined in figure 2.15.

Model	Description
Flat-Foldable Origami	All facets are flat and coplanar; creases have fold angle of 0° or ±180°; paper has zero thickness.
Polyhedral Origami	Facets are flat, creases are straight, but fold angles can vary continuously; paper has zero thickness
Curved Origami	Facets and creases can be curved; paper has zero thickness
Thick Origami	Paper thickness is explicitly included.

Figure 2.15. Hierarchy of Mathematical Models of Origami (Lang, 2018)

As a result, geometric transformations of patterns from 2D to 3D help to generate proper digital simulations, but they depend on mathematical understanding behind folding types such as flat and curved folding.

2.2.1.2. Flat Folding

Another research field on origami mathematics is flat folding which means that in the folded state, when all creases are folded $\pm\pi$, the end result lies in a plane. Mitani (2011) highlights the importance of flat foldability due to its contribution to increase the portability and storage space of industrial products. It is tried to develop a method to generate new crease patterns that are flat-foldable by using a computer with the algorithm of numerical optimization. According to Schenk (2012), the concept of flat-foldability is a great interest for deployable kinetic structures, since it allows for minimal stowed dimensions, however flat foldability also highlights a major challenge in origami mathematics: theorems defining flat foldability are available for single vertices, but the extension to multiple vertices is hard. Author also claims that theorems are essential, yet not enough to prove the flat foldability of a single vertex. Moreover, theorems only focus on single vertex flat foldability (local flat foldability, because extending it to global flat foldability which means taking into account all folds and vertices in a fold pattern is hard to be computationally intractable. Author stressed that these theorems illustrate that there are simple, yet deep, underlying rules in origami folding. Similarly, Greenberg (2012) emphasizes local flat-foldability and its rules for mechanism design. Kawasaki and Maekava theorems are conditions for flat foldability. The former is associated with the definition of a change-point mechanism while the latter is considered to comprehend how the links are connected to one another. Author also mentions that flat-folding linkages can have any number of links greater than three and the sum of the half the link lengths is equal to the sum of the remaining link lengths. In this way, mechanism design can be understood in the frame of origami.

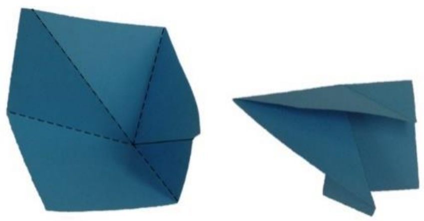


Figure 2.16. Example Showing that a 5-bar Mechanism is Fat-foldable if one of the Creases is not folded in the Fat State (Greenberg, 2012)

Tachi & Miura (2010) also work on flat foldability. Particularly, cylindrical deployable structures are examined, since deployment of these tubes depends on the in-plane deformation or the travelling of the hinges, and they cannot be implemented through large scale structures or robust and reusable mechanisms, as these structures do not have a geometrically valid continues transformation path from one state to another. Authors introduce families of rigid-foldable cylinders and three types of cellular structures based on cylinders: zonogon extrusion cells, bidirectionally flat-foldable cells, and woven cylinder cells. They show their geometric validity as one DOF structures, their generalized design method, and their kinetic properties.

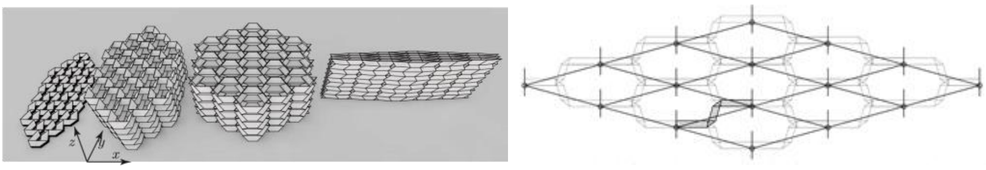


Figure 2.17. Tessellation of a Cylinder to produce a One DOF Bi-directionally Flat-foldable Cellular Structure (Tachi & Miura, 2010)

Another research regarding flat folding mechanisms is conducted by Beatini and Korkmaz (2013) by revealing a problem description: mechanisms with number of excessive rigid members can create problems especially in implementations where stiffness and stability are important. Authors claim that it is possible to get rid of excessive members in order to construct lighter, customized and cheaper systems if only the same movement is maintained. It is proven the fact that solution to the revealed problem is directly linked to the folding patterns and its movement.

On the other hand, Akiyata et al. (2013) try to generate a system providing 3D simulation of flat folding type of origami for those who are not experienced in folding patterns. Authors also argues that automatization of the 3D modelling help to facilitate doing time-consuming works. According to the authors, the method using ORIPA system emphasizes the importance of the crease pattern as an efficient way of documenting origami. Authors conclude that even though the simplified patterns are generally flat-foldable, there are some exceptions. Maekawa and Kawasaki theorems which are fundamental for the flat foldability, yet they are not adequate to guarantee it.

Another research on the idea of flat foldability is conducted by Sareh & Guest (2015). Authors study over the most famous flat folding pattern, the Muira-ori pattern, in relation to the symmetry groups. While maintaining local flat foldability, its symmetries are changed. Based on proper manipulation of initial pattern, design variations are performed either it is flat or curved.

As a consequence, flat folding type of origami is widely used to obtain mechanisms. Its rules are the conditions that should be sustained. These are mainly Miura-ori, Kawasaki, and Maekawa theorems. Constructing a kinetic structure based on these rules helps to form geometric relations.

2.2.1.3. Curved Folding

Above-mentioned researches reveal the significance of origami mathematics for constructability of geometries based on origami. It does not only concern flat surfaces. In fact, today, the boundaries of architecture are being forced especially in terms of form and materiality, and origami also becomes a research medium for curved forms. Understanding of these free forms without damaging the material, and their integration to the architectural kinetic skin have become an important research area. It can be observed that there are two important fields of study. In one side, curved folding working with 1DOF to avoid material deformation, in other side, curved folding from different topologies along with the discussions of descriptive geometries. In this sense, there are many researches which are contributed to the understanding of its mathematics. These studies make origami a powerful tool for learning through paper.

For example, Tachi and Epps (2011) create a prototype regarding curved folding by dividing curved rails into equal number of intervals (figure 2.18). The prototype is created with two-layer rigid plate model sandwiching a paper hinge. Still, assigning curvature with real materials remains hard.

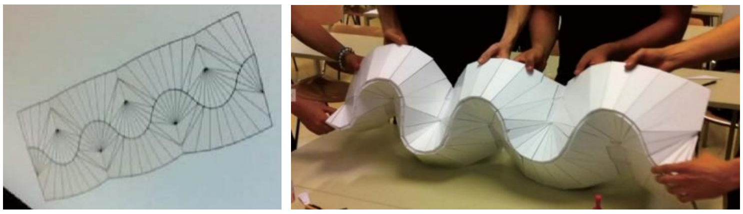


Figure 2.18. Curved Folding (Tachi and Epps, 2011)

There are also complex folding patterns creating various amorph forms which are defined as no crease, one crease patterns by Jackson (2011) which are indicated in figure 2.19. No crease pattern is created with a single point. Adding lines to this single point, one crease or more crease patterns can be created.

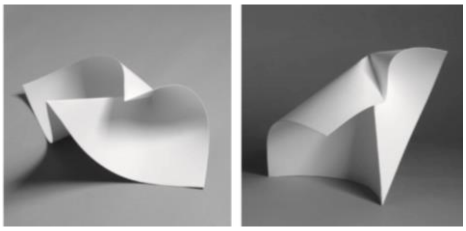


Figure 2.19. One Crease Pattern (Jackson, 2011).

Davis et al. (2013) studies over the works of Huffman's curved crease patterns in order to document patterns by reverse-engineering. That is, sketches are converted into digital model, and vice versa. According to authors, his crease patterns are significant, because they are rigidly foldable and produce no locking mechanism.

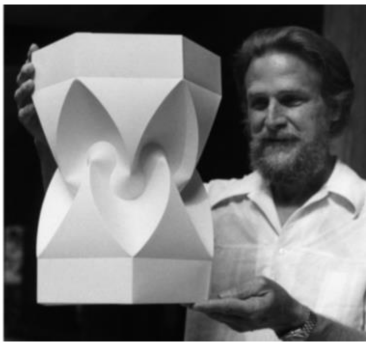


Figure 2.20. Hexagonal Column with Cusps designed by David Huffman (Davis et al., 2013)

Curved folding enables designers to use sheet metals in curved forms which is used in many manufacturing requiring mass material. It contributes to producibility of these forms such as Curved Pavilion in Rolex Center (Eversmann, et al., 2017).

Applied curved forms in architecture are generally static shells and applied kinetic curved forms are still open to search. For instance, Lebee (2015) exemplified static shell forms of Los Angeles Walt Disney Concert Hall and Water Tower in order to highlight how architectural curved forms are obtained. Accordingly, Frank Gehry obtains free forms by crumpling paper. Also, hyperbolic-paraboloid form of Water Tower is generated based on descriptive geometries. It is drawn attention to the fact that developable ruled surfaces are particularly preferred in designing 3D curved structures.

Figure 2.21. Left: The Los Angeles Walt Disney Concert Hall. Right: Water Tower in La-Roche-de-Glun (Lebee, 2015).

Mitani (2017) also work on curved folding. According to author, many curved origami surfaces were generated by Huffman and his technique depends on mirror inversion based on developable surfaces. However, they are restricted with planar curves. Creating surfaces with space curves is complicated, yet they can be obtained by discretizing. Moreover, stress occurred on the material is balanced if fold lines are arranged alternately as mountain and valley. Nonetheless, proper mathematical definition has not been defined yet. Hence, it is open for further researches concerning curved folding.

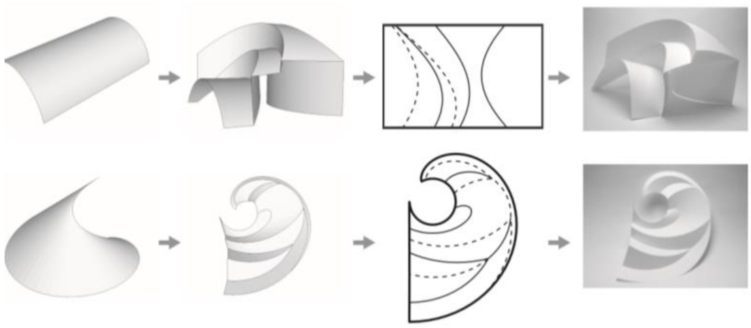


Figure 2.22. Application of mirror inversion to cylindrical and tangent surfaces (Mitani, 2017)

Kilian et al. (2017) states that generating free form curved surfaces produced by curved lines drawn onto a paper has a significant field in computational origami. It is claimed that designers seek for distinct fold patterns to create surfaces, yet they generally work on static curved surfaces. The reason is originated from the difficulty in obtaining a properly folded target shape from curved lines which should be folded at the same time. Therefore, authors represent string actuated curved folded surfaces which can be shaped by pulling a network of strings. Accordingly, the folding process is simplified, and motion occurred by this process becomes integral part of the design.

Consequently, curved folding can help to generate new architectural forms. Applied examples in literature generally focus on static applications due to complexity of its geometry. If this complex geometry is understood and solved, it opens the doors for kinetic implementations such as architectural kinetic skins.

2.2.2. Applied Thick Origami

Previous sections involve contemporary meaning of origami and its underlying mathematical ideas, which facilitate understanding of the geometric transformations and creating computational drawings so that real prototypes can be generated based on mathematical concerns. This section mainly focuses on materialization and joints of origami with ideal zero thickness. In fact, what is meant by applied thick origami is the application of origami with thickness into real projects or experimentations. Consequently, the progressive development in origami science concerning its application to materialized folding projects are explained chronologically under this title.

Tachi (2010) defines rigid origami as a linear origami which can be transformed continuously without deformation of faces. Based on this idea, a deployable mechanism which is constructed with stiff panels and hinges, offers potentials for distinct architectural and engineering implementations particularly for kinetic architectural design applications. Author claims that origami is considered as a surface with ideal zero thickness from mathematical point of view. Nonetheless, it is not valid when mechanism is implemented physically. In particular, it is crucial to take into consideration mechanism with material thickness for large-scale kinetic constructions as well as rigid origami.

Figure 2.23. Rigid Foldable Origami materialized with Cloth and Cardboards (Tachi., 2010).

Likewise, Hawkes et al. (2010) draw a similar conclusion, but authors experiment self-folding structures. The research aims to achieve different 3D shapes from a single material via embedded actuation. Authors argue that past approaches have been restricted to huge number of components, complex communication among the units, and small feature sizes. Algorithms regarding motion of these systems are presented. The work is related to the use of fluid forces in order for bending structures from 2D to 3D. Authors conclude that creation of these structures is restricted to actuator size, torque, and controlling whole actuators, even though any 3D shape can be created in digital design environment in theory.

Trautz & Künstler (2010) investigate four-fold-mechanisms like Miura-Ori-pattern, based on the mathematical description of a thin paper model. According to authors, for deployable structures, another concern is materialization and connection detailing so as to decrease the complexity of the fabrication. Authors conclude that deployable folded plate structures need stiff plate materials in order to reach large structural spans with the least material thickness as possible.

Another research regarding rigid folding has been conducted by Miura & Tachi (2010). Authors focus on collapsible cylindrical structures which has a special field iin structural engineering. They perform symmetry operations so as to synthesize space filling tessellation. The research reveals how tessellations affect the structural quality. Moreover, Schenk (2012) argues that these patterns can be combined with advance mechanical properties such as increased bending stiffness which enables folded plate roofs to span larger areas.

Also, origami is used to create nano-scale structures such as stents which are used to enlarge clogged arteries and veins. Created structure makes the diameter of clot site to enlarge (figure 2.25). The pattern consisting of three folding types allows a highly synchronized deployment process (Fei & Sujan, 2013).

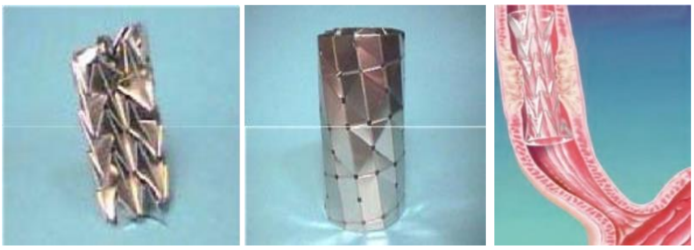


Figure 2.24. Origami Stent designed by Zhong You and Kaori Kuribayashi (Fei & Sujan, 2013)

Calretas et al (2014) hypothesize four approaches regarding architecture, morphogenesis and parametric design. Authors emphasize the relationship between paper-folding and digital systems, treating it as a methodology in a new approach to architectural logic and structural design.

Thick origami is also used to improve energy performances avoiding deformation. For example, Kusyairi (2017) studies over the influence of origami and rectangular crash box variations on MPV bumper without plastic deformation is observed.

Figure 2.25. Origami Crash Box (Kusyairi, 2017)

In recent years, origami is used to discover new structural free forms together with improving detailing solutions. For instance, Eversmann et al. (2017) experiment curved folding by developing two different connection detailing shown in pavilion-scale examples (figure 2.27). Authors claim that many studies have been conducted on the geometric definition and simulation of curved-folded elements and fabrication technologies have already been applied to single-panel folding processes. However, large-scale applications are still limited. Moreover, it is stated that structural joining techniques are a challenging subject due to the complexity of the geometry and assembly trajectories between multiple curved-folded panels. Therefore, authors develop a study employing computational design and digital fabrication technology in order to structurally connect single and double-layer curved-folded aluminum panels.

Figure 2.26. Curved Pavilion. (Source: from http://www.eversmann.fr/CURVED-FOLDING. Retrieved at: 19.08.2019)

Moreover, origami is generally regarded as plate and hinge mechanisms, yet it can also offer two different ways to create structural forms if its surfaces and lines are associated with plates and linkages. For example, Zhang & Chen (2018) develop two prototypes evaluating the same Miura-ori pattern. The pattern is turned into a layout for both plate and linkage mechanisms (figure 2.28).

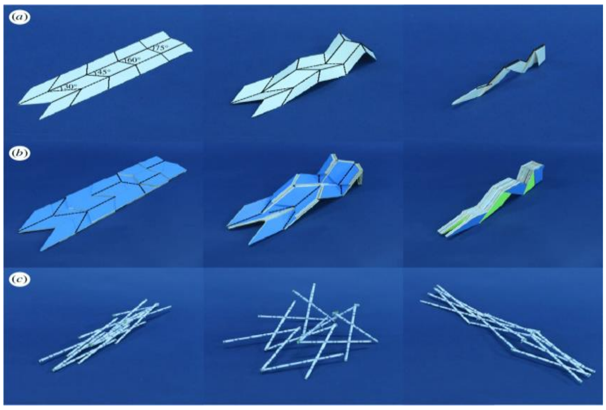


Figure 2.27. Deployment Sequences of Prototypes; A: Miura-ori Pattern, B: Miura-ori Thick Panel Pattern, and C: Bennett Linkage Mobile Assembly with α=30° (Zhang & Chen, 2018).

As a result, when it is applied thickness into ideal zero folding, it becomes a critical concern for architecture, since materialization and joint detailing are neglected in paper folding and digital simulation. However, there are materialized folding mechanisms inspired by paper folding as mentioned above. These researches give clues for the realization of origami models. They can be guidance to develop origami-based structures. Thickness should be assigned precisely based on motion in order to create real prototypes inspired by origami.

CHAPTER 3

THEORIES AND POSTULATE

This chapter presents the theories and postulate of the correlation between deployable rigid body kinetic structures and origami. It is fundamentally tried to reveal the applicability of origami to develop kinetic structures through by discussions on two main subjects: classifications and development of kinetic structures based on origami.

The former mainly focuses on the interpretation of kinetic structures by means of classifications based on the scale of moving bodies evaluated over their **motion and enabler mechanisms**. These classifications are significant for the fact kinetic structures are controlled mechanisms which need proper transmission of motion in a controlled manner to fulfill assigned function. There are many attempts to understand kinetic structures over classifications in literature, yet there is still an important gap in understanding of motion and its enablers. However, designing kinetic structures need to be considered over motion, otherwise these complex structures limit architects with certain type of systems. Hence, the author evaluates the current applications in order to specify the research field looking from larger scale, and to further evaluate kinetic structures. At the end, motion in origami is interpreted and recategorized in relation to architectural deployable kinetic structures.

The latter discusses how origami-based kinetic structures are realized. As it is investigated in many researches stated in literature, its mathematics are tried to be understood so that what is learnt from paper folding can be adapted into real folding mechanisms. Therefore, a set of case studies are illustrated in order to validate presented theories and postulate.

Apart from these two main subjects, at the end of the chapter, resultant mathematical rules and proposed stages are summarized. It is also drawn attention to the design process for the development of deployable kinetic structures inspired by origami so that it can be used in any folding type either it is orthogonal or curved.

3.1. Classifications of Kinetic Structures in relation to Origami

Under this title kinetic structures either working as individual components or entire network are to be examined together with mechanisms and type of motion that should be delivered. In this regard, it is basically concerned with possible motions on a kinetic surface as isometric transformations in space, since rigid materials without deformation is a must. Hence, rotation, translation, and reflection are the typical isometric transformations that can be observed in a kinetic façade.

Possible kinematic pairs enabling motion can be revolute (hinge), prismatic (slider or translational), helical (screw), cylindric, planar, and spherical (ball or socket) joints. They connect kinematic elements. These elements can be driven with mechanisms which are classified by Reuleaux in terms of their moving components as; screw, wheel (gear), crank (linkage), belt, cam, and ratchet (Söylemez, 1979). In addition to these mechanical devices, there are also intelligent systems which moves autonomously based on their intrinsic material property.

Classifications are respectively investigated in following sections;

- Classifications of architectural kinetic structures in terms of motion and their enabler mechanisms
- Deductions from classifications
- Origami-based kinetic structures

3.1.1. Classifications of Architectural Kinetic Structures in terms of Motion and their Enabler Mechanisms

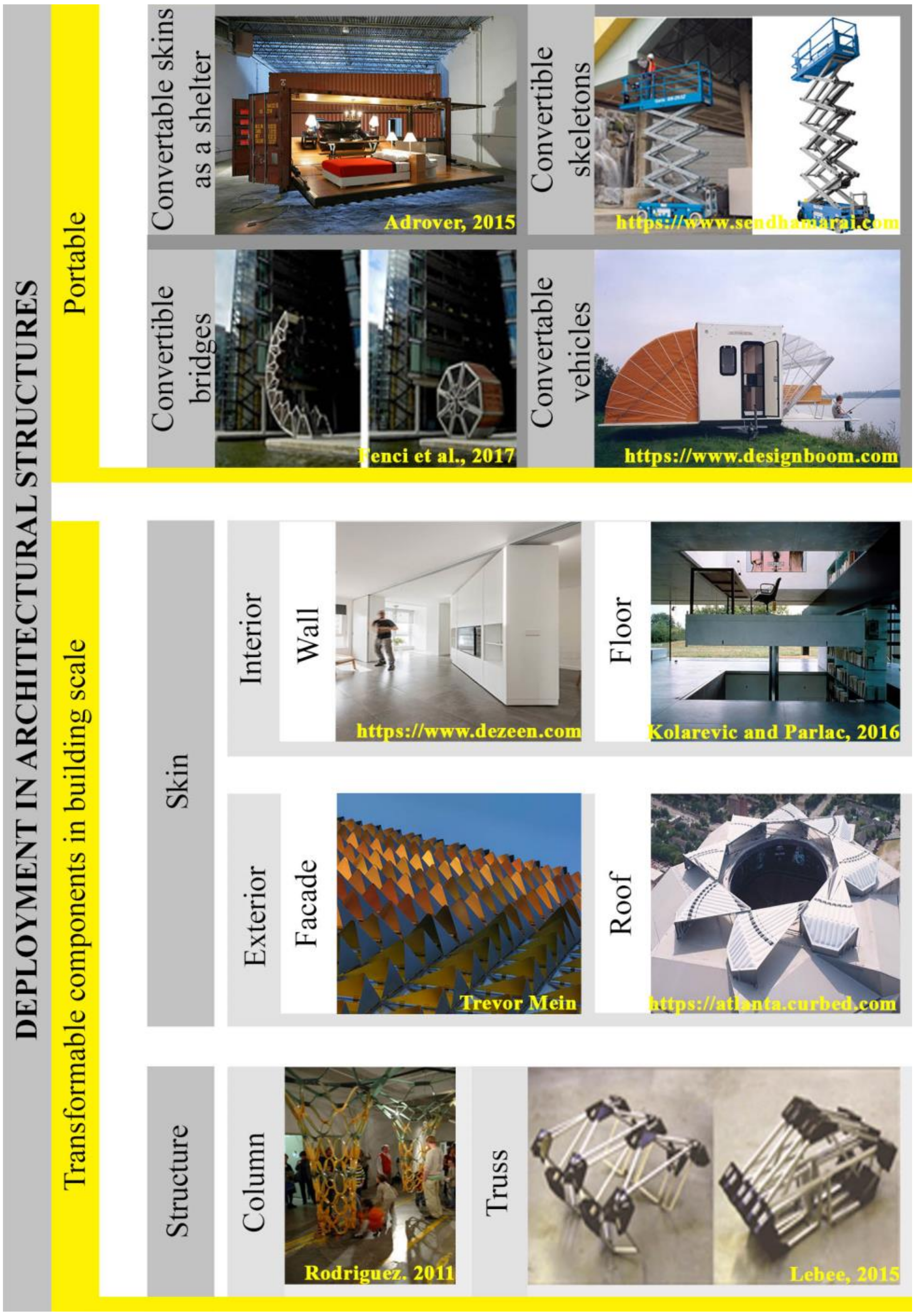
Motion in architecture is examined based on the idea of responsiveness and performative design which result in transformation of space. This transformation is depicted as “deployment in architecture” within the context of this research. In other words, deployment in architecture is defined as a transformation of space over time due to expansion and contraction as a result of alterations in topological definition. According to this definition, deployment is sustained over kinetic structures which are able to fulfill the below-mentioned feature or features;

- Open/close (Herzog et al., 2004)
- Fold/unfold (Herzog et al., 2004)
- Portable (Kronenburg, 2013)
- Retract (Pellegrino, 2014)
- Expand/contract (Adrover, 2015)
- Extend/unextend (Adrover, 2015)
- Deformable (Adrover, 2015)

Kinetic structures sustaining deployment can be relocatable portable structures or transformable structures in permanent buildings (table 3.1). Portable structures have been questioned since ancient times in need of being protected from whether conditions as a shelter or in need of transportation like hors carts. Mainly, portable structures are seen in architecture as convertible skin as a shelter, convertible skeletons, convertible bridges, and convertible vehicles such as caravans.

