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Origami inspired deployable structures: Future mobile healthcare for low resource settings

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Abstract:
Deployable structures may be defined as systems that can be packed, stored, transported, and then deployed or assembled into functional configurations. The potential applications of deployable structures includes portable or modular buildings, scaffolding, bridges for construction sites and stages for events, spacecrafts with deployable solar panels, antennas, etc, tent systems for disaster relief shelters, and medical equipment such as collapsible hospital beds, examinations tables. The literature suggests many more applications but there is a gap of how to achieve such systems from a design perspective. This study takes deployable mobile clinics as an example to delve deep into the product design, development and deployment inspired by the ancient art of origami.
Keywords: Architectural Design; Origami; mobile Primary Health Center; Healthcare delivery model; Healthcare system; Low resource settings.

1. Introduction

One of the most interesting potential applications of a reconfigurable structure is a deployable system. This type of system can be packed up into a small volume while it is being transported, and then it may be unpacked and set up in a wide volume or area to carry out its operations(S. Pellegrino, 2001)(Puig et al., 2010)(Liu et al., 2014). Origami-inspired deployable structures have gained popularity in recent years as a result of the several advantages they offer. These advantages include the simplicity with which they can be fabricated, the fact that their properties may be tuned, they only require a single degree of freedom to be actuated, and they can achieve a vast operational volume (or area) with lightweight mechanisms(Saito et al., 2015)(Zhai et al., 2018)(Deleo et al., 2020)(Melancon et al., 2021). Examples of potential uses include emergency shelters, ballistic barriers, sunshades, and star shades for space telescopes, as well as solar arrays, sails, and sailboats(Stewart, 2003). Such origami-based reconfigurable structures have a key challenge, which is to meet the load-bearing capacities after deployment. This is the case despite the numerous benefits that such structures offer. When the origami architecture is expanded, the structure needs to be sufficiently rigid in order to keep its deployed configuration and support loads. In order to find a design solution to this problem, several concepts of inventive 3D origami(Iniguez-Rabago et al., 2019)(Overvelde et al., 2016)(Tachi, 2012)(Yamaguchi et al., 2021)(Martinez et al., 2012)(Li et al., 2017)can be utilized as potential options.

Origami, the ancient art of folding paper, has had a significant influence not only on the process of form generation, but also in the development of deployable mechanisms and the mimicking of the folding systems found in nature. This is especially true given the significant progress that has been made in both the geometry of folding and the computer simulation of the folding process. Since 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, it gains an interest in the field of adaptive architecture, designing open spaces, and product design. As a result, it gains a lot of attention in the field of adaptive architecture, designing open spaces, and product design. Also, in the design of items that are deployable, meaning that they can be quickly packed into small areas and then deployed when necessary to conserve space and solve contemporary difficulties associated with compact multi-functional spaces. In this study, we attempt to provide a way for designers to derive value from this art in there designing process, based on literature review on different origami designs, state of the art applications and finally brainstorming ideas for future applications.

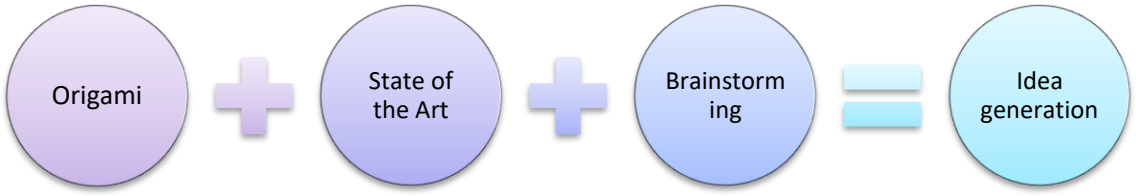


Figure 1. Structure of the Study (Developed by Authors).

3. Material and Methods

Exploration happened from sets of Origami designs proposing several applications of each design. Followed by analyzing state of the art examples in the architectural design, interior design and product design domains. This enabled us to get exposed to an array of origami applications across domains. Brainstorming was used to generate ideas and application of origami designs from literature and state of the art for future mobile Primary Health Center for low-resource settings.

