THAT WHICH TENDS TO INCREASE

Architectural Application of Auxetic Systems

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Abstract

Materials and structures that have negative Poisson’s ratio are called auxetics. This means that when they grow in one direction they also grow in the other. Contrary to for example a rubber band which gets thinner as it is stretched, an auxetic material gets thicker as it is stretched. The properties that systems with negative Poisson’s ratio offer are numerous, where opportunities related to deployable, adaptive and kinetic concepts are prominent.

This thesis investigates and develops auxetic systems in an aim to bring the concept closer towards application. A specific linkage of triangles works as a base for the research where phenomena are identified in simulation, recreated in physical models and vice versa, creating a design loop. This informs the evolution of the system both in relation to physical conditions such as friction and material strength as well as mathematical definitions and computational form finding possibilities.

As a flat configuration, the system is developed into an expandable panel where focus is put on coverage and joints. The multidimensional growth in combination with principles for layering has resulted in an adaptive system with possible application as sun shading and facade panelling. The internal movement within the system also creates a unique expression as the panel expands, which offers visual architectural qualities.

The auxetic system is also researched as deployable shells. Here, focus is put on three different deployment procedures; inflation, catenary form through hanging and minimal surface shapes through stretching. These all define their unique possible surface families and a form finding process is proposed for each of them. The process creates a specific 2D linkage of uniquely sized triangles which make up the encoded form.

The outcome of this thesis is not a traditional architectural project, but rather a collection of knowledge and proposals on how auxetics can be applied with its properties utilized.

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Student Background

Chalmers University of Technology, Gothenburg | Sept 2018 - Present
MSc in Architecture in studio Matter, Space, Structure.

Advances in Architectural Geometry, Gothenburg | Sept 2018
Workshop participant in "Design and fabrication of bending-active structures" and part of the organizing team.

Buro Happold Engineering, Bath | July 2018 - Aug 2018
Computational engineer, supporting team with parametric modelling.

Delft University of Technology, Delft | Aug 2017 - July 2018
Erasmus exchange year at the TU Delft in studios Hyperbody and MEGA.

Buro Happold Engineering, Bath | July 2016 - Aug 2017
Internship focused on parametric design, analysis and data driven modelling.

Smart Geometry, Gothenburg | 2016 April
Cluster participant in the MARS cluster in collaboration with Foster and Partners.

Chalmers University of Technology, Gothenburg | Aug 2013 - June 2016
BSc in Architecture and Engineering. Including theories, methods and tools from both architecture and engineering.

INTRODUCTION

Purpose

The properties that auxetic systems have are unique, both in terms of folding and expansion of area but also as kinetic movement. This thesis explores these properties in relation to architectural value and what might be required to take these concepts to physical application.

Objectives

The main objective of this project is the development and investigation of opportunities that are offered by a specific auxetic system. Proof of concepts support the findings both in computational simulation and physical modelling. The system is also investigated with both two and three-dimensional applications in mind.

Background

Advances in Architectural Geometry is a multidisciplinary conference involving a wide range of practices such as architects, engineers and computer scientists. The focus is on theoretical and practical development of geometry, mainly within the building industry. During the presentation of one of the papers at the conference, a quite simple question was asked.

» Have you researched how to transport or pack the structures that you are suggesting?

The specific question was not necessarily interesting but the fact that the question could not be answered sparked an idea. Concepts at the forefront of architectural geometry rarely make it to the practical built environment. They are simply not developed to enough detail and the benefits of doing so are often too few. Therefore, they stay within the computational simulation as an ideal.

What if one of them for once could find a place in the built and become more than just a pavilion. It would have to be in such a way that the inherited properties of the geometric genius within the system could be utilised. Otherwise it would be doomed a gimmick.

Method

The work is a combination of computational simulation and physical modelling. Extra focus is put on representation to be able to explain the inherited complexity for an inexperienced audience.

Phenomena have been identified computationally and then recreated physically and vice versa, creating a design loop. This informs the evolution of the system both in relation to physical conditions such as friction and material strength as well as mathematical definitions and computational form finding possibilities.

Theory

The paper "Computational Design of Deployable Auxetic Shells" and the auxetic properties presented during the AAG conference in Gothenburg (Konaković-Luković et al, 2018) has been a stepping stone into the subject of auxetics. The paper has offered insights into the fundamentals of the auxetic system that this thesis is based on. It has also been used as an inspiration for the 3D computational design scripts that have been set up.

Reference projects that apply kinetic façades have been used as inspiration for the panel system developed in the thesis. Deployable shell structures have informed about deployment concepts and physical applications.

Delimitations

This thesis focuses on a specific auxetic system of triangles and only on that system. No other systems are considered. The work is also carried out with the widening of architectural opportunities in mind but not towards a specific architectural application or program. This means that the timespan of the thesis defines how far the system is developed.

Reading Instructions

Kagome	= A pattern of triangles and hexagons.
Poisson's ratio	= The relation between compression and expansion.
Auxetic	= Materials and structures with positive Poisson's ratio.
Deployable structure	= A structure that can significantly change its size.
Boundary	= The limits of an area.
Computer simulation	= Reproduction of the behaviour of a system.
Kinetic	= Motion of material bodies.

FUNDAMENTALS

Introduction to auxetics

Poisson's Ratio

The phenomenon that a material tends to expand in the directions that are perpendicular to the direction of compression is expressed with Poisson's ratio. Conversely when a material is stretched it tends to shrink in the directions perpendicular to the expansion.

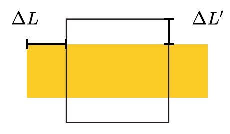
Definition

Mathematically the ratio is denoted from the Greek letter 'nu' which is written ν. To calculate ν at small expansions and compressions the transversal expansion is divided by the axial compression (**Fig. 1**).

Poisson's Ratio = ν

Thickness = $\Delta L'$

Length = ΔL



$$\nu \approx -\frac{\Delta L'}{\Delta L}$$

Figure 1: Mathematical definition of Poisson's ratio at small values.

Material examples

The properties described in the beginning of this chapter are the most common ones among materials. These properties allow for the volumes to remain the same, while the shapes change (**Fig. 2**). One can imagine a rubber band that is stretched and how it then naturally becomes thinner.

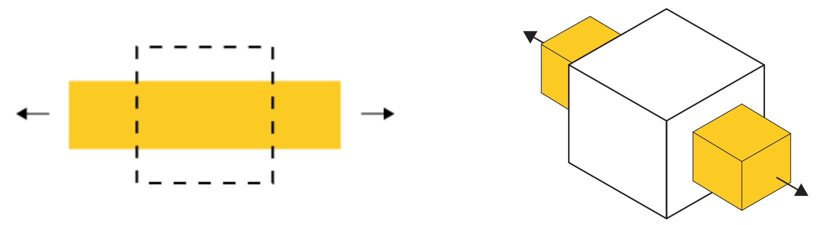


Figure 2: Behaviour of most common materials. Poisson's ratio is positive.

Some materials differ from this, as the relationship between stretching and shrinking does not occur. One of the more common ones is cork, which has a Poisson's ratio close to 0 (**Fig. 3**).

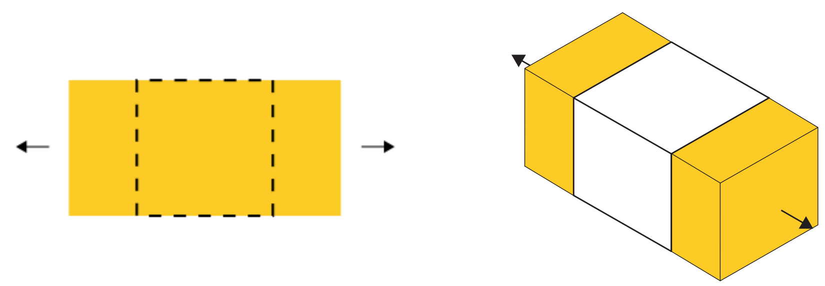


Figure 3: Behaviour of materials that have a Poisson's ratio close to 0.

Then there are those materials that expand perpendicularly to the direction they are stretched (**Fig. 4**). This is often a consequence of a specific internal structure and how that deforms. The materials and structures that have this unexpected property are called Auxetics which is derived from the Greek word auxetikos and translates to "That which tends to increase".

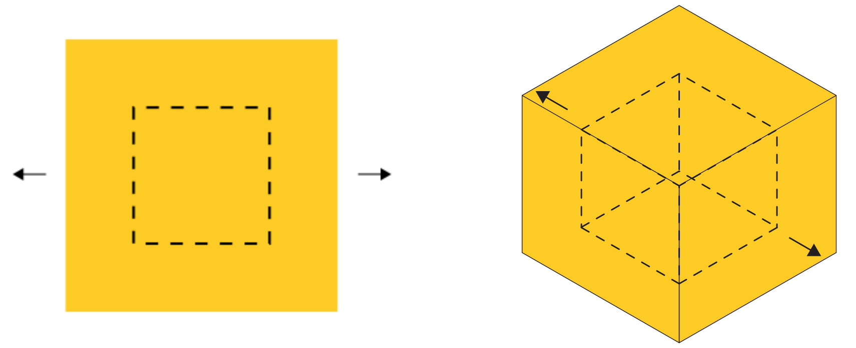


Figure 4: The expansion that happens when stretching auxetic materials. Negative Poisson's ratio.

The Auxetic System

This thesis is based on an auxetic system of triangles. They are organized in a kagome pattern and the system expands 2 dimensionally as the triangles rotate.

Rotation of triangles

Say a triangle is inscribed into a triangular boundary which holds a constant orientation. If the inscribed triangle rotates, the boundary will expand so that its sides constantly intersect with the corners of the inscribed triangle. At a rotation of 60° the corners of the inscribed triangle will pass the centres of the sides of the boundary and the boundary will start to shrink again. The scaling of the boundary will meet its maximum at an area 4 times as large as the area of the inscribed triangle (**Fig. 5**).

If the boundary is mirrored along one of its sides, a total of 5 times, a full hexagon will be created. Since the rotations are mirrored, a continuous connection between the inscribed triangles is established. The hexagons can be copied to achieve a kagome-like patterned sheet. This system can then expand its boundary by 400%, through the internal rotation of triangles.

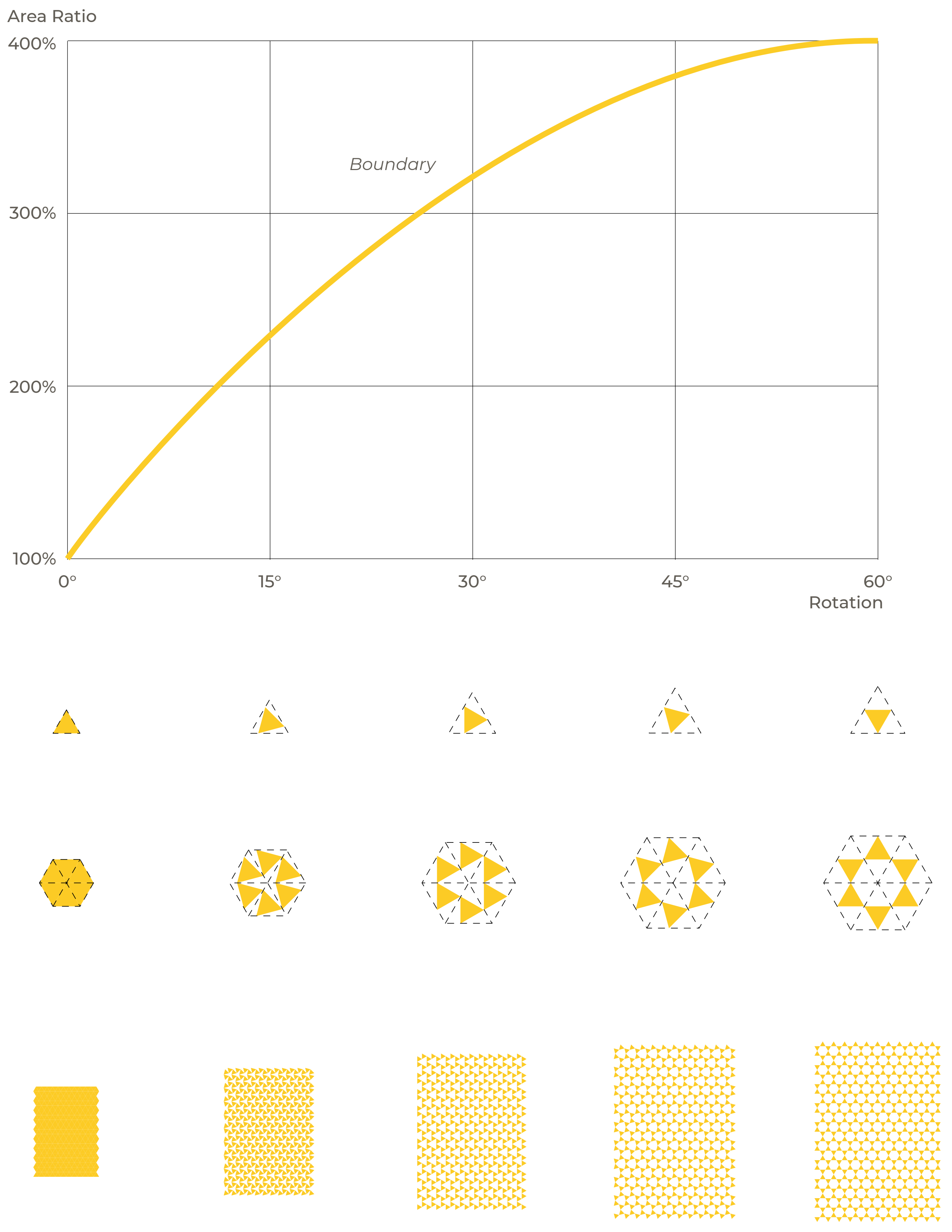


Figure 5: Mapping of the boundary expansion as the auxetic system grows. Illustrated as a single triangle, as a hexagon flower and as a full sheet.

2D RESEARCH

Development for flat systems

Understanding the Behaviour

The research was initiated by physical and computational simulations of the auxetic system. This helps in the mapping and understanding of the behaviour of the system which is crucial to be able to plan the process of development and which areas to focus on.

Computational simulation

The computer model was set up in Grasshopper which is a visual programming plug-in for Rhino 3D. It allows for a very flexible process where data easily can be examined and tracked. The programmatic work flow also forces the user to define the process mathematically which in turn gives a deeper understanding for the fundamental properties and dependencies within the system.

Relationships between rotation and scale and definitions of central scaling points had to be set up to be able to simulate the flat expansion. Initially the whole process was set up in such a way that the triangles were moving out from a central point and rotated so that the corners would intersect visually.

Additional properties

Since the model was set up in a geometric environment and because of the nature of the program, various properties could be tracked during expansion. This was helpful when identifying opportunities that might have been hard to imagine by just looking at the system (**Fig. 6**).

