



Origamic Architectural Form Design System

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Abstract

In this research we will try to define a more accurate knowledge about origami. We will be able to see the origami from the mathematical point of view. Also establish the connection between the origami, architecture and design. The methods for the exploring the use of three-dimensional symmetries in the design of spatial structures will be reviewed. Examples in architecture and decorative arts were collected and analyzed. We will define the use of origami as a method to explore shapes in the design process, which can even lead to the discovery of new forms and construction methods. The use of origami techniques as a method for exploring the use of three-dimensional symmetries in the design of spatial structures.

Keywords: origami architecture; polyhedron; origami design.

1. Introduction

Throughout the history of Interior design, there have always been attempts to shape Elements from a single piece of semi-finished industrial materials such as plywood, sheet metal, plastic sheet and paper-based sheet. One of the ways to form these two-dimensional materials into three-dimensional products is bending following cutting. Similar concepts of this spatial transformation are encountered in the origami form, which has a planar surface in unfolded state, then transforms to a three-dimensional state by folding or by folding following cutting. Conceptually it may be useful to think of one-axis bending, which is a manufacturing technique, is somewhat similar to folding paper [4].

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In this regard, the studies in the scope of computational origami, which light the way for real-world problems such as how material will behave under stress, have applications especially in ‘manufacturing phase’ of highly-developed designs. Besides manufacturing phase, origami design is also used as a product design tool either in ‘concept creating phase’ (in the context of its concepts) or in ‘form creating phase’ (in the context of its design principles). In our work, the designing of various interior elements as well as architectural shells, which are made from various materials, are presented in a framework that considers the origami design. In the theoretical framework, evolutionary progression of origami design is discussed briefly in order to comprehend the situation of origami design in distinct application fields. Moreover, the elements, principles, basics of origami design and origami structures are generally introduced. The theoretical framework is completed with the descriptions of the concepts on origami design and origamic structures. The practical framework is completed with several examples base on form generation. Finally, the study is concluded with the evaluation of the origamic design in respect of the design principles. Furthermore, designing by considering origami design is recommended to designer to design a better interior.

2. The history of development of the origami

Origami is the traditional Japanese Art of paper folding. The Japanese word “origami” is a compound of two smaller Japanese words “ori” meaning to fold and "kami" meaning paper [7].

The origin of origami in Japan is thought to be ceremonial wrappers as represented by noshi. Noshi was originally a form of folded wrappers for noshi-awabi, or stripped and dried abalone meat, although today it is just attached or printed on wrapping paper as a token of good fortune. Another example is a pair of paper butterflies known as ocho and mecho. They are, in fact, wrappers for sake bottles, although today they are just attached onto the neck of the bottle and used mainly in wedding ceremonies.



Figure 1, 2: Ocho and mecho illustrated in the nineteenth century. Source [27].

The samurai warriors of the Edo period (1630 – 1868) were supposed to fold wrapping paper in a specific way according to what was inside when they sent a gift. It is part of the etiquette of the samurai class, which was carried down from generation to generation in some houses, most notably Ogasawara, Ise, and Kira [1]. In contrast, the origin of Western origami is thought to be baptismal certificates folded in a “double blintz” that is, folding all the four corners of a square to the center and repeating the same folds on the smaller square. This custom of folding baptismal certificates seems to have been popular in Central Europe in the seventeenth and eighteenth centuries.



Figure 3, 4, 5, 6: German baptismal certificate from the eighteenth century. Source [28].

Comparing Japanese wrappers with the European baptismal certificates, we can observe the difference in the folding styles of the East and West. The crease lines of samurai wrappers run in arbitrary angles, whereas those of baptismal certificates are limited to square grids and diagonals. Actually, we can assume that the two traditions of origami in Japan and Europe emerged and developed independently of each other.

The most typical European origami model is perhaps the little bird called pajarita in Spain and cocotte in France. Another popular model in Europe is the boat and the hat. Although both the boat and the hat are made from the rectangular sheets of paper, most of the European traditional models are made from square sheet [23].

The first modern kindergarten in Germany was founded in 1837; and one of the most important occupations was origami.

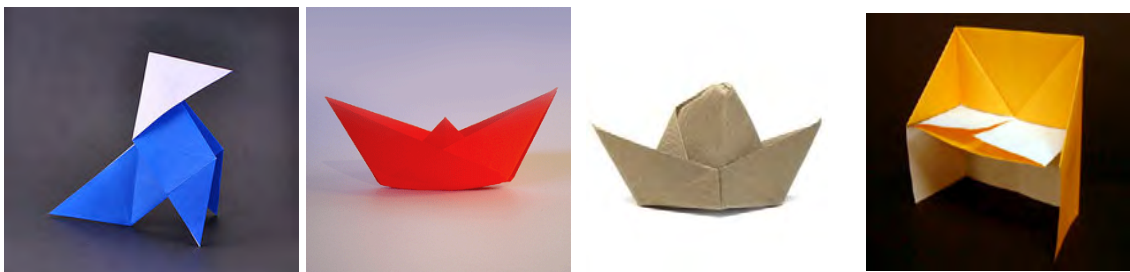


Figure 7, 8, 9, 10: pajarita, boat, hat and sofa (piano). Source [29, 31].

Many of the European origami models are not included in contemporary Japanese records. The pig, house, sofa (also known as piano or organ), balloon (waterbomb), arrow (paper plane), salt cellar (cootie catcher), bird (pajarita or cocotte), windmill were all born in Europe and imported into Japan along with the kindergarten system [11].

Looking through the European models, it can be easily noticed that most of them have only creases that are either square grids or diagonals. This is true even in the Chinese junk and the gondola, which are similar to the Japanese takara-bune, or treasure ship. The treasure ship has a pointier bow that is folded with sharp-angled

creases. This difference is so visible, because of this the Chinese junk and takara-bune developed independently on the opposite sides of the world [1].



Figure 11, 12, 13: Chinese junk, gondola and boat. Source [32].

Generally, the origami spread and mixed over the world, as people traveled internationally. The state of origami as we know it today has been developed as a consequence of such a cultural exchange. Thus, origami has never been a pure “Japanese” art.

3. The implementation of the origami in the architecture

Origami is an art of folding a single piece of paper into a variety of shapes without cutting or stretching it. Creating an origami with desired properties, particularly a desired shape, is known as origami design. Origami design is a challenge faced not only by origami artists but also by designers and engineers who apply origami to industrial purposes. [2]



Figure 14: Chinese zodiac “pop-up” card. Source: [33].

