TECHNISCHE
UNIVERSITÄT
WIEN
Vienna University of Technology

MASTERARBEIT

Design and Production of a Self-Supported Lightweight Structure

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Diplom-Ingenieurs
unter der Leitung von

Ao. Univ. Prof. Dipl.-Arch. Dr. phil. Georg Suter

E259.1 – Institut für Architekturwissenschaften Abteilung Digitale Architektur und Raumplanung

eingereicht an der Technischen Universität Wien

Fakultät für Architektur und Raumplanung

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Acknowledgment

I would like to thank my family for their unconditional encouragement and support for all of my endeavors over the years and particularly this project. My sincere gratitude goes to my supervisor, Ass. Prof. Georg Suter for his expert guidance, support and endless patience throughout the entire work process of my thesis.

I am very grateful for the talks and insightful pieces of advice received from Ass. Prof. Andrei Gheorghe. The complete information about his workshops and his support during the building of the physical structure have been invaluable to me. I am additionally grateful to my colleagues from the University of Applied Arts Vienna: Kristof Retezar, Niko Scwarz, Dietmar Kolar, Daniel Wyrobal, Deniz Önengüt and Jan Pernecky whose interest and participation in building the structure, have made building the project not only possible but so much fun.

I am in debt to dr. Michael Hofer for his constructive criticism, to Kristina Schinegger from Soma for the information on her project, to Fabian Scheurer for sharing his view on efficiency, to my colleagues from Vienna University of Technology: Martina Hatzenbichler, Markus Stürzenbacher and Hannes Tallafuss who have provided me with information about their projects, and to my two friends Naomi Morishita and Benjamin Stangl, who have been kind enough to read, correct and offer advice on my thesis.

DESIGN AND PRODUCTION OF A SELF-SUPPORTED LIGHTWEIGHT STRUCTURE

Ana Maria Marcu, Vienna University of Technology

Abstract

The latest developments in digital design and production technologies as well as material innovations have allowed architects to explore a variety of geometrically intricate forms. One of the directions concerns the construction of lightweight structures. While there are many such experiments being done in both universities and private practices, their documentation is typically insufficient for replication. Detailed descriptions of geometries, materials, and production processes could be useful to develop efficient and economically feasible structures. To understand the design and manufacturing process of such structures, a case study has been realized. The study focuses on exploring the potential of plastic, paper, foam, and cardboard materials, to realize a rigid, self supported structure made out of curved components. A structure aggregated from irregular modules made of soaked and bent cardboard strips was designed, produced, and assembled. It partitions a space, minimizes material use, and is produced without the need for secondary structures such as moulds. The design process followed a composition method. A main concern was to achieve stability of modules as well as the overall structure. Extensive tests were thus made to optimize the shapes of modules, joints, and additives such as textile hardener based on the properties of the cardboard material.

Keywords: lightweight structure; folding; digital design and production;

1. INTRODUCTION

> What would history of architecture be without experiments? For thousands of years, the process of trial and error played a decisive role in pioneering design. In the structural realm, for example, the spans of historical vaulting were often determined in this way, as indeed was the flat roof construction in the early years of the modern movement.
>
> (Schittich 2009)

The development of digital technologies over the past decade, capable to accurately represent and precisely fabricate artifacts of almost any complexity, has given rise to intricately articulated surfaces, enclosures, and structures (Kolarevic and Klinger 2008). The availability of CNC machines in teaching institutions and private practices has blurred the clear boundaries between design and production set by the 20th century and given architects the opportunity to investigate materials and techniques at much earlier stages.

The advancements in manufacturing new shapes have been supported by material innovations, meaning the “intelligent use of physical properties already inherent in the materials” (Sauer 2010). Particular attention has been given to composite materials which have the quality of combining low weight with structural strength making them very interesting not only for the automotive and aerospace industries but also for architecture. Materials which are light and strong offer structural efficiency because they achieve maximum strength with minimum use of materials. Since building weight plays an increasingly significant role when it comes to the environmental impact of a construction (Sauer 2010), lightweight building materials and consequently structures, are increasingly sought after.

Besides using material properties, achieving structural efficiency can be reached by taking advantage of the capability of materials to fold. Folding is a method of creating three dimensional shapes from two dimensional materials and it is a powerful technique to obtain structure with geometry. The folded materials can “gain stiffness and rigidity, can span distance, and can often be self-supporting” (Iwamoto 2009). Folds can cover large volumes without the requirement of large quantities of material which makes the weight to volume ratio extremely attractive from an economical point of view.