4. Results and Discussion

The method used for this study was that of literature study of origami, state of the art followed by brainstorming which resulted in proposing potential ideas. Table 1-Table 3 has three sets of origami designs with their plans, and three-dimensional views followed by proposing use cases after brainstorming. Table 4 includes state of the art origami designs in architecture, interior design and product design to show the array of applications of the ancient art of origami.

Table 1. Origami design bases (Credit: Authors Own)

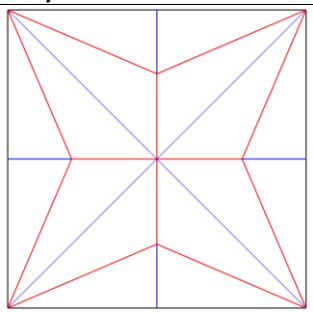
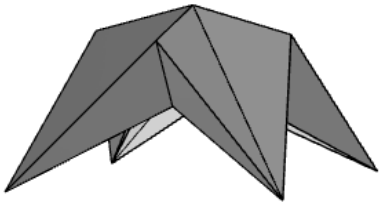
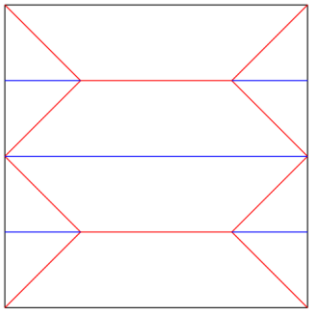
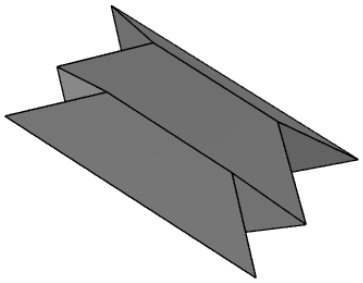
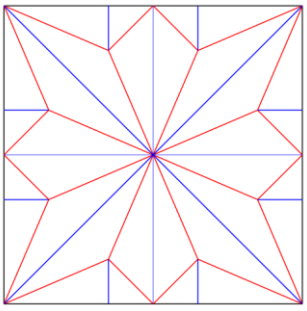
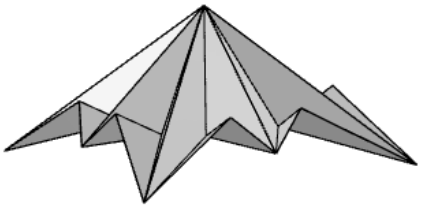
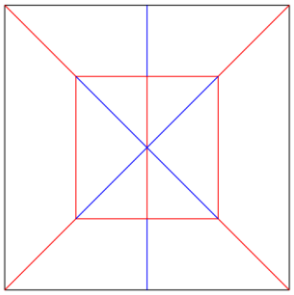
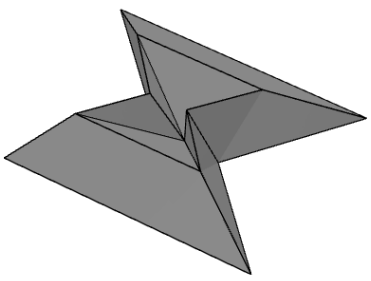
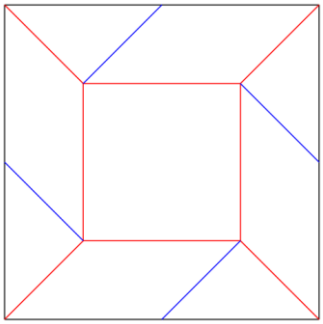
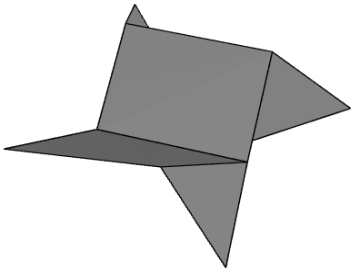
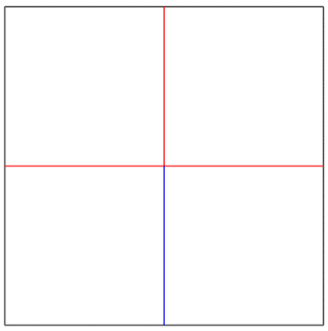
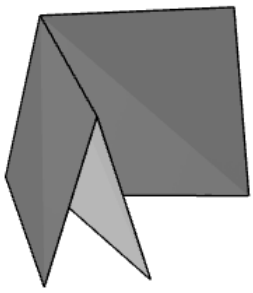
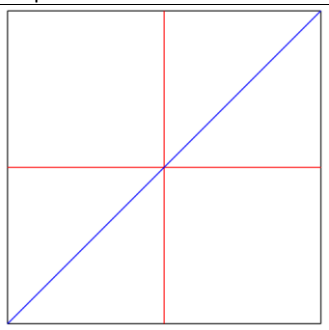
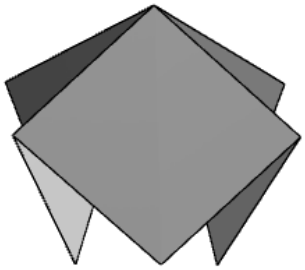
Study case	3d Designs	Use case
 Bird Base		The Bird base design is inspired by the tent structure used in disaster prone regions due to their ease of deployment.
 Boat Base		The Boat base is a more stable design for a mobile clinic having a linear form factor and floor area which serves better for a healthcare facility.
 Frog Base		Frog base designs are more complex to make but can be easy to deploy if designed according an umbrella mechanism.
 Open Sink Base		Open Sink base design is more related to a flexible two-way design where it can be used in two different configurations.