A planar paper can be transformed into a three-dimensional object via cutting, crimping, folding, and gluing. An origami architectural is a 3D structure “pops up” from a folded sheet of paper when opened at 90°, without gluing or splicing, which is stored by folding the two halves of the paper closed [2, 3]. An origami architectural structure was developing in a type of pop-up card that appears in many forms, such as extremely realistic

greeting cards [3]. In China, people send greeting pop-up cards during Chinese New Year. Chinese zodiac animals are the most common cards [2].



Figure 15: origami architectural form. Source [34].

The Japanese craft of “origami” has proved itself as being a valuable tool to develop various engineering and design applications in numerous fields. Several patterns developed by Dr. Nojima Taketoshi ranging from environmentally friendly containers (pet bottles, plastic containers, cans and et. al) to medical applications such as stents, catheters, from vehicle parts to new insulation material configurations, from robotics to education are sources of inspiration for many other innovations [8]. This wide range of applications has been named by Ian Steward as “Origamics” demonstrating the interdisciplinary nature of these studies including mathematics, engineering, biology and many other possible disciplines which may use origamics [22]. The potentials of “origamics” in general, then in architecture, as an interface to gain cognitive experience on spatial transformations, computational design, form finding etc., and as a medium of inquiry for structural design in through the examples of kinetic or deployable structural designs in architecture [14].

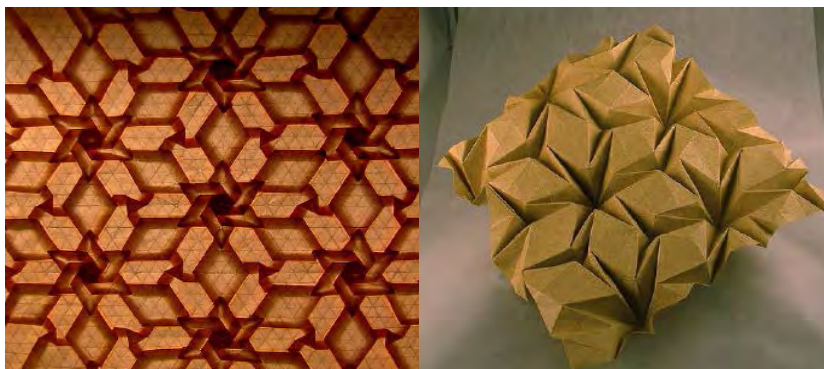


Figure 16, 17: Star tessellation. Source: [25].

In the minds of many people, origami usually recalls skillfully crafted 2-D forms of living or non-living objects those are found in nature or in the built environment. Starting with a piece of paper and just by folding, ending up with diverse range of forms and patterns has attracted many people and resulted in hundreds of books and internet sites, origami courses. However, contemporary use of origami is not only a craft or tool for education, but also a very rich medium allowing several different and complex design applications. Though origami has evolved from being a craft to an interdisciplinary methodology “origamics”, understanding the mathematics and geometrical pattern relations are essential parts of such as the mappings of “tessellations” into 2-D and 3-D space. In general, these tessellations are derived from applying isometric and/or similarity transformations of lines and line shapes in 2-D space. In the development of most of these patterns, it is possible to say that there is a grammar to be followed consisting of shapes (lines and angles) and “grammar rules” to be followed, mostly the geometry transformation, based on Huzita’s Axioms [10], Maekawa’s Fundamental Theorems [16], Miura’s Patterns [18, 19], and Kawasaki Theorems [9], which has also potentials to be generalized for higher dimensions, and theorems and axioms proposed by many other mathematicians. These axioms and theorems lately have been first converted into successful algorithms by Robert Lang and based on these algorithms commercial software has been developed [15].

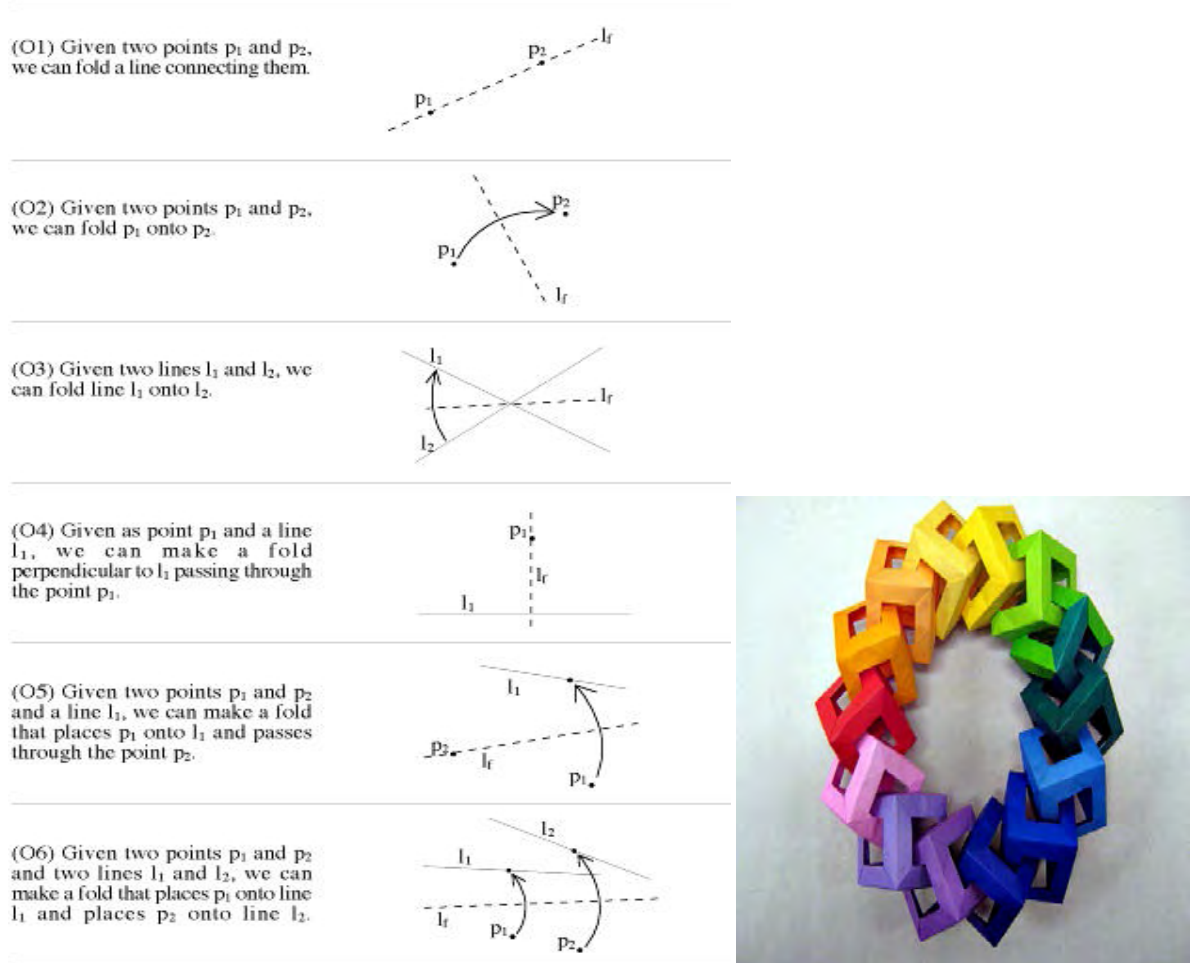


Figure 18, 19: The explanation and implementation of the Huzita Axioms. Source [30, 36].

