# Methodology for Using Origami in Designing Deployable Shelters

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Deployment, Geometry of Folding, Origami, Generative Design.

**ABSTRACT:**
Origami the ancient art of paper folding has a great effect now, not only on form generation process but also in the development of deployable mechanisms and mimicking the folding systems in nature especially with the great progress in the geometry of folding and computer simulation of the folding process. So, it gains a great interest in the field of adaptive architecture, designing open spaces and product design, as it is a source of inspiration for designing configurable structures useful for shed systems that can adapt with the changing in the surrounding climate conditions, people's needs and other surrounding environmental changeable conditions. Also, in the design of deployable products that could be packed easily in small spaces and get deployed when needed to save space and solve the contemporary problems of small multi-functional spaces. In this research, we try to suggest a methodology for designers to get benefit from this art in there designing process, depending on four main sections which are, literature review on the pioneers of this art, the basics of the geometry of folding, computer programs that help in simulating the process of folding and finally methods of fabrication of foldable structures. In the preview of previous studies in the field of architecture, analysis has been done with parameters of, static or dynamic, materials and type of folding lines, type of actuator in kinematic ones, and modularity.

**INTRODUCTION**:

Multidiscipline research now became the key to most of the innovations. And the continuous progress in new technologies whether in computer software or fabrication methods and materials, has a great effect on the emergence of multidiscipline methodologies in design and applied arts. As these progress in computer software helped a lot in the cooperation between many disciplines and blend the boundaries between them, the computer then becomes a generator of the design ideas and applied products not just a simulator. And one of the arts that has great results as a generative technique for new designs is origami. Traditionally, the term origami has been primarily associated with the ancient art of folding paper. The word origami comes from the Japanese roots (折る) oru meaning folding, and (紙) kami meaning paper (1 p. 1). There is a variety of research recently that is using origami as a generative technique for new designs. But what are the steps should the designers take to get inspired by origami in their work? The problem is that there is a need for a methodology for designers to apply origami in design. In these research we are trying to suggest a multidisciplinary methodology for using origami in the design of deployable shelters, to find their way easily in the designing process Which consists of four main points, firstly a quick survey on origami its beginning, its pioneers and their contributions and analysis of selected works inspired by origami in different fields (architecture, interior design and product design. Secondly discussing most common origami terms, folds, and folding patterns. Third point: computer programs that specialized in origami designs. And finally, the fourth one about fabrication techniques for foldable design.

**1. Literature review**

It is important to give a look at previous achievements to widen your knowledge and imagination about what could origami do in design and how.


**1.1. History of Origami & its Pioneers**

"origami" comes from the Japanese language. It is a combination of "Oru" which means "Fold", and "Kami", which means "paper". While origami was popular in Japan, its origins are believed to be pre-Japanese with the invention of paper itself. Paper, in turn, is believed to have been invented in China in 105A.D. So, it is generally believed to have begun in China, Korea, and/or Japan.

The spread of origami through the world in the twentieth century is often attributed to the influence of the origami artist Akira Yoshizawa (1911-2005), who introduced the origami notational system of dotted lines and arrows in his book in 1954 that remains in use today with slight modifications. Lillian Oppenheimer (1898-1992) played a main role in popularizing origami in the united states. She formed the origami center in New York in 1958, which developed into THE FRIEND OF THE ORIGAMI Center of America in 1980, which became ORIGAMI USA (2) in 1994, parallel developments in other countries led to the eventual formation of origami societies in nearly every country throughout the world; one that has played an important role in the English-speaking world is the British Origami Society, found in 1967 (3 pp. 167-168).

**1.1.1. Akira Yoshizawa: (1911-2005)**

Akira Yoshizawa, regarded as the father of modern origami, is a Japanese artist revived the ancient Japanese craft of origami. He used his geometric skills, precise technique and fine design concepts to create amazing dragons, birds, and elephants from a single sheet of paper. He rejects the traditional technique of cutting, which rendered flat creations and invented a system, directions for folding called (Yoshizawa Randlett System) still widely cited in origami primers (4) Accessed: 30/12/2019. His most significant works are discussed in the book (5)

Figure 1:Akira Yoshizawa, at the Institute of Japanese culture, Rome (5 p. 19)

Recently origami has taken off to new heights and accomplished amazing technical and artistic feats. It's believed that the great advance in origami design has been stimulated by a growing mathematical and computational understanding of origami (3 p. 168).
Many books about origami are discussing step by step techniques for making origami designs (5), (6), and many others. Great examples of techniques for 'paper folding' invitation cards and brochures are found in a book titled 'Encyclopedia of Paper-Folding Designs' (7).
Pioneers in computational origami such as Koryo Miura, Robert Lang, Erik Demaine and Tomohiro Tachi clarify that the principles of folding two-dimensional sheets into three-dimensional forms can lead to solutions in both art and practical engineering (1 p. vii).

**1.1.2. Koryo Miura: 1930 (age 89 years)**

Japanese astrophysicist who invented a system which allows a sheet of paper to be folded and re-folded easily by pulling or pushing the two opposite ends of the material (8 p. 117) which was named "Miura-Ori" for its inventor, it is one of the most well-known and well-studied folds in origami. It is a pattern of creases forms a tessellation of parallelograms, and the whole structure collapses and unfolds in a single motion (9) Accessed: 30/12/2019. Koryo Miura has a book that will be published on February 2020 titled "Forms and Concepts for Lightweight Structures" co-authored with Sergio Pellegrino (10) Accessed: 30/12/2019.

Figure 2: Koryo Miura

**1.1.3. Robert J. Lang: 1961 (age 58 years)**

Is recognized as one of the world's leading masters of origami and a pioneer of the kind of origami that is using math and engineering principles to fold mind-blowing complicated designs that are beautiful and, sometimes, very useful. He lectures widely on origami and its connections to mathematics, science, and technology, and teaches workshops on both artistic techniques and applications of folding in industrial design. He has been one of the few Western columnists for ORIGAMI TANTEIDAN Magazine, the journal of the JAPAN ORIGAMI ACADEMIC SOCIETY, and has presented refereed and invited technical papers on origami-math on mathematics and computer science professional meetings. He has consulted on applications of origami to engineering problems ranging from air-bag design to expandable space telescopes. He is the author or co-author of twenty-one books and numerous articles on origami art and design and in 2011 was elected an Honorary Member of the BRITISH ORIGAMI SOCIETY (11) Accessed: 30/12/2019.

Figure 3: (a) Robert J. Lang,

**1.1.4. Eric D. Demaine: 1981 (age 38 years)**

Is a professor of computer science at MIT, born in 1981, his research interests range throughout algorithms, from data structures for improving web searches to the geometry of understanding how proteins fold to the computational difficulty of playing games. He co-wrote a book about the theory of folding titled "Geometric folding Algorithm', and a book about the computational complexity of games "Games, Puzzles and Computation" (12) Accessed: 30/12/2019.

Figure 4: Eric D. Demaine.