Portable structures have a wide range of use for temporary purposes. However, today especially with the idea of performance, transformable structures applied in permanent buildings are started to gain importance. They can be re-categorized into building skin structures and building structure. Building structures are transformable trusses and columns, yet they are generally experimental projects. On the other hand, building skin structures is generally used to obtain desired comfort zone to increase building performance, or to reconfigure functional use of the building. They can be seen in kinetic facades, roofs such as retractable roofs for sport facilities like football stadiums, and interior architectural elements such as partition walls which transform the space thanks to flexible use of open plan.

Table 3.1. *Deployment in Architectural Structures (developed by the author).*



Considering the idea of responsiveness and performative design, transformable building skin structures seem more promising, so they are further evaluated in table 3.2.

Table 3.2. *Transformable Structures in Building Scale (developed by the author).*

TRANSFORMABLE STRUCTURES ENABLING DEPLOYMENT	DEFORMABLE MEMBRANE	pneumatic	Inflatable Teahouse (air inflated)		Concert Hall (air supported)		Membrane structure that is stabilized by the pressure of compressed air either air inflated or air compressed
		tensiled fabric	Montreal Olympic		Olympic Stadium		Structure with a thin, flexible fabric that carries loads through tensile stresses
	RIGID BODY	linkage	Hoberman Arch		Swimming Pool		Structures which are formed with linkages and joints
		plate	Kiefer Technique		AL Bahar		Structures consisting of moving rigid plates
OTHER KINETIC STRUCTURES	MATERIAL BASED STRUCTURES	smart materials	AirFlower (SMA)		by Chao Chen		Structures with the ability to move autonomously in response to the environment to which material of the structure are sensitive
		compressed plates	Thematic Pavilion				Structures formed with deformable membranes moving through by elastic deformation as a result of compression forces

As exemplified in table 3.2, transformable structures in buildings are formed with rigid bodies or deformable membranes. Deformable membranes can be re-categorized as tensiled fabric, and materials supported by inflated air which is called pneumatic systems. The process of contraction during deployment in deformable structures is irreversible. For instance, pneumatic systems do not work after being collapsed. In addition, tensiled fabrics like in Montreal Stadium can be exposed to material deformations especially from hanging connection parts and fabrics may not be durable enough to carry snow loads. On the other hand, rigid-body structures are controlled structures allowing expansion either they are composed of linkages or plates. In addition, it should be highlighted that in membrane systems, membrane is not a rigid body, but its structure can be a rigid body such as Swimming Pool in Sevilla designed by Escrig and Sanchez.

In addition to rigid body and deformable membrane structures, other sorts of kinetic structures exist in architecture. Those are structures with smart materials and compressed plates. Smart materials are generally experimental researches and compressed plates cause material deformations such as façade of Thematic Pavilion and also the pavilion does not move based on the idea of deployment defined in this research.

Consequently, deployment will be searched in this research as a transformation of space which occurs as a result of movement of rigid links applied as building skin components, because transformable building skin structures with rigid bodies seem more promising depending on the idea of responsiveness and performative design. However, rigid body structures are observed in responsive architecture in different scales with different motion types. Basically, they can be collected under three main categories concerning the scale of moving bodies as listed below;

- Unit scale; composing of small-scale components such as doors, windows, or interior partitions working either individual or network.

- Surface scale; composing of units or inter-connected rigid bodies which form building skin such as a façade or a roof. They can work as a whole or internally concentric.
- Volume scale; composing of volumetric units which causes volumetric change in space.

Classification based on scales is significant, as these structures require different design approaches. For example, relative motion of interconnected elements is important for structures working as a network when compared to structures consisting of individual elements. Therefore, they represent different complexity due to their detailing.

In the light of above-stated descriptions, transformable rigid body structures in building skin are exemplified according to its scale, then its global motion type (translation or rotation), and enabler mechanisms respectively. Table 3.3 focuses on unit scale, table 3.4 focuses on surface scale, and table 3.5 focuses on volume scale.

Within the context of this thesis, surface scale kinetic structures working as a network will be examined, since it is more crucial to understand global motion rather than individual components. Also, researches working on deployable kinetic structures mainly focus on individual components and there is a gap in literature regarding deployable kinetic structures working as a network in terms of motion and enabler mechanisms.

Table 3.3. *Transformable Rigid Body Structures in Unit Scale (developed by the author).*

UNIT SCALE OF TRANSFORMABLE RIGID BODY STRUCTURES IN BUILDING SKIN				
INDIVIDUAL	translation	Modulofts Flexible Living	 Source: http://www.herskhazeen.com/modulofts-flexible-living-for-the-modern-citizen/ Steel panels that can slide out from reconfigurable apartments and be stored outside the building via pulleys.
INDIVIDUAL	rotation	Transformable Attic Window	 Source: https://dornob.com Source: https://www.bloomframe.com/ Attic window transforms its function to a small balcony. 4 bar linkage mechanism.
UNIT BY MORE THAN ONE RIGID BODY	translation	Sliding Partition Door	 Source: https://www.archdaily.com.br/br/870499/apartamento-jap-metamoorfose-studio Sliding door separates the space into two volumes. 4bar linkage and pulley mechanisms.
UNIT BY MORE THAN ONE RIGID BODY	rotation	Evolution Door	 Source: https://architizer.com/ Source: http://torggler.co.at/main/objects4.html Rotating panels connected with spherical joint in the center, and they are connected to the wall with revolute joints.

Table 3.3. *Continued*

The Maison Bordeaux	 Source: Kolarevic and Parlac, 2016 Hydraulic elevator platform that changes its location within the house designed by OMA.
Pivoting Timber Door	 Source: https://www.dezeen.com/2015/07/20/uniform-wares-offices-showroom Partition pivots open to allow access to the design studio behind. A smaller door set within the wooden wall hinges open independently for moving between the two spaces more discreetly.
Bifold Door	 Source: https://www.bifold.com/index.php Open bifold door creates awning for store front. Belt mechanisms.
Bloomframe Window	 Source: https://www.bloomframe.com/ Window transforms itself from a flat surface, to a balcony. 4bar linkage mechanism.

Table 3.4. *Transformable Rigid Body Structures in Surface Scale (developed by the author).*

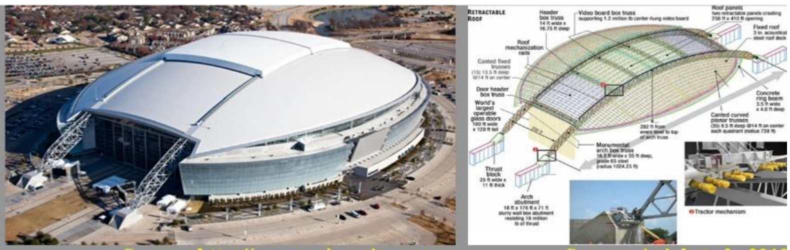
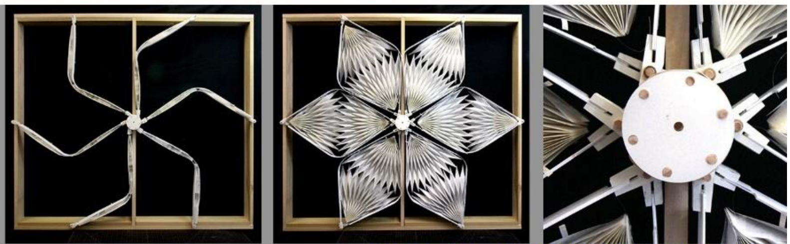
SURFACE SCALE OF TRANSFORMABLE RIGID BODY STRUCTURES IN BUILDING SKIN				
INDIVIDUAL	translation	AT&T Stadium	 Source: http://www.uni-engineer.com Source: Aniol et al., 2010	Sliding plates on the rails that are located on the arch trusses with wheels.
INDIVIDUAL	rotation	Penumbra Shading Device	 Source: https://www.dezeen.com/2014/03/19/penumbra-kinestic-louvres-tyler-short-mov	Belt and wheel mechanism rotates individual shading panels.
NETWORK	translation	Al Bahar Tower	 Source: Attia, 2016	Translational teleskopic movement of rigid bars triggers the hinged plates on the centre. Screw mechanism.
NETWORK	rotation	Snapping Facade	 Source: https://dioinno.com/Snapping-Facade	It moves with a rotary motion through by a cam mechanism located in the center of the aperture.

Table 3.4. *Continued*

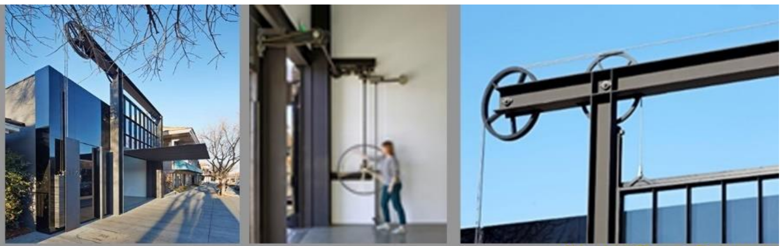
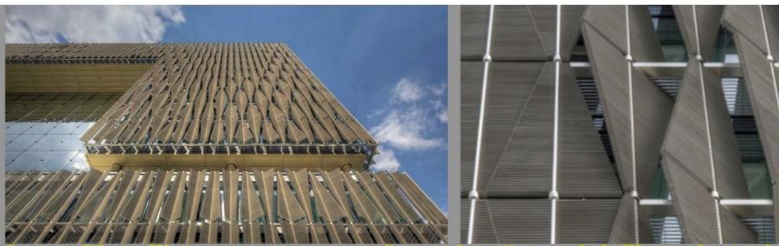
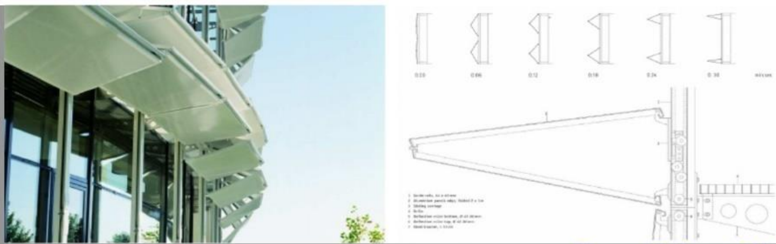
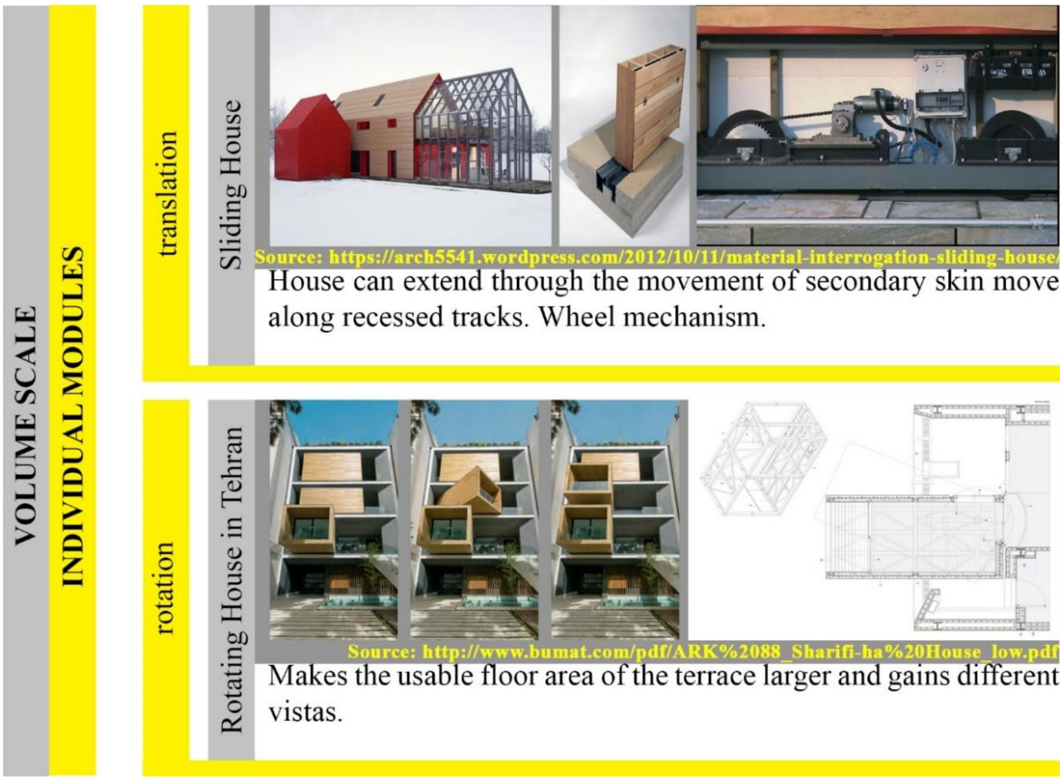
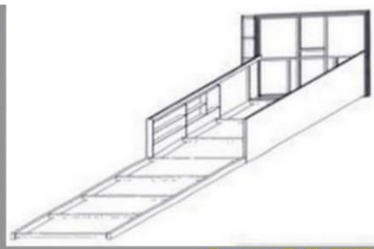
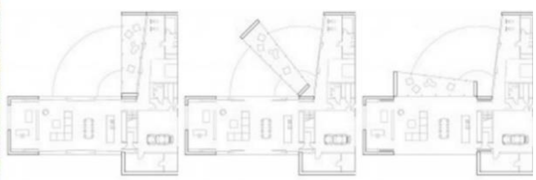
California Gallery	 Source: Bruce Damonte Tom Kundig hoists California gallery facade slides with the movement of gears and pulleys.
Thyssenkrupp Headquarters	 Source: Günter Wett Source: http://www.mitchellhattersley.co.uk Turning vertical fin made of horizontal cantilevered slats that were connected to a central stud.
Kiefer Technic Showroom	 Source: Kuipers, 2015 Sliding folded plates which move vertically on a rail. Pulley mechanism.
Hoberman Arch	 Source: https://archive.sltrib.com Source: https://archive.sltrib.com/ Rotating linkages (pantographs) like an iris of an eye. 4 bar linkage mechanism.

Table 3.5. *Transformable Rigid Body Structures in Volume Scale (developed by the author).*



Scale	Type	Movement	Example	Description
VOLUME SCALE	INDIVIDUAL MODULES	translation	Sliding House	Source: https://arch5541.wordpress.com/2012/10/11/material-interrogation-sliding-house/ House can extend through the movement of secondary skin move along recessed tracks. Wheel mechanism.
		rotation	Rotating House in Tehran	Source: http://www.bumat.com/pdf/ARK%2088_Sharifi-ha%20House_low.pdf Makes the usable floor area of the terrace larger and gains different vistas.

Table 3.5. *Continued*

Living Room House	  Source: Kolarevic and Parlac, 2016 Source: Bell, 2008 Bedroom unit can pop out of the building like a drawer and cantilever over the street below. Wheel mechanism.
Quadrant House	  Source: https://www.dezeen.com/2019/05/21/quadrant-house-robert-koniecznys-moving The mobile part of the building rotates between the living area and the spacreating transition from inside to outside. It moves on a rail onto the ground.

3.1.2. Deductions from Classifications

Based on the given examples in classification tables, following outputs are observed:

- Commonly used mechanisms in kinetic skins in architecture
- Understanding of motion in mechanical systems of kinetic structures
- Which type of motion is provided with which type of mechanism

Commonly used type of movements and mechanisms which are obtained from the given examples are indicated in table 3.6.

Table 3.6. *Common Movements and Mechanisms in Kinetic Architectural Structures (developed by the author).*

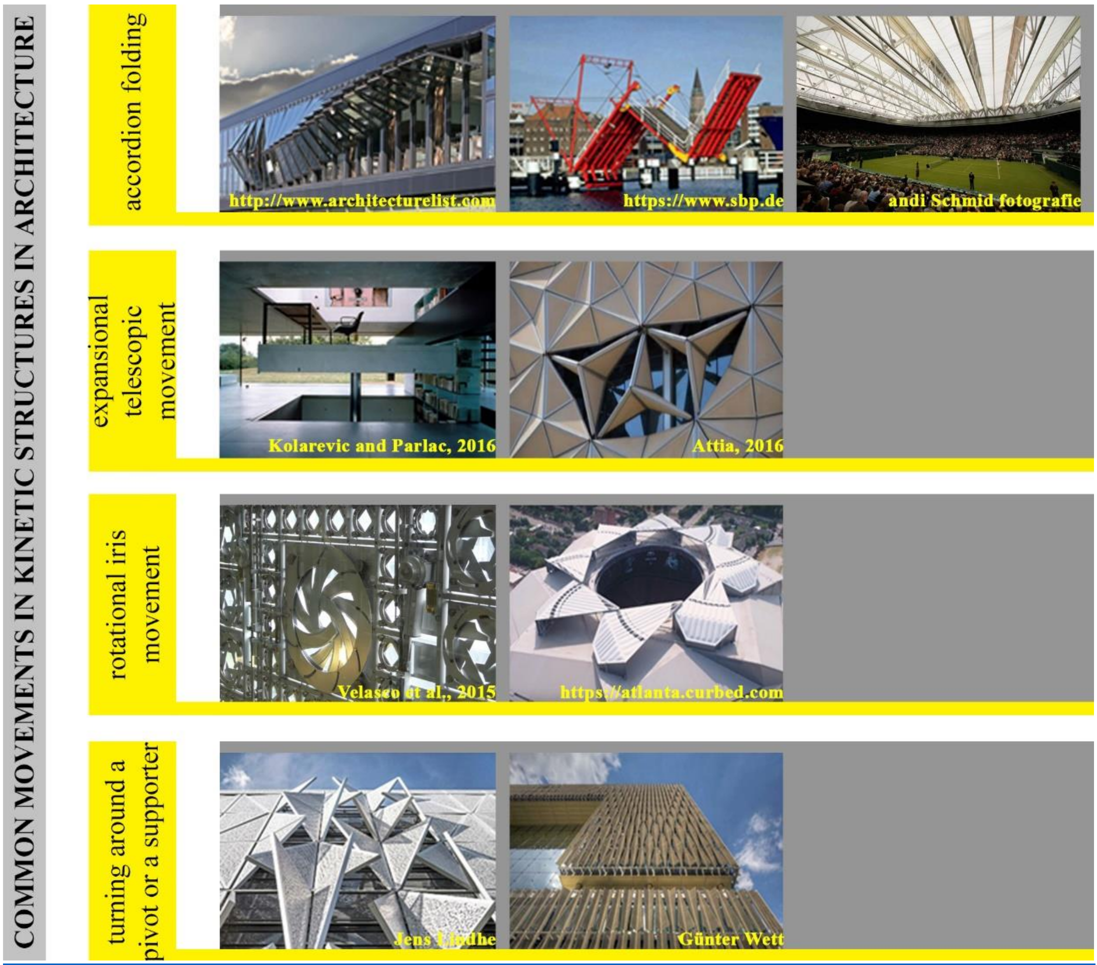
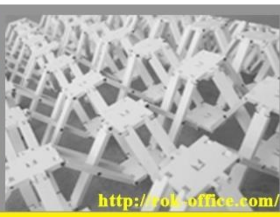
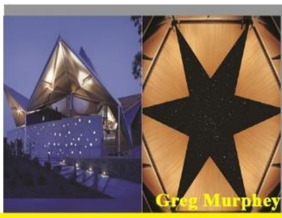
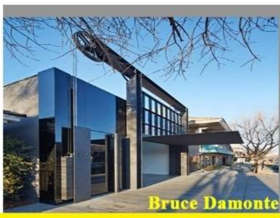


Table 3.6. *Continued*

COMMON MECHANISMS IN KINETIC STRUCTURES IN ARCHITECTURE			
scissors mechanism	 https://www.detail-online.com	 http://rok-office.com/	 https://vimeo.com/256485539
gearbox to transmit central motion to distinct directions	 Greg Murphey		
sliding on a rail with a gear mechanism	 http://www.uni-engineer.com	 Paul Ott	 https://www.dezeen.com
pulley and belt to transmit power over large distances	 Bruce Damonte	 https://www.dezeen.com	
umbrella linkage mechanism	 MDT-tex	 The SL Rasch GmbH	 Atelier Frei Otto Warmbronn
4 bar linkage mechanism in win-dows or louvers	 https://www.bloomframe.com/	 https://dornob.com	 Kuipers, 2015

Looking through the table 3.6, it is seen that there are repetitions in mechanisms, type of movement, and geometric configurations of patterns in kinetic structures. As seen, the language of folding types in applied architecture is restricted to few typopologies such as translational motions of accordion folding and rotational motions of Al Bahar Tower's kinetic facade. Motions sustained by these certain folding types are so controlled thanks to their tessellation and grid. Therefore, they are prefered in responsive architecture in common. However, they are not the only alternatives that architects seek. Also, almost all applied deployable kinetic structures were generated with certain orthogonal forms. These similarities restrict designers to discover new alternatives such as curved kinetic structures.