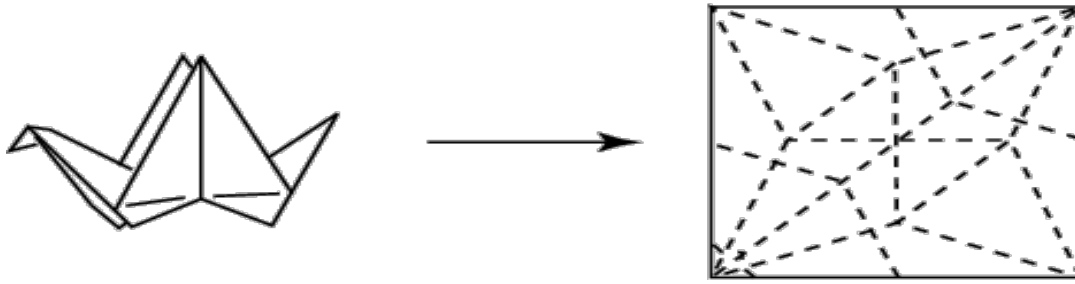


Figure 20, 21: The Kawasaki Crane according to the Kawasaki theorem. Source [35].

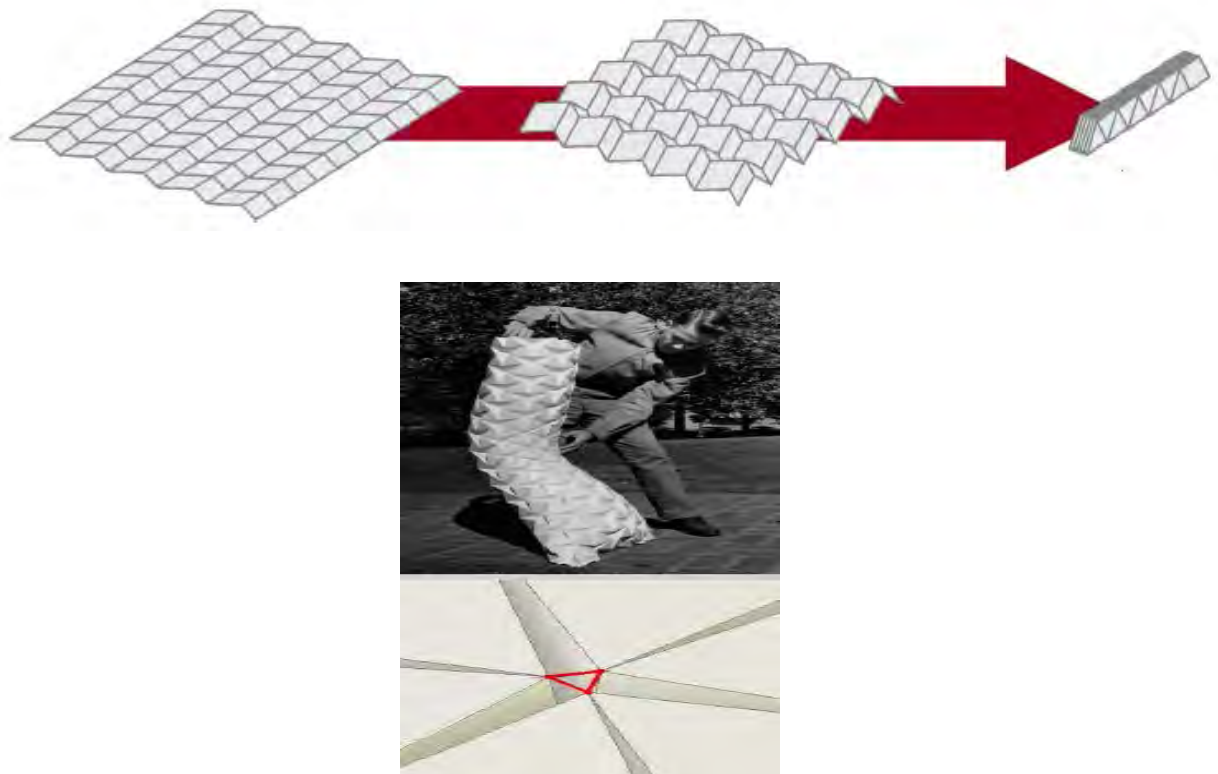


Figure 22: Miura's Patterns. Miura-Ori on practice. Source [14, 18].

The mathematical idea behind all these folding processes and their “mapping” into 2-D and 3-D space and the “grammar” of the diagrams developed in origami provides a valuable interface for education of mathematics and computation. With implementation of the mathematical relations and algorithms in design, it becomes possible to achieve more complex origami forms. This relation between 2-D diagrams and the resulting 3-D solid models have also clues for the manufacturing, fabrication of these models from simple sheets of raw materials to complex forms. At this way, the origami might be used in different design approaches [25].

The possibility to achieve a saddle surface, has been achieved by adding folded tuck-like structures between each facet. For example, the rabbit appears to be composed of triangle panels on the surface, but in fact there are

many folded tucks hidden in the interior. The ultimate challenge for origami design is whether it is possible to fold any kind of shape from a single sheet of paper, and the answer is found to this challenge.