### 1.1.5. Tomohiro Tachi: 1982 (age 37 years)

Is an associate professor, born 1982, (13) Accessed: 30/12/2019 received his M.S. and Ph.D. in engineering from the University of Tokyo. He has been designing origami since 2002 and exploring spatial and kinematic origami through computation. He developed various software tools for origami design such as "Origamizer". Tachi is also active in proposing new computational methods for designing a class of origami called rigidly foldable origami, i.e., a deployable system composed of rigid panels and hinges. He is now leading the Origami Group of Structural Mor

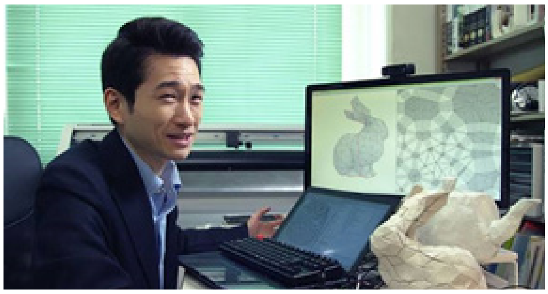


Figure 5: Tomohiro Tachi, and "Origamizer" on the computer screen developed by him (15) Accessed: 30/12/2019

phology Group in IASS. (14) Accessed: 30/12/2019
In 2017, Tomohiro Tachi has collaborated with Erik Demaine to prove that any polyhedron can be folded from a sheet of paper through an improved algorithm of Origamizer. He also collaborated with Koryo Miura to first propose the idea of cellular origami. This work won the Tsuboi Award in 2013. The cellular origami concept is now a standard technique for creating mechanical metamaterials (14) Accessed: 30/12/2019.

## 1.2. Case studies of origami-inspired designs

### 1.2.1. In Architecture

ParaPli: Designed by Ophélie Bertout & Marcus Kistner, it is inspired by origami. It is not just a static structure, as the triangle-based folding design allows the structure to be deployed in two different ways. It is a lightweight shelter that has two different forms, opened and closed (8 p. 124).

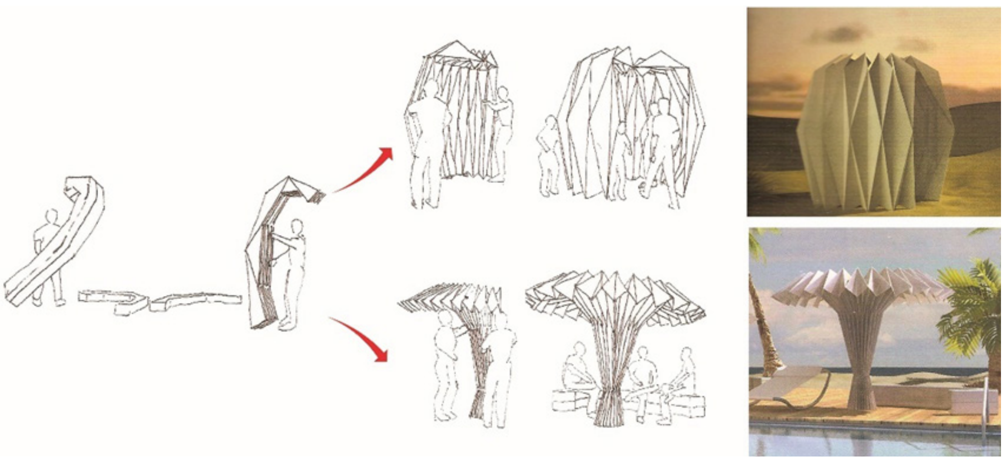


Figure 6: ParaPli design deploying in two different ways. Photos from: (8 pp. 124-125)

| | | | | |
|---|---|---|---|---|
| **Analysis** | **Material** | | **Type of the product** (static or kinematic) & type of actuator if kinematic. | Kinematic, actuated manually by hands and locked deployed by a hoop passed through the loops located at the trunk. |
| | **Folding lines** | | **Modularity** (ability t o connect two or more of it) | Not modular |

Ha-ori shelter: Designed by Joerg Student for his master's dissertation, the Ha-ori is a foldable emergency shelter that is designed to be transported, stored and set up quickly and easily. Inspired by the structure of hornbeam leaves as Ha-ori (means 'folding leaf' in Japanese), it is foldable, light (weighing 36kg in total) and very strong. It required lots of experimenting with folds, maths and prototypes to create this structure. It is folded out of a single sheet of 3.5m by 14m corrugated polypropylene. It measures 2.6m by 46cm when folded. When unfolded it provides a space measuring 3.65m across and 2.44m high. Roofing and the side flaps can be adjusted for ventilation purposes. The main structure is made of a translucent, double-skin, high-density, polypropylene sheets, which are both rigid and insulating. The lines of the folds are scored into the sheet using simple machinery. The properties of the polypropylene allow it to be folded and re-folded an unlimited number of times (8 p. 127).

Figure 7: The Ha-ori shelter is packed and deployed state (8 pp. 126-127).

| Analysis | | | | |
|---|---|---|---|---|
| | **Material** | Folded out of a single sheet of 3.5m by 14m corrugated polypropylene | **Type of the product** (static or kinematic) & type of actuator if kinematic. | Kinematic, actuated manually by hands |
| | **Folding lines** | Lines of the folds are scored into the sheet using simple machinery | **Modularity** (ability to connect two or more of it) | Not modular |

**Siesta Origami:** Designed by Helmina Sladek and Pauline Thierry. They were looking for a stable and coherent starting point to create transportable micro-architecture. Origami seems to be a good solution. It allowed them to create a design that was very easy to assemble and use. Origami is self-sufficient. It doesn't need any accessories. Panels of the shelter connected to one another with Velcro strips. Made up of eight 1.5m wide equilateral foam triangles, and works also as a reversible rug or mattress. It's a light, reconfigurable origami design. It can be reconsidered in different shapes with the panels that can fold either way easily the same. Two or more pieces can be linked and assembled together according to the need (8 pp. 114-115).

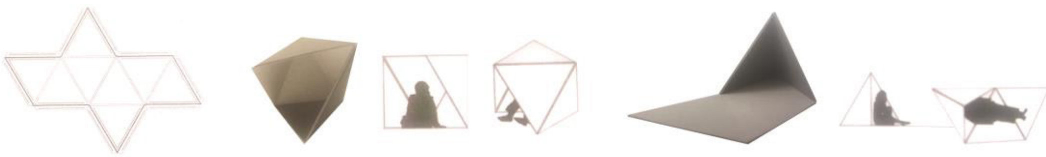


Figure 8: 'Siesta Origami' design in different configurations. Photos from: (8 p. 114)

| Analysis | | | | |
|---|---|---|---|---|
| | **Material** | Polypropylene foam | **Type of the product** (static or kinematic) & type of actuator if kinematic. | Kinematic, actuated manually by hands and locked deployed by Velcro strips. |
| | **Folding lines** | From strips of Velcro. | **Modularity** (ability to connect two or more of it) | Modular |

**Origami pavilion:** designed by Tal Friedman, is a new approach to the construction of self-supporting thin-shell folded structures. It attempts to composite aluminum boards which are photometrically designed to fold into shape by implementing the defining elements of origami folding and implement them on an architectural scale. A basic variable folding module was created that can be manipulated photometrically to form a seamless pattern. A parametric paradigm was created that could be used to accommodate the design of 4mm sheets. Throughout the project. A method for the design and assembly of rigid composite aluminum boards was developed. To calculate and optimize the structure for various fabrication restraints an algorithm was written. The project resembles origami in its fabrication method not only in its structural and aesthetical values. Which is folding the sheets rather than individual panels. This technique saves fabrication time and building tolerance. It's a proof of concept model concluding that folded structures can be fabricated to full scale while maintaining a self-supported stiffness and stability that are come from the rigidity of the surface and by locking its fold angles in a key location (16 pp. 177-183).