Moreover, it is observed that almost all mechanisms used in architectural projects are planar mechanisms. It reveals that we are not very free in the context of the mechanism when developing kinetic systems. In particular, if it had been a curved folding, it would be tried to convey motion with planar mechanisms over non-planar plates. In general, mechanisms used in curvilinear forms would be 2 DOF mechanisms, as curved folding structures shrink in two directions during deployment. Still, using planar mechanisms, new alternatives can be actuated.

It is also observed that symmetry adopted mobility is preferred in kinetic structures. Symmetries are generated based on regular tessellations. These tessellations are created by isometries such as translation, rotation, and glide reflection which construct entire kinetic surface. Formation of kinetic surfaces should be studied with topological and tectonic relations. Unless they are compatible with each other, it increases the complexity of the system and becomes harder to operate an entire kinetic surface.

To sum up, following considerations are understood from the classifications;

- how kinetic surfaces are formed based on symmetry groups
- types of mechanisms used in applied kinetic structures in architecture

- the state of change in deployable kinetic surfaces as a whole, as a module, and as a volume

As a result, these classifications are significant to overview general situation of applied kinetic structures in terms of above stated considerations. It is seen that new tools allowing new alternatives and facilitating motion are required to develop surface scale rigid body kinetic structures working as a network.

3.1.3. Deployable Structures and Origami

Origami has facets, fold-lines, and joints. They can be considered as plates and linkages to construct a kinetic surface.

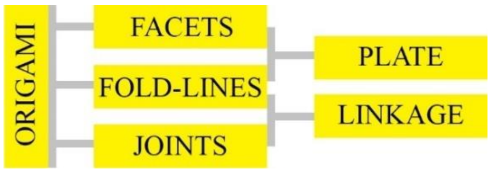
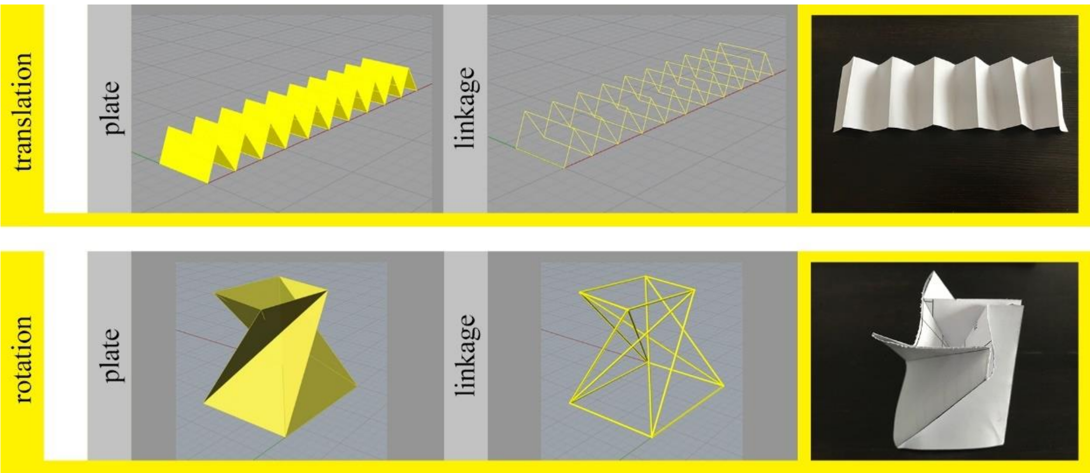


Figure 3.1. Origami Construction (developed by the author).

Any folding can be represented as linkages and plates, and any linkage can transform into a real mechanism. Whole mechanisms can be solved. They can be linear or rotational mechanisms. Translational motion of kinetic surfaces can be sustained with belt and pulleys, screw, and ratched mechanisms, while the rotary motion can be provided with cam, wheel, and crank mechanisms. For instance, in table 3.7, translational and rotational folding schemas are converted into digital model as a layout for both plate and linkage mechanisms. Those surfaces and lines define proper portions of rigid bodies, where to locate plates, linkages, and joints, and relative motions of rigid bodies.

Table 3.7. *Origami as a Template for Folding Mechanisms (developed by the author).*



If a slightest thickness is given to above mentioned layouts together with assigning joints, these templates are transformed into real plates and linkages. For instance, in figure 3.2, fold lines define the axes of rigid body links and the vertex defines the position of joint. Looking through their relative motions and considering thickness, appropriate clearance and joint are implemented.

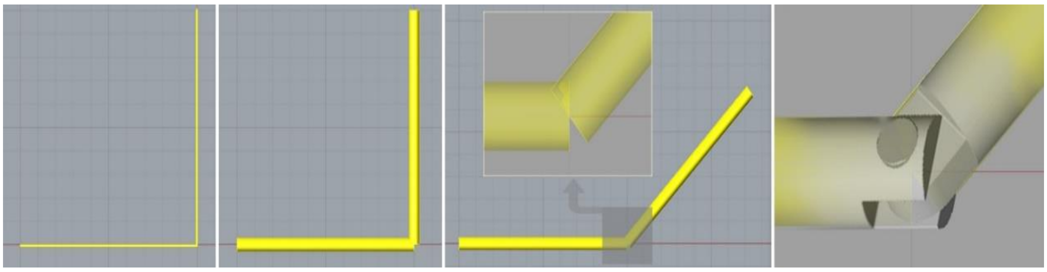
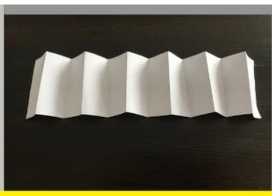


Figure 3.2. Assigning Thickness in the Digital Model (developed by the author).

Deployment in origami can be reviewed over tessellations, patterns allowing overlaps, and rigid body curved folding patterns. They are exemplified based on type of motion and motion path line (table 3.8).

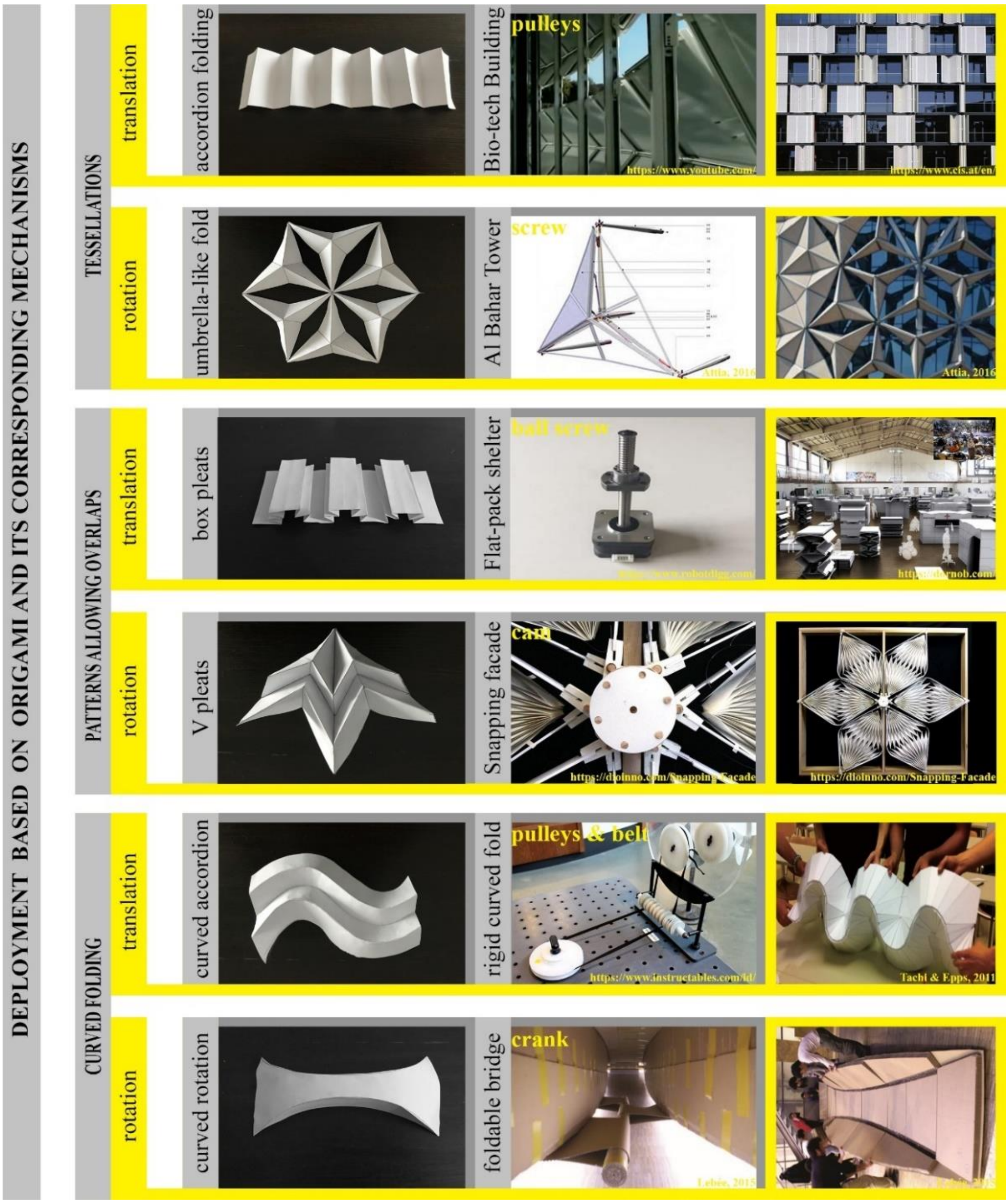
Table 3.8. *Deployment based on Origami Layouts (developed by the author).*

DEPLOYMENT BASED ON ORIGAMI

Layout	Motion	Path	Example	Path	Example	Description
TESSELLATIONS	translation	linear path		linear path		Patterns are constructed on flat surfaces without allowing overlaps or gaps, and they move based on translational motion.
TESSELLATIONS	rotation	circular path		spiral path		Patterns are constructed on flat surfaces without allowing overlaps or gaps, and they move based on rotational motion.
PATTERNS ALLOWING OVERLAPS	translation	linear path		linear path		Patterns allow overlaps or gaps, and they move based on translational motion.
PATTERNS ALLOWING OVERLAPS	rotation	spiral path		circular path		Patterns allow overlaps or gaps and they move based on rotational motion.
CURVED FOLDING	translation	linear path		linear path		Patterns are constructed with fold-lines in curved shape and they move based on translational motion.
CURVED FOLDING	rotation	spiral path		spiral path		Patterns are constructed with fold-lines in curved shape and they move based on rotational motion.

Taking consideration into origami in motion, architects can incorporate mechanical perspective in initial design steps. It is important to evaluate kinetic structures effectively. If it is observed architectural applications, it becomes apparent that existing folding structures can be developed based on origami. Table 3.10 exemplifies origami in accordance with its corresponding folding mechanism based on motion.

Table 3.9. *Origami Patterns with Corresponding Folding Mechanisms (developed by the author).*



In conclusion, origami is a useful tool offering new and different alternatives for design in deployable kinetic structures. Both flat and curved origami have potentials, pros, and cons. However, curved one is more critical than the flat folding due to its complex geometry. Still, it is a new horizon and open to research. If its geometric relations are well-defined considering thickness, curved surfaces which seem so complex to solve, can be implemented into real architectural projects in a non-deformed way. Therefore, mathematics of origami is quite important to develop surface scale rigid body deployable structures inspired by origami.

3.2. Development of Origami-based Deployable Kinetic Structures: from Flat Sheet to Real Prototypes

Under this title, the folding theorems and symmetry groups as well as relevant mechanisms are to be studied and formulated as a process. It is examined both flat and curved folding to develop surface scale deployable kinetic structures. It is asserted that even complex curved forms can be produced as much as planar forms without deformations based on origami. However, the critical thing in developing origami-based kinetic structures is assigning motion with material thickness in a non-deformed way. Therefore, it is investigated how a flat sheet of paper turns into applied thick folding step by step. It is mainly explained over mathematical assumptions as listed as follows;

- Mathematical axioms in literature is employed to ensure the foldability of a sketch.
- Simulation of ideal zero folding is generated.
- Thick folding is prominent to understand materiality and fabrication.
- Origami tessellations can be classified under one of 17 symmetry groups to generate surface scale kinetic structures.
- Electronic and physical prototyping of the model are implemented to test the applicability of mock-up models.

Above-stated considerations are investigated representing each related data in literature. Then, these represented data are evaluated in order to show what can be generated based on these rules.

In particular, transformations of origami patterns from 2D to 3D are searched in regards with “topological transformations”. In architecture, the term “topological transformation” is defined as an ability to come back to its original state without deformation by Resch (1973). It is discussed how origami patterns create very complex topological forms transforming a flat sheet to 3D geometries preserving material.

In this part, it is also examined two types of origami: orthogonal and curved folding. Their mathematics are discussed again regarding symmetry, foldability, and current theorems. From mathematical point of view, differences between these two folding types are studied in terms of their geometric formations which are necessary to ensure their proper foldability.

Besides, how thickness is given to origami patterns is examined along with the discussions of placement of joints and assigning appropriate clearance between panels. Thickness is a critical concern, as paper folding lacks its consideration. However, there are researches concerning how thickness is assigned to flat sheets in order to create tick foldable structures. They are evaluated over small mock-up models.

Also, generation of an entire surface is explored based on the way modules come together. In fact, it depends on symmetry groups such as translation and glide reflection which affect the entire system both formally and structurally. Then, folding types are associated with 17 wallpaper groups which are combinations of type of symmetry groups. Furthermore, potentials of the patterns which are related with 17 symmetry groups for kinetic structures are explained.

Finally, applicability of generated model is examined in terms of electronic and physical prototyping. It gives the idea of how mock-up models are tested before the implementation to architectural skins.

3.2.1. Foldability of a Sketch: Folding Axioms regarding Folding Types

Sketches consisting of fold-lines can be regularly, curved, or randomly drawn. Any fold line drawn onto a paper have a potential to transform into a real kinetic structure if drawn sketch is sustain foldability concerns.

Foldability of sketches depends on mathematical rules. However, there are differences between folding types in terms of mathematics, as their geometric formations such as definition of surfaces are different, so they represent different behaviors such as whether flat foldability is achieved or not. Therefore, origami is examined under two main categories: orthogonal and curved folding (figure 3.3).

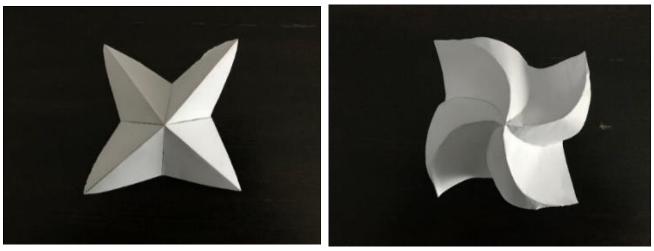


Figure 3.3. Left: Orthogonal Folding; Right: Curved Folding

The very first thing in origami structures is the check of foldability and three theorems named Miura-ori, Kawasaki, and Maekawa are shown in the table 3.10. They are the most important and relevant theorems to evaluate foldability of orthogonal lines. In curvilinear lines, however, it is significant to employ descriptive geometries of developable ruled surfaces.

Main differences of these two folding types are listed in terms of construction of lines, type of transformation, flat foldability, definition of surface, DOF, and controlling the system (table 3.10).

Table 3.10. *Main Differences between Orthogonal and Curved Folding in terms of Mathematics (developed by the author)*

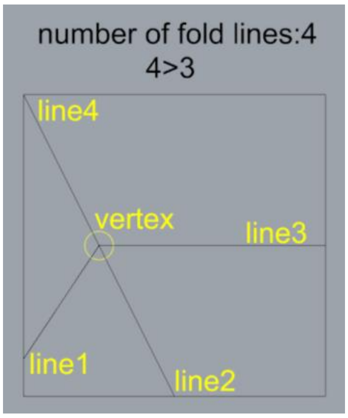
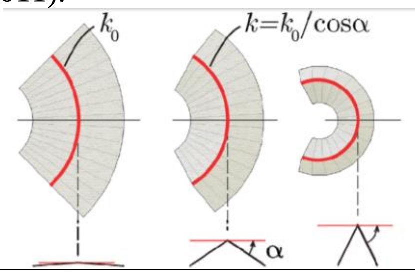
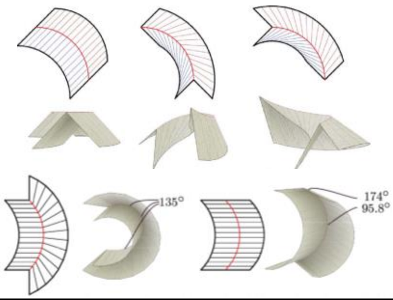
<table>
<tr><th>ORTHOGONAL FOLDING</th><th></th><th>CURVED FOLDING</th></tr>
<tr><td rowspan="4">At least 3 lines intersect at a vertex and there is not a line that do not intersect (Miura-ori theorem).

</td><td rowspan="4">CONSTRUCTION OF LINES</td><td>Lines do not necessarily intersect.</td></tr>
<tr><td>Parallelism of angles of fold lines and their relative lengths transmit rotary motion better.
</td></tr>
<tr><td>k3D = k2D / cosα, where k3D and k2D are the curvature of the fold line in the space and the crease pattern respectively; α is the half of the folding angle of the crease at the point (Tachi & Epps, 2011).

</td></tr>
<tr><td>It becomes harder to twist the folding without deformation when lines are in the same orientation and continues. Maintaining continuity of lines along a curved fold, relations between complementary angle of dihedral angle are preserved. Angular configurations are changed based on tangent value (Tachi & Epps, 2011).

</td></tr>
<tr><td>Isometric transformation.</td><td>TR</td><td>Isometric and/or similarity transformation.</td></tr>
</table>

Table 3.10. *Continued*

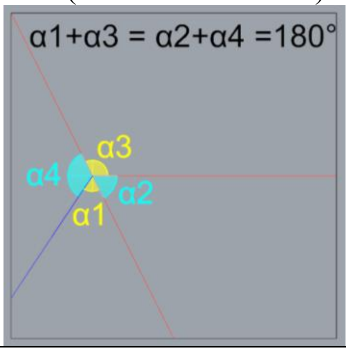
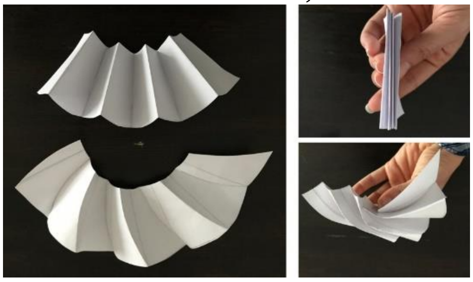
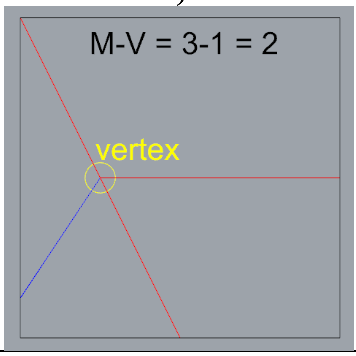
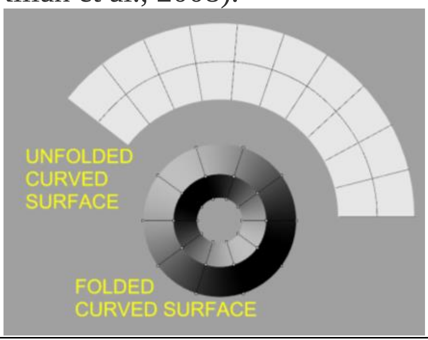
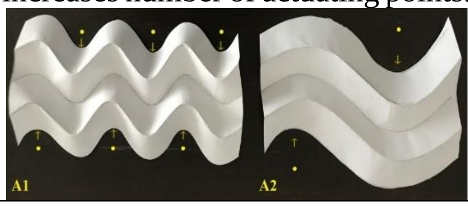
ORTHOGONAL FOLDING		CURVED FOLDING
Collection of creases meeting at a vertex are flat foldable if and only if the sum of the alternate angles around the vertex is π (Kawasaki theorem).  	FLAT FOLDABILITY	It cannot reach flat folding due to curvature. If it is forced, it deforms. 
Difference between the number of mountain (M) and valley (V) creases in a flat vertex fold is always two (Maekawa theorem).  		
It is defined by flat surfaces in Cartesian Coordinate System.	DEFINITION OF SURFACE	Smooth curved surfaces are defined by descriptive geometries of topological surfaces allowing transformations from 2D to 3D. (Kilian et al., 2008). 

Table 3.10. *Continued*

It is a 1 DOF structure.	DOF	During deployment, it shrinks in two directions unless the form ends with saddle points, so it depends on 2 DOF. 
		There can be encountered a hidden DOF when it is folded.
Increase in number of overlaps makes the system harder to move and control. 	CONTROLLING	Controlled from each saddle point. Increase in number of curvatures increases number of actuating points. 

Looking through the differences between two folding types, it is seen that there are three main axioms in orthogonal folding: Miura-ori, Kawasaki, and Maekawa. These axioms are essential to understand geometric constructions of orthogonal folding. In fact, they are required to grasp whether a pattern on the idea of orthogonal folding can be folded flat or not. Furthermore, it gives the required conditions for flat folding, however, they are not enough to guarantee foldability. Still, looking through these theorems, following deductions can be made;

- All orthogonal surface folding sustaining these 3 theorems are tessellations on 2D.
- Any module of any folding tessellation is a part of these 3 axioms.
- All regular and semi-regular orthogonal surface folding belong to one of the symmetry groups.