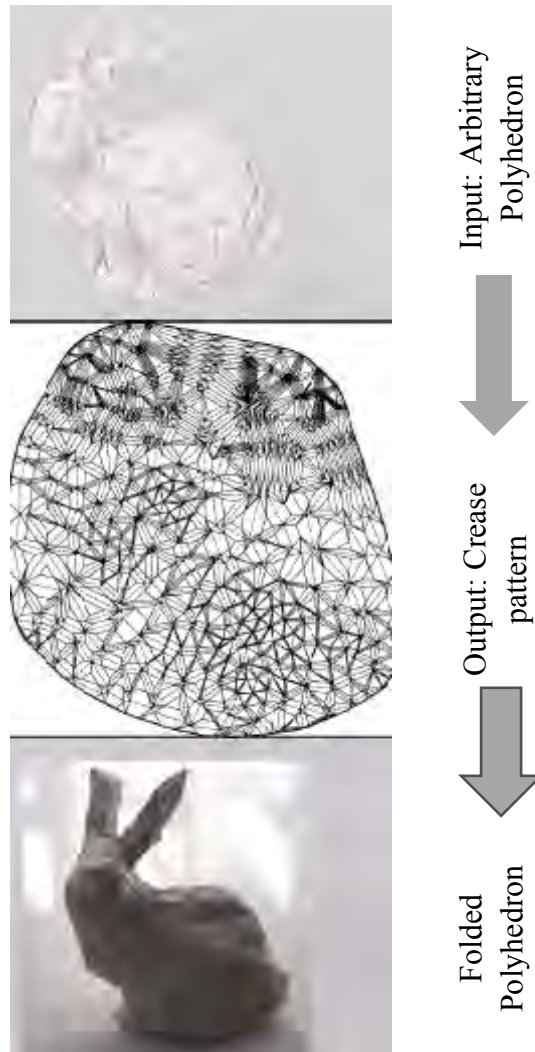


Figure 23, 24, 25: Realization of the arbitrary polyhedral surface with a developable surface. Source [25].

Today, in one hand, rapidly developing design tools and construction, manufacturing technologies, the demands for more responsive spaces and as a consequence IT and AI applications, and on the other hand serious environmental problems (depletion of energy sources, pollution, disasters, etc.) and thus demands for performance based solutions, rapid population growth and etc. make architectural design process much more complex than ever before and force architects to develop new approaches through trans-disciplinary studies. Recently, there are examples of architectural designs with their innovative forms, finding processes and structures together with their functional efficiencies revealing this complexity. However, the difficulty of finding optimized form-structure-function trilogies still imposes difficulties and researchers seek for new methods

and tools to develop new structures and thus new forms. It is no doubt that structural design is an integral part of many engineering and architectural design processes and has a direct effect on the final configuration of the “designed product”. However it is the process which constrains the design most; light weightness, static and dynamic stability, long life span, construction easiness, low cost, high strength but environmentally friendly materials and many more [14].



Figure 26: architectural origami structure. Source [14].

If to apply the theories of origami, it is possible to create a structure that can be folded up and carried. Such structures would be versatile in that their shape could be changed according to need, made smaller to accommodate only a few people, and expanded out when there are more people. When using origami on a large scale such as at the architectural level, it is needed to use thick and rigid panels and hinged folds.

However, without proper consideration of the geometry, repeatedly folding up and expanding out such structures creates stress on the materials, eventually causing them to collapse. By calculating a pattern using a theory known as rigid origami, it is possible to create an architectural structure out of origami that can be repeatedly folded up and opened out [12].

This technology is not limited to architecture. In fact, the applications for origami are truly wide-ranging. They include foldable furniture such as chairs, solar panels and solar sails for deployment in space, medical devices that open up in blood vessels to prevent ruptured aneurysms (origami stent-grafts), and packaging including cardboard. Modern origami features across diverse areas of specialization, including mathematics, information science, materials science, structural engineering, design, fine arts and education. Thus, searching for the proper structural configuration which satisfy the constraints but yet allow designers to develop their “product” is a general problem experienced in any design process [25].

4. Architectural Origami Design Methods

4.1. Tree Method

Since so much of the process of design is geometric, the prospect for the computer to design the superior model, than by a man, is not as outrageous as it may seem.

The tree method has been the only existing practical computational origami design method for realizing desired shapes. Its basic concept was first introduced in 1990 [17], which states that an arbitrary tree-shaped origami figure can be constructed from a pattern of circles and rivers packed into a square.

Lang [15] described the theory of the tree method with some proofs and proposed a computational algorithm. The proposed method generates a crease pattern that folds into a base, i.e., a folded shape whose projection to a plane is exactly the same as the given tree shape with arbitrary edge lengths and connectivity. The algorithm is implemented as an origami design software TreeMaker [5]. The tree method enables the creation of origami with vast complexities; however, it is only possible to control one-dimensional properties, i.e., the lengths of flaps. An intuitive process wherein an experienced origami artist performs the “shaping” is essential to transform such an origami base into the final shape. In addition, it is virtually impossible even for experienced origami artists to create a desired three-dimensional shape using this approach. In contrast, our method can precisely represent three-dimensional shapes without additional shaping.

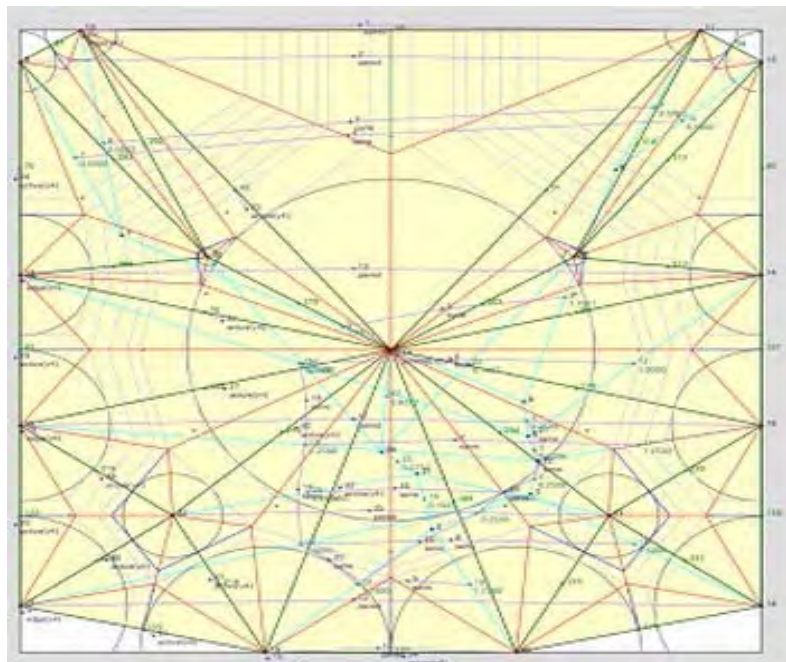


Figure 27: A screen shot of the computed crease pattern for a scorpion using TreeMaker 4. Circles corresponding to leaf nodes (terminal flaps) are shown to aid intuition. Source [13].