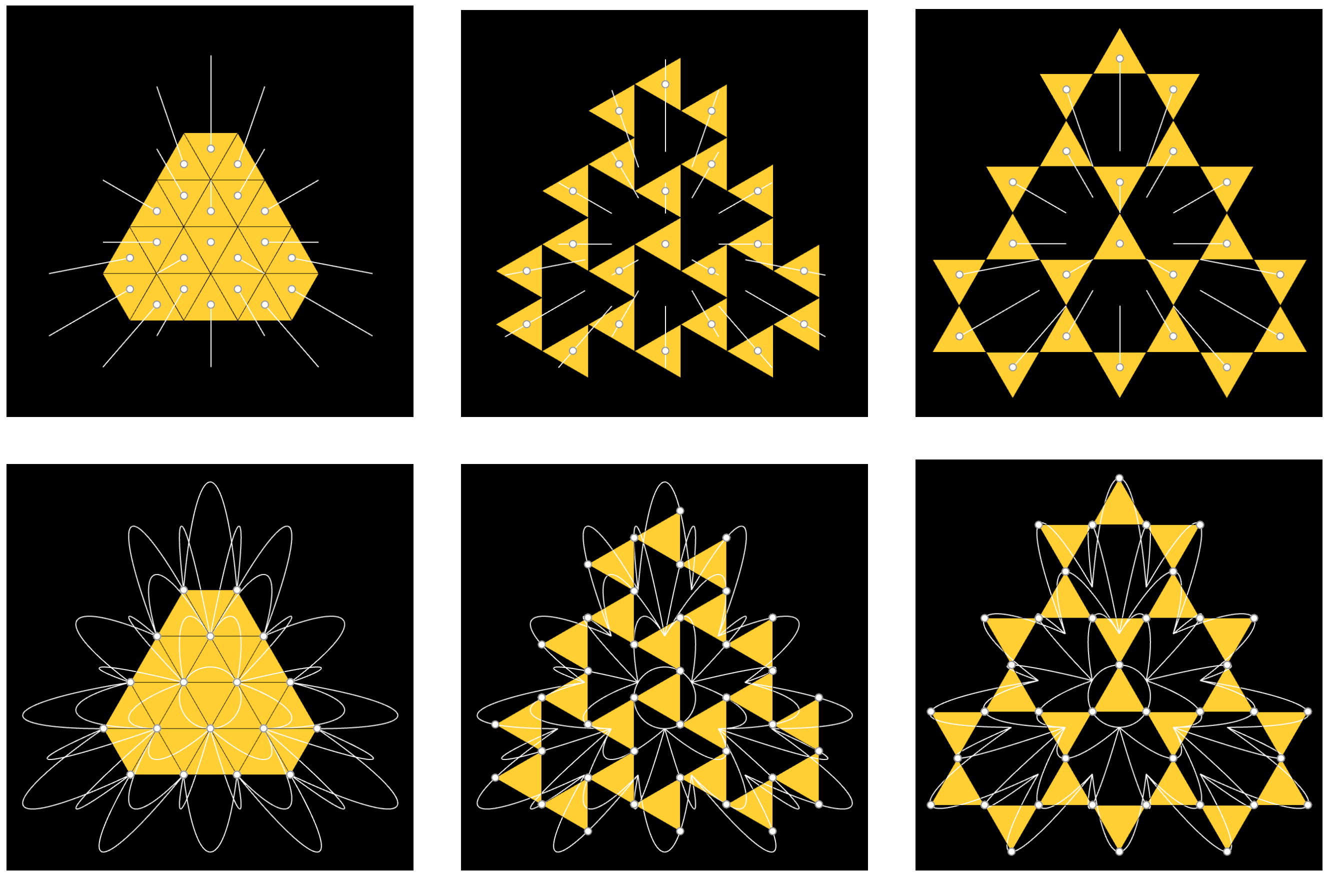


Figure 6: Tracking of nodes within the system during expansion. First centre point tracking which is affected by scale, then corner tracking which both rotate and scale.

Physical tests

The system was then tested in models (**Fig. 7**). This was done to understand how the behaviour could be controlled and guided and how the expansion could be initiated. It also gave an understanding in terms of friction and dependence within the system, where forces would concentrate and where they would not. A computer simulation can rarely inform within these aspects. The more complex the model the harder to imitate physical behaviour, especially with a system in motion like this.

The main outcome from this test was the understanding that expansion could not be initiated internally. To expand the system one has to stretch it by pulling the edges. Though internal dependencies suggest that expansion might be possible if every joint is forced simultaneously. Testing of this did not fit in the time frame.

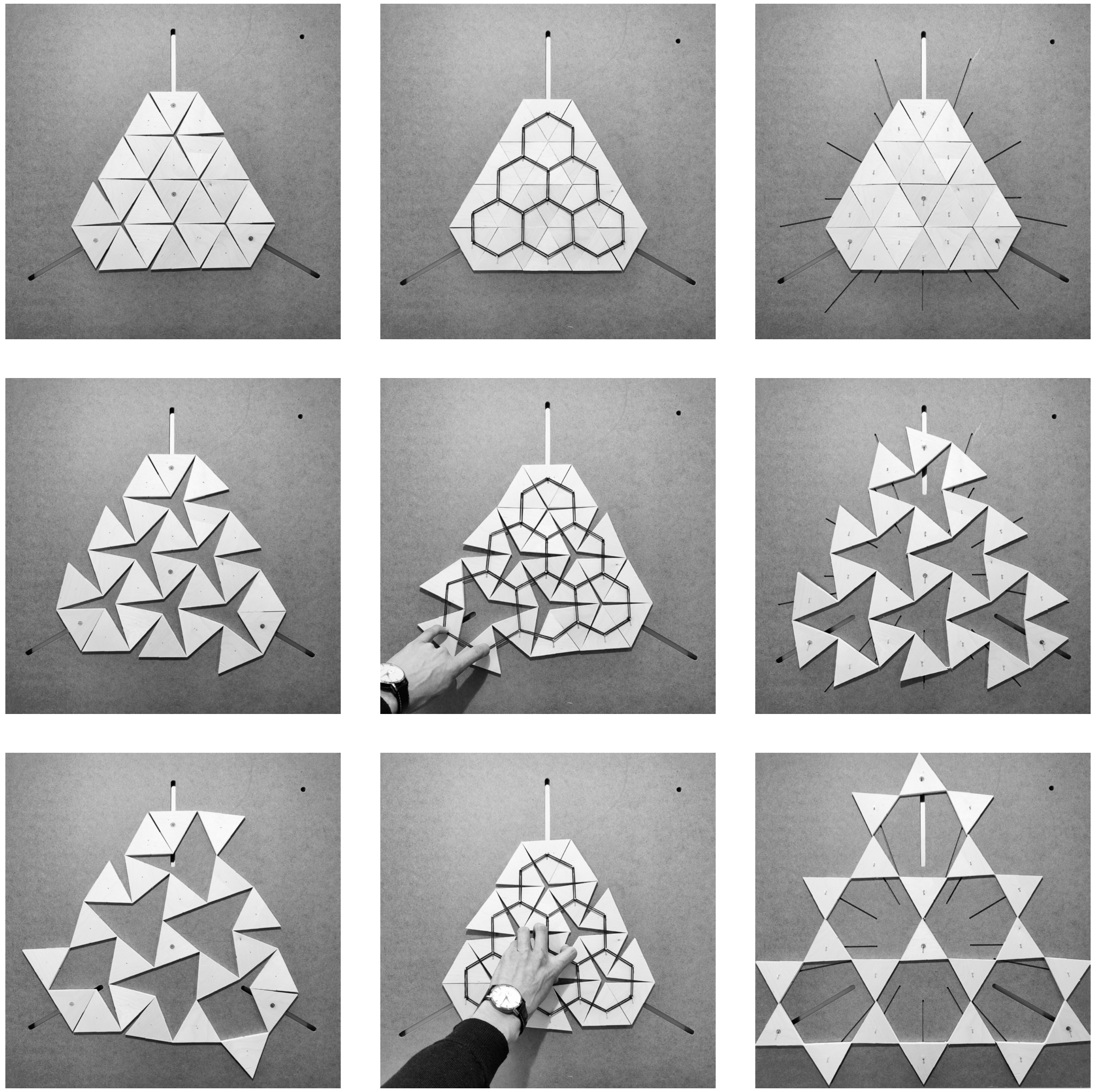


Figure 7: Development of a physical system. First with limited guidance, then with introduced tension and finally with total guidance of each triangle.

Allowing for Rotation

A crucial detail when taking the auxetic system closer to architectural application is the kinetic joint. Since the joint must allow for movement and be applied numerously throughout the system, it is the most challenging detail to design.

Fabric joint

The first test of a physical joint was made out of fabric (**Fig. 8**). By glueing fabric to each side of the triangles they could be connected while allowing movement in relation to each other. Since the corner of the triangles also met, the rotation ended up being almost around a single axis. This meant that they could be fully folded together and the rotation was somewhat controlled. The movement of the system was therefore also very similar to that of the computational simulation

But the sharpness of the triangle corners and the constant bending of the fabric proved negative to the durability. While also being under force from the system the joint could not live up to expectations.

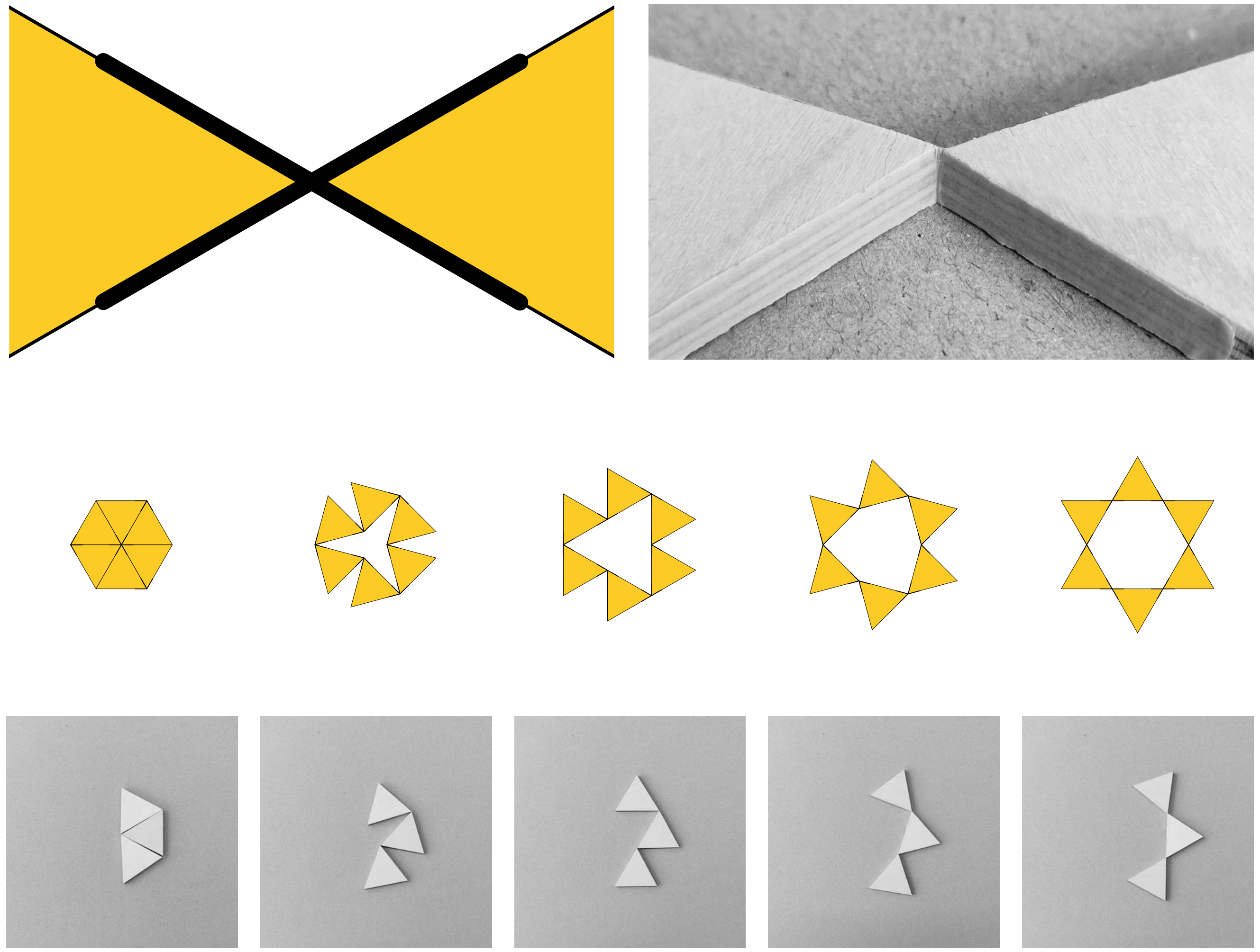


Figure 8: Testing of a kinetic joint in fabric. Built with plywood panels and tape to join them at corners.

Double action hinge

The double action hinge joint was tested to try and extend the durability of the system. It has an additional plate that sits in a gap and connects to an axis in the corner of each triangle (**Fig. 9**). This allows for a very flexible system with high durability since there is only rotation around an axis instead of constant bending as in the fabric model. This allowed for the use of more durable materials.

But the flexibility became an obstacle. The movements were difficult to control since the system now was rotating around two axes instead of one. It often lead to over rotation and the triangles would lock into each other. The axis in the triangle also had to be put with a margin to the edge which took the physical model further from the ideal computational simulation.

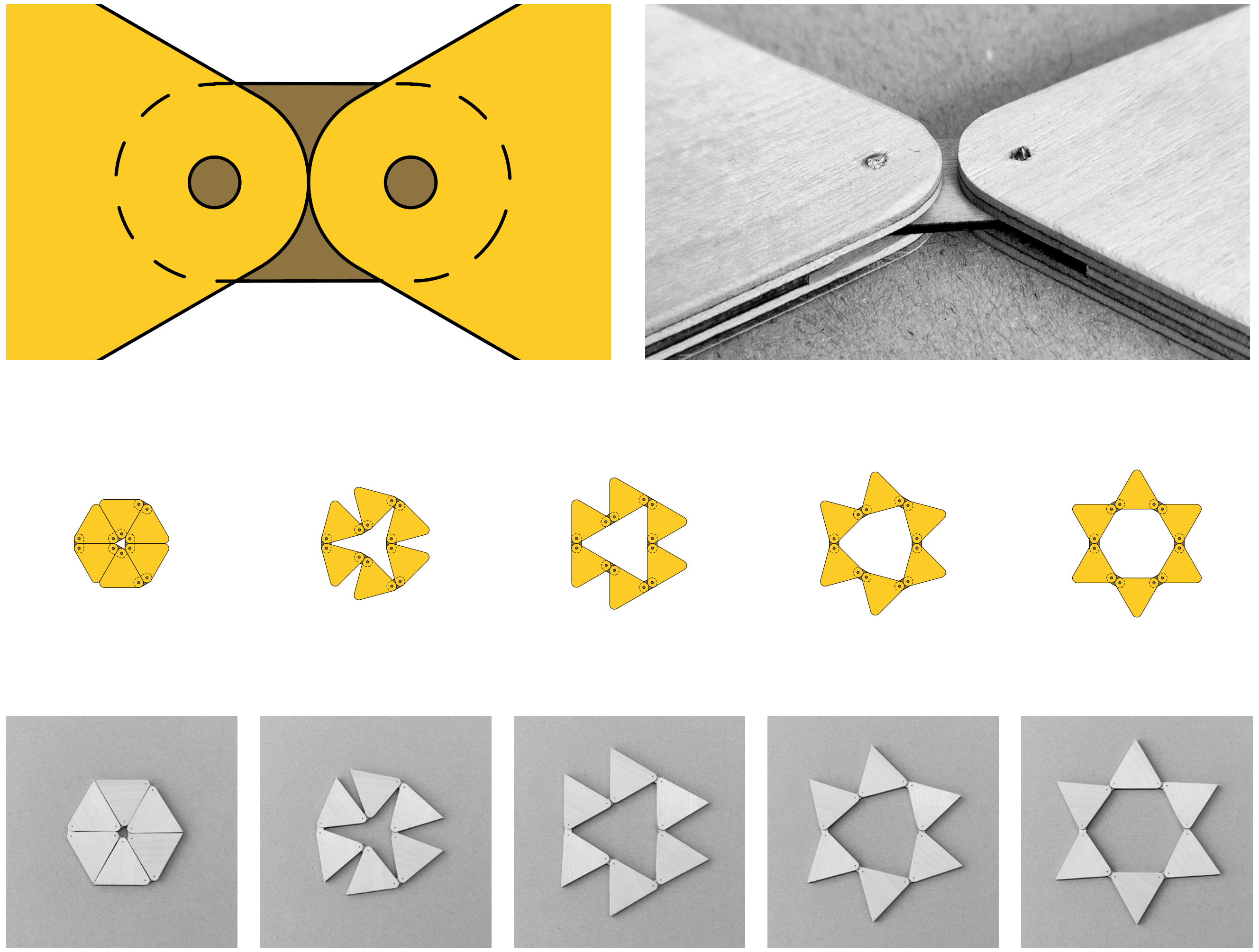


Figure 9: A very durable joint, designed as a double action hinge. A thin piece of high performance plywood sits in a gap and is connected to an axis in each panel.

Single action hinge

Learning from the two previous joint tests, the single action hinge combines the durability of the double action hinge with the controlled movement from the fabric joint. The triangular panels are put in two parallel layers where every other is placed underneath the neighbouring panels with a small overlap at each corner. The overlap then holds a steel axis to allow for rotation (**Fig. 10**).

A rotational stop is put in place by adding a second smaller triangle that tangents the larger triangles at each corner. This helps to further control the movement and stops the triangles from over rotation. One of the negative aspects of this joint is that it loses part of the expansion range. The system can not fully fold together since the axis of rotation is not in the exact corner of the triangles. But it meets enough requirements and is therefore used in the later testing of the system.