Table 1 provides an overview of four distinct designs explored. Individual designs have variety of applications. For example, the Bird base design can be used as temporary shelters in disaster-prone regions. Its ease of deployment makes it suitable for providing immediate relief to displaced populations. Secondly, the collapsible nature of the Bird base can be utilized in setting up field hospitals during emergencies. Medical teams can quickly assemble and disassemble the structures to provide healthcare services in remote areas or in the aftermath of natural disasters. Similarly, the Boat base design, with its stable and linear form factor, is well-suited for mobile clinics. These clinics can be deployed in underserved areas, remote communities, or during public health campaigns, providing healthcare services to those in need. The Boat base can be used as a base structure for disaster response units. These units can quickly move to affected areas, setting up as operational command centers and providing medical support during emergencies.

The Frog base design, with its umbrella mechanism, can be utilized as rapid response shelters. These collapsible structures can be easily transported and rapidly deployed in areas hit by disasters, providing immediate shelter to affected populations. The complex and adaptable nature of the Frog base makes it suitable for field research stations in remote locations. Scientists and researchers can utilize these structures for studying wildlife, conducting ecological surveys, or monitoring environmental conditions. In contrast, the Open Sink base design, with its two-way configuration, can be used as a flexible workspace. It can serve as a temporary office or collaboration space that can be easily reconfigured to accommodate different work requirements. Further, the Open Sink base can be utilized as a collapsible structure for community centers. These centers can host various activities, such as workshops, meetings, or educational programs, and can be adapted to the specific needs of the community in different configurations. Though these have potential uses, their actual execution and usefulness in a given setting would rely on a number of factors such as local rules, available resources, and the desired purpose. Following section will discuss another set of similar systems with notable solutions.

Table 2. Origami design twisted (Credit: Authors Own)

Study case		Use Case
 Pinwheel Base		The Pinwheel has a wider base which will provide more space for circulation and working on the ground. It will help in faster operations of the clinics.
 Simple vertex		Simple vertex was a two-wall design which is foldable and can be attached to an existing clinic. It will act as an auxiliary system to the main clinic.
		Square base is designed to experiment with the higher roof space for better air circulation than the standard height clinic.