Within the few years, the powerful design techniques of circle-river packing had been discovered and systematized by multiple folders, including Toshiyuki Meguro in Japan. After several months of work he has created a computer program TreeMaker, since it started with a particular type of stick figure (called a tree in

graph theory). Initially, TreeMaker was little more than a mathematical curiosity and a tool for exploring the mathematical theory of how to design a base.

The version 4.0 of TreeMaker, which, in addition to including many algorithms for the origami design, incorporated a powerful numerical optimization code, CFSQP. And suddenly, TreeMaker was no longer an academic curiosity; it had become a powerful tool, capable of constructing the full crease pattern for a wide variety of origami bases.



Figure 28: The folded base, and a finished model folded. Source [13].

In fact, version 4 of TreeMaker could solve for crease patterns that couldn't construct by any other way — by which mean, using pencil and paper. TreeMaker allows one to set up quite elaborate relationships between flaps, their lengths, and their angles: far more complex relationships than are possible using pencil-and-paper origami design. Which meant that it was now possible, with TreeMaker, to solve for origami bases that truly were more complicated than anything a person could design by hand.

But the value of TreeMaker is that it combines novelty with efficiency: the patterns constructed are commonly the most efficient solutions possible for a given stick figure, and they are just as often totally new structures in the world of origami.

TreeMaker is a program for the design of origami bases. What is needed is to draw a stick figure of the base on the screen; each stick in the stick figure (the "tree") will be represented by a flap on the base. It is possible to place various constraints on the flaps, forcing them to be corner, edge, or middle flaps, and/or setting up various symmetry relationships (forcing pairs of flaps to be symmetric about a line of symmetry of the paper, for example). Once the tree is defined the tree, TreeMaker computes the full crease pattern for a base which, when folded, will have a projection (roughly speaking, its "shadow") equivalent to that specified by the defining tree. The crease pattern can be printed out, or copied and pasted into another graphics program for further processing. Crease assignment (mountain or valley) are not computed, but with a few simple rules and some exploration by hand, the proper crease assignment can usually easily be found.

Toshiyuki Meguro has developed TreeMaker 5. With its help it is possible to draw a stick figure that represents the base which after, specifying the lengths and connections between flaps, and lets to set various types of constraints that enforce symmetries in the base (e.g., mirror symmetry) and in the crease pattern (e.g., forcing particular crease angles). What TreeMaker 5 adds to the mix is [14]:

Screen shot of TreeMaker 5, showing the full crease pattern, folded form, and the new Inspector for editing the design.

- Full mountain-valley crease assignments;
- An x-ray image of the folded form of the base;
- Numerous new options for display and simplified editing.

The figure to the right shows TreeMaker 5's take on the scorpion design shown above, with the complete mountain, valley-assigned crease pattern, the folded form of the base, and the new "Inspector" window for editing the tree and its conditions.

4.2 Folding a Polyhedron

It is proved [5] that any polyhedron can be created by folding a square piece of paper. The basic idea of the algorithm provided in the proof is to fold the square sheet of paper into a thin strip, and then, wrap the strip around the desired polyhedron. It is practically impossible to design any actual model using this approach, because of the inefficiency arising from the algorithm, which relies on an extremely narrow strip. In addition, the strip does not stably sustain the three-dimensional shape if it is constructed by the above mentioned approach. Tanaka [24] proposed another technique based on folding a paper into the development of the given polyhedron. This technique is also not practical for the same reasons — the generated crease pattern is inefficient, and the folded shape is unstable, because the algorithm begins with the formation of a complex tree-shaped polygon.

4.3 Tucking

It is a well-known fact that a flat sheet of paper can be curved by tuck folding. Some origami artists empirically apply the tuck-folding technique to shape a three-dimensional surface.

Based on the idea of tuck-folding, the technique for the designing a three-dimensional origami surface by tucking and hiding the unwanted areas of a paper, has been previously suggested [25]. The work proposes the concept of tucking molecules, fragments of crease pattern specially designed for tucking. However, no algorithm or system has been developed, and the entire design process relies on trial and error using a conventional paper craft software [13] and a vector drawing software. It sometimes takes several weeks to create a crease pattern for realizing a three-dimensional origami model using this technique [26].