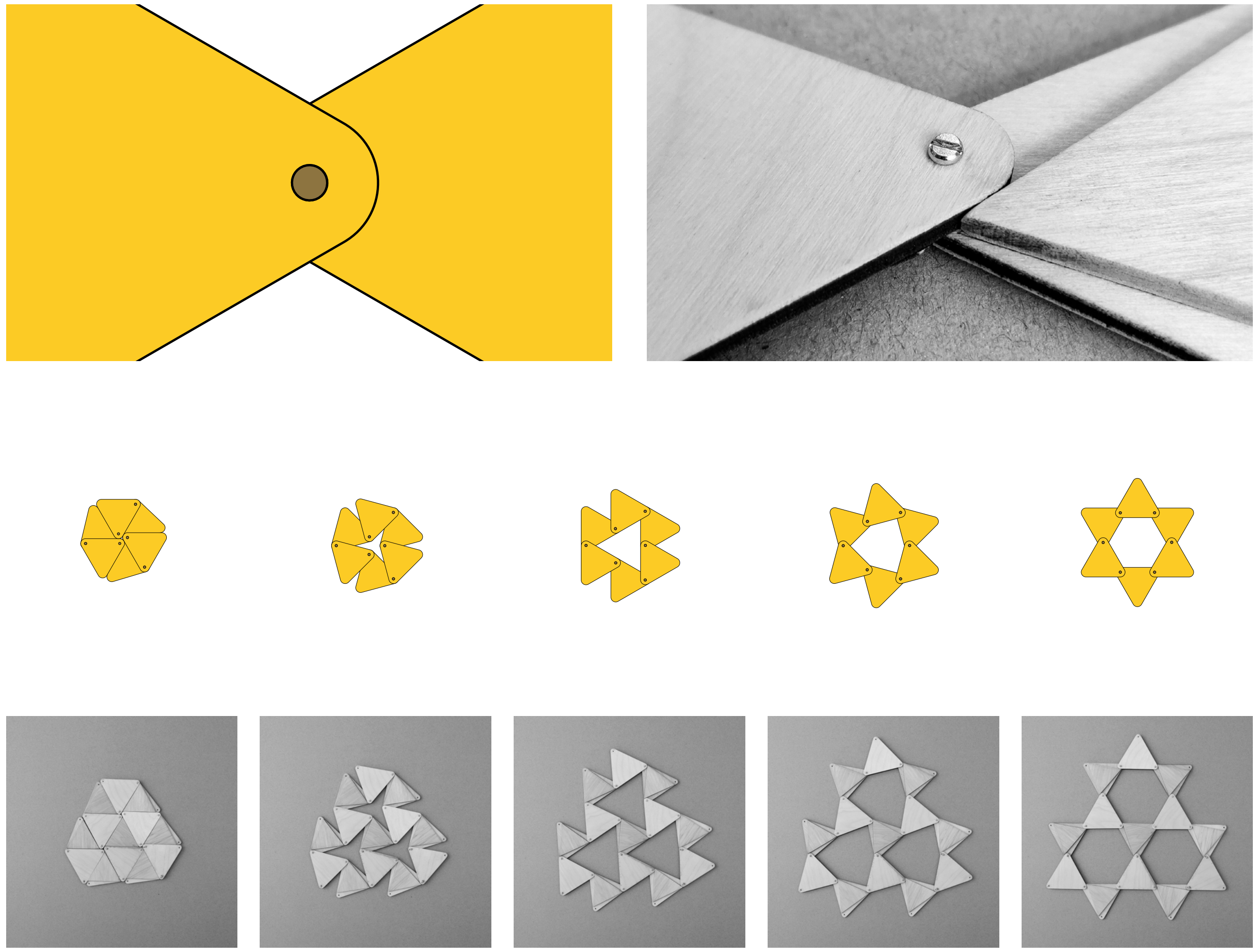


Figure 10: A joint where the triangles overlap to allow for a single axis hinge. Requires a thicker system since it is made of parallel layers but has a very controlled movement.

Covering the Surface

Only the boundary expands as the fundamental system folds out. The covering area still stays the same. Concepts for an extended coverage was therefore a crucial focus area. Something that adds complexity to the system but also extra value to the kinetic process.

Integrated panels

A concept of internal panels that only become visible as the system unfolds was tested initially. It gives an opportunity to introduce a new material at expansion which has an interesting visual value, similar to the unfolding of a butterfly (**Fig. 11**).

This system proved complex when trying to fully cover the surface at complete expansion since three layers of panels would have to move independently. The guidance of the internal panels also weakened the triangular panels significantly.

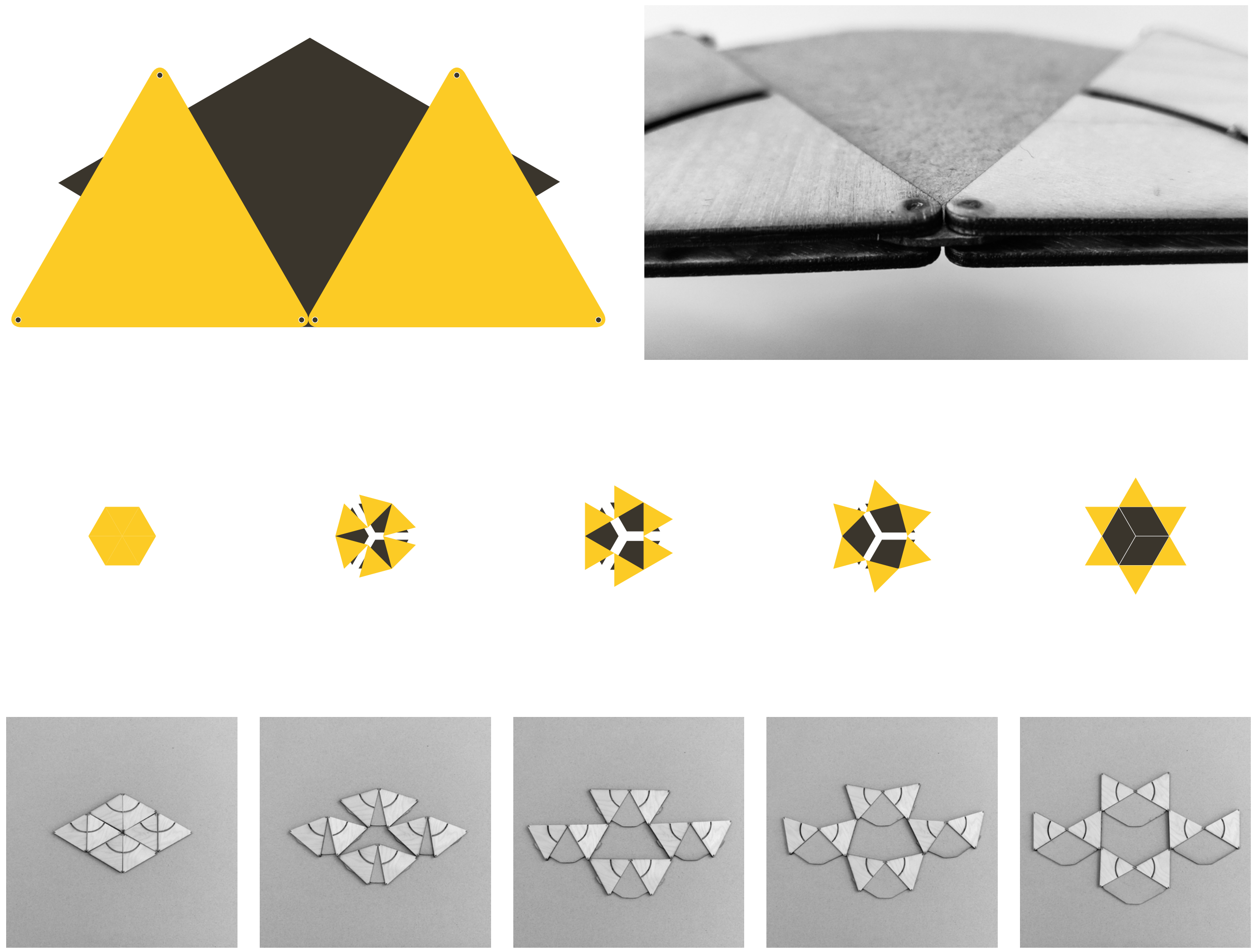


Figure 11: A model that examines the possibility to extend coverage through internal panels. Built out of two layers of plywood and an internal layer of cardboard.

Extended triangles

A model that avoided the extra independent panels from the previous concept was created by extending each triangle with an extra triangular panel on each side (**Fig. 12**). The central panel would then allow for the neighbouring panels to slide into gaps that were created through layering. This made it possible to fold the system together similarly to the way that the fundamental system works.

The system almost covers the surface but the extended triangles has to be chamfered to be able to pass the corner joints when they slide in which ultimately leaves a gap in the middle. There is also a large amount of friction between the panels which negatively affects the movement,

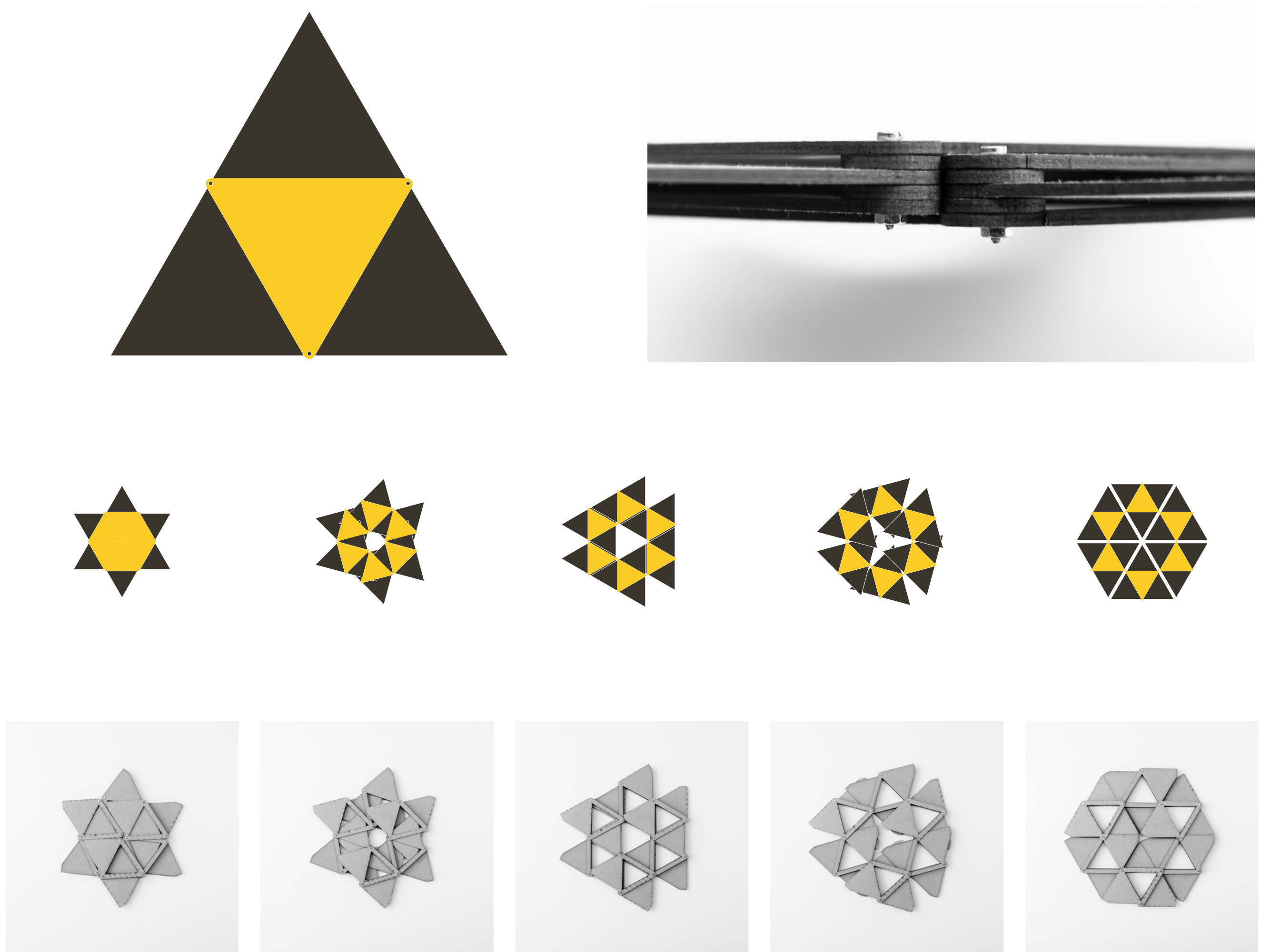


Figure 12: Full coverage achieved by extending the triangular panels on each side. Model built out of cardboard where the panels slide into each other.

Parallel Layers

The parallel layers concept is a combination of the learnings from the previous joint and layer investigations. But it further introduces a concept of inter-connected layers.

Shared paths

Four layers with individual scaling centres were simulated computationally to identify shared paths (**Fig. 13**). These paths can inform the design of connections between the layers while also giving an understanding of the system as a whole.

Each possible position for connection together with its coherent layers are mapped. The order of the layers are then decided so that intersections during the unfolding is avoided while all the layers can be connected (**Fig. 14**).

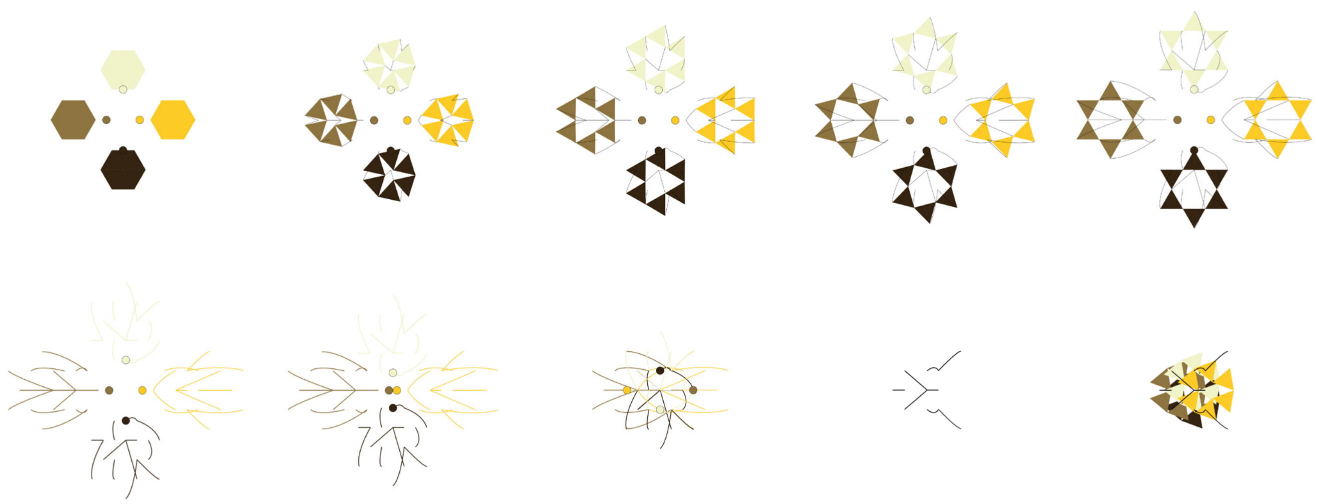


Figure 13: Steps in the computational simulation with expansion of parallel layers and partly offset scale centres. Overlay curves from the corner tracking to identify shared properties between the layers.