Figure 9: (a) (b) Prototypes of the principle in paper and cardboard, (c) CNC-milling the folding pattern into ACM boards, (d) Origami pavilion on the Campus Emilie in Detmold (16 pp. 177-183).

| | | | | |
|---|---|---|---|---|
| **Analysis** | **Material** | ACM (Aluminum Composite Material) boards | **Type of the product** (static or kinematic) & type of actuator if kinematic. | Static |
| | **Folding lines** | CNC-milling the folding pattern into ACM boards | **Modularity** (ability to connect two or more of it | Not modular |

### 1.2.2. In Interior Design:

Origami-mi kitchen: designed by Olga Kryukova, inspired by origami. The basis of this kitchen is a metal tube frame on which the storage boxes are mounted so that the kitchen unit stands without the need of any walls (17) Accessed: 30/12/2019.

Figure 10: Origami-inspired kitchen designed by: Olga Kryukova. Photos from: (17) Accessed: 30/12/2019.

**Just Fold It:** Designed by studio Kutarq, is a flexible and lightweight room divider, consisting of individual panels that fold together for easy transportation and storage. By adding or subtracting the number of modules, its length could be adjusted, so it is usable in a variety of spaces regardless of size. The panels are perforated to increase stability by counteracting wind resistance and generate a pleasant visual effect (18) Accessed: 17/1/2020.

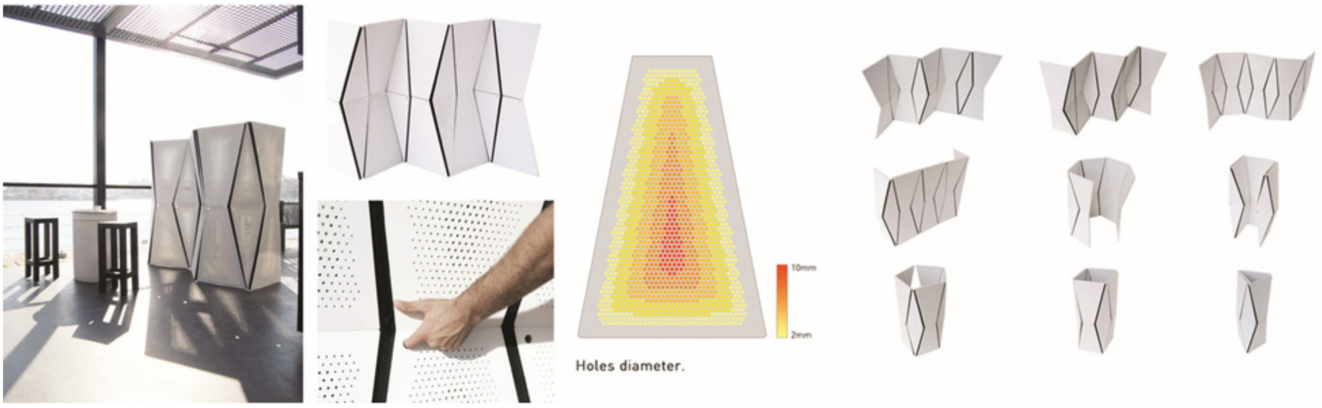



Figure 11: (shadow dual effect of drop shadow due to perforation on the panels. (b) holes for adjusting the folding angle. (c) The gradual decrease in the diameter of the holes from the core to outside (d) different configurations by changing the folding angles or/and the number of panels. Photos from: (a) (b) (19) Accessed: 17/1/2020 (c) (d) (20) Accessed: 17/1/2020

**Faceted curtains:** Designed by Hannah Allijn, the triangles fold by pulling the cord of the curtain, which led to changes in the curtain's shape. Geometric forms are created during the folding of the curtain (8 p. 75).
**Magnetic curtains:** Design by Florian Kräutli, it uses magnets to create a sturdier and more permanent shape as you push and pull the fabric (21) Accessed: 1/2/2020.

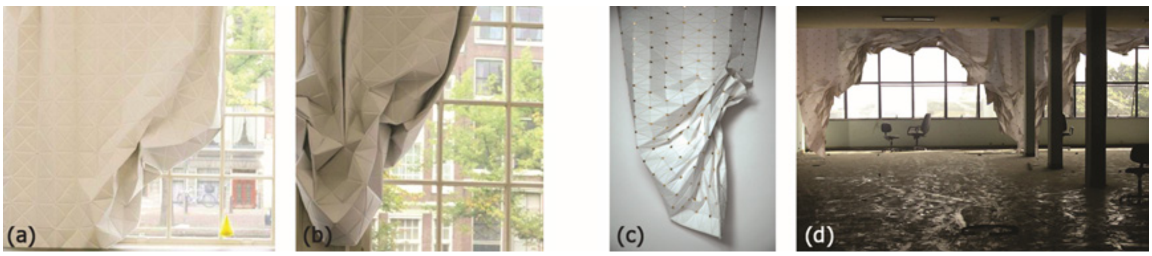



Figure 12: (a) (b) Faceted curtain (8 p. 75). (c) (d) Magnetic curtains (22) Accessed: 1/2/2020.

**Wood wall panels flip up to reveal light:** A modular lighting system designed by Francesca Rogers and Daniele Gualeni consisting of wood panels that can expose energy-efficient electroluminescent light by flipping it back. It could be fixed to any wall (23) Accessed: 1/2/2020.

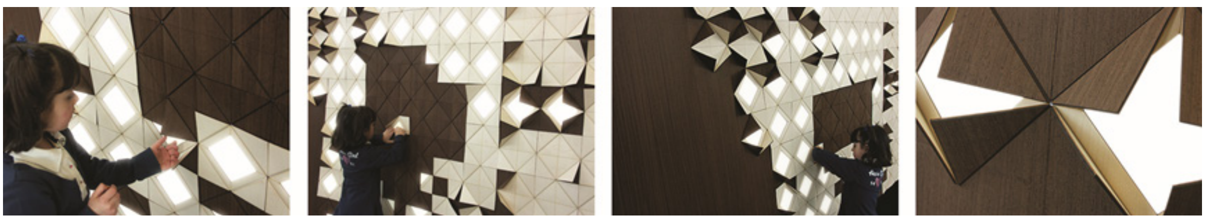


Figure 13: Wood wall panels (23) Accessed: 1/2/2020.