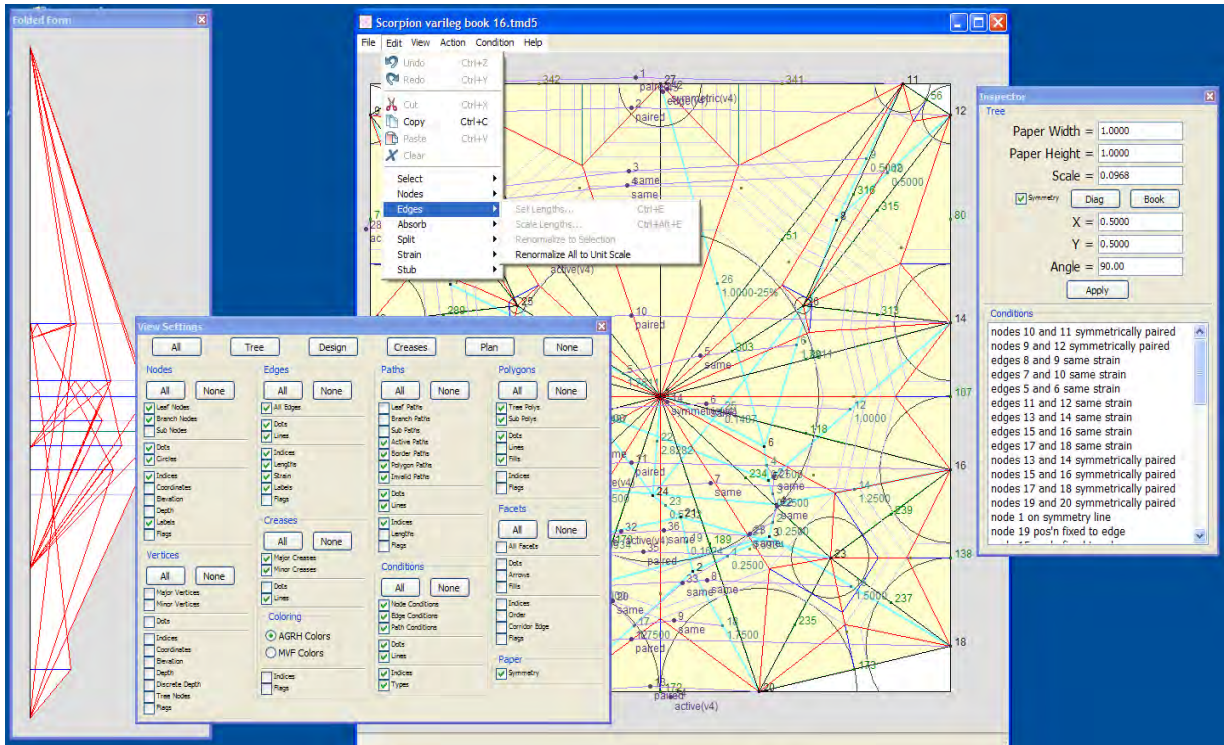
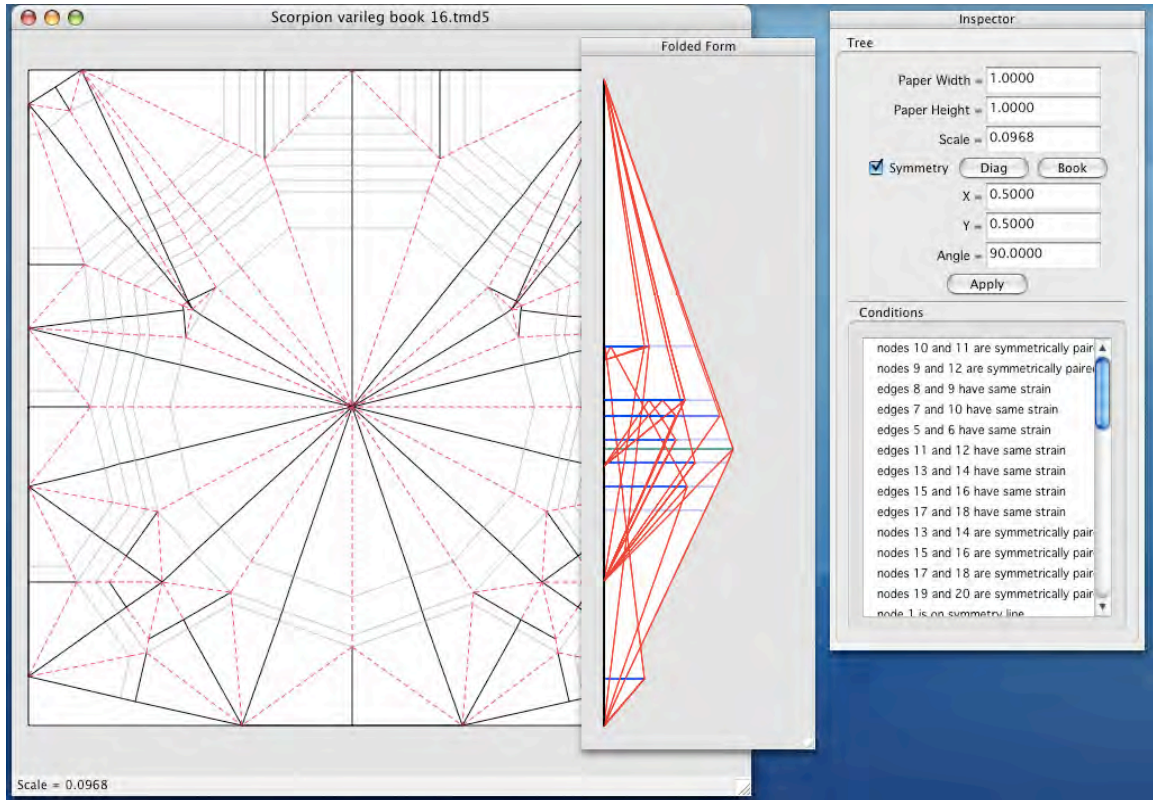


Figure 29: Screen shot of the program TreeMaker 5. Source [13].

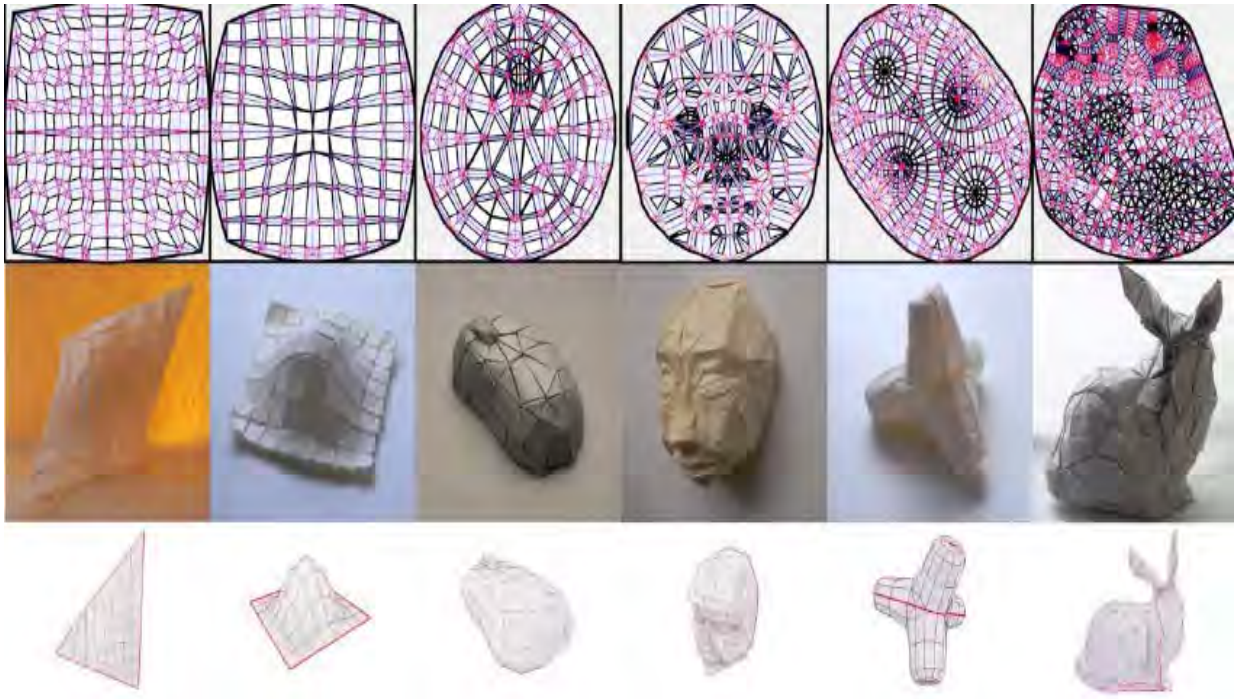


Figure 30: The polyhedron actual models – (a) Hyperbolic Paraboloid, (b) Gaussian, (c) Mouse, (d) Mask, (e) Tetrapod, (f) Stanford Bunny. Source [24].