Foldability of a flat folding sketch are exemplified as shown in the figure 3.4.

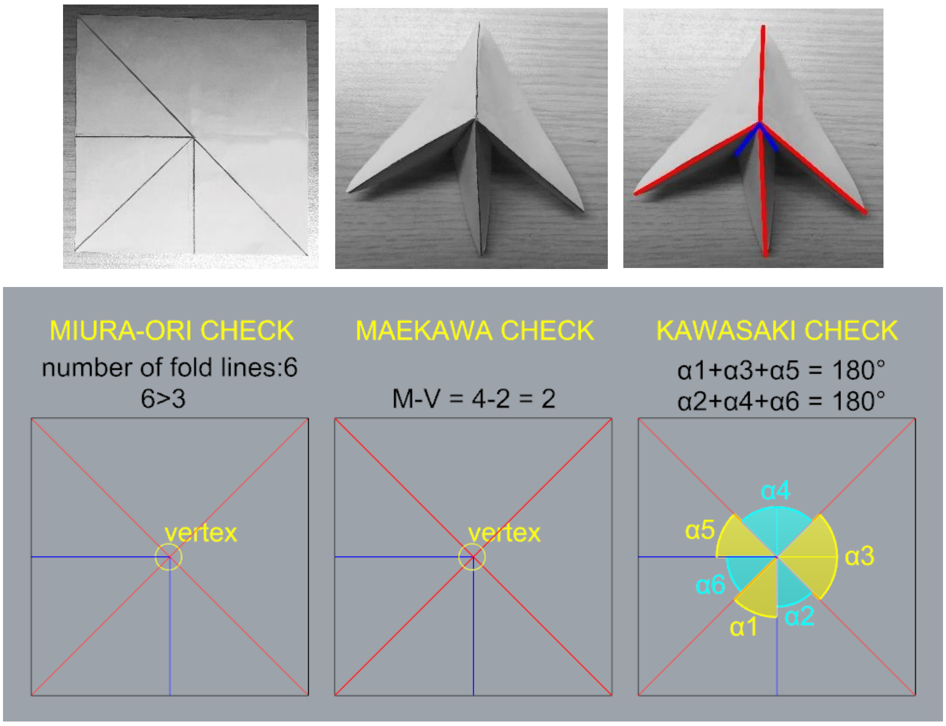


Figure 3.4. Top Row: Paper Model and Mountain-Valley Assignment. Bottom row: Application of the Theorems (developed by the author)

Starting with the implementation of these rules to folding surfaces allow better defined geometric relations. Otherwise, it becomes harder to control the system. For example, figure 3.5 does not encapsulate these theorems. In fact, increase in number of surfaces which is folded into the other makes a deployable kinetic structure harder to control due to excessive numbers of overlaps.

Figure 3.5. Left: Origami Model; Right: Top View and Cross Section of Rigid Folding

On the other hand, in curved folding, its foldability is determined by the assignment of descriptive geometries in a proper way. It is recommended to start with developable ruled surfaces in order to avoid from deformations from the beginning of the design process.

Curvilinear fold lines are assigned based on the references of initial generated surfaces. For instance, if it is cut from a cone, rulings should be generated according to conic references (figure 3.6). First, lines are projected from the peak point of a cone. A curved line is drawn after folding straight lines, so convex and concave relations are confused. Folding direction is dominated by tangent value of curvature. Hence, folding directions of orthogonal lines is changed to define folded surfaces.

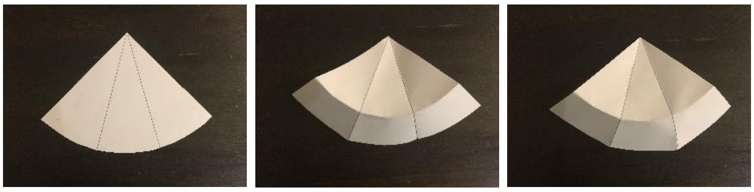


Figure 3.6. A Curved Surface Generated from a Cone

When assigning descriptive geometries, there are indeed three main steps to create curved folding. These steps are stated as follows, and they are to be employed respectively.

- Drawing curvilinear fold lines.
- Drawing rulings based on curvatures between consecutive curvilinear fold lines until they intersect and draw a flat surface passing from points where offset lines intersect.
- Transforming these drawn lines from 2D to 3D.

Figure 3.7, for instance, is created based on above-described steps.

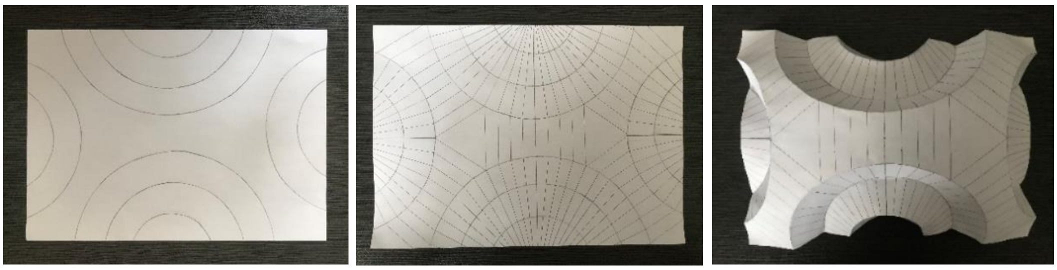


Figure 3.7. Paper Model Representing 3 Deductions

In addition, above-mentioned rules regarding curved folding can also be used to describe randomly folded surfaces. That is, even if a surface is defined by randomly drawn fold-lines, these rules can be applied to find the definition of its surface. For instance, figure 3.8 shows an arbitrarily drawn curved folding model. Its simulation is created in accordance with what is learnt from the rules stated above.

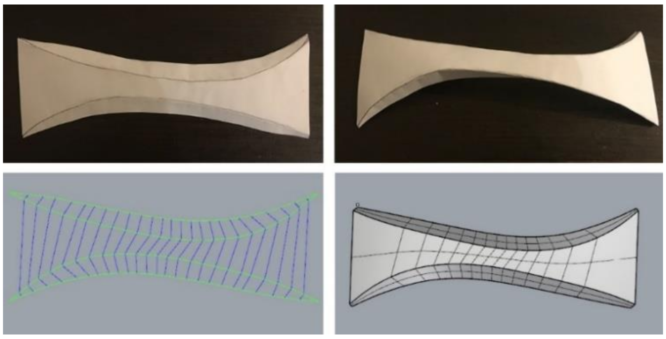


Figure 3.8. An Arbitrarily Drawn Surface. Left: Unfolded State; Right: Deployed State

As can be seen, understanding and implementing mathematical axioms for the construction of fold lines create basis for generating kinetic surfaces in a proper manner. Ensuring foldability is an essential part of the design process so that sketch can turn into a foldable kinetic structure. After foldability check, drawn fold lines are converted from 2D to 3D either using readymade programs or simulating manually based on above mentioned rules.

3.2.2. Simulation of Ideal Zero Folding

Origami is regarded as a mapping of lines and points from 2D to 3D. It defines how patterns drawn on flat sheets are converted into 3D deployed surfaces. These transformations can also be called as topological transformations, as transformations in folding schemas ensure the relations between fold-lines sustaining continuity during transformation. Besides, if mathematical relations of geometries are well-defined, transition between 2D and 3D can be performed without deforming material. Hence, construction and deconstruction of objects and their two-way transformations between 2D and 3D become significant to create properly defined kinetic surfaces. In fact, these transitions are related with descriptive geometries which give the idea about how complex forms can be unfolded, and relations among transformed lines.

Even if a surface is a free form which is defined randomly, it still represents the relations among its descriptive lines, because it maintains relations between tangent points of curvatures, distances between consecutive lines, and their symmetry axes. Unless descriptive lines were related to each other, it becomes harder to be able to fold precisely.

Looking through descriptive lines, it is possible to claim that formations of many patterns represent symmetry adopted mobility. Understanding geometric formations is essential, because even in creating digital simulations, mathematical understanding of origami patterns allows designers to create appropriate mappings of lines instead of using readymade codes. Hence, symmetries turn into a way to understand transitions. For instance, the example in figure 3.9 are simulated based on symmetries, and it represents above-mentioned mathematical axioms and deductions.

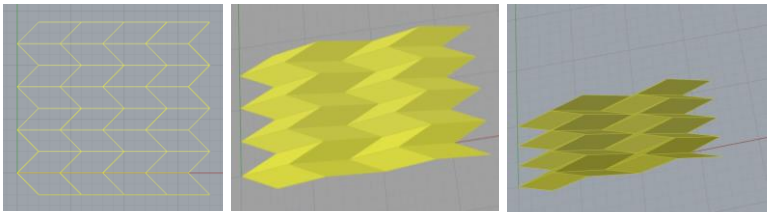


Figure 3.9. Digital Models Sustaining 3 Axioms (developed by the author)

Curved folding needs more afford when compared to orthogonal folding, since it is hard to generate curved surfaces due to its complexity. If it is found the right surface to generate curved folding together with assigning proper mathematical rules, the language of curved folding systems which seems hard to understand can be understood easier and many curved surfaces can be implemented in architectural projects. Curved surfaces are obtained by double curved or developable (single curved) surfaces. Developable surfaces ensure transformations between 2D and 3D without deformations. Hence, it can be an effective way to start with developable surfaces to obtain curved folding in order to avoid deformations from initial design phases.

There are two main ways to create curved folding: topological mapping and projection. The former gives clue about topological space of curved surfaces. On the other hand, the latter explains unrolling of curved surfaces together with topological relation of a projected shape. Difference between mapping and projection is related with how to convert lines onto curved surfaces. It is possible to claim that how curved folding is generated from which kind of surface is significant, as it brings its rules together. For instance, if a cone is cut, parabolic, circular, elliptic, and hyperbolic surfaces can be created.

Curved folding can be obtained by mirror reflection technique (Mitani, 2017). It is created by intersecting curved surfaces with a mirror plane either they are basic topological surfaces or randomly created developable surfaces. Then, digital file can be printed so that motion can be understood over physical model. Motion is converted into computational domain again. That is, it is a reverse engineering or analogue-digital conversion.

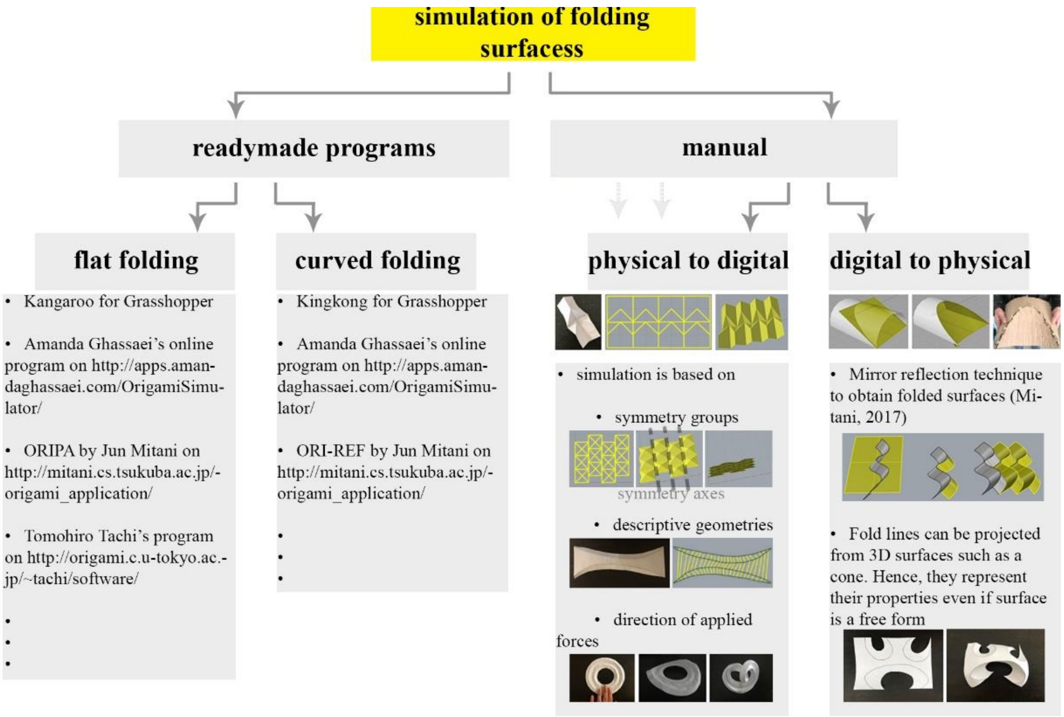
In addition to mirror reflection method, curved surfaces can be obtained from curved lines drawn on a paper. In this sense, desired deployed surface can be manipulated based on applied forces. Resultant 3D shapes will be different, because motion path lines and applied forces are different.

After understanding transformations over paper model, it can be implemented into computational design environment. It is important to transform the geometry with proper portions of links into computational domain. In this regard, precision is sustained by measuring lines and angles of the paper model, or by digital scanning in order to determine proper positions of vertices.

Finding actual mathematical relations of descriptive geometries is also essential to generate digital simulations for prototyping, because what is produced in digital fabrication tools such as 3D printers is actually unrolled version of the shapes which are modelled in computational design environment.

As a result, descriptive geometries are necessary to understand geometric relations of topological transformations in a proper way. If geometries are composed of developable surfaces, it facilitates transformations, because it ensures movements without distortions. Even very complex shapes such as curved ones can be folded and unfolded without deformations in this sense. For instance, ORI-REVO and ORI-REF programs developed by Jun Mitani use descriptive geometries to create curved surfaces. However, it is not enough to guarantee flawless transformations, because it is also required to assign proper mathematical rules. Table 3.11 exemplifies above-stated considerations together with a short summary.

Table 3.11. *Simulation of Folding Surfaces (developed by the author)*



3.2.3. Materialization of Ideal Zero Folding: Thick Folding

The critical thing in creating origami-based kinetic structures is assigning motion with material thickness, because thickness is not considered in paper model and digital model. It is important to understand how these surfaces and lines are transformed into real plates and linkages.

The author generates algorithms based on techniques stated in literature in order to assign thickness to origami models. Techniques which are used in generating algorithms are briefly explained in table 3.12. Then, developed algorithms are tried to be explained in a flowchart.

Table 3.12. *Thick Folding Rules which are used to form the basis of Generic Model*

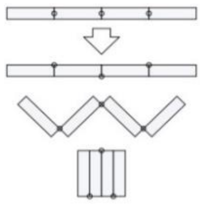
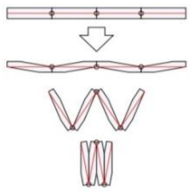
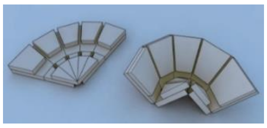
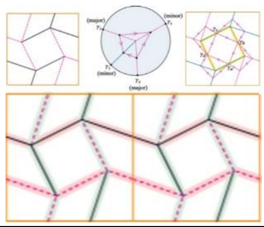
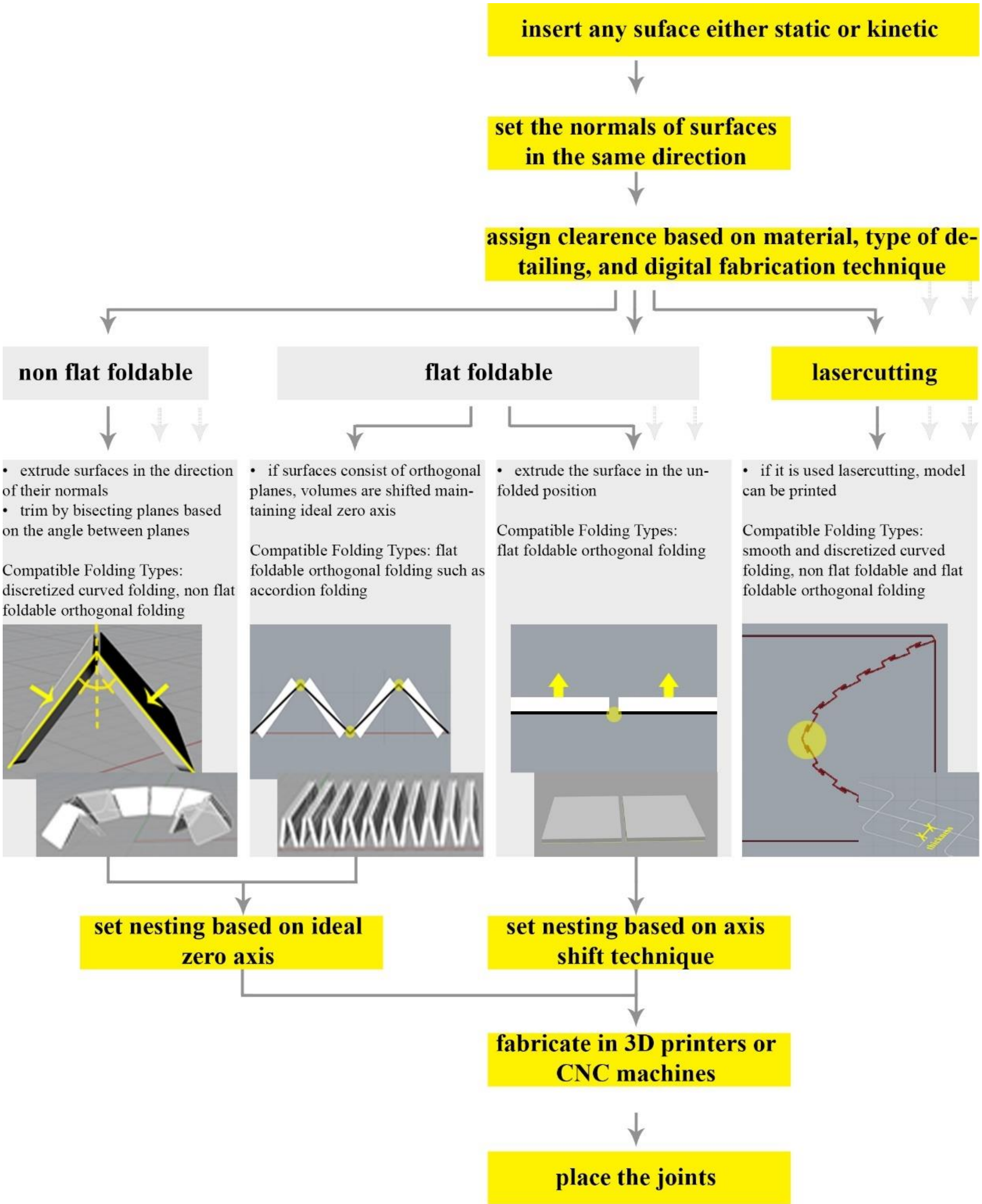
axis-shift	Ideal zero axis which is the cross section of paper model in the unfolded state, hold all connection points. If a slightest thickness is given to this flat surface, the connection points shifted based on the direction of folding. Concavity and convexity of the rigid model decide the placement of joints by shifting ideal-zero folding axis. (Tachi, 2010).	
changing section of solid	Maintaining ideal zero folding axis in rigid origami, cross section of the material is changed. That is, folding axis of the thick origami coincides with the axis of the zero-thickness paper model (Tachi, 2010).	
trim by bisecting planes	Solid is tapered by trimming each facet with the bisecting planes of dihedral angles determined by the adjacent facets to avoid colliding adjacent faces (Tachi, 2010).	
offset lines up to material thickness	Looking through a single vertex folding, flat foldability is questioned. Fold angle of this vertex in zero-thickness model is maintained in rigid folding. Then, it is offset edges of each surface. Offset distance is determined by material thickness (Lang, 2018).	

Table 3.13. *Process Flow regarding Thick Folding and their Digital Fabrication Process (developed by the author)*



Illustrated flowchart can be extended based on needs, demands, and evolving technology. It is significant to guarantee the digital fabrication which maintain proper portions of links, otherwise it becomes harder to construct geometrical relations. If desired geometry cannot be achieved, it becomes nearly impossible to sustain structural unity. Therefore, assigning clearance is a critical concern. In fact, clearance between panels does not always equal to material or joint thickness. Tolerance of the machine, type of construction material, and selected type of detailing should also be considered, because any smallest mistake in assigning thickness affects the overall geometry. Therefore, following equations are developed through by taking consideration into above mentioned rules as well as type of fabrication. The symbols used in the equations are explained below.

- t_{mt}: thickness of the material
- t_j: thickness of the joint (knuckle diameter for hinges)
- t: tolerance of the digital fabrication machine
- t_{mc}: thickness of the cutting tool of digital fabrication machine
- α: folding angle between adjacent plates in the folded position

In flat folding and discretized curved folding, surfaces are constructed with rigid materials such as wooden plates. However, it should be noted that in curved folding it is hard to fully open or closed the kinetic surfaces, so it cannot be placed hinges as easily as in flat folding. Still, below mentioned rules are valid for both folding types.

- If these rigid materials are fabricated in laser cutting machine, clearance is equal to $t_j - t$. Tolerance is changed based on fabrication machine and construction material.
- If it is fabricated in 3D printers, clearance should equal to t_j
- If it is fabricated in CNC machine, clearance depends on orientation of cutting tool of the machine. If it is cut based on;
    - exterior of lines, clearance is equal to t_j
    - center of line, clearance is equal to t_j - (t_{mc}/2)

- interior of line, clearance is equal to t_j - t_{mc}

Depending on these three rules, figure 3.10 is created. It is shown that tapered panels facilitate rotation, as it avoids overlapping of adjacent panels. Besides, offset lines are filleted (images on the bottom) to allow smooth transformations.

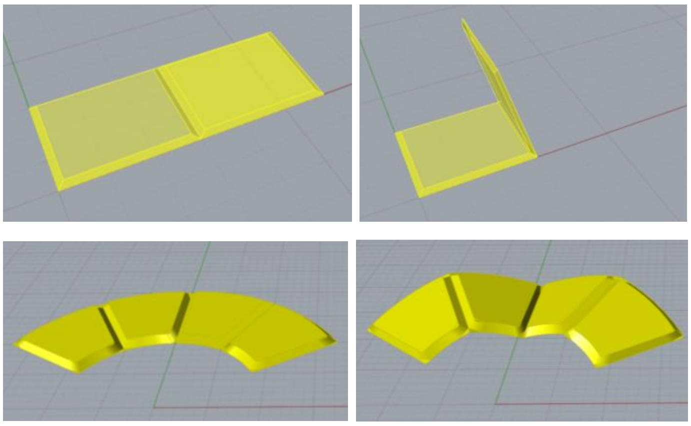


Figure 3.10. Digital Thick Folding Model (developed by the author)

In curved folding, curved surfaces can be discretized, or they can be smooth curved surfaces. It depends on what designers want to see in kinetic surfaces. If it is a smooth surface, construction material should allow bending without deformation.