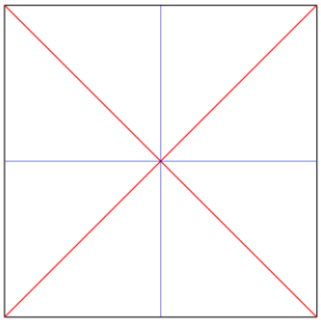
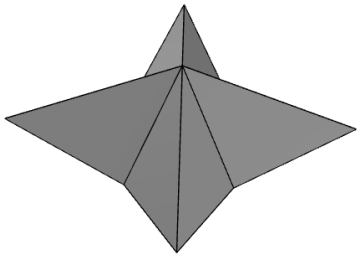
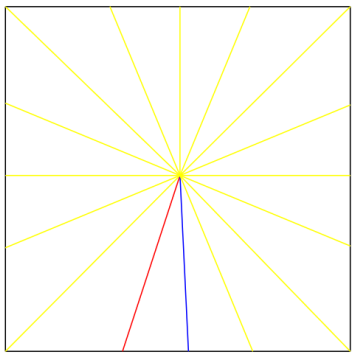
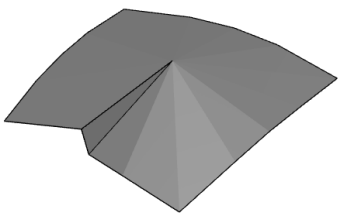
Square Base		
 Water Bomb Base		Water bomb structure was uniquely designed to serve the purpose of a bigger volume and an aesthetic appeal to the space.

Table 2 discusses an overview of four designs of Origami with each designs having purposeful applications. For example, the pinwheel base design, with its wider base and ample space for circulation, can be used as emergency triage centers. It can accommodate multiple patient assessment areas, allowing healthcare providers to efficiently assess and prioritize patients during emergency situations. Another application is due to the spacious design of the Pinwheel base, that it can be utilized for mobile surgical units. These units can provide on-site surgical procedures and medical interventions in remote or underserved areas, enhancing access to critical healthcare services. Similar to Pinwheel, the Simple Vertex base design, with its foldable and attachable nature, can be used as an auxiliary system to existing clinics. It can serve as additional space for patient examination, waiting areas, and administrative functions, expanding the capacity and capabilities of the main clinic. The Simple Vertex base can be utilized for outreach programs and mobile healthcare initiatives. It can be easily transported and attached to mobile vans or vehicles, providing medical services in communities with limited access to healthcare facilities.

On the other hand, the square base design, with its higher roof space and improved air circulation, can be used as rehabilitation centers. The enhanced ventilation can contribute to a better healing environment for patients recovering from surgeries or undergoing rehabilitation therapies. Otherwise, the square base can be utilized for specialty clinics that require additional vertical space, such as dental clinics or physical therapy centers. The higher roof allows for specialized equipment or treatment setups that require more vertical clearance. In conjunction to the use of square base design, the water bomb system with its unique and aesthetically appealing design of the water bomb structure can be utilized as community event spaces. It can serve as venues for cultural events, exhibitions, or gatherings, providing a visually striking and functional space for community engagement. The spacious volume of the water bomb structure can be utilized for mobile educational units. These units can be equipped with interactive displays, educational materials, and multimedia resources, traveling to schools or communities to provide engaging educational experiences.

The purposes for which these systems were designed, the resources at hand, and the specific needs of the area in question would all determine the extent to which they would be useful. The following section will describe another set of designs with potential applications.

Table 3. Origami design folds (Credit: Authors Own)

Study case		**Use case**
 Bistable		The bistable design is to experiment with bistable structures which can be further iterated to a workable design for a mobile clinic.