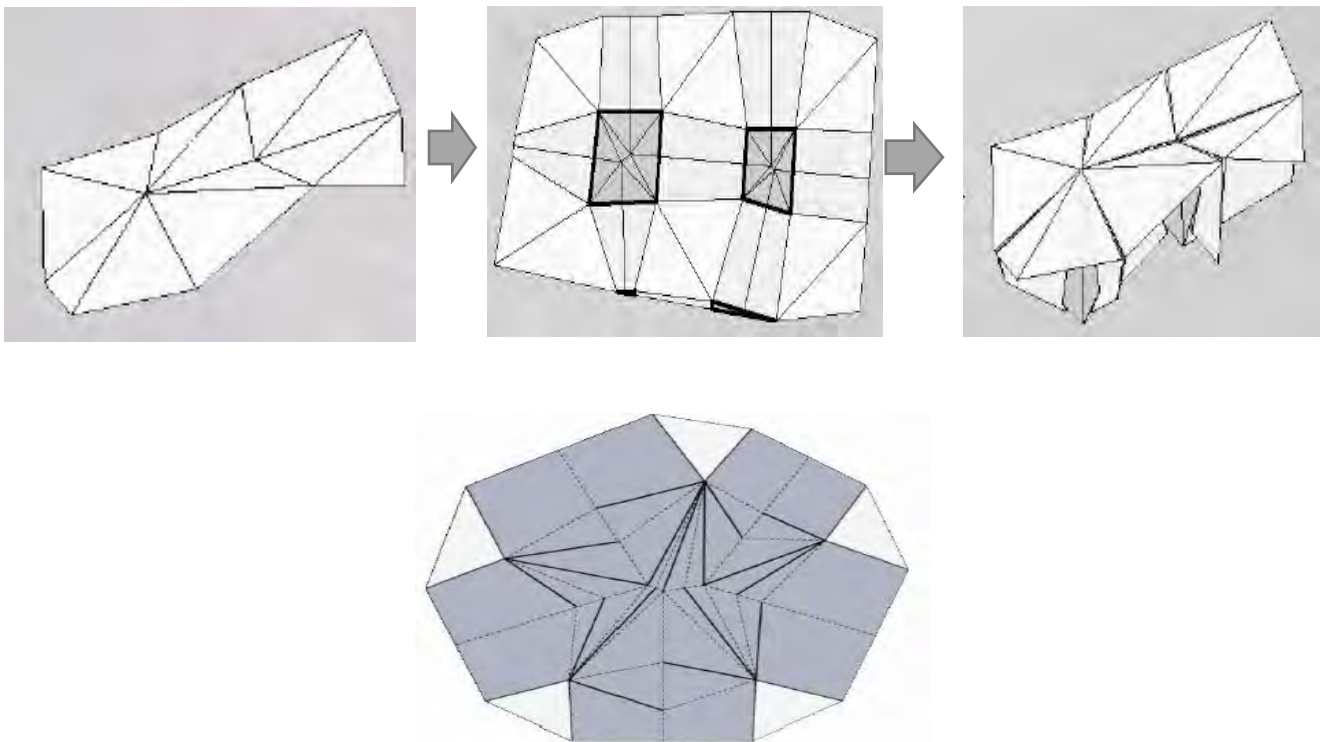


Figure 31, 32, 33, 34: Tuck develops into a plane. Tuck folds into a flat state hidden behind polyhedral surface. Source [13, 14].

5. The prominent examples of the implementation origami on the practice

Obviously, nowadays origami it is something new, modern and fresh. In the period of the Information technologies, it is difficult to impress; however, origami shapes renewed the Interior design. Origami is not only for Japan and Japanese art now. Such an elegant and distinguished forms has become an important source of inspiration for Architects and Interior designers. Origami-inspired designs are extremely creative and work well in the office or home. The simple designs are visually interesting and appealing while remaining comfortable. The sculptural and artful origami allure can be used to design walls, furniture and any accessories. The analyze of the creations below, will make a clear picture of the impressive origami shapes [6].



Figure 35, 36, 37: The transformation of the Origami house. Source [6, 30].

The Designer David ben Grunberg, inspired by origami, created a dynamic transforming house. In the winter, thick walls can face outward and insulate the home; in the summer, everything can be flipped inside-out so glazed walls let heat escape. The shape of the home can even change throughout the day. A user could position the house to watch the sun rise in the morning, and continue to rotate it so they stay in the sun all day long. The configuration can change to adapt to weather, too.

For example, in the summer plan, bedroom one faces east and watches the sun rise as its inhabitant wakes up. It can then rotate so that the user is constantly in sunlight, while the house generates energy through its solar panels [21].

The revolutionary home is based on the work of an early 20th Century mathematician who discovered a way to dissect a square and rearrange its parts into an equilateral triangle.

The flexibility of the house allows adaptation from winter to summer and day to night by literally moving inside itself.

Thick heavy external walls unfold into internal walls allowing glass internal walls to become facades; doors can become windows, and vice versa.

The layout consists of two bedrooms, an open-plan living room and a bathroom, but it too can be adapted to suit the needs of different living situations.

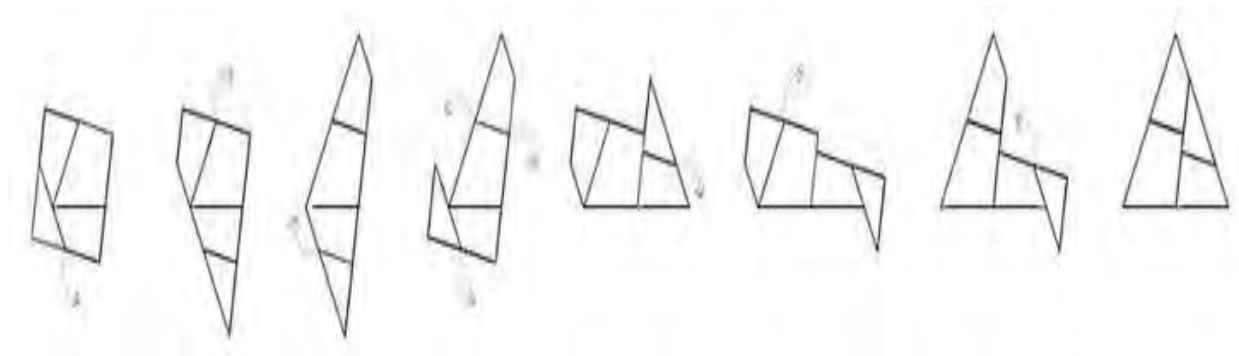


Figure 38: the scheme of the Haberdasher's Puzzle. Source [21].