If it is not discretized or constructed with materials allowing bending, folding surface is deformed as shown in figure 3.11.

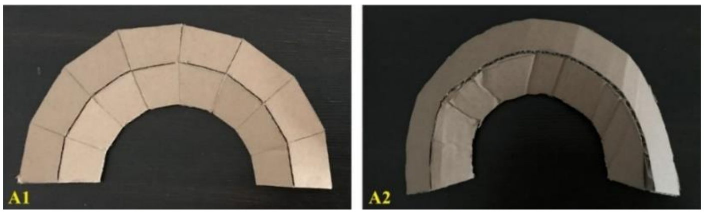


Figure 3.11. Discrete Curved Folding to avoid Deformation

If it is a smooth curved surface which is developable, it becomes easier to construct physical model with sheet materials such as a thin aluminum plates and a cardboard. In this case, connection edges become interlocking joints. As material itself turns into joint, clearance is determined by the material thickness.

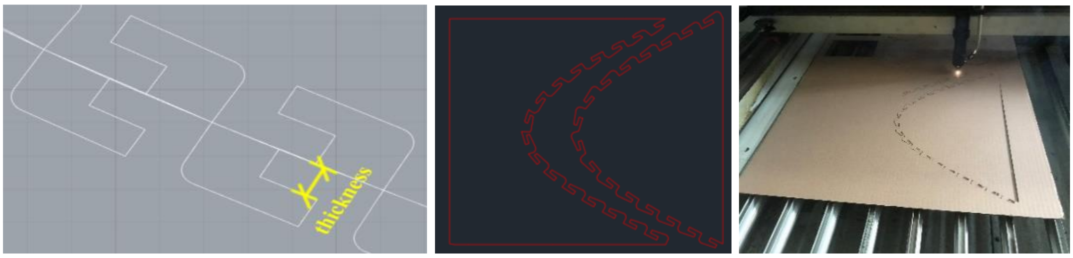


Figure 3.12. Laser Cutting of a Developable Surface (developed by the author)

After applying thick folding rules, mock-up models are created to decide suitable detailing before real scale prototyping. For instance, in figure 3.13, it is performed over three different edges with two different material thicknesses as 5mm and 2mm. These folding cardboard models are tested with the same material thicknesses, and the clearance between adjacent edges is equal to material thickness. Results are explained respectively as follows;

- "V" shape edges can resist to some extent in the deployed position due to friction, yet it collapses, since the opening should have been narrowed towards the edges. On the other hand, a pin is placed in the section to hold the system together (figure 3.13 on the top).
- In "C" shape edge models, thicker folding model resists more against slipping. The increase in thickness also increases friction. However, it still collapses, because it was neglected precision of laser cut machine. Therefore, edges should be interlock in a way that it cannot slip.
- In "L" shape edge models, L shapes are deformed in the thinner model, since they are not durable enough to allow folding. It should have been thicker. Nonetheless, it still collapses during deployment, as parts slip from each other. It is then shifted to cope with slipping, and it works. It should also be stressed that interlocking units particularly with manual labor needs adequate void. Otherwise, connection parts are forced to bend manually.

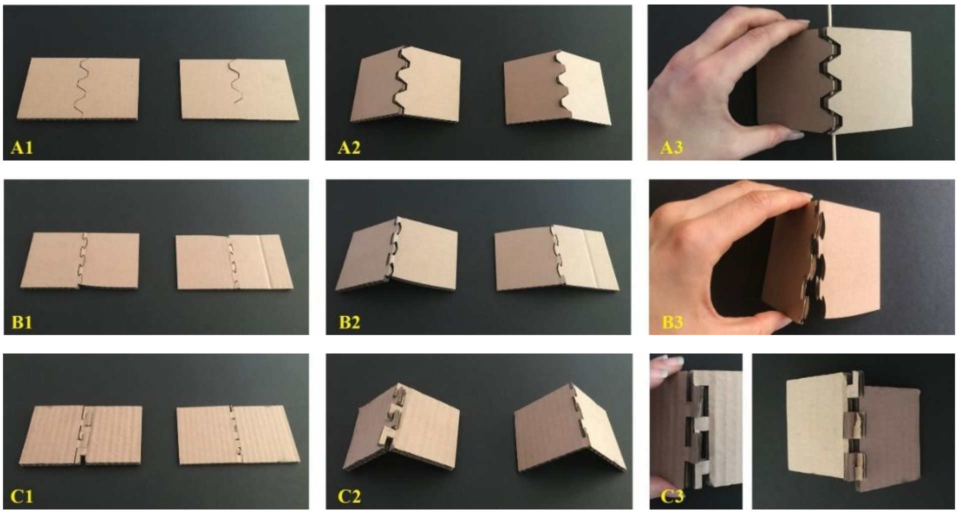


Figure 3.13. Three Different Edges with Two Different Material Thickness

Consequently, there are only three main rules that can be used as a layout to assign thickness into ideal zero folding as listed below;

- Boundary lines of surfaces are offset towards the center of each surface. Offset distance is determined by selected material, type of detailing and fabrication technique.
- Joints are placed according to the folding direction.
- If kinetic surfaces are not folded flat, rigid panels are tapered based on the offset distance: t_{mt} x tan (α/2). Tapered connection edges are filleted to avoid friction at the edges.

Above-proposed steps can be used as a guidance to develop thick folding models. If proper clearance is arranged between adjacent panels sustaining desired motion, it can be implemented into real prototypes. As seen, learning from thick folding provides solutions for the detailing of kinetic surfaces.

3.2.4. Evaluation of Origami Patterns in regards with 17 Symmetry Groups

It is significant to understand what type of forces should be applied to folding types, because some of them are linear that may work with tension and/or compression. Some of them are rotational and there are very few types which are hybrid type of forces. Therefore, symmetry groups are to be employed to analyze this type of motions. We use symmetry groups, because they are related with tessellations. These tessellations are indeed grid systems that are very versatile in architecture.

Symbols used to describe symmetry groups are illustrated in table 3.14. Those symbols depict the graphical layout of the isometries to indicate key points or lines where transformations occur.

Table 3.14. *Symbols used in isometries of the Euclidean plane*

	center of rotation of order two (180°) (two-fold rotation / half turn)
	center of rotation of order three (120°) (three-fold rotation)
	center of rotation of order four (90°) (four-fold rotation)
	center of rotation of order six (60°) (six-fold rotation)
	axis of reflection
	axis of glide reflection

Table 3.15 is prepared to exemplify both folding types in accordance with 17 symmetry groups. The table shows how patterns are analyzed based on reflection axes and/or rotation centers. However, selection of a motif is important for assigning symmetry groups. For instance, in figure 3.14, if motif can create P4 or PMM symmetry group. The important criteria should be stressed is that assigning symmetry groups are based on the way motion is delivered.

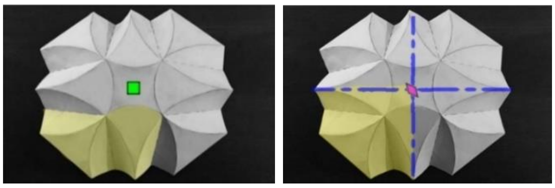
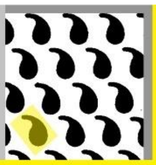
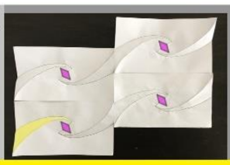
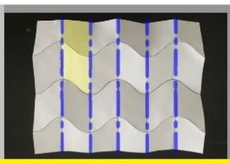
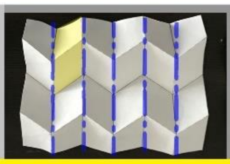
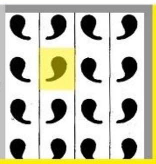
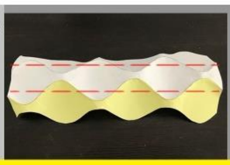
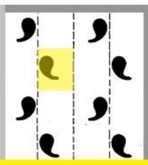
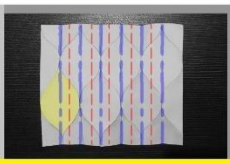
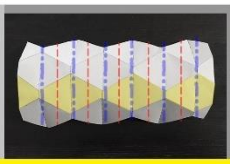
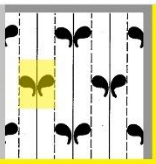
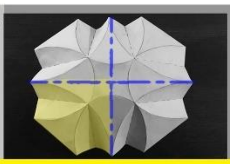
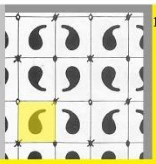
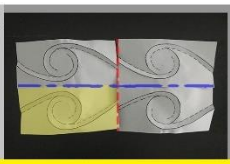
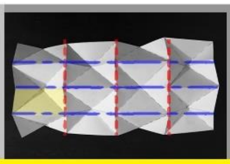
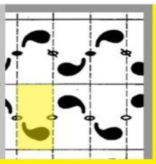
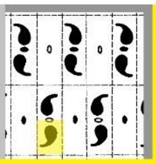


Figure 3.14. Selection of Motif Changing Symmetry Group (developed by the author).

Table 3.15. *17 Symmetry Groups in Folding Patterns (developed by the author).*

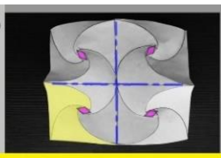
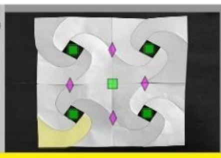
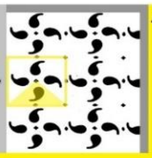
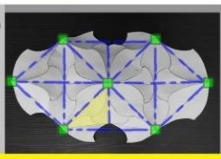
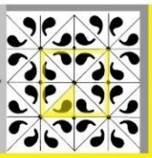
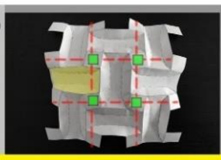
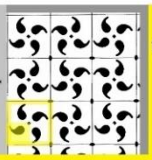
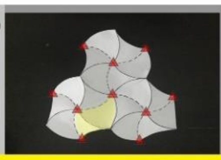
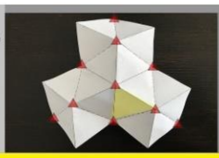
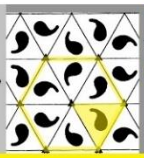
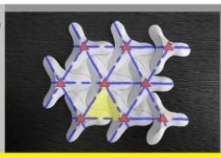
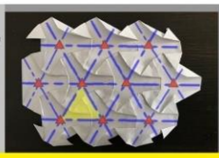
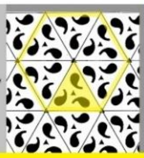
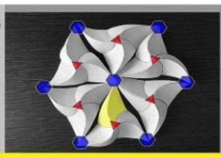
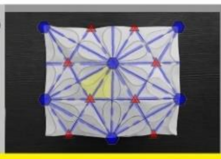
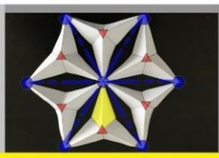
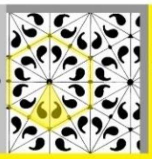
17 SYMMETRY GROUPS IN CURVED FOLDING AND FLAT FOLDING PATTERNS

Group	curved folding	flat folding	template	Description
p1				translations parallelogram grid
p2				half turns and translations parallelogram grid
pm				reflections and translations rectangular grid
pg				glide reflections and translations rectangular grid
cm				reflections and glide-reflections with parallel axes and translations rhombus grid
pmm				reflections whose axes are perpendicular and half-turns rectangular grid
pmg				reflections, glide reflections, and translations rectangular grid
pgg				glide reflections, half turns, and translations rectangular grid

(Source for images labeled with template in table 3.15: https://www.york.ac.uk/depts/maths/histstat/symmetry/welcome.htm. Retrieved at: 19.08.2019)

Table 3.15. *Continued*

17 SYMMETRY GROUPS IN CURVED FOLDING AND FLAT FOLDING PATTERNS

	curved folding	flat folding	template	
cmm				reflections and 2-fold rotations rhombus grid
p4				4-fold rotations and translations square grid
p4m				4-fold rotations, translations, and reflections square grid
p4g				reflections, glide reflections, and 4-fold rotations square grid
p3				3-fold rotations and translations hexagon grid
p3m1				reflections, 3-fold rotations, and glide reflections (all of the centers of rotation lie on the reflection axes) hexagon grid
p31m				reflections, 3-fold rotations, and glide reflections hexagon grid
p6				6-fold rotations and translations hexagon grid
p6m				reflections, 6-fold rotations, translations, and glide reflections hexagon grid

In literature, these symmetry groups are investigated as a pattern generation tool. Nonetheless, beyond creating new patterns, in this thesis both flat and curvilinear origami are studied in relation to symmetry groups to understand surface scale kinetic system working as a network. In fact, following considerations are obtained based on symmetry groups.

- It helps to understand global motion of kinetic surfaces. Hence, it facilitates generating digital model of a kinetic surface either it is an orthogonal or a curved folding working as a single motif or an entire surface.
- It gives the understanding of overall actuating system coinciding symmetry axes and points with the placement of actuating mechanisms.
- It gives the understanding of grids of kinetic surfaces.

Above stated considerations are exemplified in figure 3.15. In the top row, the shape is simulated based on rotation of initial motif which is yellow in color around the half-turn rotation center. The shape can also be simulated based on glide reflection axes. It is not necessary to use all rotation centers or reflection axes as actuation centers. These points define possible control scenarios.

In the middle row (figure 3.15), actuators of the base module are placed where four-fold rotation centers locate. Symmetric two forces are applied to a single module triggered by belt and pulley mechanisms.

In the bottom row (figure 3.15), rectangular grid of the symmetry group is altered based on direction of applied forces. In fact, rotational motions are sustained with triangular and hexagonal tessellated grids, whereas translational motions are sustained with square and rectangular ones, because the way which tiles come together to create tessellation is already rotational. However, grid can change based on motion or overall appearance in a manner which designers want to create.

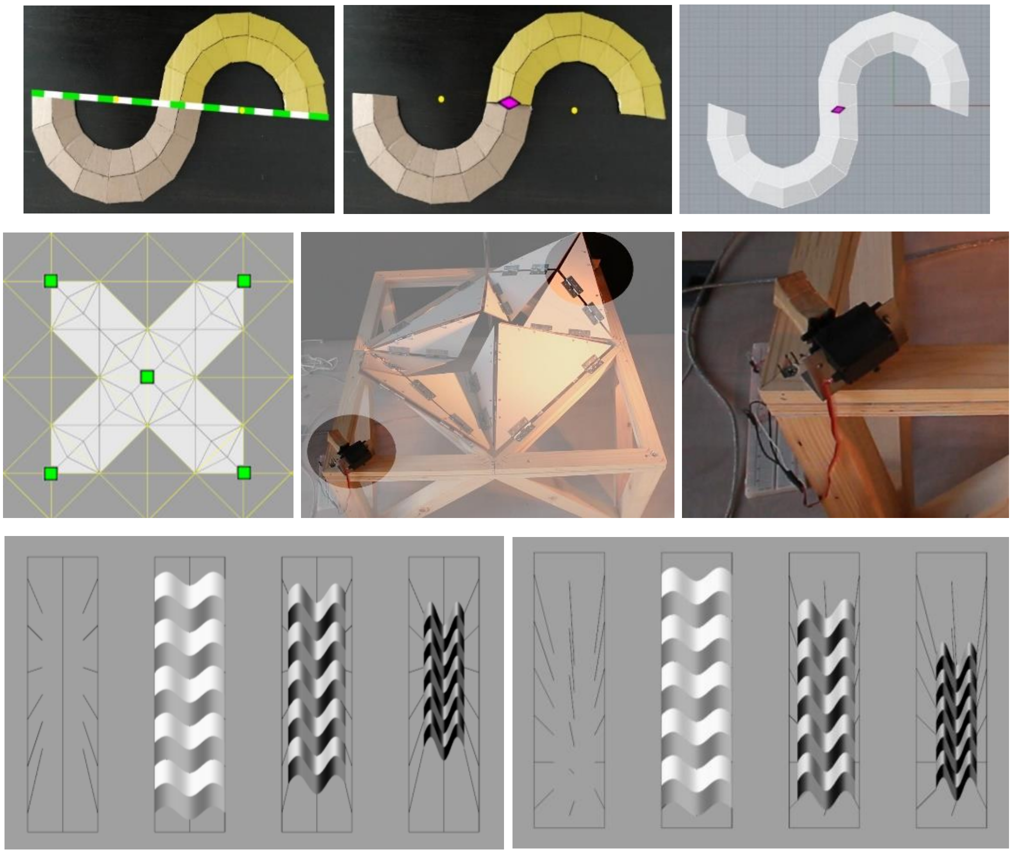


Figure 3.15. Top Row: Generating Motion based on Symmetry Group. Middle Row: Matching Actuators with the Four-Fold Rotation Center of the Base Motif. Bottom Row: Generation of the Grid based on Applied Forces and the Symmetry Group. (developed by the author)

In curved folding, the grid may not be linear or perpendicular in shape, as the pattern shrinks from two directions during motion. Hence, it depends on 2 DOF. These two directional forces can be eliminated to some extent, if curved system is ended with its saddle points. Otherwise, remaining parts require additional forces for actuation.

As it can be seen, symmetry groups together with tessellations have many important clues about types of mechanisms and motion. These mechanisms are briefly explained in table 3.16. We can group mechanisms as rotational and translational ones. They can be implemented in that way. Rotational mechanisms are

Table 3.16. Classification of Mechanisms based on Motion according to Reuleaux (developed by the author)

Screw	Wheel (gear/roller)	Crank (linkage)
TYPES OF MOTION: • It converts rotational motion to linear motion, and a torque (rotational force) to a linear force USAGE: • used to compress an object or to move forward with rotating components	TYPES OF MOTION: • Gears rotate together in which a force is transferred from one to the other. USAGE: • used to carry high load compared to most belt and pulleys.	TYPES OF MOTION: • It converts straight-line motion to rotary motion, or rotary motion to straight-line motion USAGE: • used in one side is fixed, other sides are pinned systems such as windows.

Belt and Pulley	Cam	Ratchet
TYPES OF MOTION: • If belt and pulleys are in parallel angle, it conveys the motion in the same direction. • If the belt is crossed, the direction of the driven shaft is reversed. USAGE: • used to transmit power over large distances.	TYPES OF MOTION: • A cam converts rotary motion into linear motion. USAGE: • used to push an object forward and pull back it	TYPES OF MOTION: • It allows continuous linear or rotary motion in only one direction while preventing motion in the opposite direction USAGE: • used to pull an object in only one direction such as in lifting heavy weights

These patterns are then implemented into building skin. Scale of kinetic surface modules as well as their grids should be compatible with the building form, floor height, and structural components of the building so that kinetic surfaces can be implemented to the building as an integral part. Therefore, it can be beneficial to start with modifying grid accordingly. Then, kinetic motifs can be mapped to the scaled grid. For instance, in figure 3.16 grid is mapped into a building skin created according to the ruled surface. The significant thing should be stressed is that motion remains the same regardless of the change in scale.

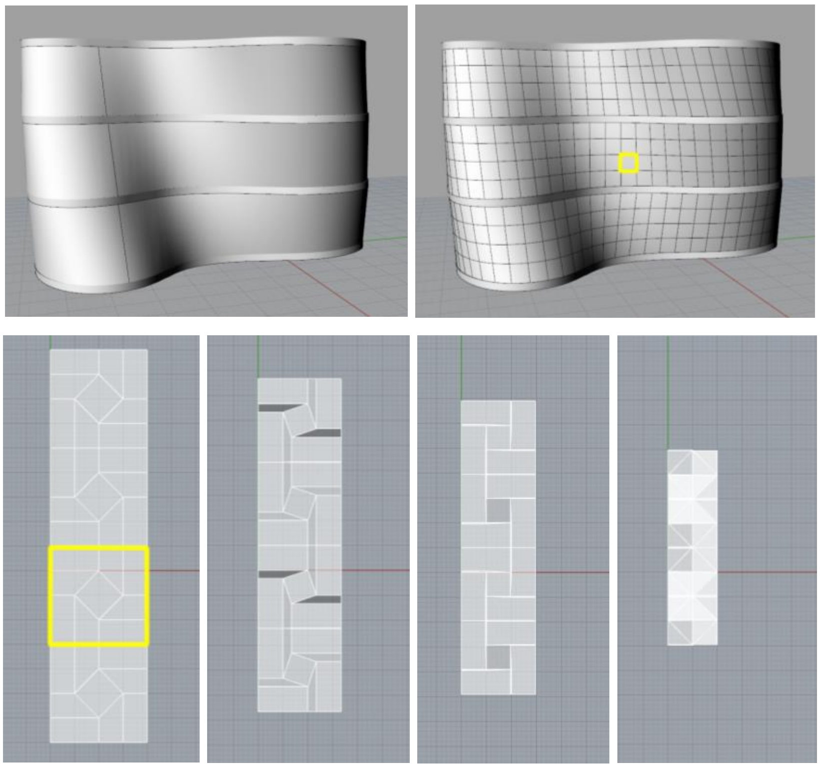


Figure 3.16. Arranging the Grid based on Building (developed by the author)

As a result, matching symmetry groups with origami patterns allow architects many potentials. As illustrated, these symmetry groups give clues about not only pattern generation, but also folding schemas with its global motion, driving mechanism, and structural grids.

3.2.5. Electronic and Physical Prototyping of the Model

Electronic prototyping platforms such as Arduino is used to create interactive projects sensing its surrounding environment by receiving inputs from sensors. Arduino boards read instructions coming from the Arduino programming language. The circuit on the board is determined based on electrical components such as potentiometer circuit (figure 3.17). These instructions are sent to the microcontroller on the board and it activates motors, and the system operates. Finally, using Arduino, and determining materialization and joint details, real scale prototype is performed.