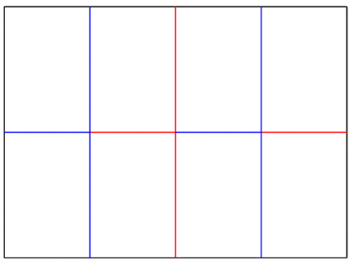
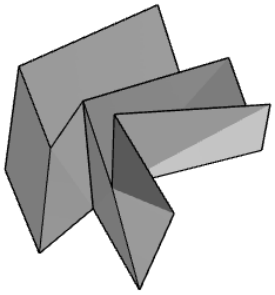
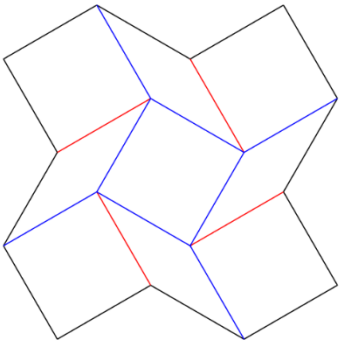
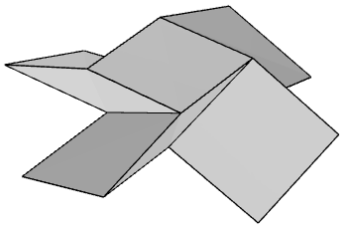
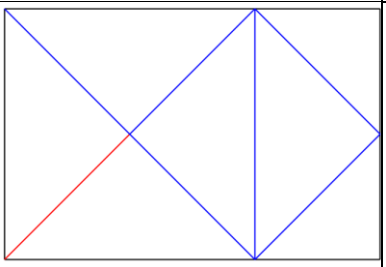
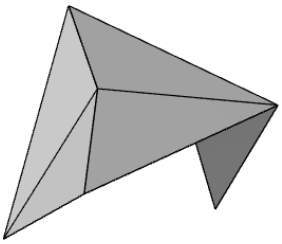
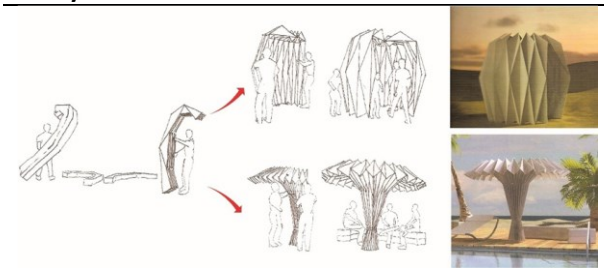
 Map Fold		The Map Fold is same as the Simple vertex design but with more floor space when extended to its full scale.
 Square twist Single		Square twist design is better for weather and has the highest floor area to accommodate several activities of a clinic.
 Russian Triangle		Russian Triangle is designed for a higher roof clearance and for better visibility of space from a long distance which helps in awareness.

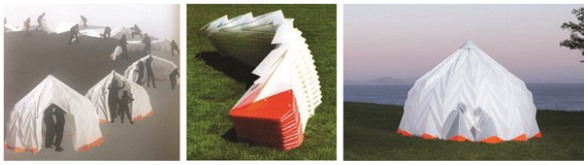
Table 3 discusses another set of origami designs. For example, the Bistable design can be utilized for research and development purposes in the field of collapsible structures. It serves as a platform for experimenting with bistable structures and exploring their potential applications in mobile clinics or other portable healthcare facilities. The bistable design can be used for prototyping and testing different configurations and functionalities. It allows for iterative improvements and adjustments to create a workable and efficient design for a mobile clinic. The Map Fold design, with its extended floor space, can be utilized as mobile diagnostic units. It can accommodate medical equipment for diagnostic testing, such as imaging devices or laboratory instruments, providing on-the-go diagnostic services to remote or underserved areas. The larger floor space when extended makes the Map Fold design suitable for rehabilitation and therapy spaces. It can accommodate exercise equipment, therapy mats, and other resources required for various rehabilitation programs.

The Square Twist design, known for its weather resistance, is ideal for setting up field hospitals in areas prone to extreme weather. It provides a stable and weatherproof structure, ensuring the safety and comfort of patients and healthcare providers in challenging environmental conditions. The Square Twist design, with its high floor area, can be utilized as multi-functional clinics. It can accommodate different activities within the clinic, such as consultation areas, treatment rooms, waiting areas, and administrative spaces, providing a comprehensive healthcare facility in a compact and collapsible structure. The Russian Triangle design, with its higher roof clearance and enhanced visibility, can be used as mobile awareness and education units. These units can be deployed to raise awareness about healthcare issues, provide health education, and conduct screenings or preventive health campaigns in communities from a distance, attracting attention and engagement. The Russian Triangle design, with its distinctive shape and visibility, can serve as mobile command centers during emergencies or large-scale events. It provides an elevated viewpoint for coordinating response efforts, disseminating information, and managing resources effectively.