**1.2.3. In product design:**

Miyo Lamp: Designed by Silke Steinberg, inspired by origami. The regulation of light originates from the qualities of the folding. There is a link between the intensity of the luminous power and the form of the structure. By opening more star-shaped segments are opened the brighter the lamp gets. As the complete folding is made out of one piece of paper all elements of the structure are connected. If you move a few segments only the movement will be transferred to the surrounding ones and finally changes the appearance of the whole figure. The surface material on the equilateral triangles can be chosen by every user individually. The possibility to easily change the form of Miyo again and again creates varied light-sculptures in a fascinating shaping process (24) Accessed: 25/12/2019.

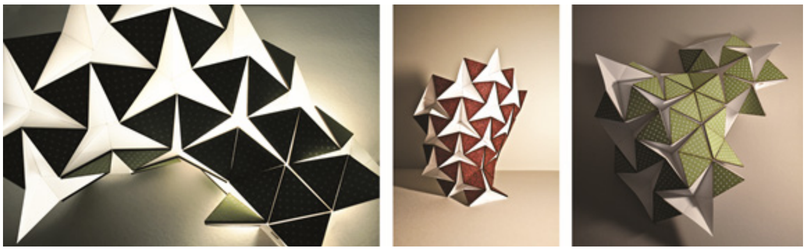


Figure 14: different configurations and materials of the Miyo Lamp. Photos from: (24) Accessed: 25/12/2019

**Flux Chair**: Designed by Flux company, it resembles a giant envelope that could be transformed into a chair. Made from one sheet cut craftily of sustainable polypropylene. It weighs 5kg, max load it can tolerate 160kg (25) Accessed: 30/12/2019. It takes about 10 sec. to be assembled or disassembled. It is also suitable for indoor and outdoor (26) Accessed: 21/12/2019.

Figure 15: Flux Chair in packaged and unfolded situations. Photos from: (25) Accessed: 30/12/2019

**Papton Chair:** Designed by Wilm Fuchs & Kai Funke, made from foldable honeycomb cardboard, it's weight (2.4kg). Its dimension is 800mm high, 620mm width and 530mm depth. When disassembled it measures 1335 × 1180 × 10mm (8 p. 92).

Figure 16: Papton Chair folding steps (27) (28) Accessed: 28/2/2020.

**The Flat Stanley Origami Chair**: It was named after a children's book about a boy named Stanley who becomes flat after the falling of a corkboard on him. To solve folding geometry, prototypes were made. Rabbit joints were made for the canvas to be recessed in to create folding between panels then covered with vinyl coating sheets (29) Accessed: 01/01/2020.

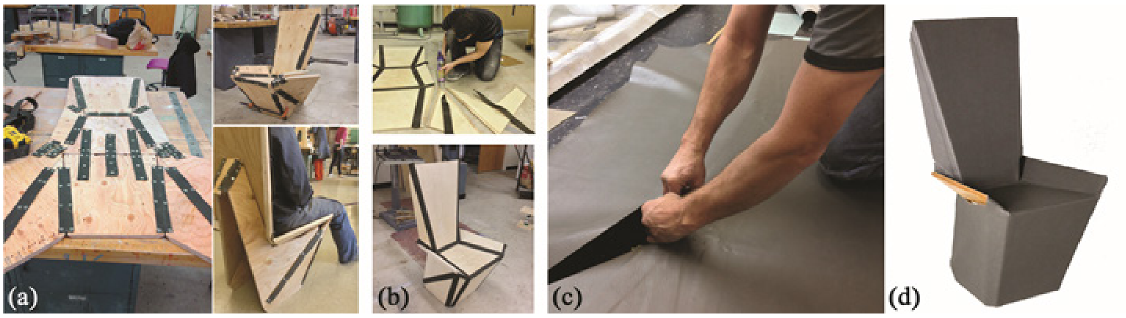



Figure 17: "Flat Stanley Origami Chair" designed by: Brett Mellor (a) Prototype. (b) Assembling (c) Covering with vinyl coating sheets (d) Final product (29) Accessed: 01/01/2020.

## 2. Thinking with paper

Developing good folded paper design resembles developing ideas by sketching, it is important to work fluently and quickly. To save time you should work somewhat roughly at first, then when you reach an idea remake it again with care, don't spend time in unnecessarily folded detailed folding, when quick folded sketches are only needed. Also, you should work with a medium-scale at first, to save time. Later, you can make your designs with the correct scale when you know the scale and the material that will be applied (30 pp. 10-11).


### 2.1. Origami Terms:

#### 2.1.1. Basic terms:

**Mountain fold:** The formation of a designed trough, often displayed as a dashed line or/and blue color.
Valley fold: The formation of jutting ridge, often displayed as a dash-dot pattern or/and red color (3 p. 169).
**Crease**: If a paper is folded and unfolded, a line will be left on the paper (a crease). Creases are leftover marks that can provide guidelines ("fold that edge to that crease") as in the clearest stage of folding, the use of measuring tools, such as rulers are embedded (6 p. 11).
Crease pattern: This is a combination of creases drawn on paper, only meeting at common endpoints.
**Mountain-Valley assignment:** Is identifying whether each crease is a mountain or valley fold.
Folding motion of paper: Is the moving of a paper continuously in which it's configuration changes without any stretch, tear or self-penetration caused to the paper (3 p. 169).

#### 2.1.2. Important terms:

Composite origami: Composite forms are those in which more than one sheet is used, each folded apart until reaching a specific shape, then joined to others forming a unique model (5 p. 33).
**Fabrigami:** Is the art of folding fabrics (31 p. 5).
Active Origami structures: Is a self-folding structures that could be folded or/and unfolded without any external mechanical loads applied on it but instead by stimulation of a non-mechanical field (chemical, thermal electromagnetic) (1 pp. 13-14).

### 2.2. Common Folds and Folding Patterns:

#### 2.2.1. Common Folds:

While all the models of origami are created from mountain and valley folds, they often occur in distinct combinations that occur often enough that they have been given specific names such as 'reverse fold', 'rabbit-ear fold', 'squash fold', 'swivel fold', 'petal fold', 'pleat fold', 'crimp fold' and open sink fold', to name but a few (6 p. 22).

##### 2.2.1.1. Reverse folds

Inside reverse fold is used to change the direction of a flap. It combines both mountain and valley, in which the mountain fold line occurs on the near layer and the valley fold occurs on the far layer. It is indicated by a push arrow, since to form the reverse fold, the spine must be pushed and turned inside-out. The tip of the flap ends up pointing away from the spine in the inside reverse fold as shown in (Figure 18), if it is wanted to be pointed to the right, then the other type of reverse fold would be used, the outside reverse fold, which is illustrated in (Figure 19). It also combines both mountain and valley folds but unlike in the inside reverse fold, in the outside reverse fold, the valley fold occurs on the near layers and the mountain fold on the far layers. It is indicated by a push arrow, because it is typically made by pushing at the spine with one's thumb while wrapping the edges of the paper around to the right. It is also possible to make a sort of hybrid reverse folds (6 pp. 23-24).