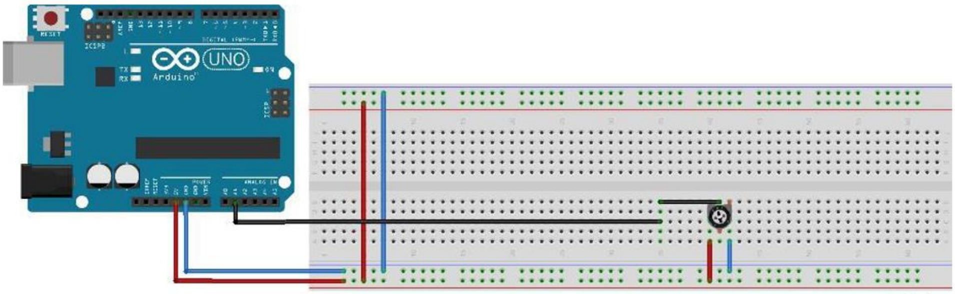


Figure 3.17. Potentiometer Circuit

For example, figure 3.18 is actuated by two symmetric forces triggered by using Grasshopper, Firefly, Arduino, and servo motor.

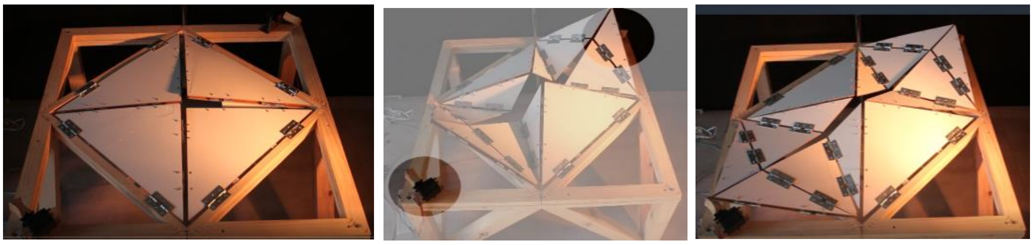


Figure 3.18. Prototyping with Arduino and Servo Motor (developed by the author)

3.3. Summary of the Chapter and Proposed Design Process for Development Origami-Based Deployable Kinetic Structures in Surface Scale Applications

In this thesis, it is investigated properly understanding and transmission of motion in surface scale kinetic structures working as a network. On the one side, applied architectural kinetic structures highlight the necessity of new formal and functional alternatives to avoid from replications of existing projects. Hence, it is tried to show that even curved surfaces which are thought as if they have complex geometries to construct, can be implemented into real surface scale kinetic projects in a non-deformed way. In this sense, paper is examined as a medium to understand folding. Learning folding from paper is beneficial for finding different languages on architectural skins.

Under this chapter, it is mainly examined associated rules to define geometric constructions of folding types through by briefly experimenting the process from flat sheet of paper to thick folding models. In particular, 17 symmetry groups are investigated in literature as a pattern generation tool, yet in this thesis they are introduced as a way to define kinetic surface grid, global motion, and actuation mechanism. Through by matching folding patterns with its symmetries, it is possible to find suitable enabler mechanisms, if movement is understood correctly. It is therefore possible to apply developed model to entire kinetic skin.

When designing kinetic surfaces working as an entire network, 2D layout of patterns are indeed tessellations. Nonetheless, the geometry of irregular tessellations is so complex that it is harder to solve and control its kinetic system. As earlier discussed, it is therefore beneficial to focus on regular and semi-regular tessellations. They are based on symmetry-adopted mobility either it is a single motif or an entire pattern. Looking through their symmetry groups, global motion is understood, which helps to create digital model for the fabrication.

Thick folding is quite critical for digital fabrication, since portions of links in paper model should be preserved in fabricated model to ensure geometric relations and structural unity. Also, digital fabrication machines generally work with 3D model. Even if they work with 2D model like laser cutting machines, the file to be sent to the fabrication machine should be prepared considering thickness in order to give desired clearance.

Thick folding is indeed important for the fact that any folding is able to turn into a real mechanism through by understanding motion over paper model, since it leads to grasp materiality of ideal zero folding surfaces.

To sum up, all considerations mentioned above will be guidance for design process regarding origami-based deployable kinetic structures in surface scale applications.

As a starting point for proposed design process, any sketch drawn onto paper is implemented into digital file. Its foldability is then tested based on mathematical theorems such as Miura-ori. These theorems are essential to create properly working mechanisms. If fold-lines sustain these theorems, they are translated from 2D to 3D.

There are many software programs such as Oripa or plugins such as kangaroo for Grasshopper to generate 3D folding surfaces. However, they do not give any information about folding with real material and joint thickness and their fabrication. In fact, these kinetic surfaces can be defined precisely without using readymade codes, if its mathematics is understood properly. Still, readymade programs are beneficial for development of kinetic structures.

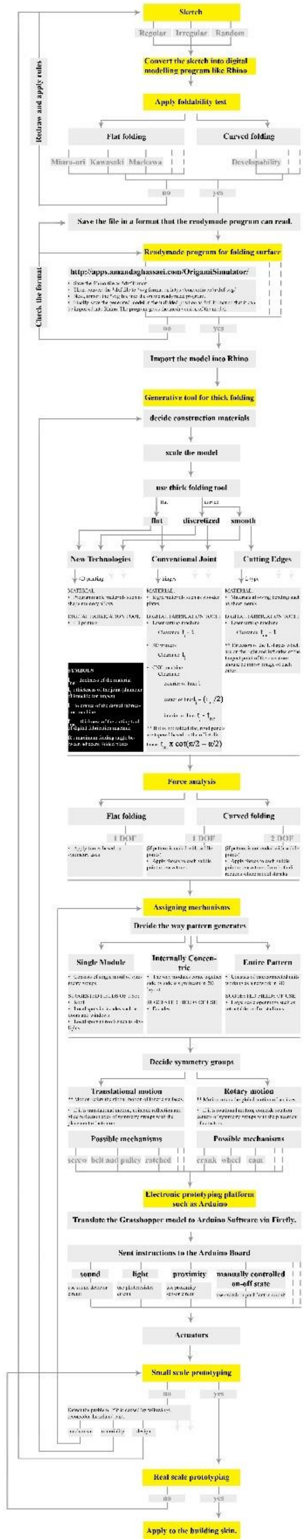
Readymade programs give ideal zero folded surface as an output. This surface becomes an input for thick folding algorithms developed by the author. That is, developed algorithms work with the integration of readymade programs. Besides, they can work with any foldable surface generated in Grasshopper. In fact, these algorithms are created in association with generative rules of thick folding so that they convert foldable sketches into thick folding. In this way, generated model is prepared for fabrication. There are Grasshopper libraries developed by the author. They can be extended and developed based on design requirements in future.

After applying thick folding rules, symmetry and force analysis are conducted so that enabler mechanisms can be matched. It is recommended possible mechanisms in regards with the type of global motion of kinetic surfaces.

Then, small scale prototypes are tested. If they perform in a desired manner, they can be applied to the building skin.

All these briefly mentioned steps enable architects to convert any sketch into real folding mechanisms which can be applied in architectural skins. These steps are represented in table 3.17.

Table 3.17. *From Flat Sheet to Applied Thick Folding (developed by the author)*



CHAPTER 4

CASE STUDIES

Under this chapter it is basically examined design approach for the development of rigid-body deployable kinetic structures based on origami. First, research materials are explained. Case studies are then briefly introduced.

In evaluating case studies, steps based on mathematical rules which are presented in the flowchart (table 3.17) will be guidance for architects to develop both flat and curved kinetic surfaces. Basically, foldability theorems are applied so that digital model can be defined properly. Then, recursively used algorithms for assigning thickness to folded surfaces are implemented. It is intended to precisely give clearance for digital fabrication. Finally, symmetries of patterns are examined to generate pattern matched with suitable actuators. When proposed steps are implemented respectively, architects are able to create tessellated kinetic surfaces whose details have been solved and possible mechanisms are offered. Therefore, learning from folding will become a pre-design tool for architects.

4.1. Research Materials

Rhino is used as a 3D modelling program to create fold lines so that they can be transmitted into readymade program. It is used Amanda's online program to generate folding surfaces. As readymade program works with *svg file format, Rhino files are saved as *dxf format and then translated into online *dxf to *svg converter. Created folding surface is saved in the unfolded position as *stl file so that it can be directly imported into Rhino. Then, Grasshopper for Rhino is used as a parametric modelling program to generate thick folding.

Thereafter, digital model is translated via Firefly plug-in from Grasshopper to Arduino Software and boards. It is actuated based on potentiometer circuit.

4.2. Case Studies

Three case studies will be implemented representing basic typologies of sketches: arbitrary, regular, coarse curved, and fine curved. The reason to select these main typologies is to stress that any sketch which is foldable has potential to produce a kinetic surface and its mechanism.

All four case studies are examined under five categories; foldability test, simulation, thick folding for fabrication, type of mechanism recommendation, and mock-up models.

4.2.1. Arbitrary Sketch

The suggested process flow includes any line. Hence, first case study is related with an arbitrary sketch proposed by any designer. In this case study, it is aimed to show how any arbitrary sketch can turn into a foldable kinetic structure.

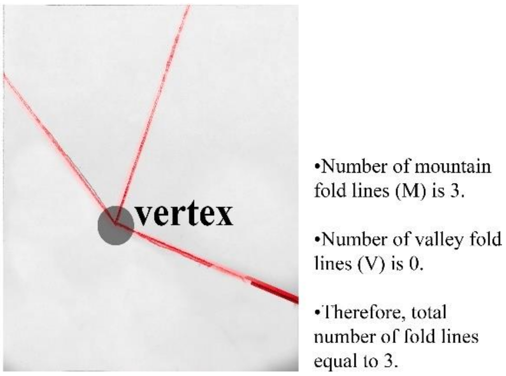


Figure 4.1. An Arbitrary Sketch (drawn by the author)

First of all, the arbitrary sketch is interpreted with respect to foldability and three theorems are to be employed respectively as illustrated in figure 4.2.

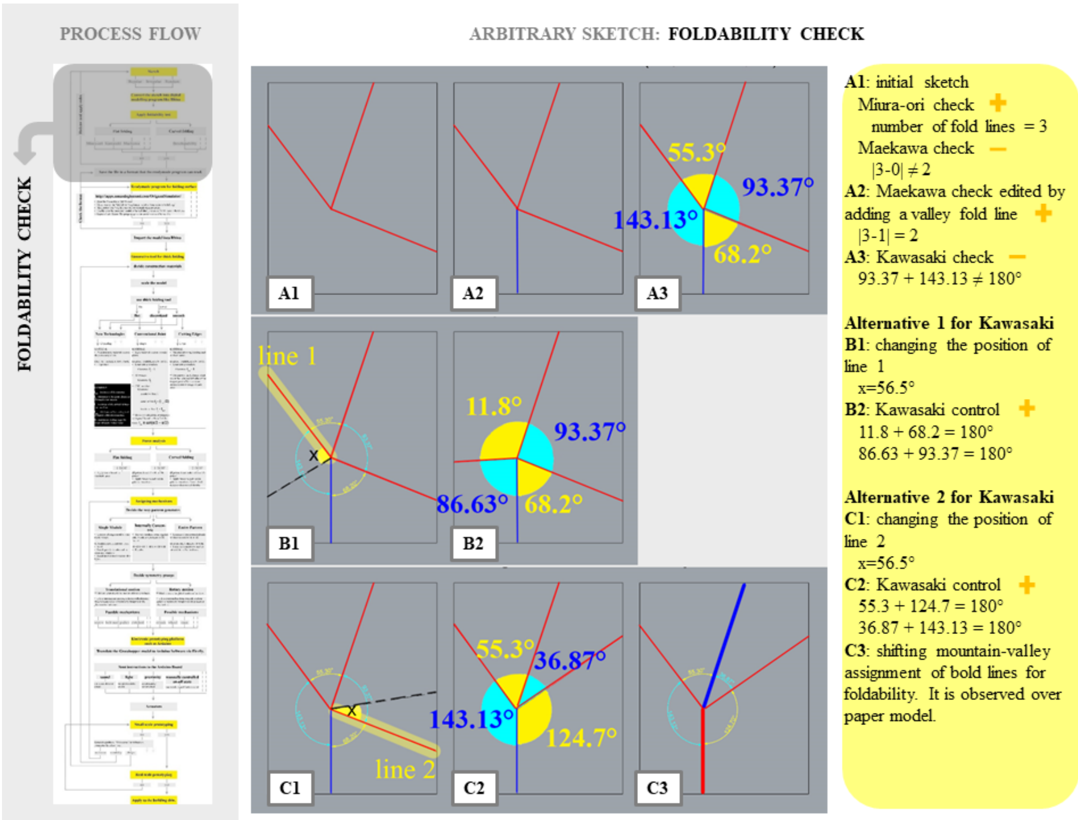


Figure 4.2. Foldability Check for Random Sketch (developed by the author)

Looking through the figure 4.2, existing lines (A1) already sustain Miura-ori theorem. However, the second check is necessary. Therefore, it requires one more line assigned as a valley fold line (A2) in order to guarantee Maekawa theorem. Lines in the new configuration are indicated as follows:

- Number of mountain fold lines (M) is 3.
- Number of valley fold lines (V) is 1.
- Therefore, |M-V| = 2

Hence, the second check is done. However, the third foldability check should also be maintained. Therefore, two different cases are tried: changing the angular position of line 1 (B1) and line 2 (C1). In the first case (B1), the sum of alternating angles is stated as follows;

- 11.8 + 68.2 = 180°

- 86.63 + 93.37 = 180°

In the second case, the sum of alternating angles is mentioned as follows;

- 55.3 + 124.7 = 180°
- 36.87 + 143.13 = 180°

The third foldability check is done in both cases. However, it is observed over paper folding that model in C2 cannot be folded physically because of the assignment of mountain-valley fold lines. Therefore, bold lines in picture C3 are switched so that the model can be folded.

After guaranteeing foldability, the models (B2, C2, and C3) in figure 4.2 are simulated as shown in figure 4.3. Accordingly, the best result among the alternatives are obtained from C3, so it is further evaluated.

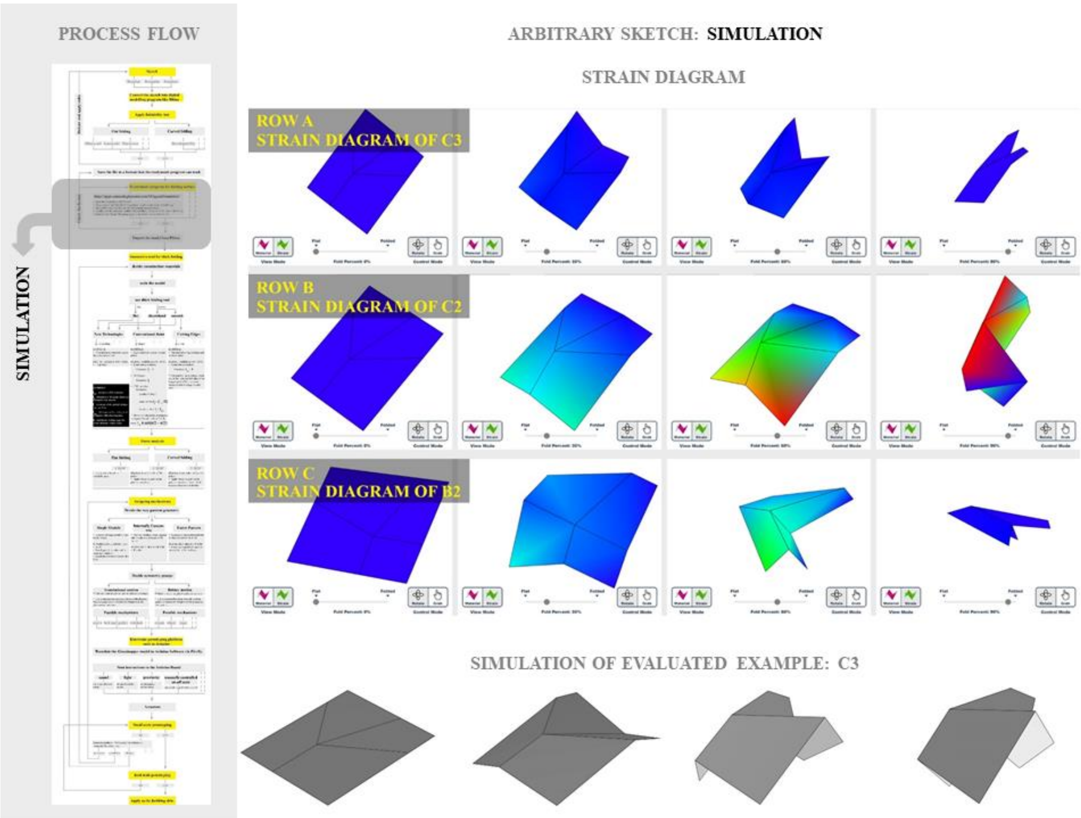


Figure 4.3. Strain Simulation for Foldability Check for Random Sketch. B2, C2, and C3 represent the pictures in figure 4.3. (developed by the author)

The next step is thick folding. Thickness is assigned based on laser cutting machine and construction materials. These materials are a hardboard with 6mm in thickness, fabric, and cardboard with 2mm in thickness. Symmetry analysis is then conducted as shown in figure 4.4.

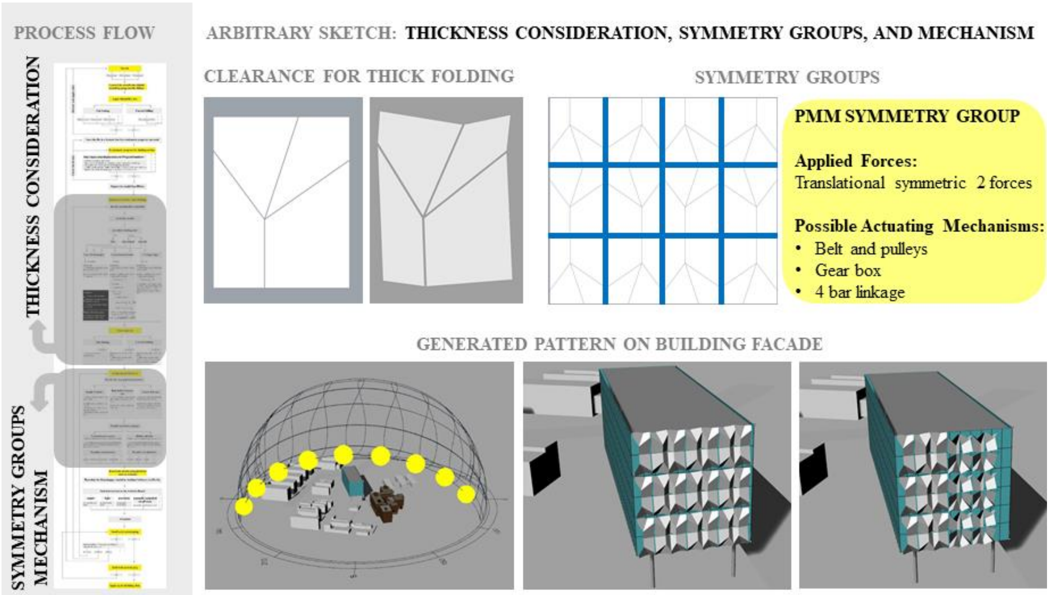


Figure 4.4. Thickness Consideration, Symmetry Groups, and Mechanism for Arbitrary Sketch (developed by the author)

Finally, the model is to be prototyped. In the first prototyping, hinges are placed depending on axis-shift technique, while in the second one, textile is used as a flexible joint sandwiched between cardboards. They are shown in figure 4.5.

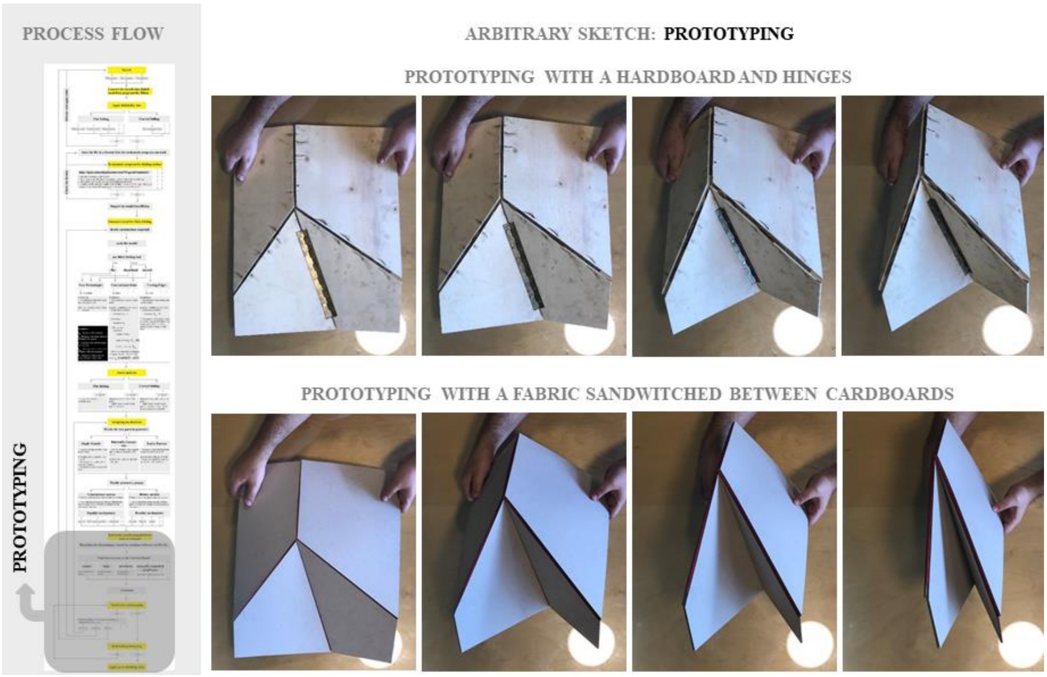


Figure 4.5. Prototyping for Arbitrary Sketch (developed by the author)

As a result, the first case study illustrated how arbitrarily drawn lines can turn into a real prototype through by following the steps in the proposed flowchart.

4.2.2. Regular Sketch

The second case study intends to exemplify how a regular sketch can convert into a foldable kinetic structure. The example is indicated in figure 4.6.