When deciding how to deploy such collapsible systems for their intended use, it is important to analyse the need specific to the context. Next section will describe state of the art origami designs and applications.

Table 4. Origami applications (Credit: Authors Own)

Study case	Description
 Foldable Wheelchair(Trebbi & Corkett, 2015)	Origami served as the model for Ophélie Bertout and Marcus Kistner's creation of the ParaPli language. It is not simply a fixed structure because the folding design, which is based on triangles, enables the structure to be set up in a couple of distinct configurations. It is a portable shelter that may either be opened or closed, depending on the user's preference.
 Siesta Origami(Trebbi & Corkett, 2015)	Helmina Sladek and Pauline Thierry came up with the design for the Siesta Origami. In order to design a microarchitecture that could be moved easily, they looked for a place to begin that was both reliable and logical. It would appear that origami is a viable option. It made ipossible for them to construct a design that was incredibly simple to put together and operate. Origami is able to stand on its own. There is no requirement for any other equipment. Velcro strips were used to link the various panels of the shelter to one another. It is constructed out of eight triangles of equilateral foam, each measuring 1.5 meters wide, and it may be used as either a rug or a mattress. It is a simple origami design that may be reconfigured in several ways. It is possible to rethink it in a variety of different designs while keeping the panels' ability to fold easily in either direction. According to the requirements, two or more parts can be connected with one another and put together.
 Origami Pavilion(Hemmerling & Cocchiarella, 2017)	Origami pavilion is a revolutionary approach to the construction of self-supporting thin-shell folded structures. It was conceived by Tal Friedman and was built by him. It makes an effort to composite aluminum boards that are photometrically engineered to fold into shape by employing the distinguishing characteristics of origami folding and employing them on an architectural scale. This is done in the name of architectural innovation. It was decided to design a basic variable folding module that could be controlled photometrically in order to produce a seamless pattern. The design of 4mm sheets required the development of a new paradigm that was parametric and could be employed in that regard. over the entirety of the project. It was determined how to design and assemble rigid composite aluminum boards, therefore they were developed as a method. An algorithm was developed in order to calculate and optimize the structure taking into account the many different fabrication constraints. Not just in terms of its structural and aesthetic qualities, but also in terms of its construction process, the project is analogous to origami. Which involves folding the sheets as a whole rather than the panels individually. This method reduces the amount of time spent fabricating and improves building tolerance.

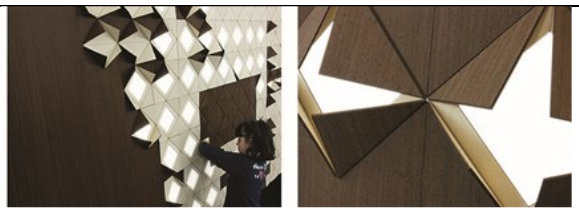
	It is a proof-of-concept model that concludes folded structures can be built to full scale while still preserving a self-supported stiffness and stability that originate from the rigidity of the surface and by locking its fold angles in a key position. This model was created to show that folded structures can be fabricated.
 Ha Ori(Trebbi & Corkett, 2015)	The Ha-ori is intended to be transported, stowed, and set up in a rapid and easy manner. It is foldable, light (weighing a total of 36kg), and highly strong; it was inspired by the structure of the leaves of hornbeam trees, which are known in Japanese as ha-ori, which means "folding leaf." In order to develop this structure, a great deal of trial and error with folds, mathematics, and prototypes was required. It is created by folding a single sheet of corrugated polypropylene measuring 3.5 meters by 14 meters. When measured, it is 2.6 meters long and 46 cm wide. In order to design a microarchitecture that could be moved easily, they looked for a place to begin that was both reliable and logical. It would appear that origami is a viable option. It made it possible for them to construct a design that was incredibly simple to put together and operate. Velcro strips were used to link the various panels of the shelter to one another. Consists of eight folded pieces. When it is opened up, it creates an area that has a diameter of 3.65 meters and a height of 2.44 meters. Ventilation may be controlled by making adjustments to both the roof and the side flaps. The primary framework is comprised of sheets of high-density polypropylene that have a translucent double skin and are double-sided. These sheets are strong and insulating. Straightforward piece of machinery is used to score the sheet along the lines of the folds. Because of the way polypropylene is constructed, it can be folded and refolded an infinite number of times without losing its shape.
 Origmai-mi Kitchen(Kryukova, 2011)	Origami-mi kitchen developed by Olga Kryukova, inspired by origami. This kitchen is built on a metal tube frame, and the storage bins are installed to the frame. This allows the kitchen unit to stand without the need for any walls to support it.