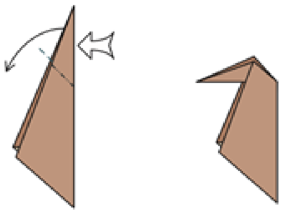


Figure 18:
The inside reverse fold.

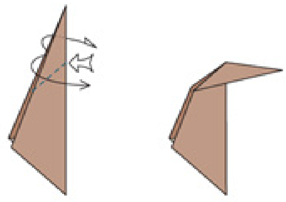


Figure 19:
The outside reverse fold

### 2.2.1.2. Rabbit-ear fold

It acquired its name from some rabbit design. The rabbit-ear fold is mostly performed on a triangular flap, and it combines three valley folds along the angle bisectors of the triangle and fourth mountain fold, extending from the point of intersection perpendicularly to one side. When a rabbit-ear fold is formed, all of the edges lie on a common line. This procedure works for a triangle of any shape (6 p. 25).

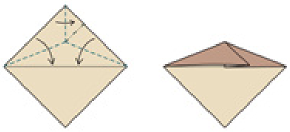


Figure 20: Rabbit-ear fol

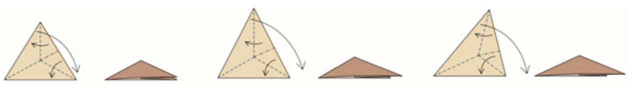


Figure 21: Rabbit-ear fold with different triangles (32 p. 26).

### 2.2.1.3. Squash & swivel folds

In this fold, the layers of a flap are spread to the sides and the folded edges flattened. Mostly it is formed symmetrically, it combines four creases: two valleys on each side of two mountains, all of them come together at a point (6 pp. 26-27).

Figure 22: Steps to make squash fold: (a) (b) Turn the flap that you want to squash towards you (c) (d) Then twist apart the layers of the paper (e) Finally press down to squash the paper that creates two new mountain folds (33) Accessed: 28/1/2020.

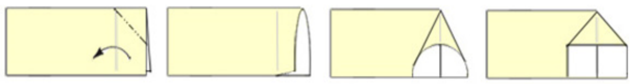


Figure 23:
Another example of the Squash fold (33) Accessed: 28/1/2020.

However, a squash fold can be made asymmetrically and sometimes the two valley folds are not side-by-side, a portion of the visible flab can then be seen to rotate. This asymmetric type of a squash fold is given its own name (a swivel fold) because it occurs often (32 p. 27).

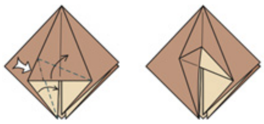


Figure 24: Swivel fold (32 p. 27).

### 2.2.1.4. Petal fold

It is formed from two mirrored swivel or squash folds formed side by side and sharing a common valley fold (32 p. 28).

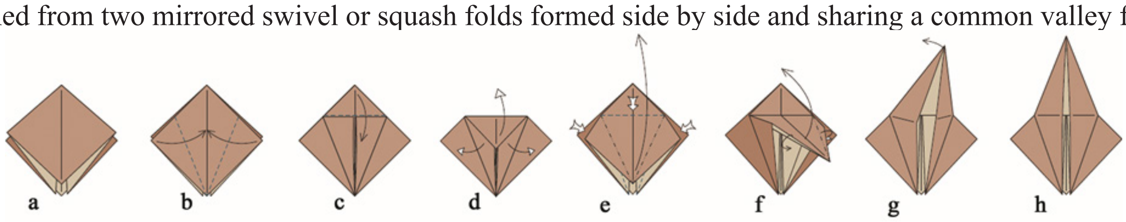



Figure 25: steps of making petal fold, (a) Start with preliminary fold (b) Fold the two sides in making the row edge lie along the centerline. (c) Fold down the top point. (d) Unfold the three flaps. (e) Lift up the first layer of the bottom corner while holding down the top of the model just above the horizontal crease, allowing the sides to swing in. (f) Reverse the direction of the two creases running to its tip. (g) Continue lifting the point all the way, then flatten. (h) Final petal fold (32 p. 29).

### 2.2.1.5. Pleat & Crimp folds

It consists of side-by-side mountain and valley folds. When there are multiple layers, there is a related fold, called a crimp. It is the combination of a pleat fold with its mirror image on the far layer of paper.


Figure 26: (a) Pleat fold. (b) Crimp fold (6 p. 31).

The two folds of a pleat or crimp are often parallel, but they don't have to. In case they are not parallel, the flap will change in direction by a value equal to twice the difference between the angles of the two creases (6 pp. 31-32)

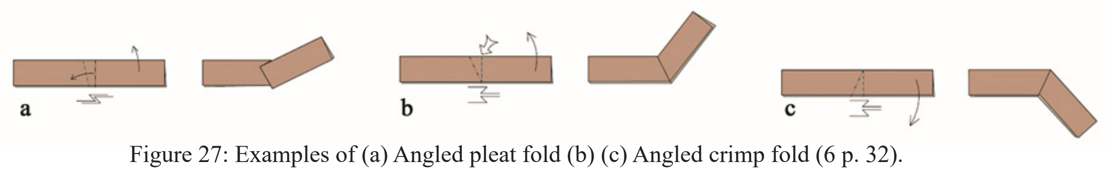



Figure 27: Examples of (a) Angled pleat fold (b) (c) Angled crimp fold (6 p. 32).

**2.2.1.6. Open sink fold**

It is an important folding technique that is being used frequently. It consists of two diagonal valley folds and one horizontal mountain fold inside a square shape mountain folds (34) Accessed: 29/1/2020

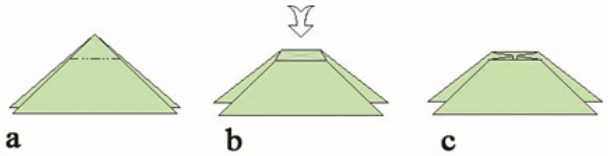



Figure 28: Steps for making sink fold, (a) fold the dashed line back and forth. (b)Open the paper a little then push down. (c) continue to push until the tip of the paper sunken in between the layers of the paper (33) Accessed: 29/1/2020.

**2.2.2. Famous Folding Patterns:**

Here we highlight specific folding patterns that help in generating useful functionalities.

**2.2.2.1. Yoshimura Pattern (diamond pattern)**

It was named after Yoshimaru Yoshimura, the Japanese researcher who was the first to provide an explanation for its development in Japan in 1951. The pattern's basis is a diamond shape, fold in one of its diagonals. It also referred to as the diamond pattern (35 p. 4).

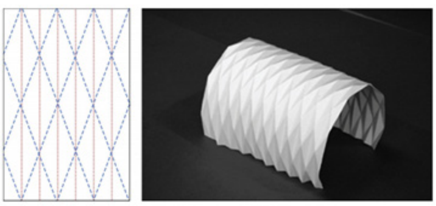


Figure 29: Yoshimura buckling (35 p. 5).