The design uses the Haberdasher's Puzzle, a mathematical discovery from 1902. By cutting an equilateral triangle in a specific way, it can be folded into a square, and folded back again [6].

A remarkable feature of the solution is that each of the pieces can be hinged at one vertex, forming a chain that can be folded into the square or the original triangle. The Haberdasher's Puzzle can be used as the basis of every design, from coffee tables to lights. The house, called "D*Dynamic", isn't available yet, but you can see how it works in the video below: (<https://www.youtube.com/watch?v=v2gQM8DxSNg>).

The origami art can be applied at any place in the house from the wall cladding to the lamp designs. The Designer can use the pure paper elements in the Design, or the décor that was created inspired by the origami.

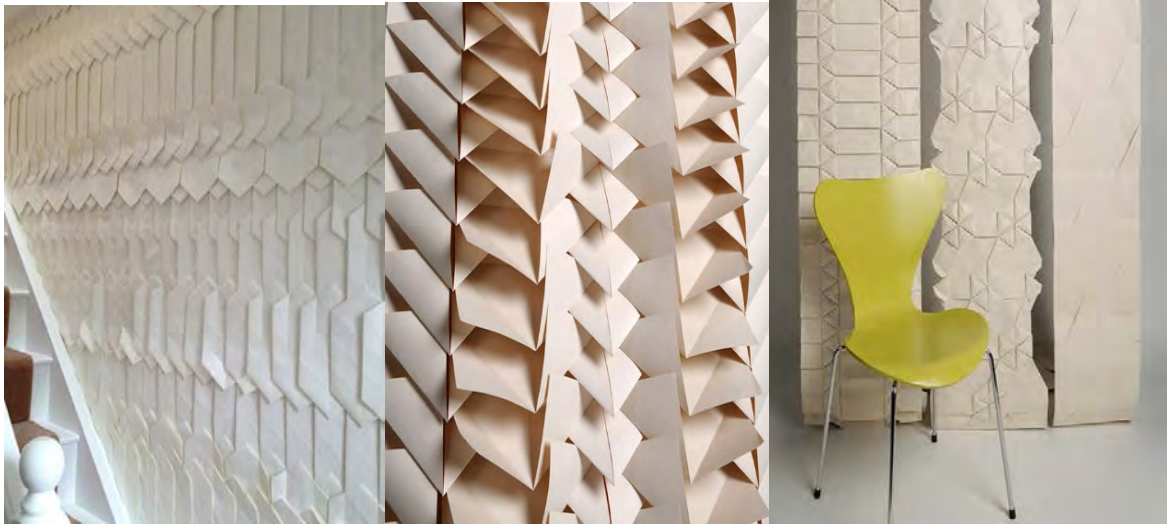


Figure 39, 40, 41: Tracy Tubb origami wall cladding creation. Source [20, 30].

The habitants get used to see in the house the functional and durable walls; however a folded paper wall-cover doesn't seem to tick any of those requirements. But paper it is certainly an attractive and interesting element. In addition it is replaceable, so the small sections of it can be easily transformed, when they get damaged, rather than having to do a whole wall [20].



Figure 42, 43: The scheme and the prototype of the origami chair. Source [30].

Furniture designers inspired by the simple elegance of this ancient art are creating incredibly beautiful and functional chairs, tables, sofas – even curtains, lamps and wall hangings – that transcend the ephemeral nature of paper sculpture, making it an integral element in the home.

Folding a thick sheet of steel is no easy task, but that’s exactly what engineers did to create the origami table. The Japanese origami-inspired design is laser-cut from a single sheet of steel to minimize waste. The development of such kind creations is long and extensive, requiring complex mathematics and precision engineering (figure 44).

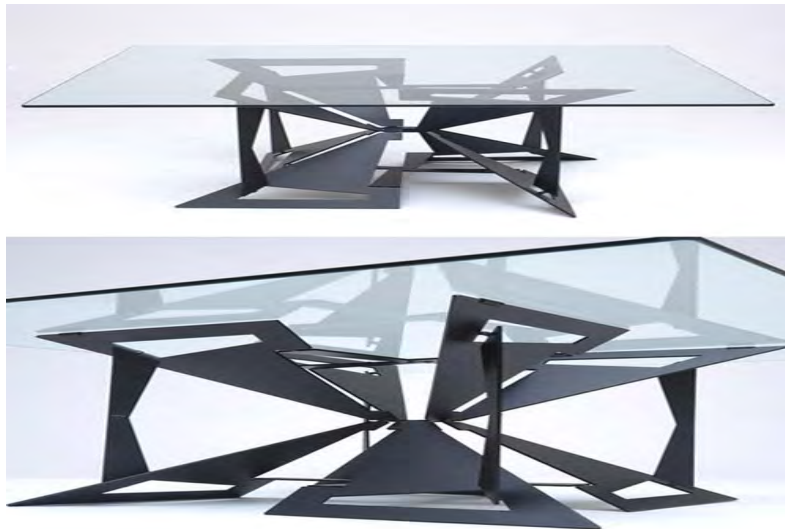


Figure 44, 45: The steel origami table. Source [30].



Figure 46, 47: The example of the comfort of the sofa, made in a origami shape. Source [30].

Origami Modern Sofa is a leather sofa design. It can be converted into a bed with a simple maneuver of the frame.



Figure 48: Stealth light, folded into an origami like pyramid. Source [30].

6. Conclusion

According to the material that we have reviewed we are able to confirm that:

- The origin of the origami is not following purely from Japan. When comparing hundreds of traditional models recorded in the eighteenth and nineteenth century, it is appearing that only a few models were common to Europe and Japan at that time.
- Origami, from an ancient Japanese craft to today's recently recognized "engineering discipline", offers many opportunities to mathematicians, designers and engineers to explore mathematical relations, new forms and dynamic or static structures.
- During the last decades, studies conducted in Japan have shown the transformation of origami from 2-D to 3-D and has found important fields of applications in industry. These studies have also contributed to the recognition of origami as an "engineering discipline" allowing transdisciplinary studies from biology to nano-technologies, from automotive to structural design.
- Before we were not able to imagine that the stainless steel might be composed as the paper. Nowadays the computer technologies have developed, and are able to create the scheme of the origami shapes, that can be done without cutting and gluing. They are: TreeMaker, Folding a Polyhedron, Tucking.
- Origami it is a process of repetition: thinking about the theory, then folding, then thinking once again before making another fold. By continuing to use both the head and hands, the Designers are able to create the comfortable, practical and fresh Interiors. The origami furniture is creative and innovative and at the same sustainable and not harmful for the environment.

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