Just Fold It(Aguilo, n.d.)

Just Fold It is a flexible and lightweight room divider that was designed by studio Kutarq. It is made up of individual panels that fold together for simple transit and storage. It is possible to modify its length by increasing or decreasing the number of modules, making it adaptable to a wide variety of settings regardless of the dimensions of those settings. The panels are perforated to provide a pleasing visual effect as well as to strengthen the panels' stability by reducing the effects of wind resistance.

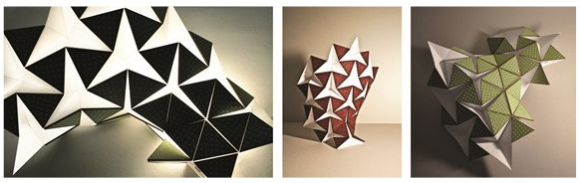
faceted(Trebbi & Corkett, 2015) and magnetic Curtains(Karautli, n.d.)

Pulling on the curtain's string causes the triangles that make up the faceted curtains to fold, which in turn causes the shape of the curtain to shift. These curtains were designed by Hannah Allijn. During the process of folding the curtain, many geometric forms are produced. Magnetic curtains are a design by Florian Krautli that make use of magnets to create a shape that is more stable and long-lasting regardless of how much the cloth is stretched or pulled.



Wood Panel Light(Pham, n.d.)

Wooden wall panels that can be flipped back to reveal energy-efficient electroluminescent lighting were designed by Francesca Rogers and Daniele Gualeni as part of a modular lighting system. The panels are made of wood and can be flipped back to reveal the lights. It was capable of being mounted on any wall.



Miyo Lamp(*Miyo Hanging Light*, n.d.)

Miyo Lamp designed by Silke Steinberg, inspired by origami. The characteristics of the folding are the source of the light regulation that occurs. There is a connection between the level of luminous power that is being emitted and the shape of the structure. The more of these star-shaped parts that are opened, the light will emanate from the lamp. Because the entire folding is done using a single sheet of paper, all of the components of the construction are connected to one another. If you merely move a couple of the segments, the movement will be transferred to the segments that are surrounding them, which will ultimately modify the appearance of the entire figure. Each user is free to make their own individual selection for the surface material that will be applied to the equilateral triangles. The ease with which Miyo can modify its form multiple times leads to the creation of a wide variety of light sculptures through a fascinating shaping process.

Flux Chair(*Flux Chair - Flux*, n.d.)