**2.2.2.2. Diagonal pattern**

It's based on a parallelogram folded from its diagonal; a series of parallelograms form helical distortion when folded (35 p. 5).

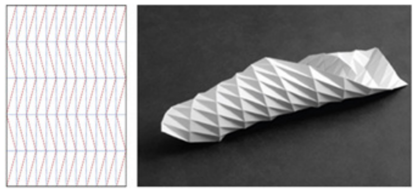


Figure 30: Diagonal buckling (35 p. 6).

**2.2.2.3. Miura Ori pattern**

It was named after its inventor Koryo Miura, a Japanese astrophysicist. Its crease patterns consist of repeating parallelograms. The creases form straight lines in one direction. And forming a zigzag path in the other direction. Each zigzag path is either mountain folds or valley folds, alternating from mountains to valleys from one zigzag path to the next one (35 pp. 5-6).

There are also many books that contain techniques & examples of folds and folding patterns that teach designers how to fold. The most recommended one is titled 'FOLDING TECHNIQUES FOR DESIGNERS FROM SHEET TO FORM' by Paul Jackson (30).

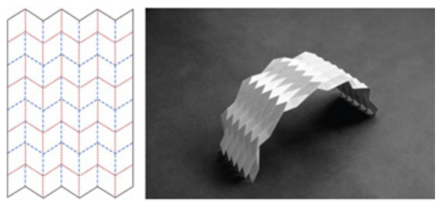
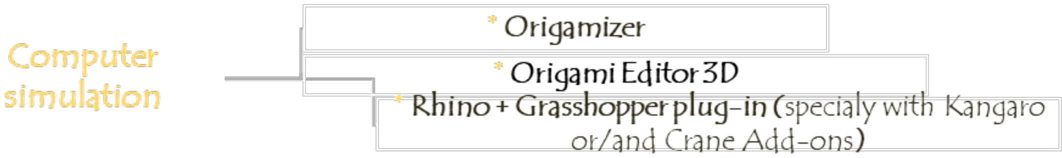


Figure 31:Miura Ori buckling (35 p. 6).

**3. Computer simulation**

This section will provide highlights on computational Origami, which is the simulation of the folding process with various materials with computer programs specialized in such issues. It is a new branch of computer science that studies algorithms for solving paper-folding problems. It essentially began with the work of Robert Lang on algorithmic origami design, starting around 1993 (36) Accessed: 02/01/2020.




### 3.1. Origamizer:

It generates the crease pattern on a sheet of paper that folds to a given three-dimensional polyhedra mesh, developed by Tomohiro Tachi (2008).

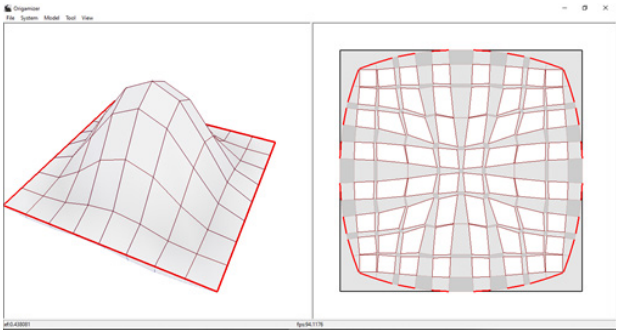


Figure 32: "Origamizer" Free origami software developed by Tomohiro Tachi, downloaded from (37) Accessed: 30/12/2019

### 3.2. Origami Editor 3D:

It is a computer program that simulates the paper folding process. It operates with a geometric abstraction of the (Yoshizawa Randlett system). Files created with the program maintain the entire folding process, and can be exported as folding diagrams in PDF, animated GIF files, or even as standalone java programs. The main purpose of the program is to design origami (38) Accessed: 01/01/2020. Using it requires a basic understanding of geometry and some familiarity with origami techniques. There is also a forum open for everyone who wants to suggest a new feature (39) Accessed: 02/01/2020.

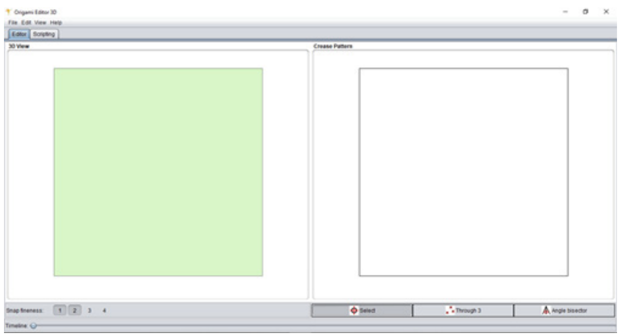


Figure 33: Origami Editor 3D, downloaded from: (38) Accessed: 01/01/2020

### 3.3. Rhino + Grasshopper + (Kangaroo or/and Crane add-ons):

Rhinoceros 3D, or "Rhino" by McNeel software is a software used to create digital models. It is a precise tool that provides a high degree of control over the objects. Rhino is the host software of another software (plug-in) called Grasshopper that is a visual scripting platform. It allows the user to write computer algorithms to build rhino objects by simply dragging components or batteries on the screen (Canvas) and connecting them with wires. Furthermore, countless plug-ins are available that expand Grasshopper's functionality (40 pp. 1-3) For example some plug-ins add physics-based simulations like Kangaroo add-on by Daniel Piker and another that contains an algorithm for simulating folding process like Crane an add-on, which is specialized in generating origami designs and participate in its fabrication, it is developed by Ki Suto and Kotaro Tanimichi. (41) Accessed: 01/12/2019. Users with programming experience can even create their own Grasshopper components by writing scripts in Visual Basic.C# and/or Python (40 p. 3).

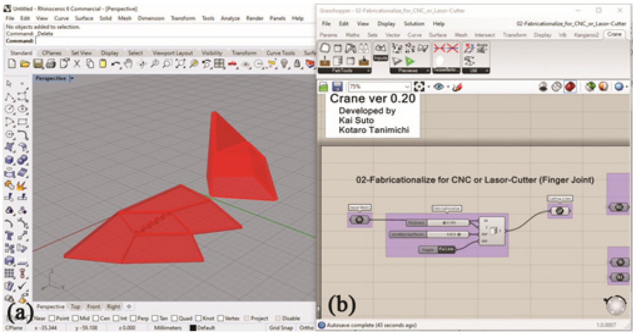



Figure 34: (a) Rhino software. (b) Grasshopper plug-in & Crane add-on within it. Downloaded from: (41) Accessed:20/11/2019

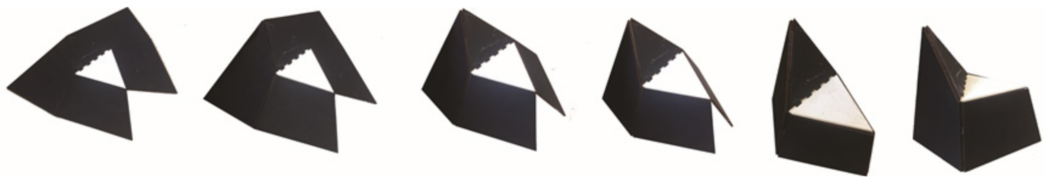
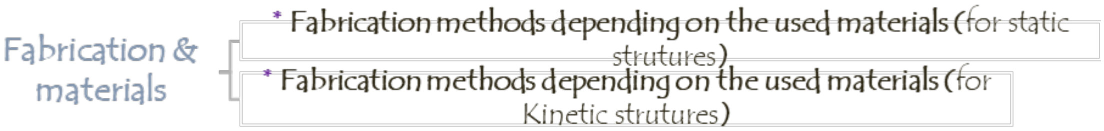


Figure 35: Folding steps of a chair model fabricated by laser cutting of the cutting list generated from grasshopper.