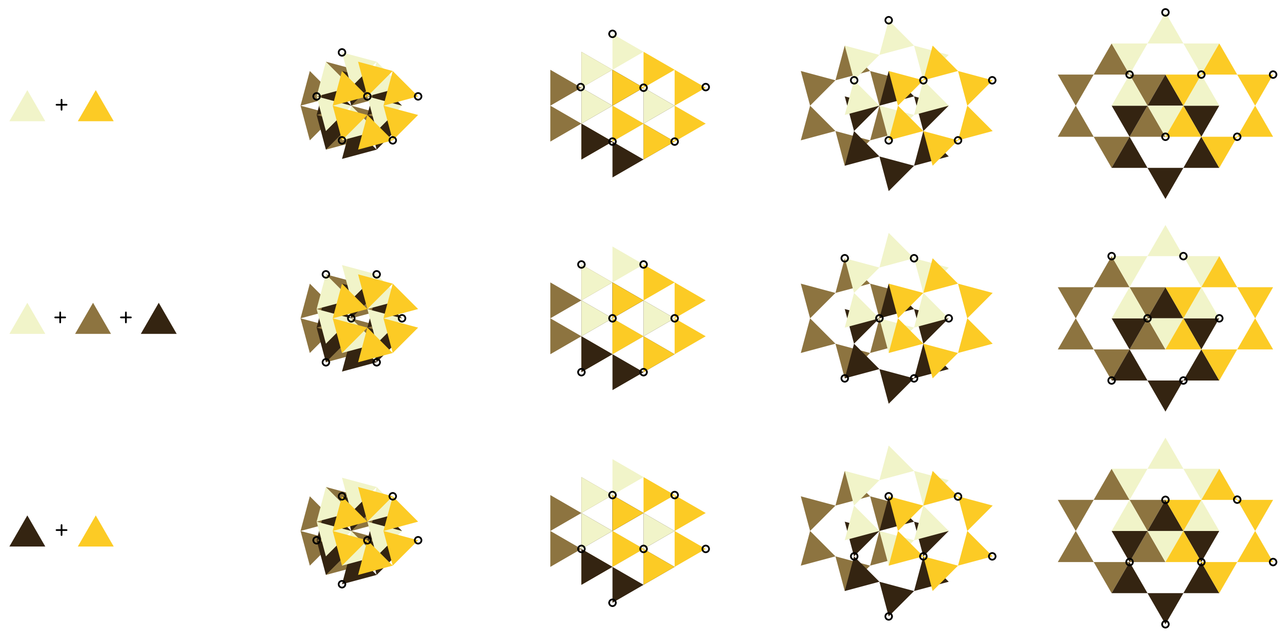


Figure 14: Corner tracking as the layers expand. Ideal points for connections between the layers.

Coverage

The coverage of the expanding surface is tracked to identify efficiency and opportunities within the system. Different amounts of coverage is achieved throughout the expansion as a consequence of layer alignment (**Fig. 15**).

The varying amount of coverage brings an opportunity to control the permeability. The system starts as a fully covered, four layers thick panel. When fully expanded it is 4 times the area of the initial and fully covered one, but only a single layer thick.

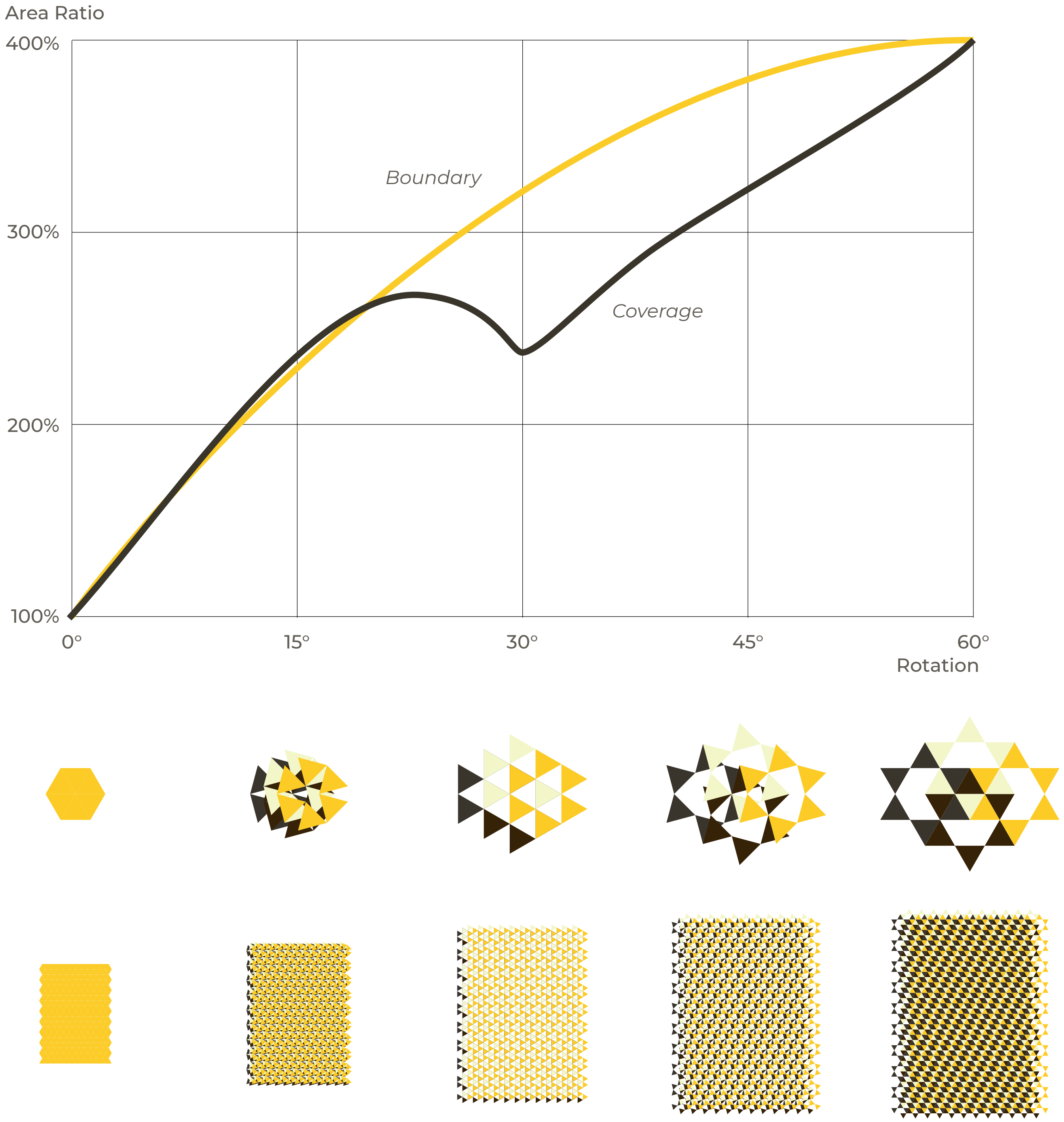


Figure 15: Diagram of coverage in relation to boundary with the parallel layer system. Illustrated as a single flower and as a rectangular panel.

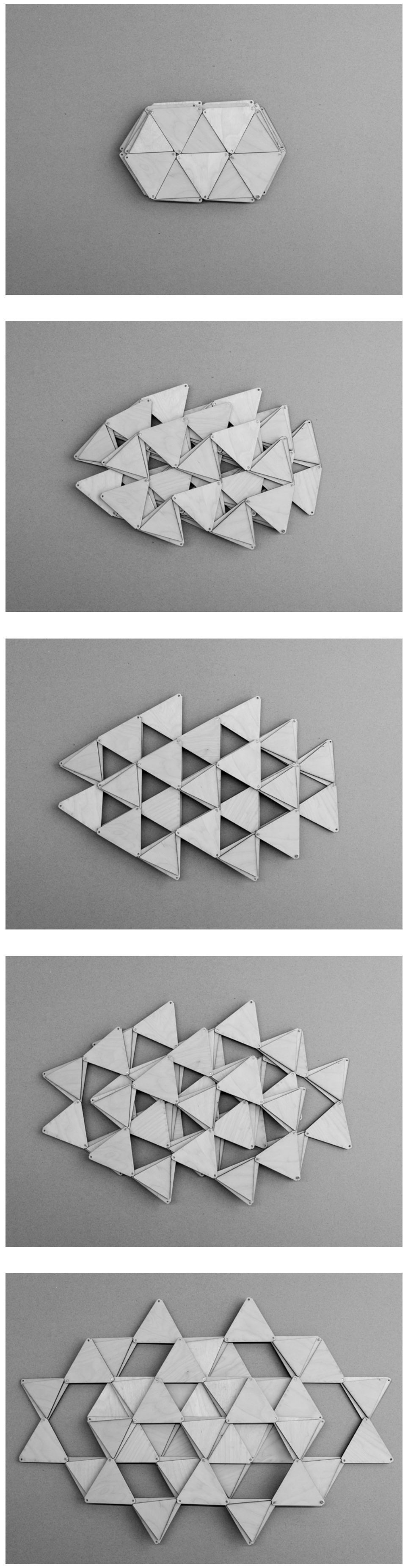


Figure 16: The expansion as the parallel layers model unfolds.

Physical test

The proof of concept for the parallel layers presented many challenges. But even though the expansion of this system looks very complex, the underlying rules are fairly simple (**Fig. 16**).

Produce a set of identical panels. Join them together while flipping every other panel so that the panels overlap to create a joint. Do this four times so that you have four identical layers. Expand them fully, put them on top of each other and then offset them individually two triangle widths in each orthogonal direction, up, down, left and right (**Fig. 17**). Then join the corresponding layers according to the outcome of the computational simulation by replacing the single layer pin with a longer multi layer pin.

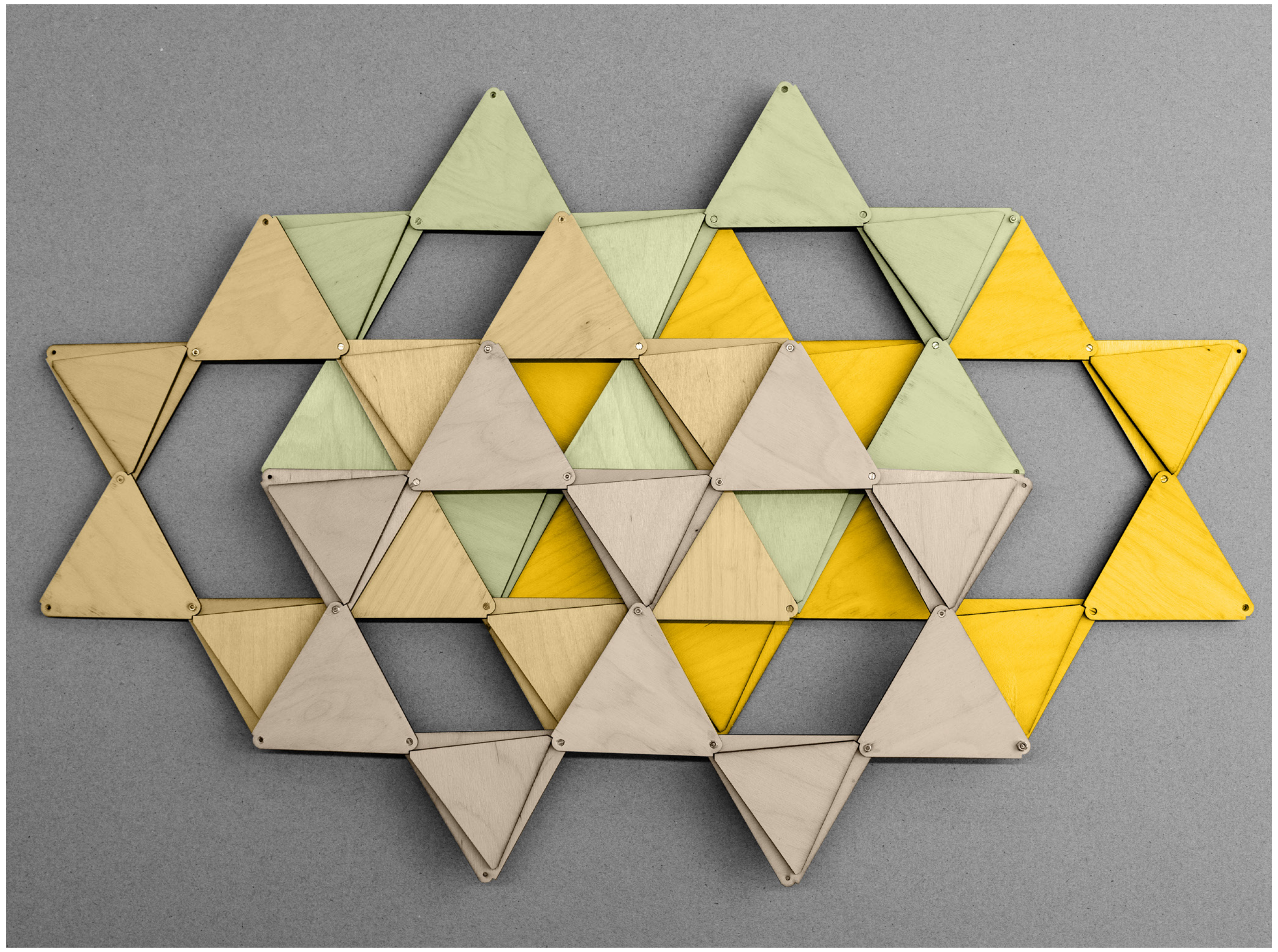


Figure 17: Proof of concept for a panel with the parallel layers. Built out of plywood and small bolts. Each layer visualised corresponding to the computational model.

2D APPLICATION

Utilization as flat systems

Reference Projects

One application of this suggested system is a sun shading panel. Similar projects with these kinetic systems and adaptive shading façades are explored.

Institut du monde arabe

The shading system of the Arabic institute is based on a shutter system similar to that of a camera. It can be manually controlled to change the buildings exposure to sunlight. The internal dependencies and the complexity has had its consequences and the system is difficult to maintain.

Al Bahr Towers

The Al Bahr Towers have an external sun shading system based on large triangular, panels that fold together. They react to the sunlight and lower the energy demands of the building while increasing comfort.

Louvre Abu Dhabi

The Louvre Abu Dhabi is not a kinetic system like the previous examples but it is a sunshading roof. What it does better than the previous examples is that the small rays of light that emerge form a pattern, making visitors appreciate the space more. A more dynamic space is created, where the position of the sun significantly impacts the sunlight inside.

Architectural Value

One of the values of this system is the visual complexity it generates while only being built from two different kind of parts.

Pattern

The surfaces go from being a fully covered into 50% open and then fully covered again. Throughout this whole unfolding, different repetitions and patterns in the system occur (**Fig. 18**). This has architectural value, not only functionally in the way that it lets the user control the amount of light that it lets through but also in the visual complexity and unique expression that the system has as it unfolds (**Fig. 19**).

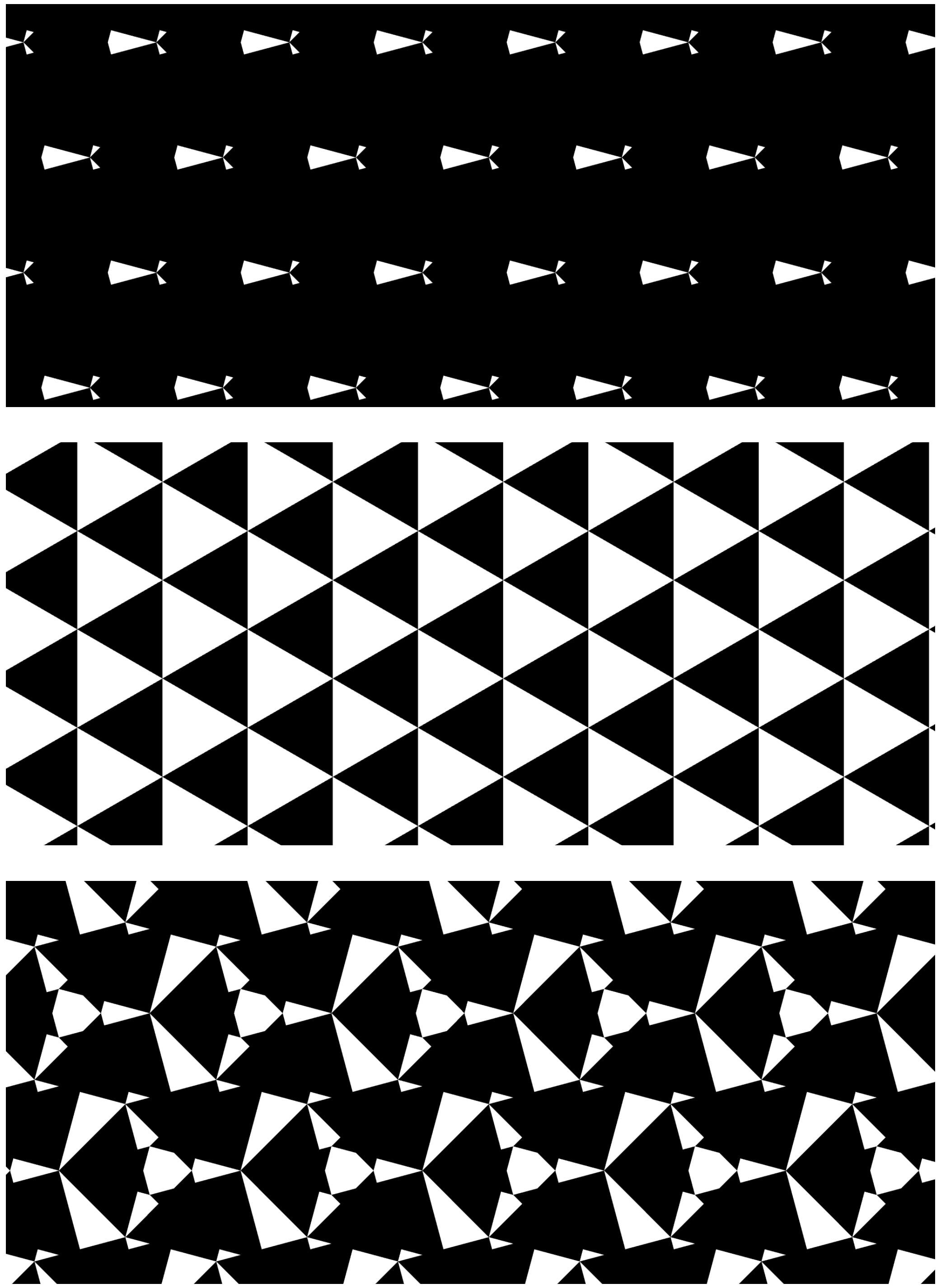


Figure 18: The 2 dimensional patterns that are generated as the system unfolds.