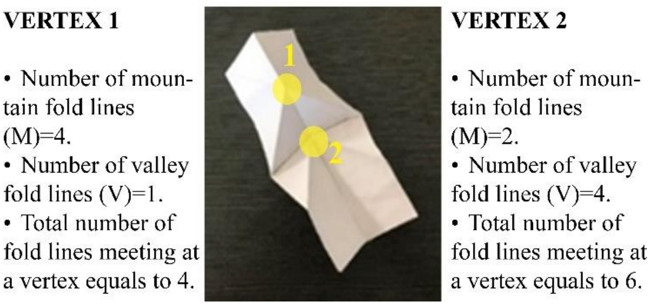


Figure 4.6. Regular Sketch

Folded paper is converted into digital file and foldability rules are then checked. In the vertex 1, 4 lines meet at the vertex, and sum of alternating angles equal to π

(135+45=180°). Furthermore, subtraction of number of mountain and valley fold lines equal to 2 (3-1=2).

On the other hand, 6 lines meet at the vertex 2. Also, sum of alternating angles equal to π (90+45+45=180°). Moreover, difference between the numbers of mountain and valley fold lines equal to 2 (4-2=2).

As a result, the sketch sustains three main theorems: Miura-ori, Kawasaki, and Maekawa respectively in both vertices.

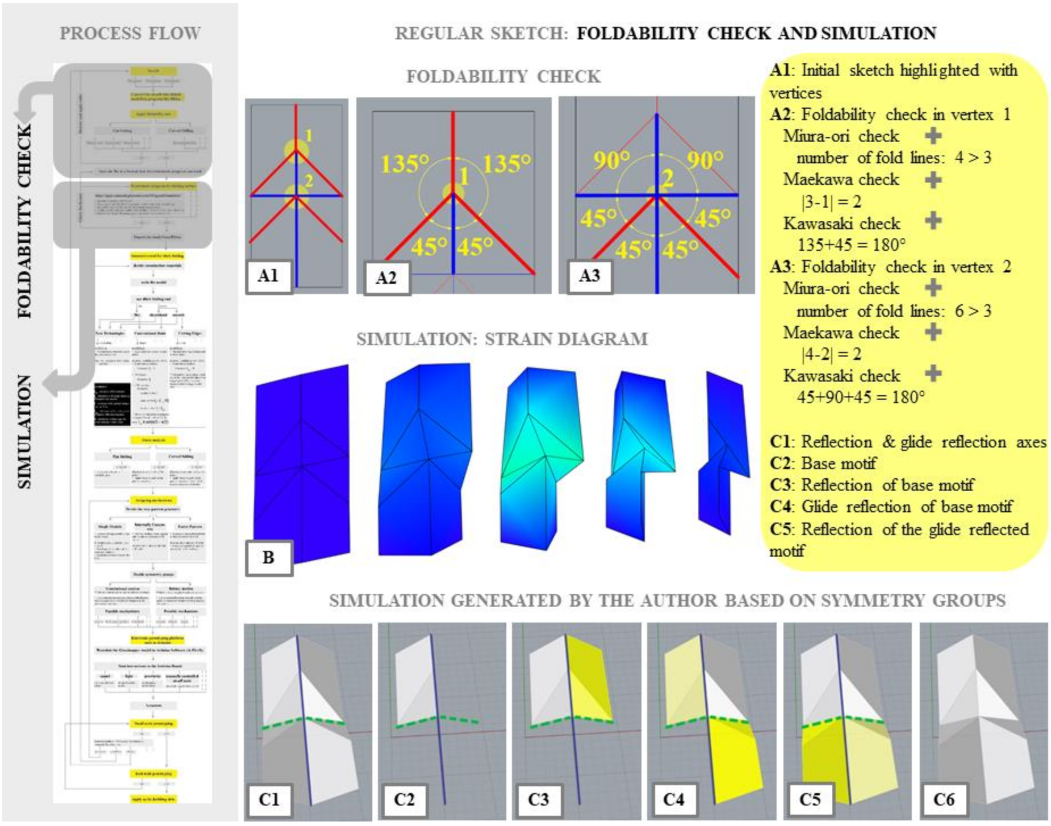


Figure 4.7. Foldability Check and Simulation of Regular Sketch (developed by the author)

After ensuring that sketch satisfies foldability theorems, fold lines are translated from Rhino to the online readymade program developed by Amanda Ghassaei so that simulation can be tested as shown in figure 4.7. Then, the author creates the simulation based on symmetry axes. Tessellation of the model belongs to pmg group, so model is generated depending on its reflection and glide reflection axes. However, when simulating the model, reflection axes are not static. Rather, mirror planes are defined by the moving edges shared by adjacent surfaces.

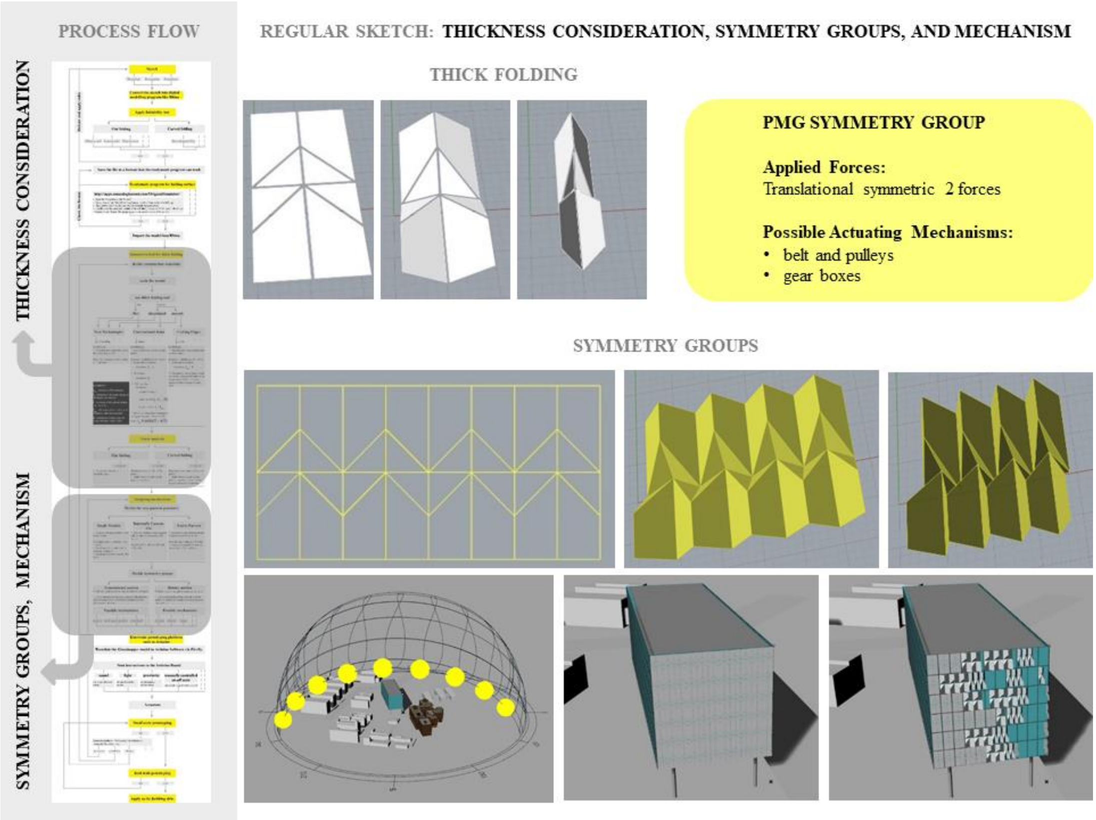


Figure 4.8. Simulation based on Symmetries. Top Row: Formation of Geometry based on Reflection and Glide Reflection Axes. Bottom Row: 2D Tessellation and its Simulated Model (developed by the author)

Thereafter, clearance is given by the algorithm created by the author. Offset distance is determined by the thickness of the joints, as it is fabricated in the laser cutting machine.

The entire pattern is generated based on pmg symmetry group (figure 4.8). Looking through the entire pattern, symmetric two forces should be applied to operate the kinetic motifs. It works with translational motion of kinetic surfaces. Therefore, possible type of mechanisms can be belt and pulleys or gear boxes.

The model is tested with Arduino Software and boards based on switch button circuit (figure 4.9). Accordingly, kinetic mock-up models become ready.

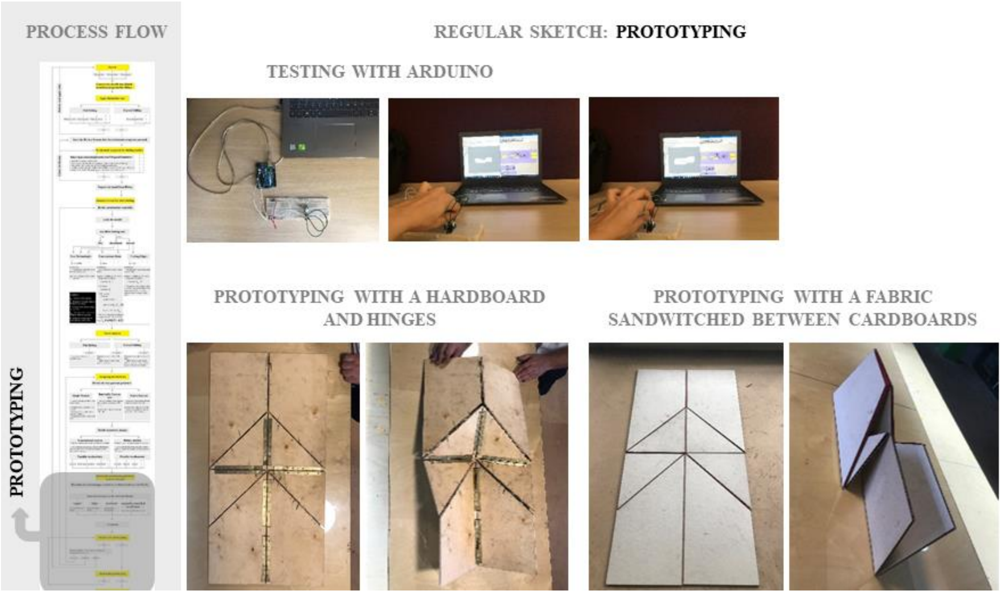


Figure 4.9. Testing with Arduino (developed by the author)

4.2.3. Coarse Curved Sketch

The third case study aims to illustrate how a coarse curved sketch can turn into a foldable kinetic structure.

It is started with developable ruled surfaces for the generation of the pattern. Therefore, its foldability is automatically checked. Descriptive geometry of the pattern depends on cones, so it represents conic references in the folded and unfolded states. Accordingly, surfaces are described by the approximation of curved lines as shown in figure 4.10.

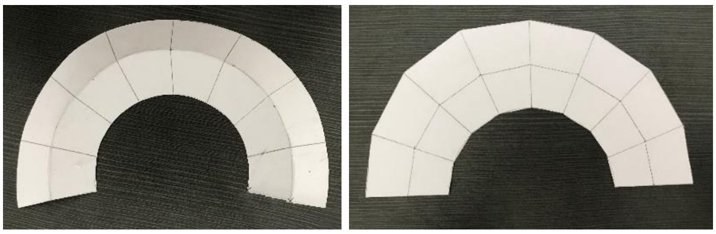


Figure 4.10. Ruled Surface. Left: Approximated Curvatures; Right: Smooth Surfaces

After foldability check, the model is to be simulated as illustrated in figure 4.11. Semi-circle is radially divided into eight segments, so it creates an octagon in the folded state. Layouts of initial and final shapes are observed over paper model in order to understand point transformations.

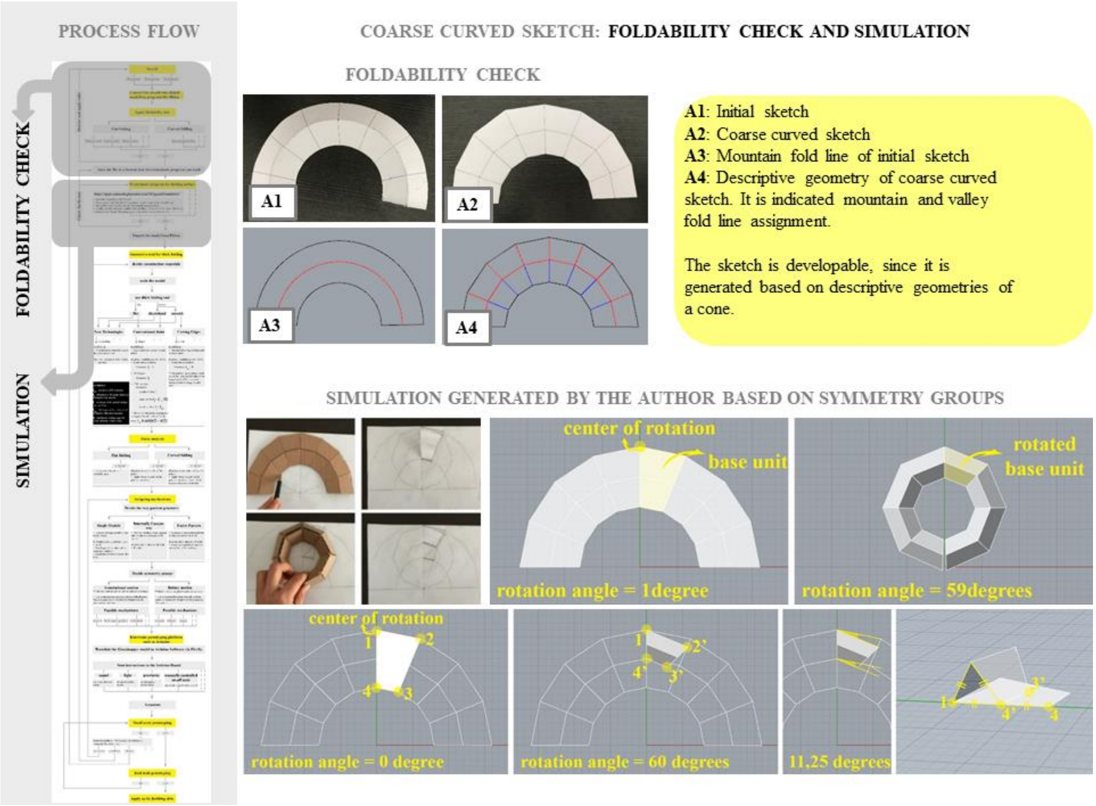


Figure 4.11. Understanding Transformation of Folding of a Semi-arch over Paper Folding (developed by the author)

Rotation angles of the surfaces come from the geometrical displacement of boundary lines of surfaces. For instance, the outer edge of the semi-circle rotates 11.25 degrees. First, the sum of the inner angles of the octagon is subtracted from the sum of the internal angles of the polygon composing of sixteen edges in the same length (157.5 – 135 = 22.5). Second, the result is divided into two (22.5 / 2 = 11.25).

Then, simulated single module is mirrored based on reflection planes of symmetry groups (figure 4.9 on the bottom). These planes pass from the rotating points of common edges of adjacent surfaces.

Simulated model is ready for thickness consideration. Clearance is given depending on non-flat foldable hinge-based fabrication in laser cutting machine (figure 4.12). Then, symmetry analysis is performed as indicated in figure 4.12.

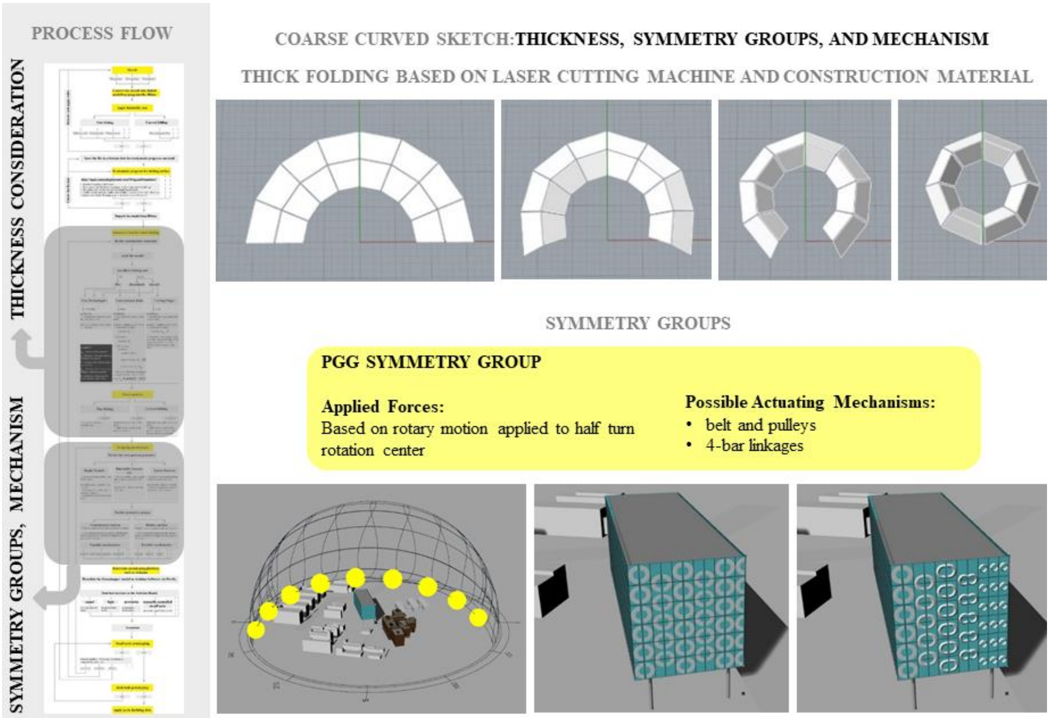


Figure 4.12. Simulation (developed by the author)

After symmetry group assignment, kinetic motif is tested with Arduino Software and boards based on switch button circuit (figure 4.13). Next step is prototyping with real materials. Two different alternatives are implemented to deliver the same motion. Accordingly, detailing and clearance are changed based on construction material. In hardboard model, conventional hinges with 4mm in thickness are placed depending on axis shift technique. On the other hand, in cardboard model, a fabric is used as a flexible joint that bound two layers of cardboards with 2mm in thickness. No matter what type of material is used, if motion is delivered precisely. For instance, it can be used a programmable material instead of a fabric. Detailing and cost will be different but trying to transmit assigned motion helps to find appropriate detailing.

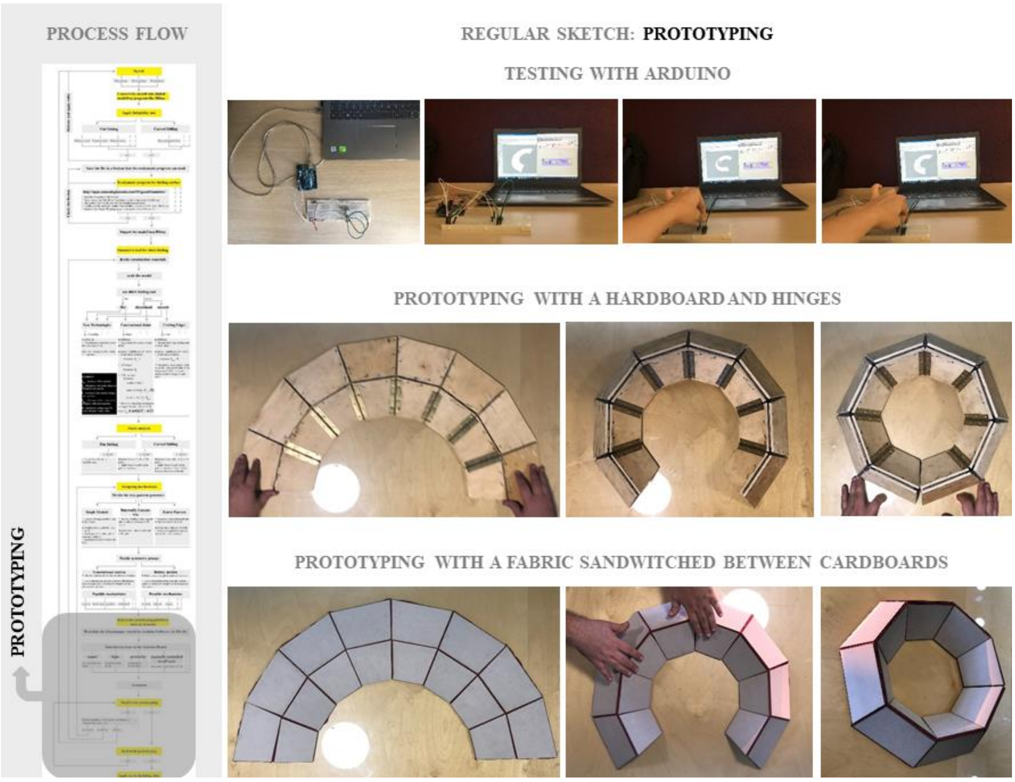


Figure 4.13. Testing with Arduino (developed by the author)

4.2.4. Fine Curved Sketch

The last case study exemplifies how a fine curved sketch can transform into a foldable kinetic structure.

It is checked three alternatives. The firs alternative case consists of arbitrarily drawn descriptive lines (curvature and rulings). The second alternative is created based on descriptive geometries of a cylinder by using mirror reflection technique. The third alternative is created by changing initial boundary of the second case preserving the same rulings and curvature. All three models have equal number of rulings. The first two cases have the same boundary conditions. The last two cases have the same rulings, but with the different in length (figure 4.14).

Strain diagrams of the alternatives are compared, and second example perform better under stress-strain diagram, since its rulings are not defined randomly, and it is based on ruled surfaces. As it is generated based on descriptive geometries of a developable ruled surface, its foldability check is done.