### 4. Fabrication & materials

Choosing a fabrication method is a very important step as it depends on many parameters such as materials used, the scale of the product, function, lifetime, kinematic behavior and actuator. These are just a few examples to show how do fabrication methods depend on the previously mentioned parameters. Designer should have an overview on the available fabrication methods for such structures (origami-inspired) to decide which is the most suitable for his design, he could also fabricate with a novel method specified for his design that resembles to some extent one of the available methods or combination of more than one of them.




#### 4.1. For static designs (using origami as a form generator)

Cut'n fold: developed by Hannecke, a company that is mastering the art of working with plexiglass. Is a three-dimensional shaping technique for folding acrylic glass-sheets, it is an internationally patented process. (42) Accessed: 25/12/2019. In which the pieces are pre-cut, and only the fold lines are heated. All other parts are kept cold and adapt to the new shape during the shaping process. It has potential new creative applications in the fields of design and architecture. The technique that has developed fixes the shortcomings of the traditional methods of beveling or thermo-forming which change the transparency or the properties of the material. Dr. Stefan Delecat, an origamist, works for the company, was closely involved with the development of this process (8 pp. 106-107).

Figure 36: Cut'n fold in manufacturing and final products. Photos from: (a), (b) and (c) (8 p. 106) (d) (43) Accessed: 25/12/2019.

Bent (Perforated folding lines in metal sheets): designed by Stephan Diez and Christophe de la Fontaine, it depends on laser-cut, pressed and folded 3mm-thick aluminum sheets. The hallmark of it is the perforations of its folds, that allow the material to be folded in a single stage.

Figure 37: Laser cut and bent aluminum. Photos from: (a) & (b) (44). (c) (45). Accessed: 01/01/2020.

Also, a similar technique of perforated folding lines was applied on sheets of paper by Marie Compagnon, in her creative works, in which a series of perforations marked out the folds, which act as a guide also allow the pieces to retain their shape and rigidity by using a thread that passes through them. So, there are two processes for creating fold: firstly, cutting the pattern out, using automated processes, and then assembling it manually (8 p. 34).

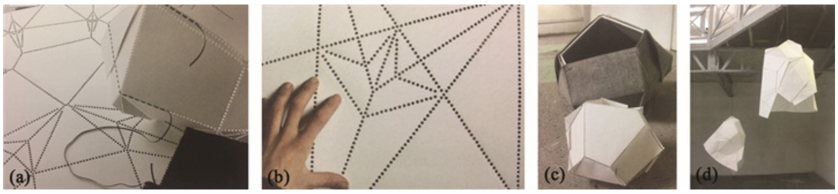



Figure 38: (a)Using thread for keeping the shape of the pieces. (b) Punch-perforated paper. (c) Felt and paper containers, punch-perforated leather fastening. (d) other sculptures with the same technique (8 pp. 34-35).

**4.2. For kinetic designs** (using origami as a source of inspiration for deployable structures)
'Deployable structures' is a general name of a broad category of prefabricated structures that can be transformed from a closed compact configuration to predetermined, expanded form, in which they are stable and carry loads (46 p. 3). It can expand and/or contract due to their geometrical, material and mechanical properties. Sometimes referred to as foldable, reconfigurable, auxetic, extendible or expandable structures (47 p. 13).

**Foldio:** Proposed by Simon Olberding, Sergio Soto Ortega, Klaus Hildebrandt and Jurgen Steimle, is a new design and fabrication approach that produce shape-changing interactive objects with foldable printed electronics. "Foldio" (Foldable Interactive Objects) is a foldable interactive lightweight object with embedded input sensing and output capabilities. It enables designers to create highly custom interactive foldable objects. It can sense user input and provide system output through customized printed electronic components that are embedded within the foldable structure (48 p. 223).

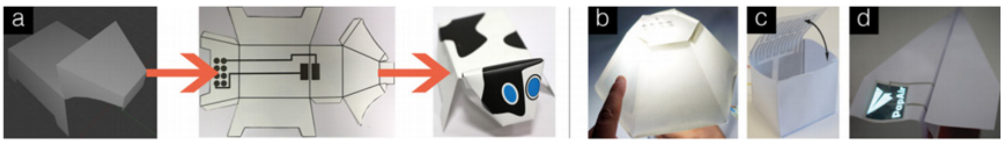



Figure 39: Applied products by Foldio technique (48 p. 223).

Rigid -foldable thick origami: Proposed by Tomohiro Tachi Is a mathematical model that produces a motion in which fold lines of all the structure fold at once. Its geometric configuration allowing it's easy deployment, Tachi applied the ideal kinetic behavior of zero-thickness origami to rigid thick foldable origami, as he used 'tapered panels' in which rotational axes of the thick origami coincides exactly with the axes of the ideal rigid zero-thickness origami (47 p. 110).

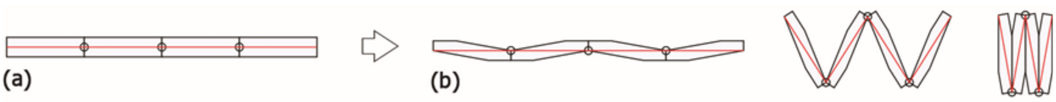



Figure 40: (a) Normal panels. (b) trimming the bisecting planes, red lines represent the ideal origami without thickness (47 p. 110).