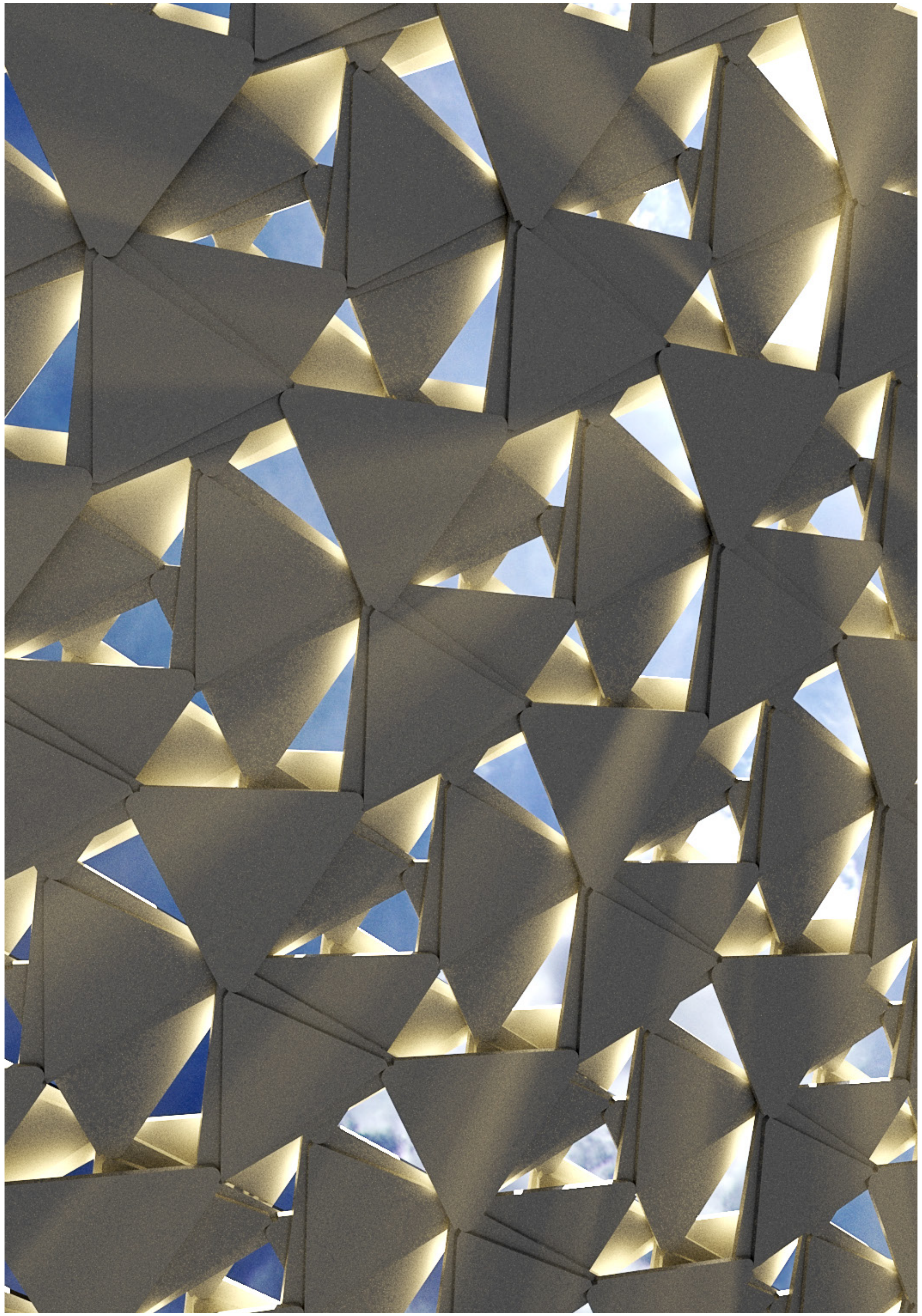


Figure 19: Simulation of light that shines through the system as it unfolds.

SPATIAL SYSTEMS

Principles for auxetics as envelopes

From Planar to Double Curved

The kagome pattern can make a curved surface if the triangles are scaled in relation to each other. The surface can then go from curved to flat through the internal folding.

Scaling of triangles

The triangles are gradually scaled in relation to each other. This creates a smooth curvature where the triangles together create a double curved surface. This organisation defines a very complex shape only through a specific combination of planar panels (**Fig. 20**).

The triangles become larger the further they are from the base plane. The curvature also increases in relation to the difference in scale between the triangles.

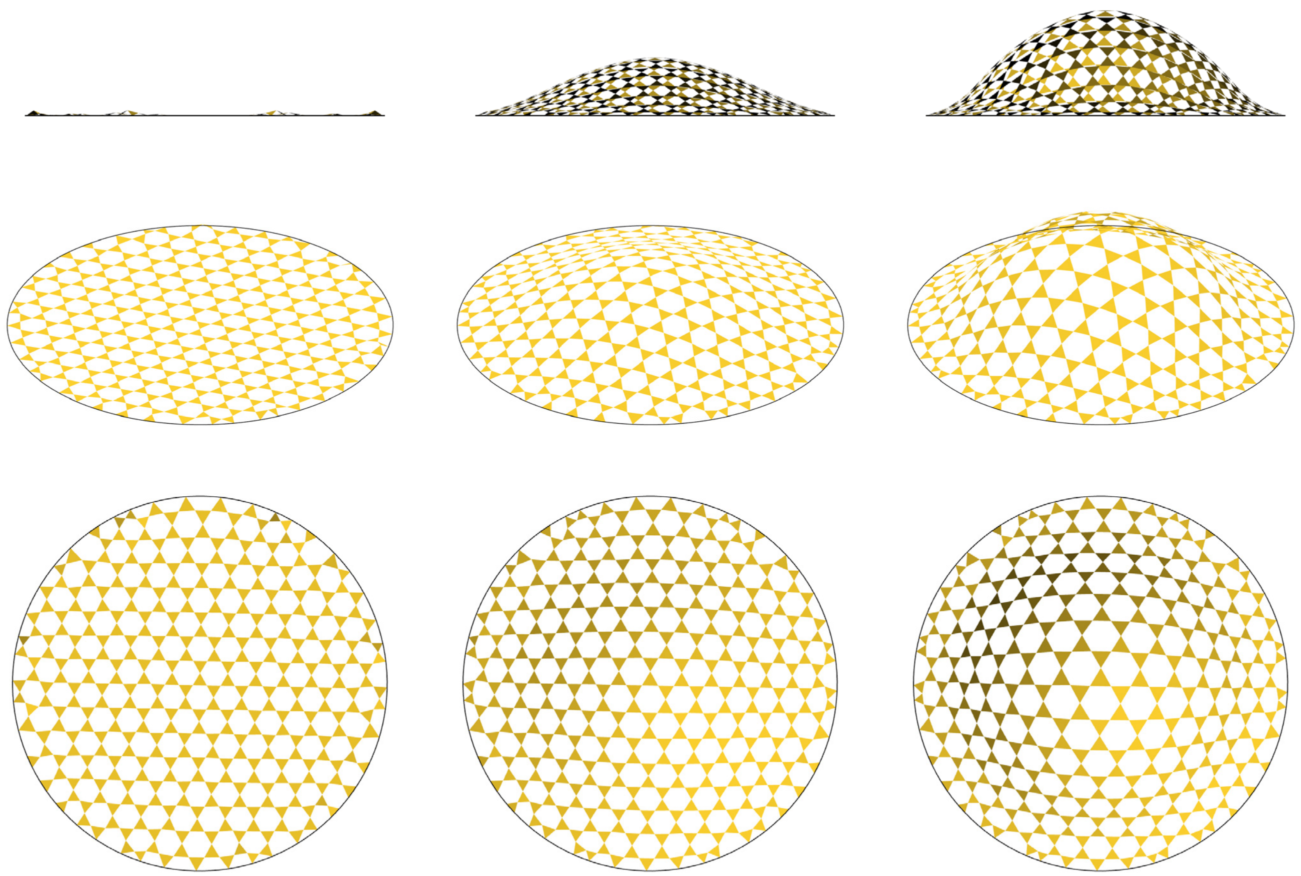


Figure 20: Gradually scaled triangles to increase curvature.

Folding the internal system

As the system folds together it goes from being a double curved surface into a flat one. Therefore making the overall area become smaller even though the boundary does not necessarily shrink (**Fig. 21**).

Design boundaries

The design of the double curved surface has to stay within certain triangle size imits. This is to make sure that it can become completely flat when folded together.

The hexagon which the smallest flower is inscribed in when flat has to also be able to hold the largest flower. This means that the area of the largest triangle can't be more than 4 times as big as the area of the smallest triangle within the same system (**Fig. 22**).

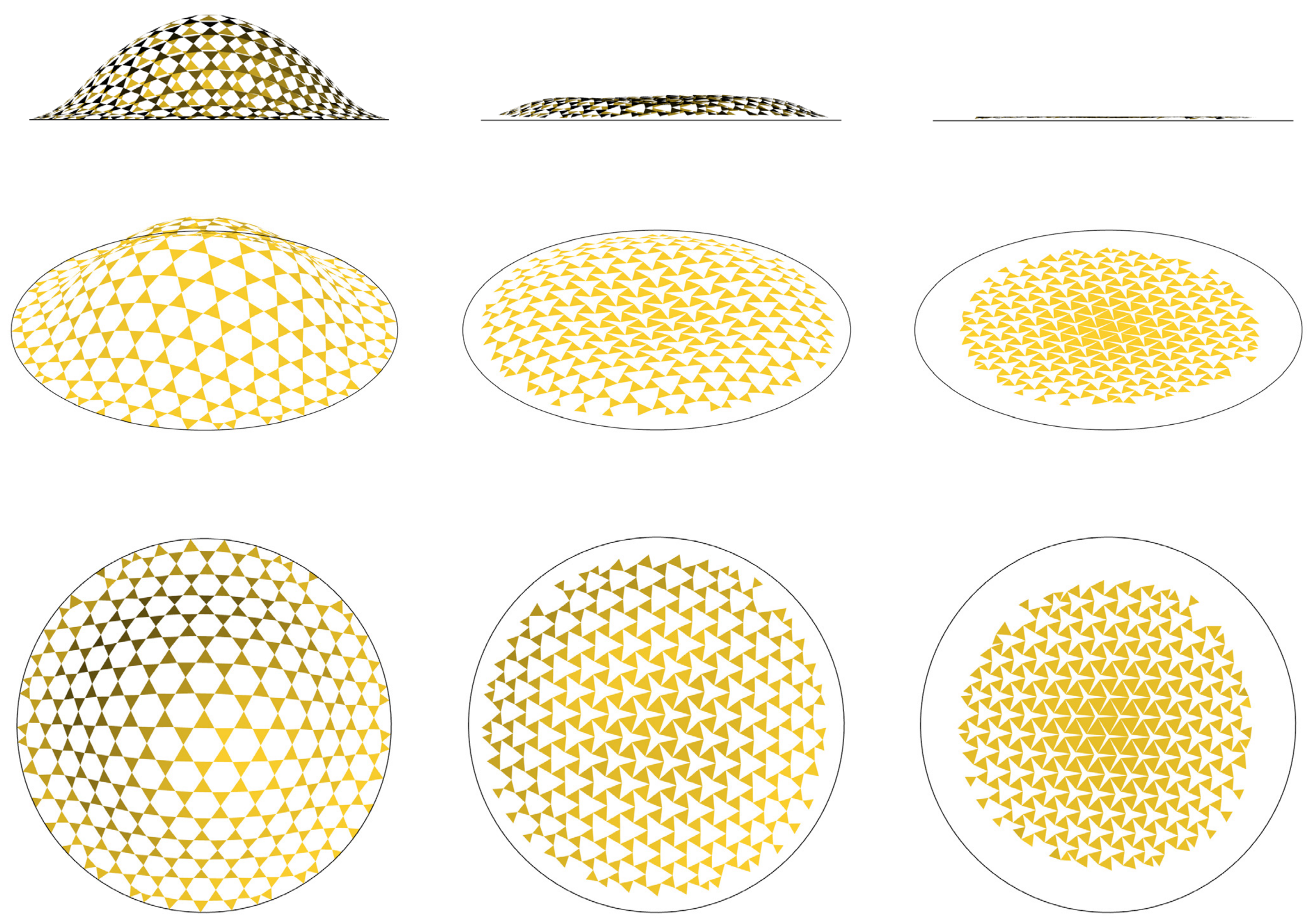


Figure 21: Folding of spatial system from double curved to flat.

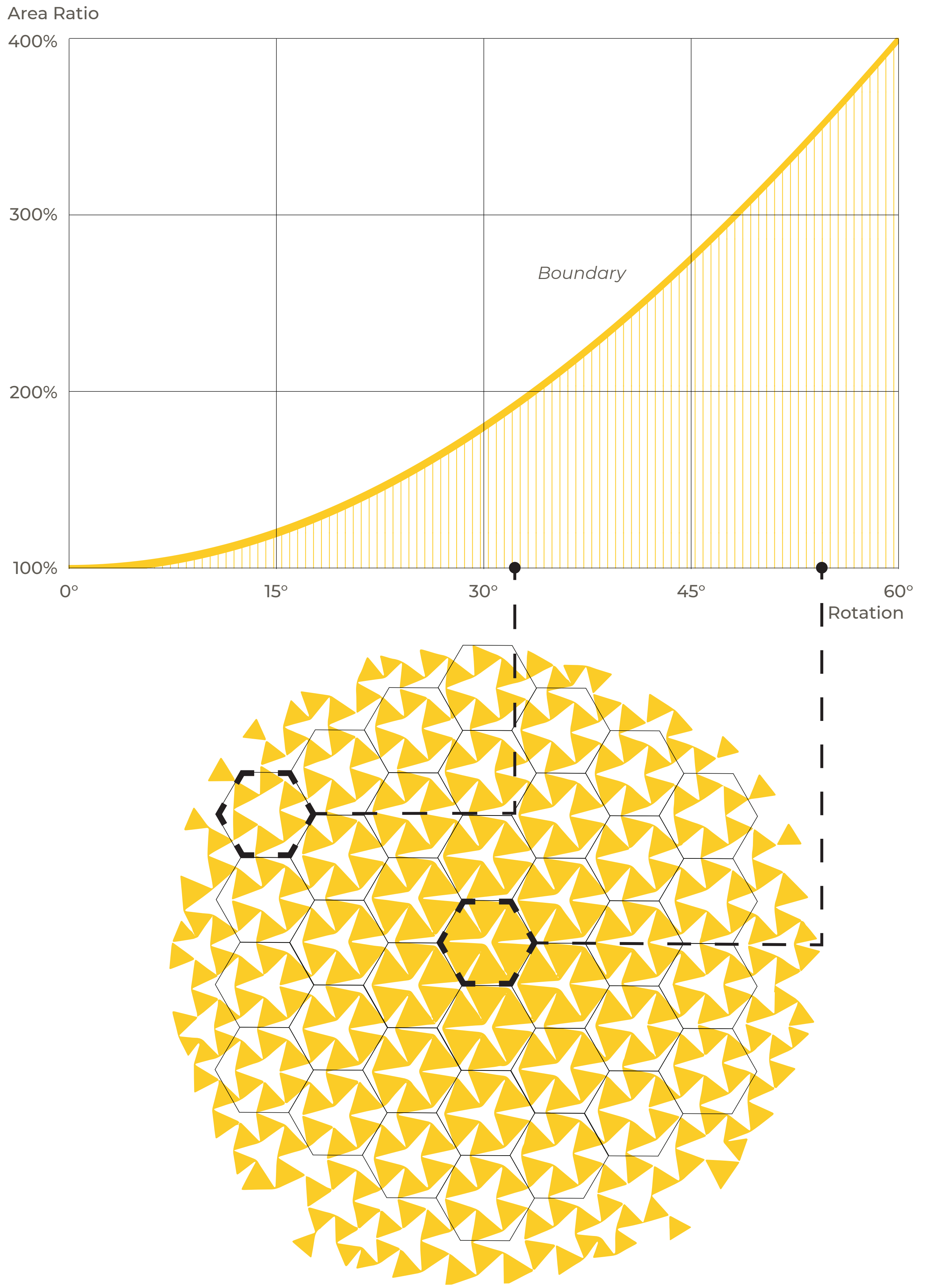


Figure 22: Design boundaries as triangle sizes in relation to deployment.

