Abstract. Folding strategies in architecture have been explored since the 1990s — if not before — as a method to generate spatial and structural concepts by applying complex geometries. These strategies are generally related to an analogue working method that involves paper folded models rather than digital form finding processes. Against this background the paper focuses on the impact and possibilities of folding principles from origami for the digital design process in using parametric software to generate integral and adaptive systems within an experimental and intuitive design approach.

1. Introduction

Origami (from ori meaning "folding", and kami meaning "paper") has evolved over the centuries from a traditional Japanese folk art to a design strategy for contemporary architecture and products. In traditional origami, the folding sequences and titles are passed down as something anonymous, not as something made up by a specific person. Modern origami, which started in 20th century, is based on the completely different paradigm. The folding sequences of modern origami are regarded as "models" "designed" by "origami creators." One of the most influential origami artists and theorists of or time is US-American physicist Robert J. Lang. He has not only contributed many publications on folding strategies but also made great advances in making real-world applications of origami to engineering problems.

The basic origami folds include valley and mountain folds, pleats, reverse folds, squash folds, and sinks. The number of basic folds is small, but they can be combined in a variety of ways to make intricate designs. The
miura fold is one type of a flat fold rigid origami model, which consists of a combination of basic folds and has a strong resistance in one direction and a weak resistance in the other (Figure 1).

Since the art of paper folding is strongly related to geometric principles origami has received a considerable amount of mathematical study. The knowledge of geometric rules is at the same time an essential condition for the development of architecture in the design as well as in the realization process. Starting from the initial form finding, geometry guides the project through the optimization of the shape, the implementation of parameters regarding manufacturing and assembling circumstances in the realization process.

2. Folding in Architecture

The process of folding a two-dimensional surface into a three-dimensional, sculptural object involves three important aspects for the architectural design, production and performance. First of all, folding paper represents a classical design technique to build geometric models, which can be seen as an extension of dimensions from the two-dimensional sketching to a three-dimensional modeling. In that respect folding as a generative process in architectural design is highly experimental, non-linear and process-orientated. Its spatial, structural and organizational diagrams give insight into new possibilities of unexpected outcomes. Secondly folding is an effective and material-efficient production process, which results in a structural model that can support itself due to the stability of its folds and can as well be unfolded to enable the production of single parts from flat panels for the intended building or product in scale 1:1. The third and for our research most important aspect is the adaptability of the folded model. Most of the origami techniques, like miura-, tesselation- or waterbomb-
folds allow a kinetic transformation of the overall shape, while maintaining a general stability of the model. These spatial patterns can be seen as physical parametric models that react on external forces and conditions with internal modifications to achieve the best possible balance of form, structure and material.

In that respect the morphogenetic process of folding results in a highly adaptive and performative design model that provides a high degree of freedom for the designer. Architectural concepts that take into account the parameters of construction and manufacturing as well as the spatial qualities of these folding strategies are often based on a highly integral approach as shown in the project for the Yokohama terminal by Foreign Office Architects from 2002 (Figure 2).

![Figure 2. Paper folded model (left) and roof structure (right) of the Yokohama Terminal by Foreign Office Architects.](image)

3. Case Study Origamics

3.1 METHODOLOGY AND PROCESS

Against this background the case study „Origamics“ was set-up with the aim to generate a digital design model that is based on the paper-folding techniques in Origami and to make use of its integral capacity to connect complex spatial ideas with traceable structural concepts. In the first step several folding techniques were analyzed regarding their geometric and performative properties, relations and abilities of transformation. Before entering the digital modeling process a series of experimental folding strategies were tested in an analogue mode to generate spatial concepts.

Based on the expertise, taken from the physical models, the different principles were translated into a digital parametric model using a graphical algorithm editor (Grasshopper) that is linked to a 3D-modeling software (Rhinoceros) to represent the result geometrically. In order to test the ability
of the so generated digital design tool within the academic project, the students were asked to design architectural spaces that can adapt to changing external conditions - using the origami-based, parametric design tools.

Starting from a 2D- to 3D-approach in the physical modeling the process in the digital model generation was initiated as well by geometrical principles but resulted instantaneous in a three-dimensional method of working. After finishing the parametric model the digital geometry was again transferred to a physical model by developing the triangulated surfaces to two-dimensional patterns. As a consequent mimicry of the origami principles the digital models were unfolded at the end of the design process and then rebuilt from paper again as a physical model.

3.2 TOWARDS AN ADAPTIVE ARCHITECTURE

The ability of paper folded models to adapt to external and internal forces by changing its shape and still maintaining a geometrical principle inspired the design for an adaptive wall system by Philipp Meise within the case study. Based on a hexagonal prism he developed a module that is able to change its opening percentage in relation to a rotation shift of the upper and lower end of the constricted prism (Figure 3). The model allows for a gradual transformation in between $0^\circ$ and $120^\circ$ by changing its height at the same time. A rotational angle of $0^\circ$ results in a maximum opening percentage and a maximum height of the module while a $120^\circ$ rotation reduces the opening percentage and the height of the prism to a minimum value.

![Figure 3. Hexagonal module for an adaptive wall system by Philipp Meise.](image)
The principle was developed in the further process towards an adaptive wall system that is able to react on changing sun loads. The wall is supposed to operate as a sunscreen by reacting on changing condition with a transformation of the opening-percentage of the module. After setting up a sun radiation model in Rhinoceros the geometry of the wall was linked to the so defined external loads, using Grashopper as a visual programming. The interconnections of the sun radiation with the wall surface were represented by affecting points on the wall geometry and the resulting color representation was again defined as a parameter in Grashopper. The sun load defined the wall thickness by generating an outer and inner layer. Both sides of the wall then were tessellated by using a hexagonal grid that allowed for an integrative connection referring to the geometric principle of the hexagonal module described before.

Figure 4. Sunlight system (left) and Grasshopper model of the adaptive wall by Philipp Meise

Figure 5. Visualization of the adaptive wall system by Philipp Meise.
4. Conclusion

The case study proved to be a good exercise for understanding geometric principles and the benefits of an integral design process. Furthermore approaching the design from a folding strategy that relates to origami showed similarities as well as differences between an analogue (2D to 3D) and a digital process (3D to 2D). Finally one can state that the programmed logic in Grasshopper proved to be a flexible and intuitive tool for the generation of adaptive design models that take into account aspects of the design as well as functionality and methods of production.

Folded structures can surely be identified as effective and performative systems, since they allow for material-efficient and adaptive solutions for complex design problems. Furthermore folding strategies that take into account structural principles and material properties create a sustainable architecture due to a highly integral approach, both in the result as well as in the design process. An adaptive architecture, based on these aspects, could react on changing external (e.g. climate related) and internal (e.g. user related) demands - similar to natural structures - as shown in the case study. Moreover it could replace fixed and immobile buildings and contribute to a more flexible, human-centered and sustainable spatial surrounding.

5. Outlook

Future research will focus, next to the programming of more geometric dependencies, on aspects of material properties and structural principles within this origami-inspired approach. Another question involves the translation of digital adaptive transformations to physical implication by developing concepts for the implementation of reactive and interactive computational technologies in our physical environment, e.g. within kinetic wall systems or media facades.

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References