## 5. Results

The invention of new materials is a driving force for a new art technique.
The designer's relation with the computer as a design tool is cyclic it depends on feedback from both until reaching the desired design.
Design processes can't flow in one direction. It depends on feedback between each step.
Computer is the main reason behind the success of multidisciplinary work, or we can say it's the new computer programs that emerged as a result of progress in algorithms and embedding it in computer programs.
To innovate in the field of design you have to get a general view on the neighbor sciences and not just staying in the center of your field, as the inventor of the Grasshopper software which is related to computer science was David Rutten an architect, his achievement made a big shift in architectural design.
Also, the Miura pattern which discovered by astrophysicist Koryo Miura was inspired by folding in plant leaves, which then affect the industry of space solar cells and then deployable structures for (architectures, medicine, robotics… etc.)
Fabrication methods for origami-inspired products depends on many parameters like the materials used, thickness needed, functions, lifetime, scale (as deployable mechanisms range from few millimeters such as stent graft to huge structures that extends to thousands of meters like solar arrays),
To reach new designs inspired by origami, it is important to go through four main steps, firstly reviewing the previous designs inspired by origami in different fields of application, not just the field you are working in (shelters) & the pioneers' contributions in origami, secondly start playing with paper with keeping in mind the bases of paper folding like mountain and valley folds, some types of common folds and folding patterns, in these step you don't have to make accurate models at first but working roughly until reaching an idea then start making it with details to save time, thirdly modeling your design on the most suitable software and testing its performance and fabrication sheets, you can go back and forward between these step and the previous one until reaching the final accurate design then start choosing the suitable fabrication method making models and prototypes also here you can go back and forward between these step and the previous one to reach the final product.

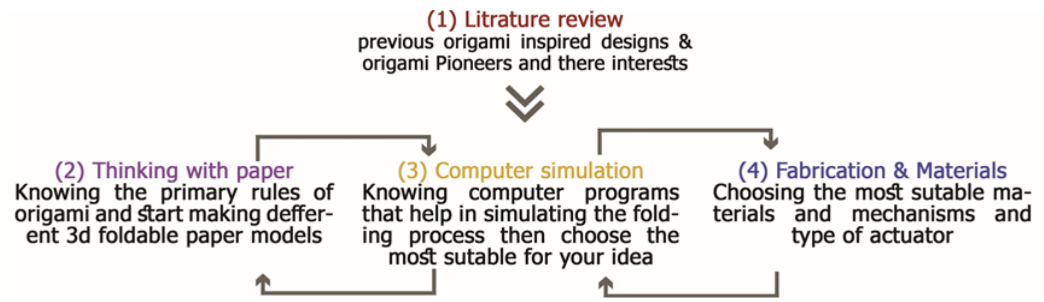



Figure 41: Shows a Methodology for using origami in design by the Authors.

## 6. Application:

Proposed shelter design, its dimension 5m*7m, firstly models were made from paper until reaching the final desired model (Figure 42). Then crease pattern was drawn on Rhino 3D software with grasshopper (plug-in) & Crane (add-on) to produce the 3D model and to examine the folding processes (Figure 43), and adjusting the crease pattern tell reach the desired form (Figure 44).

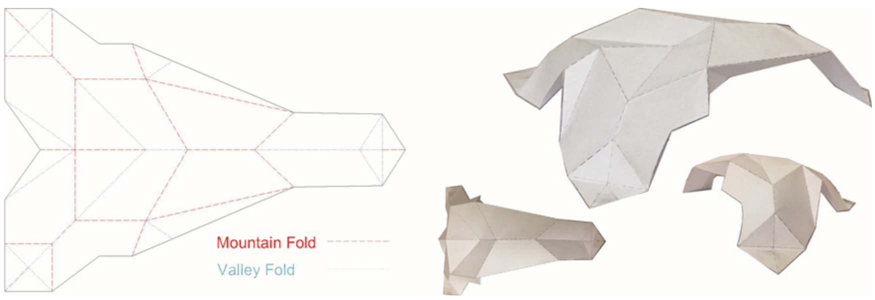



Figure 42: (a) Crease pattern of the proposed shelter (b) Paper models of the shelter, designed by the Authors.

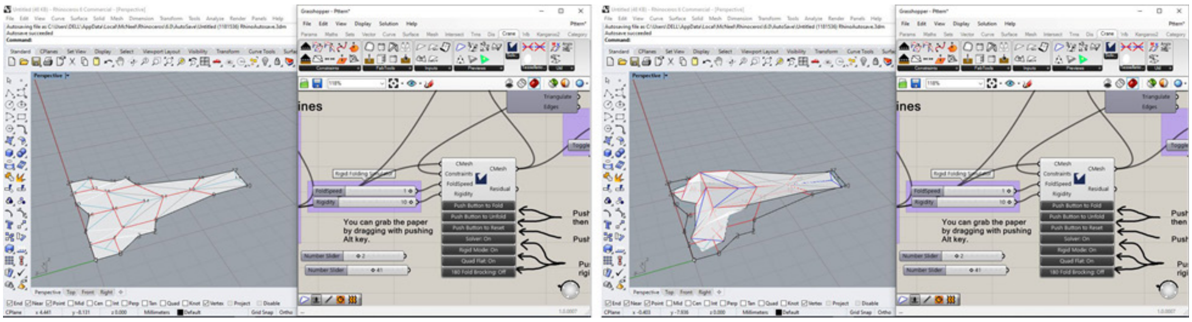



Figure 43: 3D-simulation of the folding process of the proposed design on Rhino 3D software with Grasshopper (plug-in) & Crane (add-on), designed by the Authors.

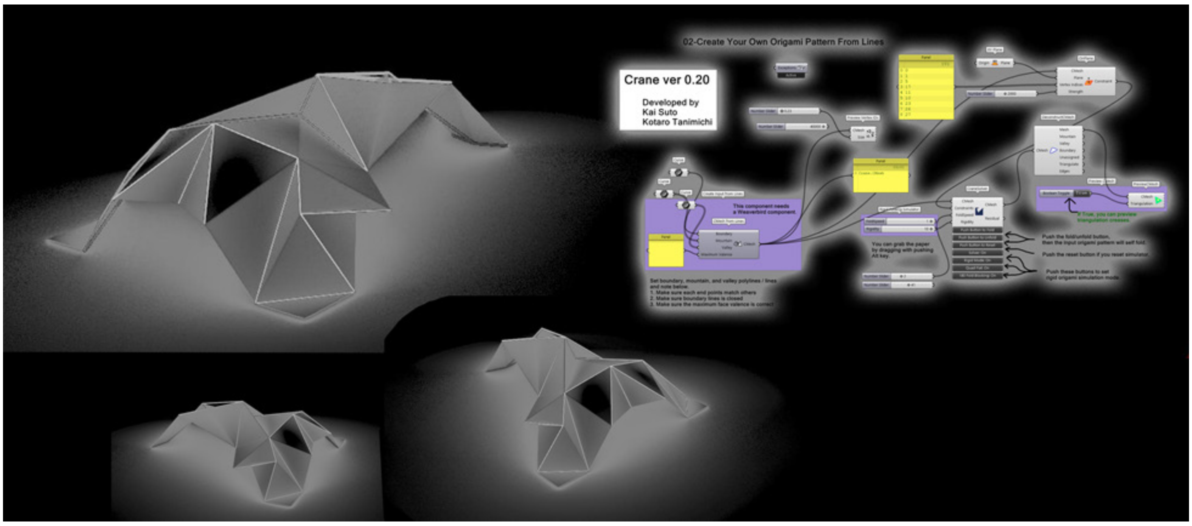



Figure 44: 3D-simulation of the final folded design when fully folded and the algorithm generating it in Grasshopper designed by the Authors.

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