Surface Definitions

The specific surface that can be created through this concept is defined by the applied deployment concept. This thesis has investigated three different deployment procedures, inflated shapes, gravitational shapes and minimal surface shapes (**Fig. 23**). All of which define their own family of possible surfaces.

Inflated

The inflated deployment is based on internal pressure that expands the surface and eventually creates an equilibrium. By pushing the system outwards it generates constant tension between the panels and thereby a fully deployed system.

Gravitational

When deploying a gravitational system one has to hang it in it's boundary. Gravity then pulls each panel down towards the ground and deploys the system from its flat configuration.

Minimal surface

A minimal area surface is based on an approximate surface between input boundary curves which have the minimal possible area while also being attached to all boundaries. It is deployed simply through the attachment of the system onto each boundary and can internally be supported by for example columns.

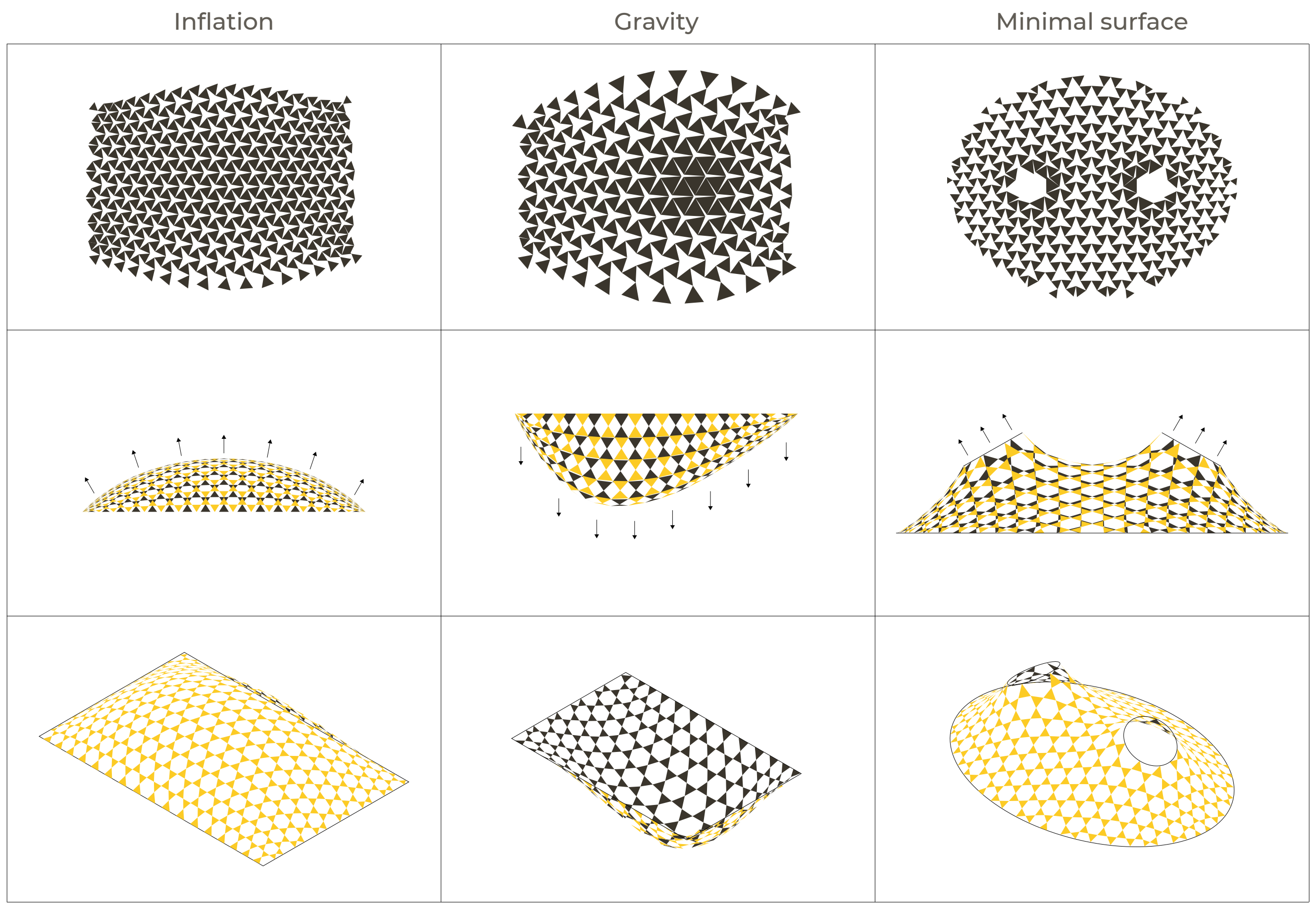


Figure 23: Surface definitions in relation to deployment concepts. Each opening up their own possible family of surfaces. Illustration of flat system, deployment procedure and the deployed state.

3D RESEARCH

Development of spatial systems

Computational Form Finding

The form of the 3 dimensional system is generated computationally in a scripting environment in Grasshopper and Rhino 3D.

Goals and form finding

A certain set of goals are created and strived towards throughout the process of generating a shape. These goals make sure that the final system can not only become flat but that it also comes as close to the desired deployed shape as possible. Equilateral triangles within the system except those at boundaries, hexagons as close to regular as possible and points pulled towards the desired shape are just some of these goals that guide the process (**Fig. 24**).

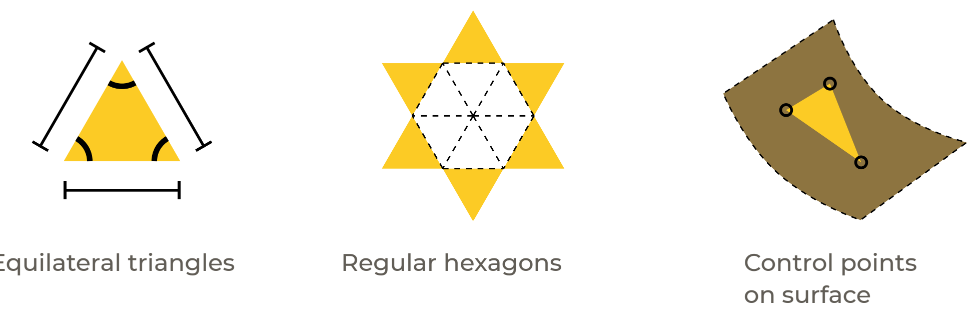


Figure 24: The goals of the form finding which are the criteria that should be fulfilled for the system to work and meet requirements.

The design process

The computational process of generating a shape is mostly automated, whether it be by use of inflation, gravitaty or minimal surface. There are steps within the process which require the designer to take design decisions and control that the outcome aligns with the intent.

Initially one has to define a boundary for the shape. That is the most crucial step of the process since it has a direct impact on the whole shape. To then control and approximate the desired deployed shape a grid of lines is mapped between the boundaries. This grid is then put through a live, interactive physics engine where the designer can input forces or manipulate the boundaries while getting a live update of the form. If a minimal surface is the goal then no forces are applied but each line in the grid is told to try and become as short as possible while still staying connected. If an inflated or gravitational form is desired then the corresponding forces are applied to the grid.

As the form is found a surface is wrapped over the grid which then is used to map the kagome pattern. The previous mentioned goals are applied to the system and it is put through another iteration of the physics engine to try and find a state where the system meets all the required goals.

Finally the system is folded together to ensure that both the flat and the deployed state is possible before production (**Fig. 25**).

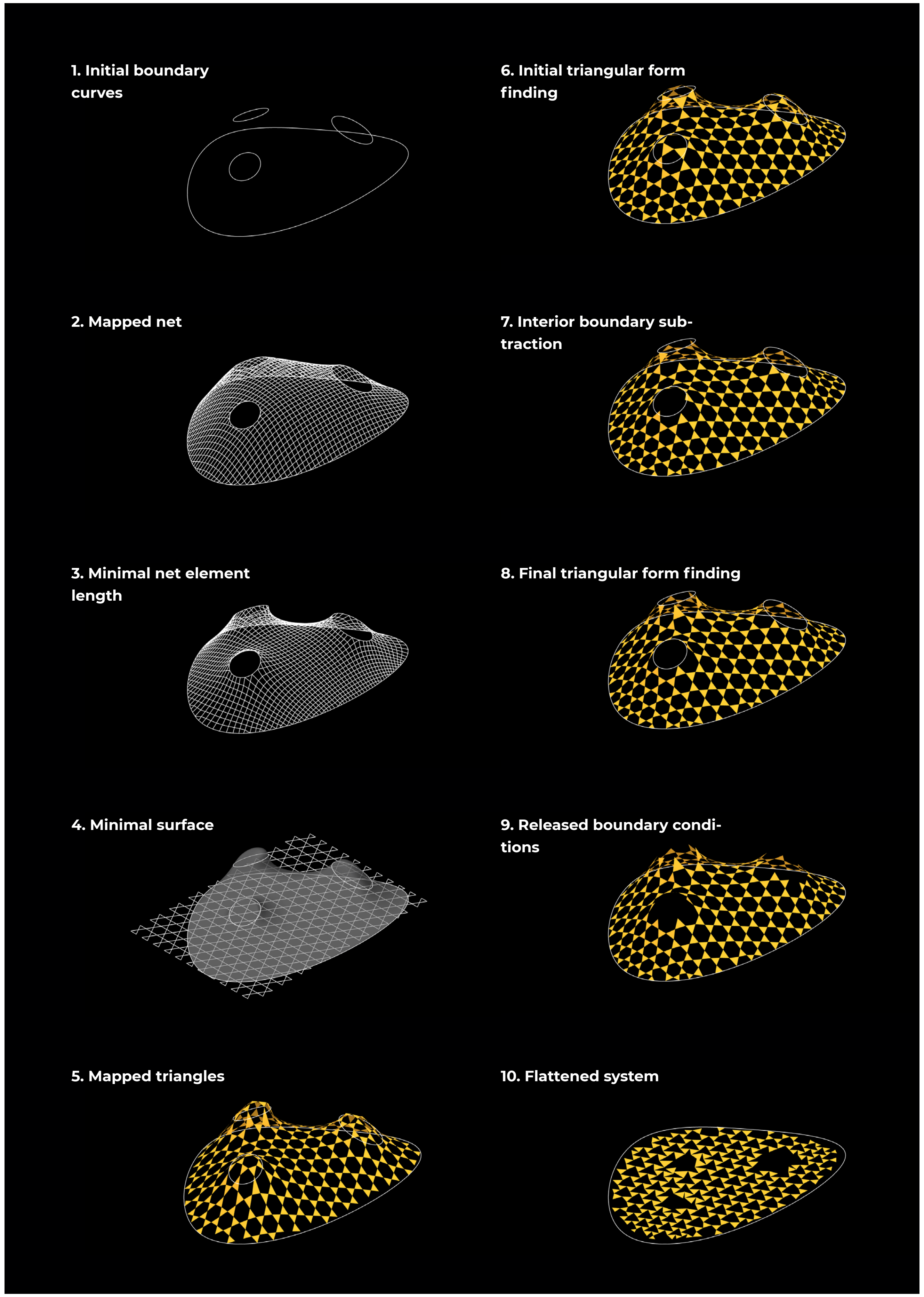


Figure 25: The procedure of generating a model exemplified in a set of steps. From the input information to the final form and its flat organisation.

Digital Production

The system is produced through the use of digital machinery such as laser cutters or CNC mills since it is made out of all unique triangles and requires a high standard of accuracy.

Output

Data for the production is generated as an output from the computational script. The script also sorts all the panels by numbering them so that the system later can be assembled (**Fig. 26**). There is also a possibility to print the system already interconnected. This takes away the need of post production assembly but requires the joints to be in the same material as the panels (**Fig. 27**).

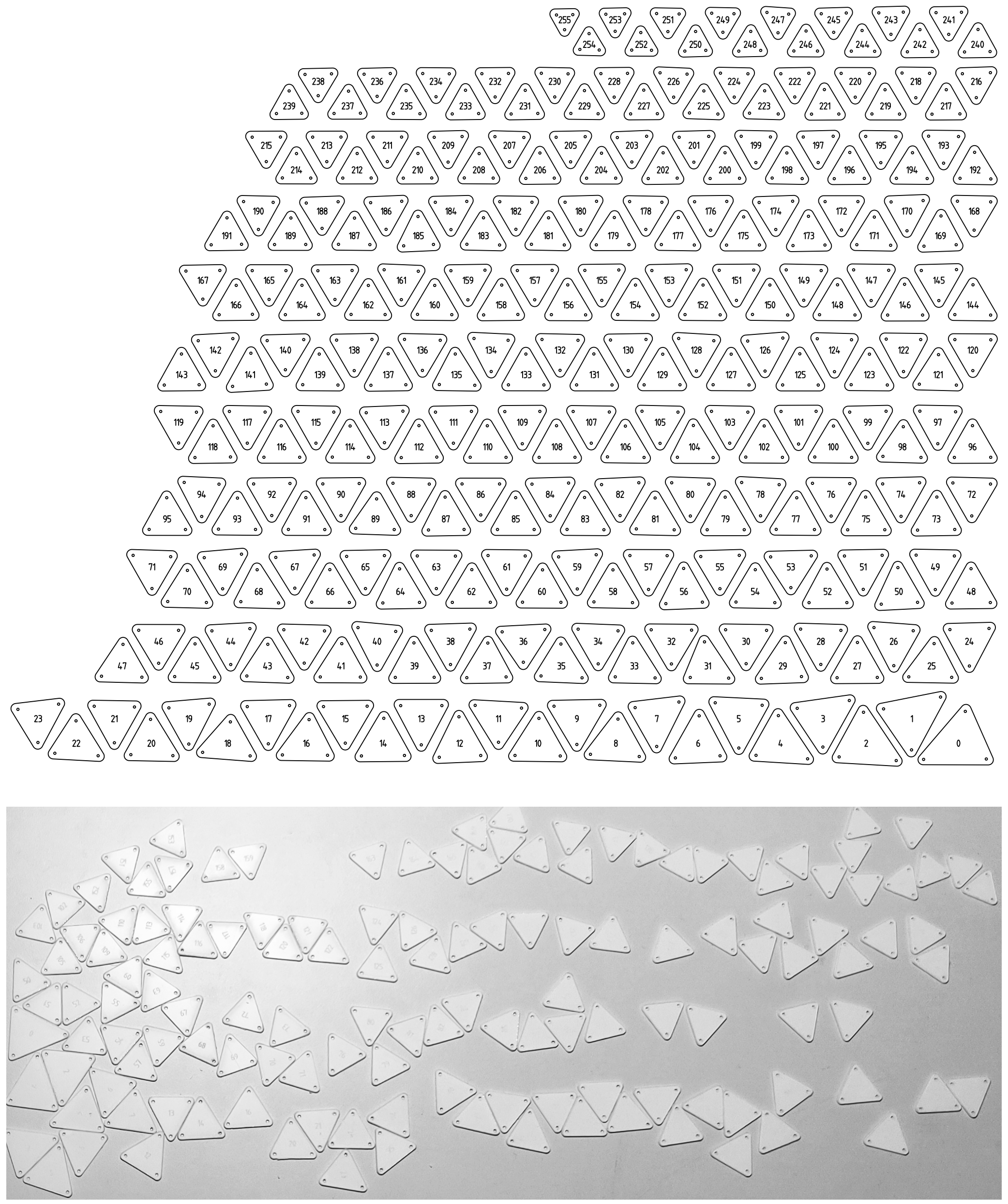
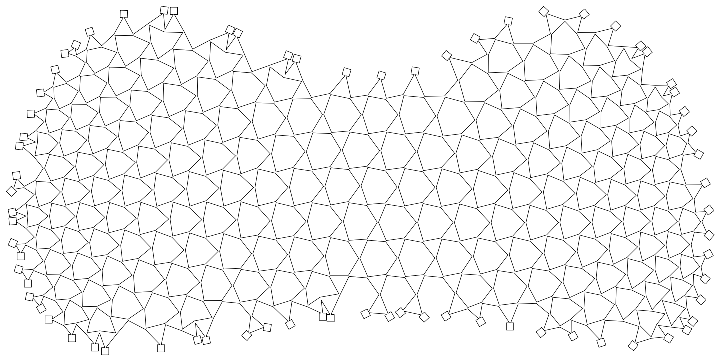


Figure 26: Input data for laser printer and produced triangles in pet plastic.