Achieving novel and intricate shapes made possible by the development of digital technologies and material innovations by keeping (or raising) the level of efficiency of standardized building components, seems to be the direction in which architecture is heading and consequently the building of lightweight structures. However, digitally manufactured lightweight structures are still in their incipient stage, either part of universities prototype projects or gallery installations made by private practices. Many of them are not documented to the extend that they can be replicated. The design phases, the inherited intelligence of the parametrical models and the material tests are not shown, instead architects opting for a classical presentation of the end form. With “consumer CNC” machines being more available and as easy to use as office printers, together with the scarcity of material diversity needed to build lightweight structures, as well as the many functions lightweight structures can have, it is easy to believe that this particular segment of architecture will gain a wider interest for both design professionals and amateurs. As such, a detailed description of the already made experiments is important to attract more ideas which could shift these structures from the experimental field to an economical feasible project.

The aim of this thesis is to understand what the challenges are in coming up with efficient, economically feasible solutions of designing and producing a 1:1 self supporting lightweight structure. Since "planar parts are easier to build than straight ones" (Pottmann, Asperl et al. 2007), an additional attention goes to building curved components without molds. This case study is the result of the group effort of seven people and it's meant to simulate a real project in which resources and people have to be managed within a fixed period of time (one semester) to meet the requirements.

The thesis is divided in four main chapters. The first chapter defines terminology, introduces the subject and the research question. The second chapter explains the two main design methods used in the development of digitally manufactured lightweight structures with the help of existing examples and it explains the potential of composite materials in building lightweight strucutures. The third chapter is a detailed description of a realized experiment while the fourth chapter is the discussion of the results of the experiment in light of the set requirements and the research question.

2. RELATED WORK

The following examples depict the outcomes of various digitally manufactured lightweight structures dealing not only with different materials but also with different functions trying to meet one or more requirements which were important in developing the built project explained in this thesis. These experiments are divided into two different design methods: the composition and decomposition method. However, the designer can switch back and forth between the two methods until the set requirements are met. Additional to that, particular attention has been given to composite materials which offer great potential in building lightweight structures.

2.1 Design methods

2.1.1 Decomposition method

The decomposition method is based on subdividing an overall shape into a smaller number of components such that they can be manufactured.

According to Scheurer (2005) the translation of the model from the design idea to its production takes place in 6 steps. It starts just after design and it ends right before production:

1. Definition of geometric, functional and constructive requirements. Depending on the type of project, the focus might shift between the three.

2. Definition of materials and constructive details by integrating manufacturing specialists such that optimum solutions for material and constructive detail are found.

3. Definition of the structure's geometry: start of the digital chain. Describing the exact geometry of the structure.

4. Generation of the geometry for every single part.

5. Optimization for production. Which involves arranging the individual parts together on the raw material so that the waste of raw material is minimized. Also holes for fixing the boards and other additional details are done at this stage.

6. Generation of the production code, which is basically telling the machine which tool to use and where to move it.

Tesselion

Skylar Tibbits, Philadelphia University Architecture & Design Building, 2008

A tessellation is a collection of pieces that fit together without gaps to form a plane or a surface. In digital design, the term refers to approximating surfaces, singly or doubly curved with polygonal meshes (Iwamoto 2009). Tessellion is a project which demonstrates a system of flat panel tessellation derived from a complex surface (Fig. 2.2). To enable ease of constructability the system takes advantage of the efficiency of digital fabrication by cutting individually shaped components, while coded parametric relationships allow an emergent structural efficiency (Tibbits 2008). Folding was used in order to add rigidity to the components. The tabs are folded inside the shape (Fig. 2.3). However, saving material has not been a driving design requirement in this project because the material was sponsored and the arrangement of the components has been done manually (Fig. 2.1). Metal on the other hand, is a recyclable material. Should a designer have that in view, this type of project could be both sustainable and economically very attractive.

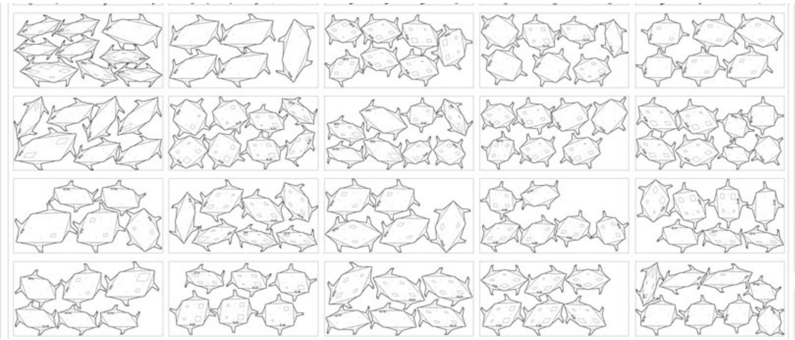


Fig. 2.1 Arrangement of components for cutting on the standard sheet of metal.