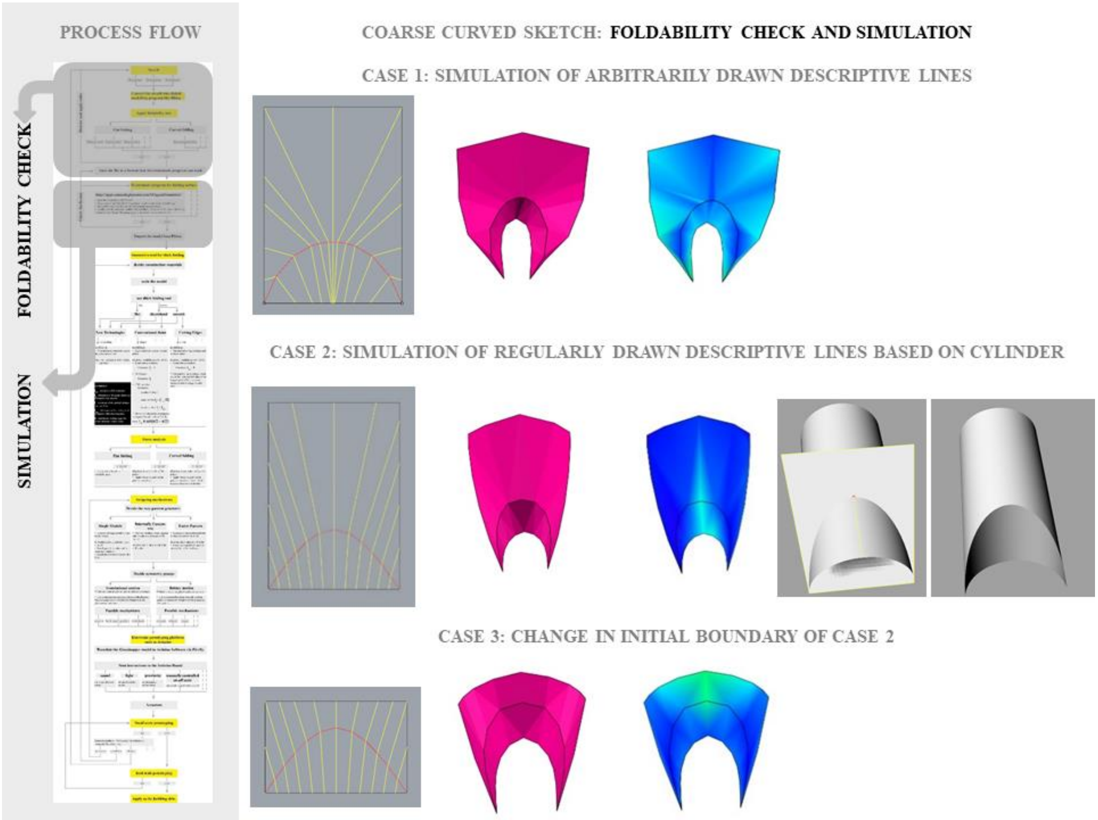


Figure 4.14. Simulation Check for Randomly Drawn Lines in Readymade Program. Left: Translated Fold Lines. Middle: Folded Model. Right: Folded Model with Strain Diagram. (developed by the author)

The second alternative is evaluated in terms of thickness for fabrication. It is used cutting edges technique, because it will be constructed with materials allowing bending in laser cutting machine. Then, symmetry group, type of forces, and possible mechanisms are assigned as illustrated in figure 4.15.

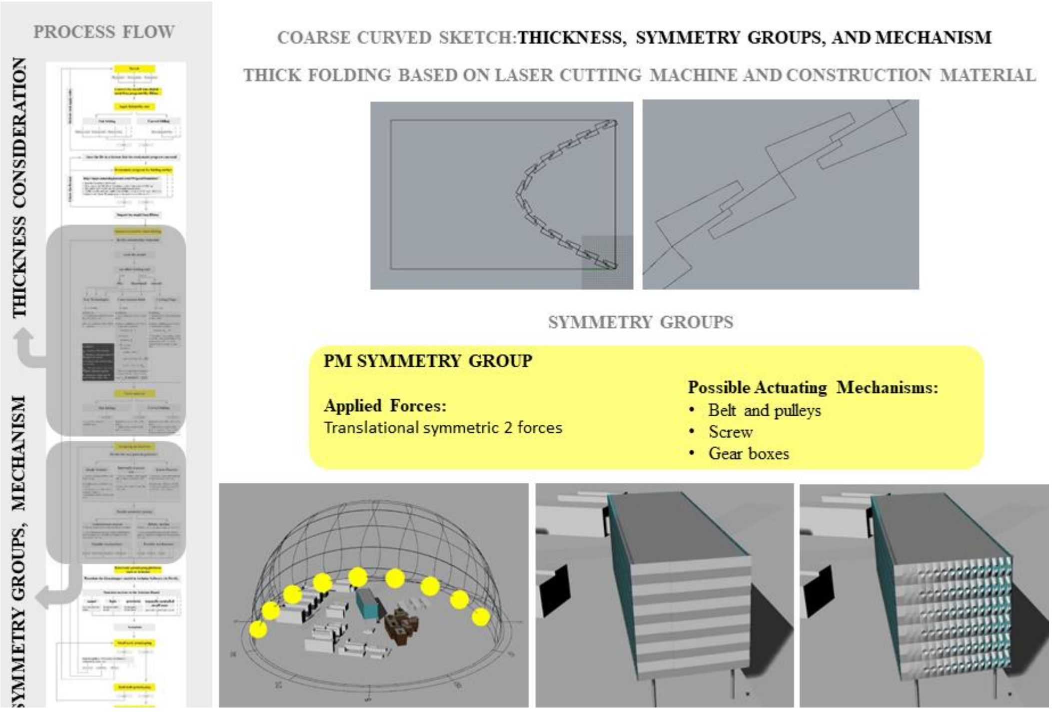


Figure 4.15. Simulation (developed by the author)

The model becomes ready for fabrication. It is used three different materials with different thicknesses as stated in figure 4.16. The first model at the top of figure 4.16 is deformed where strain diagram warns, because cardboard with 2mm in thickness does not allow bending as planned. However, the same material with 1mm in thickness allow bending in the second case that is shown in the middle row in the figure 4.16. In the last case at the bottom of the figure 4.16 let smoothest transition between folding states among the alternatives. These three cases important for the selection of the material. If motion is maintained, construction material should be selected compatible with assigned motion. If construction material is preserved, its maximum and minimum opening angles should be considered before the implementation to the building, because it will not achieve desired conditions as planned such as desired level of interior thermal comfort.

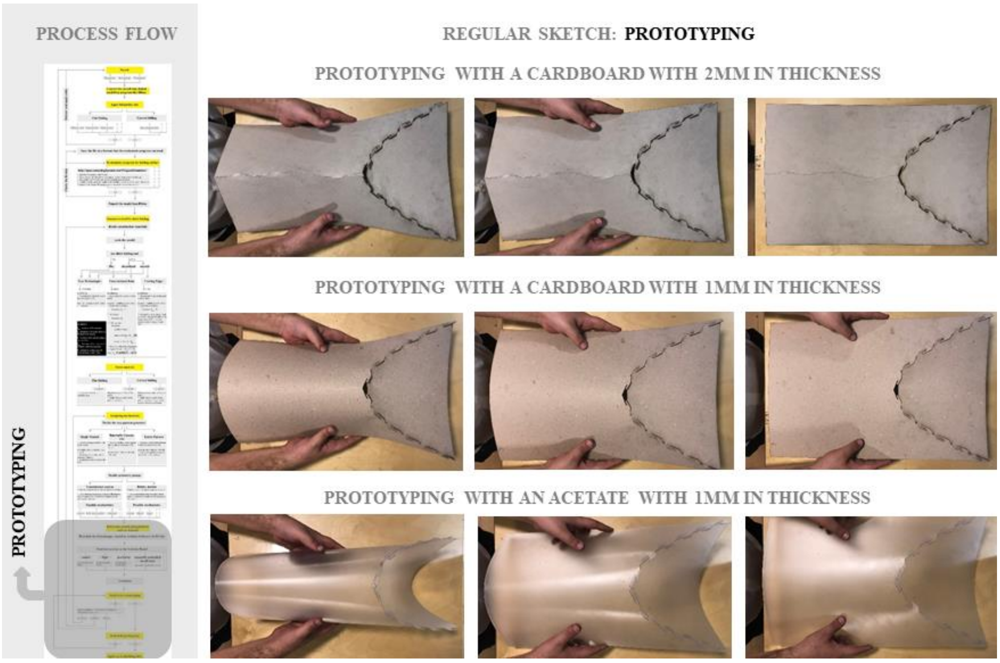


Figure 4.16. A1: Excessive Sequences of Connection Parts; A2: Decreased Sequences of Connection Parts (developed by the author)

As a result, the last case study exemplified how fine curved sketch can turn into a foldable kinetic structure in architectural sense.

CHAPTER 5

CONCLUSION

In this chapter, conclusions from the case studies are discussed. Then, the research conducted in this thesis is taken into account in terms of the importance for the literature. Also, it is respectively discussed potentials of curved folding, and recommendations for further studies.

5.1. Conclusions from the Case Studies

In this thesis, it is shown that any arbitrary sketch can turn into a fold and then can be a source for new inspirations for kinetic structures. In this regard, it is suggested and tested a process flow.

The process is so systematic that everyone can understand and develop foldable kinetic structures in architecture. It gives architects the proper side of learning from folding material such as a paper. That is, folding paper is not enough to guarantee foldability of kinetic structures. It needs to be considered together with mathematical rules.

It is a design research, so the essence of this study is the process, rather than aesthetical concerns. As long as any initial sketch sustains foldability check, the process can always allow to generate real foldable kinetic structure. The remaining part is a matter of the architect's taste, project’s context, material, technology, and cost.

The proposed process flow also aims to seek form-finding. No matter what you fold, and whatever you draw. It does not make any difference. In fact, the process is valuable to offer architects to search for not only the form, but the structure and mechanism with proper potions of links simultaneously.

In curved folding, once descriptive geometries are employed precisely, it always works. Benefitting from ruled surfaces for the assignment of descriptive geometries is a wise start, because it ensures unrollment without deformations. Hence, ruled surfaces let smooth transitions between folding and unfolding states. For instance, in fine curved sketch, three distinct alternatives were tested, and best result in strain diagram is obtained from properly addressed descriptive geometries of ruled surfaces.

Especially it is proven that if it is assigned thickness to any folding template, it has potential to generate a foldable surface which can be implemented into real architectural projects. Taking consideration into relevant rules, it is possible to advocate that architects can learn from paper and each crease line which is foldable creates its own kinetic surface and mechanism.

Once the motion is understood in a proper way, its enabler mechanisms can be different in material, technology, and cost. For instance, regular and coarse curved sketches are constructed with both cardboards and hardboards with distinct detailing. Although they are different, the same motion is delivered in both situations, because detailing is employed based on construction material as well as motion. That is, trying to deliver assigned motion makes to solve appropriate detailing. It is, however, always bound to mechanical factors such as torque of the actuating mechanisms. Still, enabler mechanisms can also be re-designed based on motion, if it is understood correctly.

As a consequence, regardless of folding types, any folding template has potential to turn into a controlled mechanism. Potentials of learning from paper were tried to be shown, and its applicability is proven.

5.2. Importance of the Thesis for the Literature

The research conducted in this thesis makes contribution to the literature, because it offers a systematic process which harmonize structure and its mechanism with the architectural form. The combination of form, structure, and mechanisms and understanding how to use them in this design process facilitate the work of an architect for efficiently design deployable kinetic structures. In fact, the process is prepared based on architectural sense. For a mechanical engineer, for example after foldability check, his process will be different. An architect, however, sees how to implement relevant rules in an architectural manner.

As discussed earlier, in applied responsive and performative architecture, existence structures are generally limited with certain types of motion and its enabler mechanisms like accordion folding or single panels turning around a pivot in kinetic skins. However, proposed flowchart offers architects to discover new forms, and also wisely use enabler mechanisms. Hence, it makes possible to efficiently benefit from potentials of kinetic structures in architectural design and practice.

In literature, symmetry groups are used as a pattern generation tool. Nonetheless, in this thesis, understanding mathematical thoughts behind folding and matching folded tessellations with symmetry groups allowed to understand global motion, grids of kinetic surfaces, and enabler mechanisms. It reveals the fact that folding systems which is matched with symmetry groups helps to create a new language for architectural kinetic surfaces working as a network.

Besides, offered algorithms assign clearance based on material thickness and type of detailing. There are readymade programs to simulate ideal zero origami, yet they lack thickness. In this thesis, it is tried to prepare folded surface for the fabrication. Therefore, it is checked type of construction material, digital fabrication machine, detailing as well as material and joint thickness.

Moreover, in this thesis it is tried to overview general map of architectural kinetic structures. These structures are analyzed over classifications in terms of scale of kinetic surfaces as unit, surface, and volume. In literature, these structures are tried to grasp over classifications, yet there is still a gap regarding classification based on motion and its enablers. It is significant to understand how existing applied examples work. As these structures are actually controlled mechanisms, and their forms are not static, design in these structures cannot be considered without motion and its enabler mechanisms. In fact, these classified structures are then tried to matched with origami. That is, it aims to give clues about how origami-based kinetic structures could be.

Last but not least, modest contribution of this thesis to the literature can be summarized as listed as follows;

- Offering architects or designers a systematic process flow which harmonize structure, mechanism, and form in order to develop deployable kinetic structures from any foldable sketch through by learning from mathematical idea behind folding
- Introducing curved folding as a discovery tool for free-form kinetic architectural structures working as a network in a non-deformed way
- Introducing symmetry groups as a template for global motion, structural grids, and actuating system of deployable rigid body kinetic structures which are integral part of the building
- Considering folding surfaces with ideal zero thickness as thick folding surfaces in order to prepare them for the fabrication
- Classification of kinetic structures in architecture with respect to application scales based on motion and its enablers, and matching them with origami

5.3. Potentials of Curved Folding

Today, curved folding applications in the field of architecture still remain sculpture-like objects or small-scale pavilions, as it is a complex system to be generated. However, if its applicability is solved, its transformation from 2D to 3D opens new fields of applications as it is done in automotive and aerospace industries. Therefore, its applicability in architecture provides different potentials in design and practice. For example, prominent wind direction is an essential factor for design in tall buildings. Directing the wind can be sustained with the building form either with a static movement or a dynamic movement as El Razaz (2010) grouped kinetic architecture into two. Static movement is defined as shaping building exterior form based on environmental factors during drawing phase, while dynamic movement is defined as incorporating technologies into buildings in which transformative mechanized structures change with climate, need or purpose. Either it is static movement or dynamic movement, it can be better to work with curvilinear forms to guide the wind in a smoother way. Barozzi et al. (2016) also draw similar attention to the use of curvilinear forms in exterior shading devices particularly in the hot climate regions such as Middle East. Authors mention that these traditional blinds and shutters fail at high wind speeds and are restricted to planar façades and rectangular grids. Nonetheless, curved surfaces have potentials to cope with potential problems occurred by high wind speeds.

Besides being used for functional purposes, curved folding can also provide building different formal expression together with the improved strength and stability. Nonetheless, it is crucial to allow bending without deformation in creating kinetic curved surfaces, yet curved origami can also provide non-deformed curvilinear forms, if its mathematical rules are understood and applied properly.

5.4. Recommendations for Future Studies

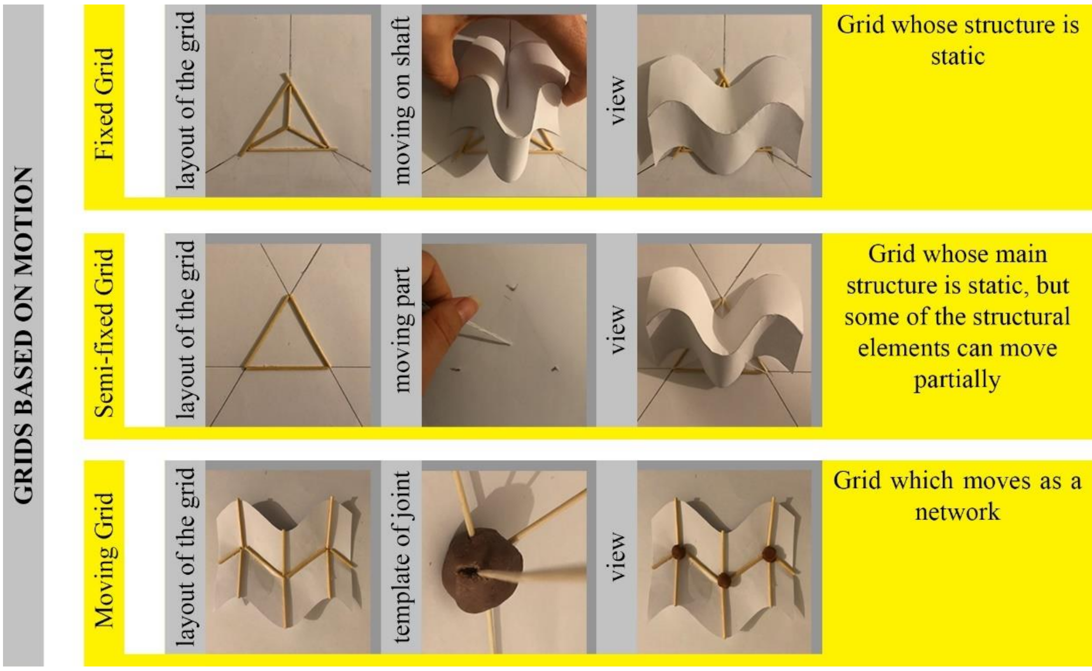
Construction of folding mechanisms depend on selected state-of-art technology. Combining origami with the evolving digital fabrication technologies, novel prototypes can be implemented. In fact, 4D printed structures are the future of deployable kinetic structures opening new research areas especially for curved kinetic structures. Especially, in the case study regarding coarse curved sketch, it is prototyped with the fabric sandwiched between rigid cardboards. If joint would be a programmable material instead of fabric, the same system could be generated. That is, once the motion is understood correctly, its enabler mechanisms can be implemented based on available technologies as long as project budget allow.

In literature, kinetic flat or curved origami are used for many purposes such as a form-finding tool and metamaterial. However, they can be also used for various purposes such as kinetic formworks for complex surfaces and structures for space studies thanks to its deployment and less consumed energy for the actuation. As it has many potentials for architecture, understanding of these structures is significant, and proposed flowchart can be extended based on changes in needs, demands, and technology. As kinetic surfaces in responsive architecture require interdisciplinary approach, it reveals the importance of new tools such as origami which facilitate development of kinetic surfaces for architects.

In particular, the flowchart can be extended in terms of symmetry groups. In this thesis, it is classified certain types of folding in regards with symmetry groups, but it is hard to find symmetries of randomly drawn fold lines. At this point, symmetry groups can give both a kinetic motif and an entire pattern. If it turns into whole pattern, it becomes critical to find symmetries between kinetic motifs. If it is found, any randomly drawn sketch can turn into entire kinetic surface. Therefore, mathematical idea behind origami should be paid more attention.

Furthermore, structural grid of kinetic skins is not considered together with the design in kinetic surfaces in literature. Gridal design is also significant, since it holds the kinetic surfaces, and it changes the appearance. It can be classified under three types of grid based on motion: fixed, semi-fixed, and moving grid. It is determined by symmetry groups and also applied forces. For instance, triangular grid holds the belt-like mechanism (ropes) to pull the curved folding shape towards the center of the triangle (table 3.14 on the middle). This belt can also be a telescopic bar fixed to the corners of the triangle. Moreover, it can be applied sub-grids into its fixed grid to transmit motion in a balanced way particularly in curved folding (table 3.14 on the top). Sticks are associated with structural grids, and also rails to allow motion of curved folding. Furthermore, grid can also alter their configuration to allow assigned motion. Instead of actuating directly the panels, actuators can trigger the structural grid so that the grid itself triggers the panels or coverings (table 3.14 on the bottom). However, definition of joints is different in this case. Sticks are placed in a play dough based on their associated angles and they are moved to observe their motion path lines inside the play dough. This observation gives the clue about how joints should be, since those holes in the play dough define where to place rigid links and their range of rotation angles.

Table 5.1. *Alteration of a Grid based on Motion (developed by the author)*



Moreover, proposed flowchart can be extended in terms of materiality. Motion remains the same regardless of scale, yet factors like material weight, gravity, and fatigue of mechanisms are changed.

Last but not least, whole process can transform into a software including relevant mathematical considerations. If it is achieved, all the steps in the flowchart can turn into a pre-design tool for architects, and they can share what they have experimented with engineers. In this regard, the design process will be shortened, and accurate results can be obtained automatically.

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APPENDICES

A. Tables regarding Enabler Mechanisms of Motion

Table A.1. *Classification of Joints based on Motion (developed by the author on the basis of works of Korkmaz (2004)).*

		TYPES OF MOTION	MOTION PATHLINE	DOF
TYPES OF JOINTS USED IN RIGID BODY STRUCTURES	Revolute (Hinge)	Rotation in XY plane	Circular	1
	Prismatic (Slider / Translational)	Translation in X direction	Planar	1
	Helical (Screw)	Rotation in XY plane and translation in X direction	Spiral	1
	Cylindric	Rotation in XY plane and translation in X direction	Circular and/or linear	2
	Planar	Rotation in XY plane and translation in X and Y directions	Circular and/or linear	3
	Spherical (Ball / Socket)	Rotation in XY, YZ, and XZ planes	Spherical	3
	Joint based on material property	Different expansion property of inner and outer layer to achieve convex or concave position. Used in material-based joints such as 4D printing and shape memory alloy		

Table A.2. *Symmetry Groups (developed by the author based on the work of Schattschneider, (1978)).*

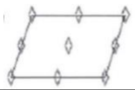
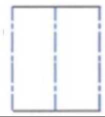
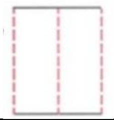
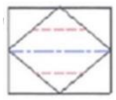
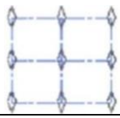
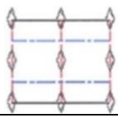
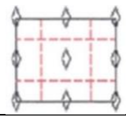
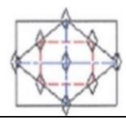
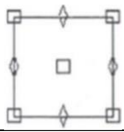
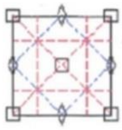
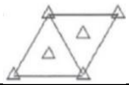
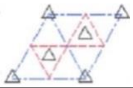
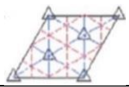
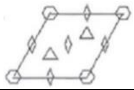
Type	**Lattice type**	**Rotation orders**	**Reflection axes**	**Glide reflection axes**	**Lattice representation**
p1	parallelogrammatic	none	none	none	
p2	parallelogrammatic	2	none	none	
pm	rectangle	none	parallel	none	
pg	rectangle	none	none	Yes	
cm	rhombus	none	parallel	Yes	
pmm	rectangle	2	90°	none	
pmg	rectangle	2	parallel	Yes	
pgg	rectangle	2	none	Yes	
cmm	rhombus	2	90°	Yes	

Table A.2. *Continued*

p4	square	4	none	none	
p4m	square	4	45°	Yes	
p4g	square	4	90°	Yes	
p3	hexagon	3	none	none	
p31m	hexagon	3	60°	Yes	
p3m1	hexagon	3	30°	Yes	
p6	hexagon	6	none	none	
p6m	hexagon	6	30°	Yes