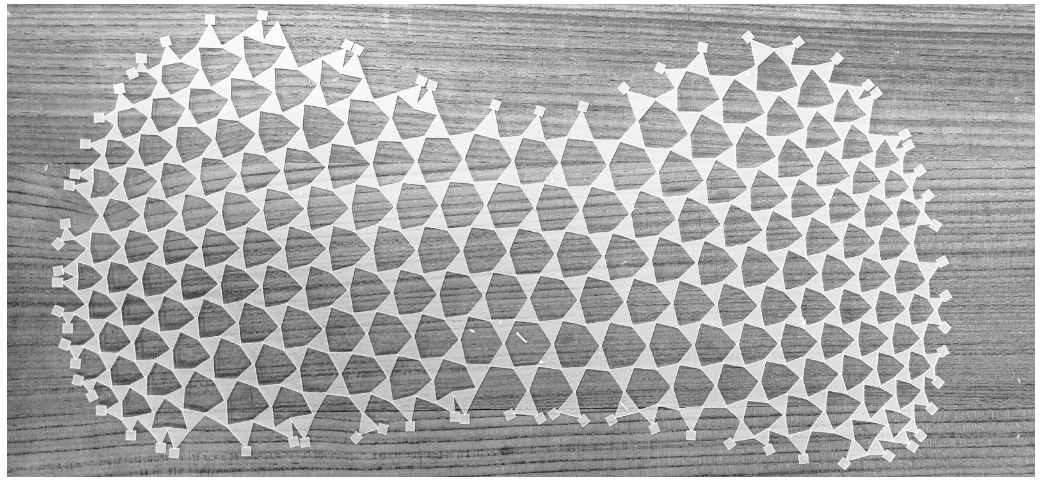


Figure 27: Input data for aristomat and a produced triangle net. The joints are in the same material as the panels which avoids the assembly process.

Joint Investigation

Joints for the 3 dimensional system are not necessarily complicated but they have to account for a lot of forces while also facilitating rotational flexibility.

Rotations

As the system deploys from flat to 3 dimensional all the different rotations need to be facilitated in the joints between the triangles. They are different around different axes and both the amount as well as the axis need to be considered when creating an efficient joint (**Fig. 28**).

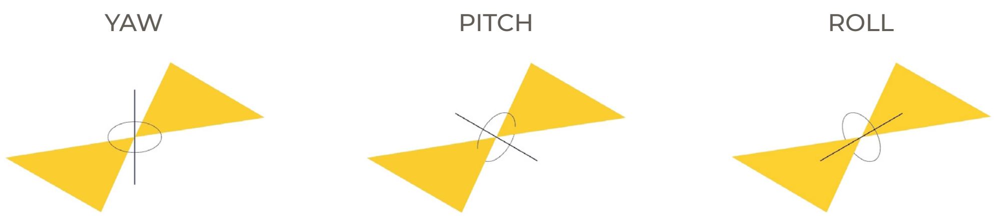


Figure 28: The different rotations that need to be taken into account when designing joints for 3 dimensional systems.

Physical tests

Two joints were tested throughout the research. Firstly a joint in plastic which is of the same material as the panels. (**Fig. 29**) The plastic has a certain flexibility which made this joint possible. The durability of this solution is limited since the plastic can be worn out after a large amount of bending but it simplifies the production as previously mentioned.

A system using joints that were added later on was also tested in the research (**Fig. 30**). By connecting the triangles with a metal ring a double axis rotation was created that allowed for all needed flexibility while also being durable since it required no bending.

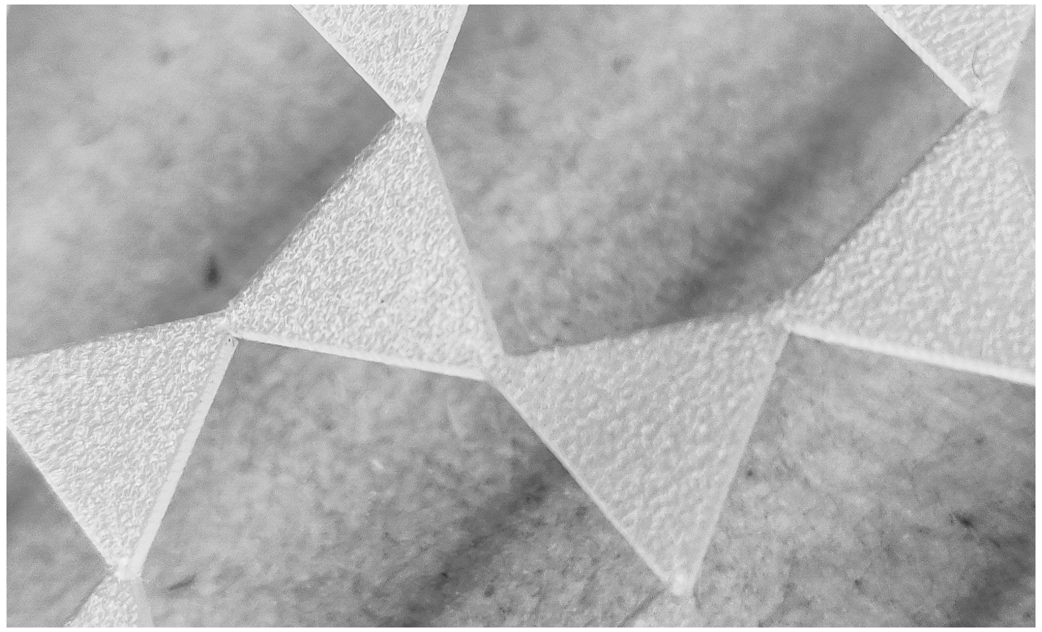


Figure 29: Physical models of same material joint.

Figure 30: Physical models of added joint as additional material.

3D APPLICATION

Utilization as envelopes

Reference Projects

There are many examples of deployable shells in the built environment. Here are examples that have inspired this research.

Sheltair

By inflating a balloon under a flexible mesh of rods and then attaching the rods to a fixed boundary Gregory Quinn manages to create a deployable pavilion through the use of inflation.

Mannheim Multihalle

By lifting a grid of wooden beams while the connections within the grid are flexible a state of active tension in the grid appears. If the joints then lock into position the grid becomes rigid. This is how Mannheim Multihalle was deployed.

Air dome DUOL

An air dome is a double layered inflated structure. The pressure difference is between the space between the layers and the outside which means that the pressure in the actual hall can remain constant. An example of this can be found in Karlstad and is designed by a company called DUOL.

Formwork for Rigid Shell

Using the auxetic system as a formwork utilizes the simple planar production and efficient deployment procedure as a base for a more permanent intervention. This can be done as in the presented example where the surface is deployed, locked and then in filled with additional panels (**Fig. 33**). Another way of using the kagome pattern as formwork could be to weave flexible rods through the system or use it as a form for casting something permanent.

The formwork concept can work with any of the presented deployment procedures. The minimal surface system would create a tension compression system where the triangular net can take the tension while the panels together take the compression. If inflation or gravitational deployment is used an only compression shell would be created.

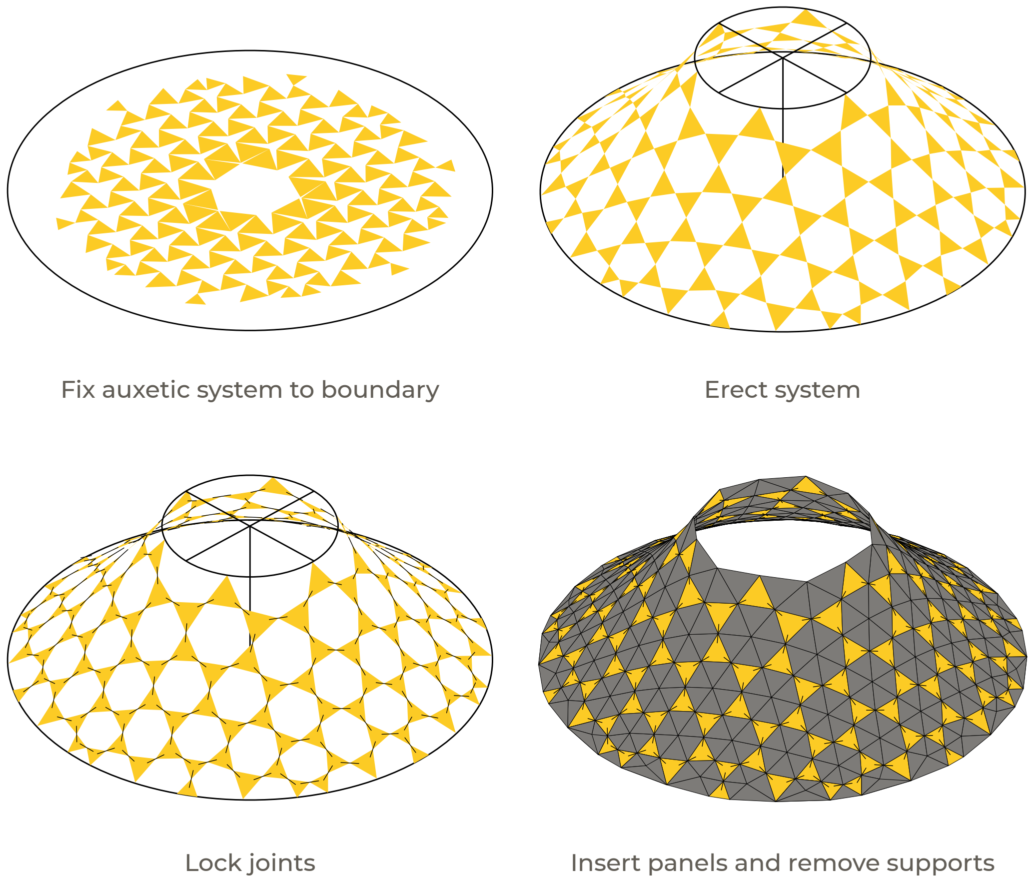


Figure 31: Proposed design and deployment procedure for a rigid shell system.

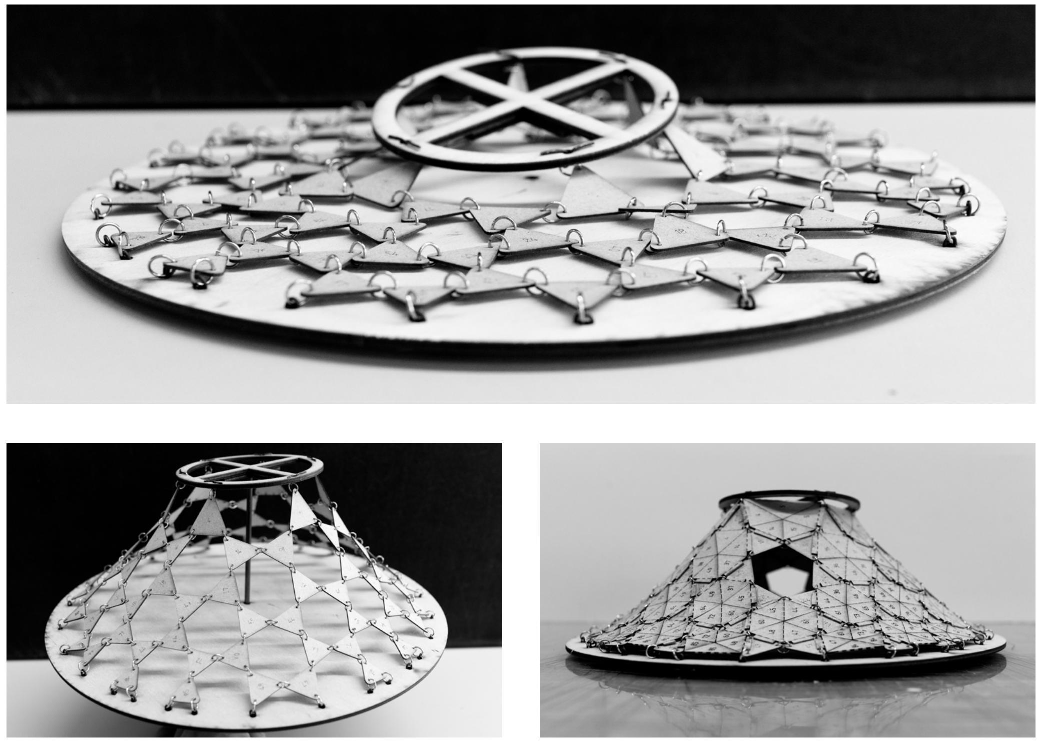


Figure 32: Physical investigation of a rigid shell.

Figure 33: Illustration of a greenhouse on the Chalmers campus. A rigid shell structure with glass panels.

Tensile Membrane

The tensile membrane application of the system aims at more temporary applications. Internal supports can be taken away and the surface folded together since it is constantly flexible. It is suggested in the proposal that an extra membrane is applied on top of the triangular system as weather protection while the triangles work as support for the surface. A system where the triangles are incorporated in the fabric could also be possible.

A good aspect of the design process is that a wide range of boundary curves can be used as inputs. This makes it possible to exactly adapt the intervention to the site (**Fig. 36**). When the site for example is very inflexible, a system that follows the topology and thereby requires minimal intervention can be designed easily.

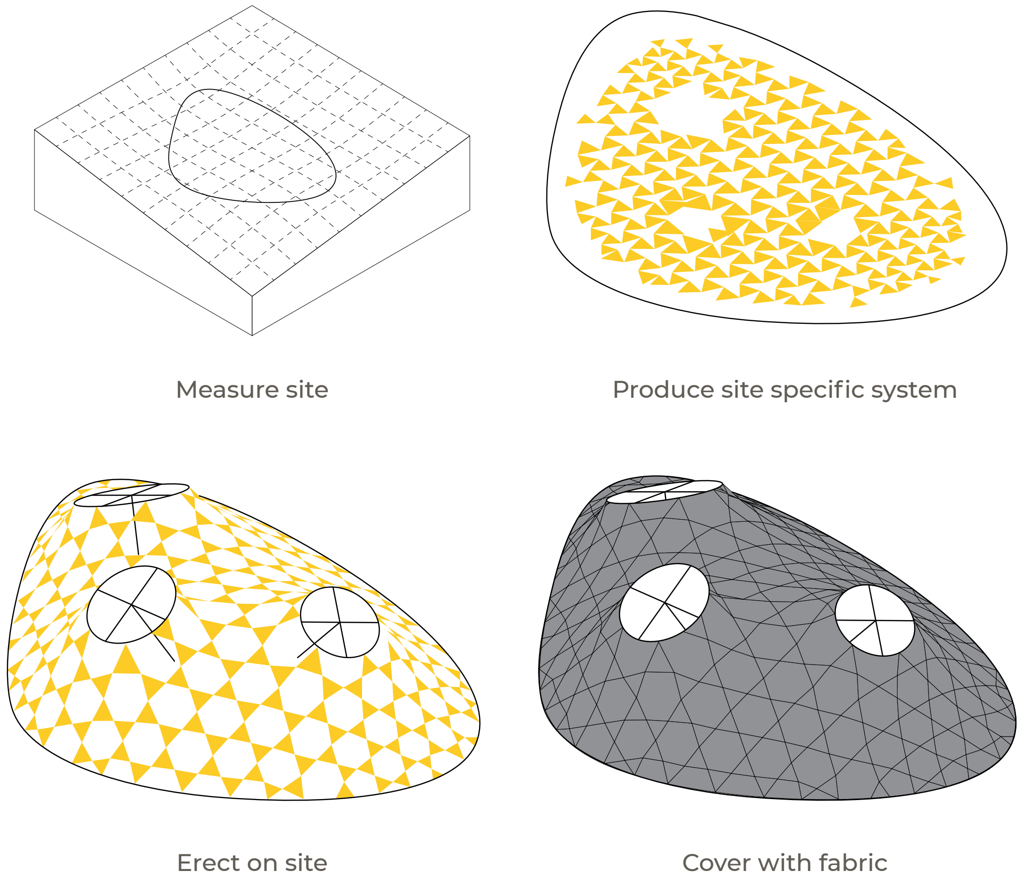


Figure 34: Proposed design and deployment procedure for a tensile membrane system.