The Flux Chair is a product designed by the Flux firm and has the appearance of a large envelope that can be converted into a chair. Produced by cutting one sheet of eco-friendly polypropylene in a crafty manner. It has a mass of 5 kilograms and a maximum load capacity of 160

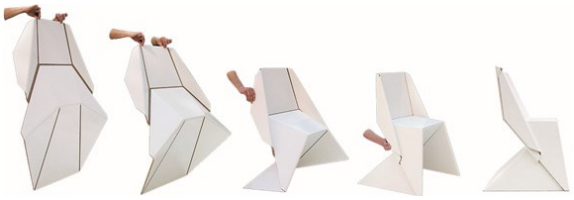
	kg (25). The process of either putting it together or taking it apart takes roughly ten seconds. Additionally, it can be used both indoors and outdoors.
 Papton Chair (*FUCHS+FUNKE Papton Chair*, n.d.)	Designed by Wilm Fuchs and Kai Funke, the Papton Chair is constructed out of foldable honeycomb cardboard and weighs 2.4 kg. It has a height of 800 mm, a width of 620 mmm, and a depth of 530 mm. It has dimensions of 1335 by 1180 by 10 mm when it is disassembled.
 Flat Stanley Origami Chair(Mellor, n.d.)	The Flat Stanley Origami Chair got its name from a children's novel with the same name about a boy named Stanley who gets squashed flat when a corkboard falls on him. The folding geometry problem was solved by making prototypes. After creating rabbit joints for the canvas to be sunk into in order to provide folding between panels, vinyl coating sheets were applied over the top.

Table 4 discusses origami-influenced artwork and consumer goods, demonstrating the plasticity and adaptability of folding structures. Among these patterns are a movable shelter that can be folded into many shapes thanks to its triangular construction, as described in the ParaPli language. Siesta Origami is a microarchitecture consisting of folded panels of corrugated polypropylene that can be used as a rug or a mattress. Origami Pavilion is a thin-shell folded building that can stand on its own, created from composite aluminum boards, showcasing the possibilities of architectural origami folding on a bigger scale. Ha-ori is a portable shelter manufactured from a single sheet of corrugated polypropylene that is foldable, lightweight, and robust; it takes its design cues from the hornbeam leaf. Origami-mi Kitchen is a space-saving modular kitchen that doesn't require any walls for support thanks to its metal tube structure and folding storage bins. Simply Fold is a lightweight and versatile room divider that can be used in a variety of contexts because to its modular design.

There are many unique ways to design a curtain, such as using magnets to keep it in place or folding it to make a geometric shape. The Miyo Lamp and matching wooden wall panels are origami-inspired, foldable, and adjustable light fixtures that provide both practical and aesthetically pleasing illumination. The Flux Chair is an eco-friendly piece of furniture that can be folded out of its huge envelope form and used as a chair. The Papton Chair and the Flat Stanley Origami Chair are two examples of foldable chairs that demonstrate the structural flexibility of honeycomb cardboard and vinyl-coated sheets, respectively. The folding concepts and origami-inspired techniques used in these designs allow for the creation of lightweight, versatile, and visually beautiful objects.

5. Conclusions

In conclusion, the enormous potential for future development in this domain is demonstrated by the origami-inspired designs and products discussed in the preceding paragraph. Folding structures present intriguing possibilities in a wide range of fields, from architecture and furniture to shelter and lighting design, thanks to their portability, flexibility, and adaptation. Folding concepts and techniques from origami can be further explored and refined in future work to produce novel and environmentally friendly solutions. In order to improve the stability, longevity, and beauty of folding structures, new materials and fabrication techniques may need to be developed. Research can also be done to enhance the practicality and efficiency of designs inspired by origami. The goal is to maximize space efficiency, simplify assembly and disassembly, and enrich the user's overall experience, all of which may need exploring new folding patterns and combinations. The frontiers of origami-inspired designs can be expanded through the combined efforts of architects, designers, engineers, and material scientists. By pooling their resources, they may innovate cutting-edge computational design tools, simulation models, and fabrication methods for making complex and efficient folding structures. Origami-inspired designs that include technology, including smart materials and sensors, may potentially lead to unexpected discoveries. This has the potential to lead to self-assembling or adjusting structures with improved functioning and comfort that dynamically respond to

environmental circumstances. The future of origami-inspired design holds enormous potential for developing novel, environmentally friendly, and malleable answers in a wide range of fields. The entire potential and useful applications of folding structures can only be realized through exploration and experimentation with different origami designs.

"Stay folded, Stay origami" - Author

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Conflict of Interests
The authors declare no conflict of interest.

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