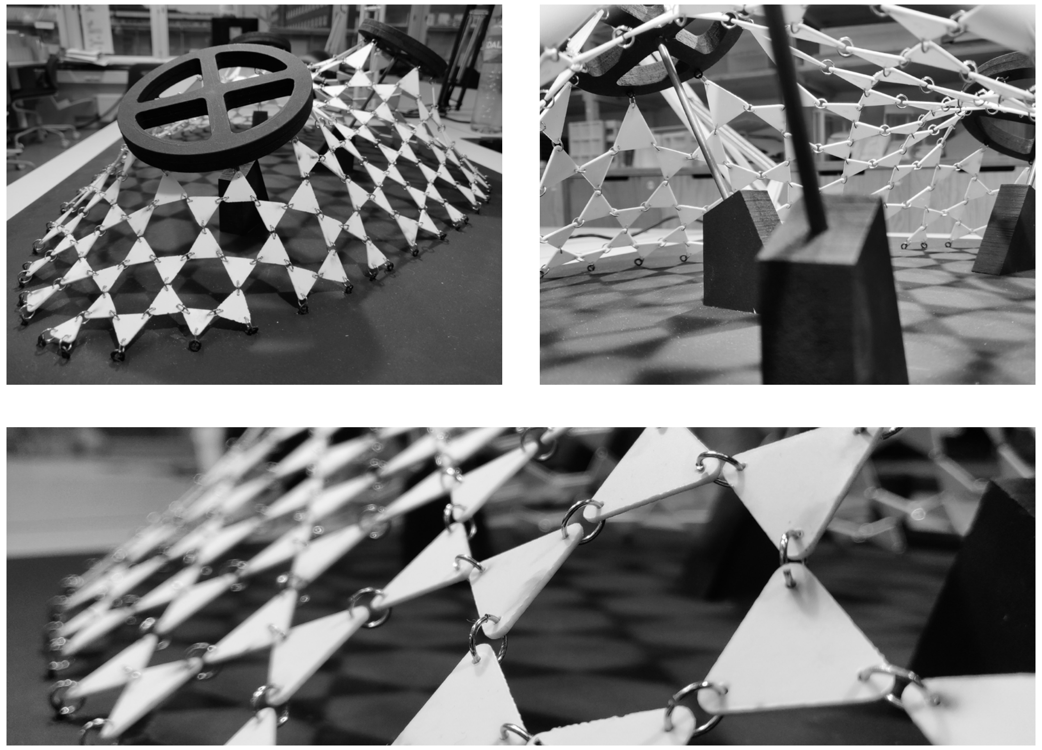


Figure 35: Physical investigation of minimal surface system.

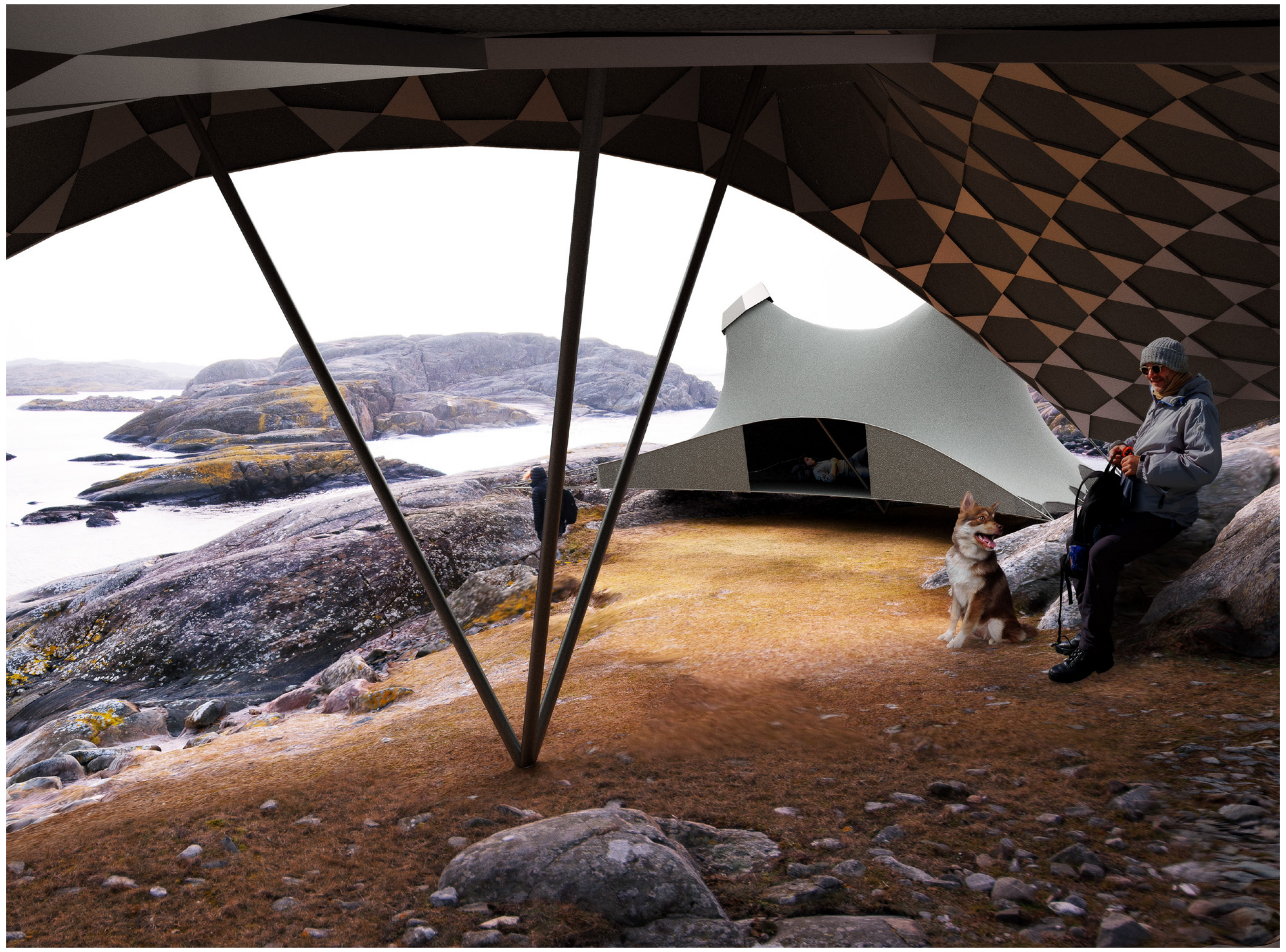


Figure 36: Illustration of a tent structure based on the minimal surface concept. Located in the Bohuslän archipelago.

Inflated Structure

The inflated system requires a pressure difference between the inside and the outside. Suggested applications for this is in environments where a pressurized environment is required for humans to survive (**Fig. 39**).

The system could here be created in a fabric or any other soft tensile material since this concept only requires the kagome system to control the internal inflated shape and therefore only takes tensile forces. Applying this in space would also give the opportunity to utilize the folding and deployment properties of the system.

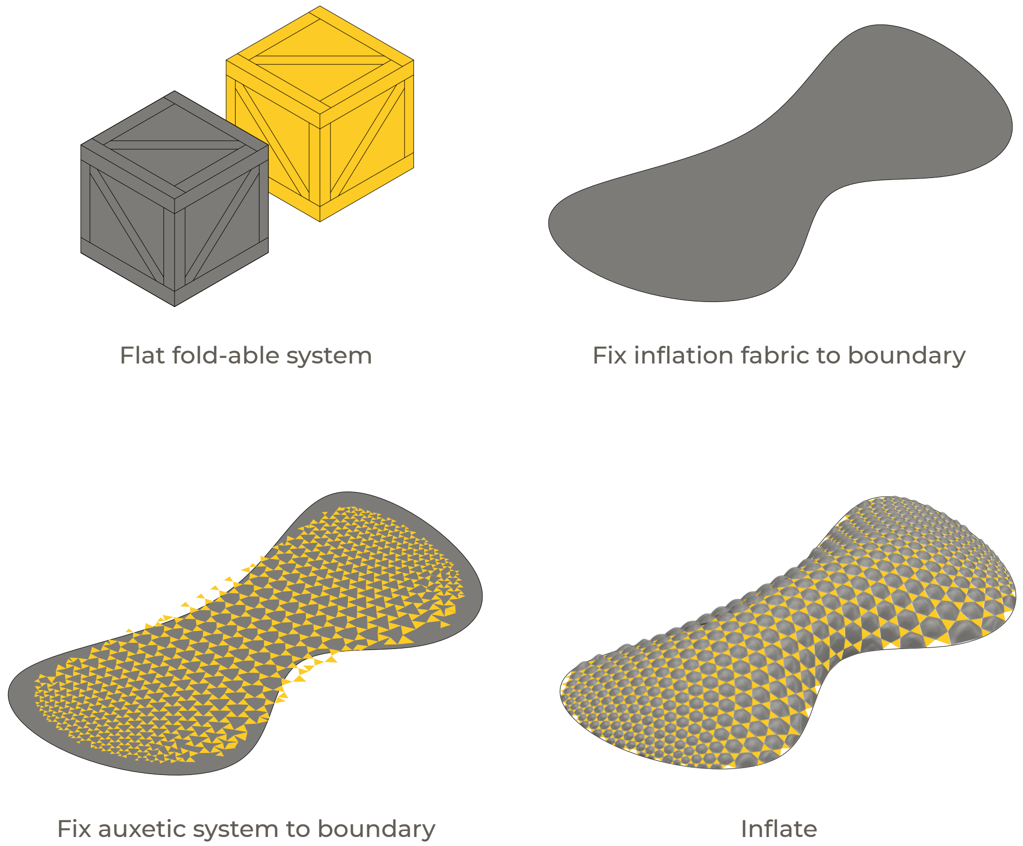


Figure 37: Proposed deployment procedure for an inflated system.

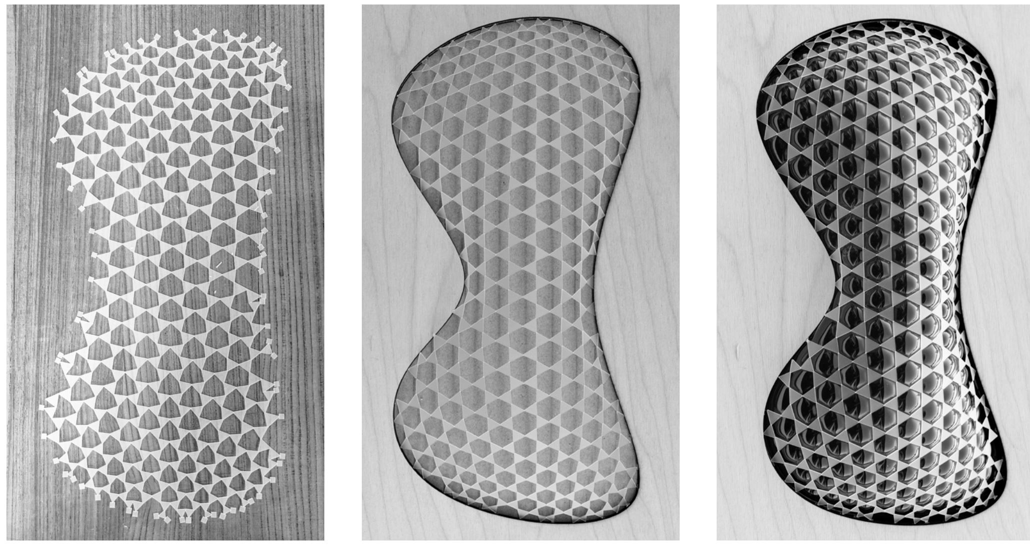


Figure 38: Physical investigation of inflated system.

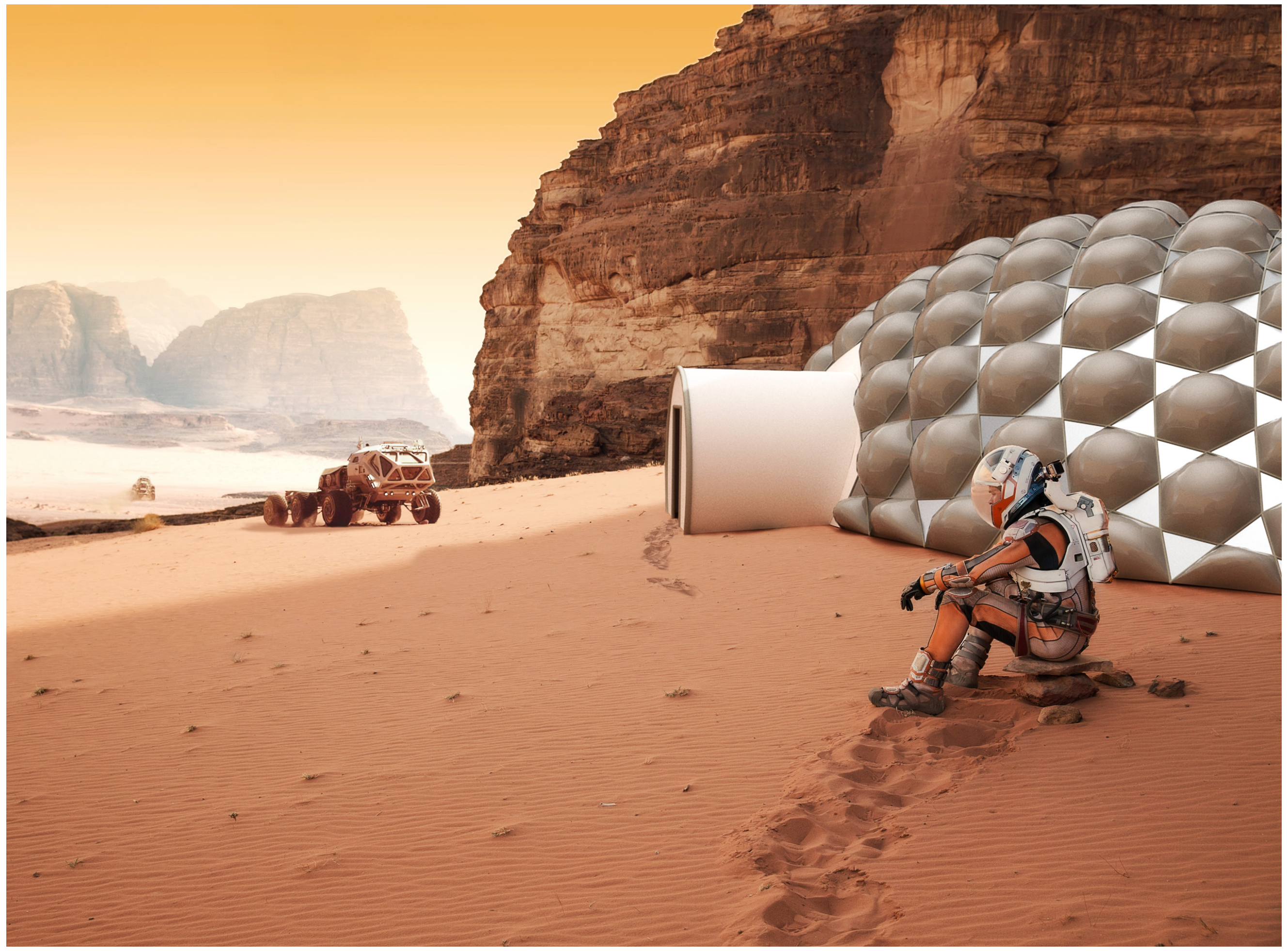


Figure 39: Illustration of an applied inflated system on Mars. Pressure difference between inside and outside is utilized for deployment.

DISCUSSION

Findings

The most interesting outcomes of this investigation is the 2 dimensional layered system. The visual complexity of that system and the possibility to expand it four times its original area while still being fully covered are interesting and important properties.

The research opens up new ground for the auxetic systems that it handles by not only introducing 2 dimensional concepts for auxetic systems but also new definitions of 3 dimentional systems. It also proves and supports its findings through a generous set of concept models.

Future Work

As future work takes on this subject a variety of possible extension of the initiated research can be examined. Deployment procedure for the 2 dimensional systems and a further step towards application of the concepts investigated in this research for example.

The next step for the 3 dimensional systems could be to develop a dynamic joint that can support the deployment or maybe even take away the need for an exernal deployment procedure.

References

Konaković-Luković, M, Konaković, P, Pauly, M. (2019). Computational design of deployable auxetic shells. *Advances in Architectural Geometry 2018,* p94–111.