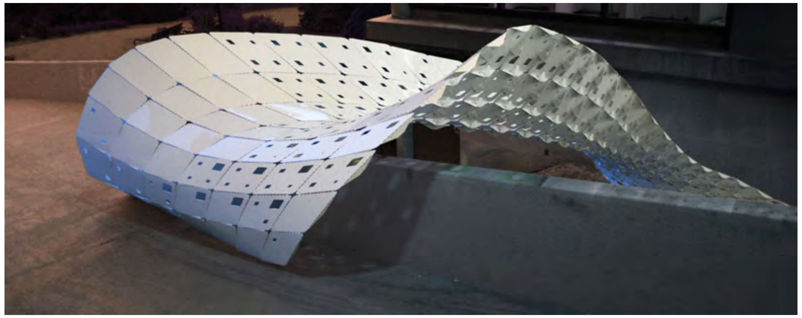


Fig. 2.2 Overall shape of Tesselion.

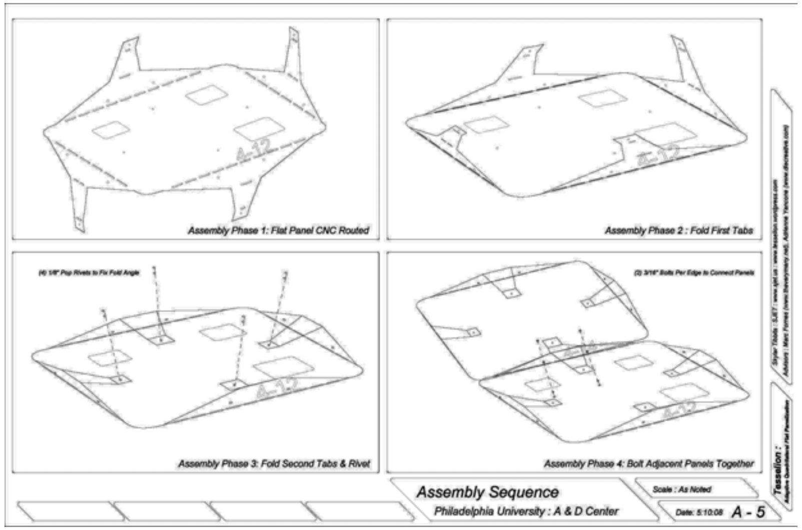


Fig. 2.3 The assembly sequence of the components.

Inventioneering Architecture

Instant Architects, Design to Production, 2005

Inventioneering Architecture is a travelling exhibition of the four Swiss Architecture Schools: Zürich, Lausanne, Geneva and Mendrisio (Fig. 2.7). For this exhibition, the office Instant Architects in Zürich designed a double curved exhibition platform which resembles an abstract crosscut through the Swiss topography (Fig. 2.5). The platform is 40 m long, 3 m wide and has the maximum height of 1.5 m and it is crossed on its length by a path. The manufacturing strategy of the stage was to cut the 3D model into 1100 cross sections, each 40 mm wide. Each section defines an individually curved rafter milled out of medium density fiberboard (MDF). The rafters are assembled in a comb shape (Fig. 2.6). Each rafter follows the upper edge of the platform and is supported by a vertical board at the back. In order to translate the geometry of the platform into the geometry of the single parts and into the code of the computer controlled mill, a set of scripts in the CAD package Vectorworks was developed. The rafters were cut out of 120 MDF boards within roughly 50 milling hours (Fig. 2.4).

> By choosing a rather cheap material and implementing a continuous digital chain from the definition of the surface geometry in the CAD software Maya until the control of the five-axis CNC mill that the parts are manufactured with, production costs could be lowered significantly.
>
> (Scheurer, Schindler et al. 2005)

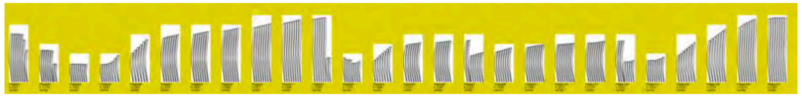


Fig. 2.4 The rafters optimally positioned on the MDF boards.

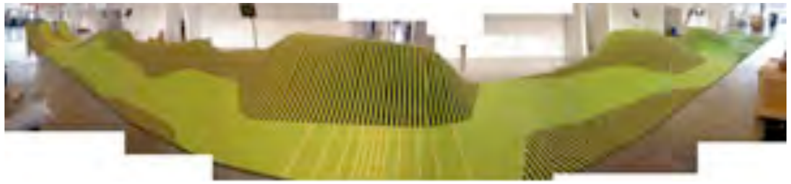


Fig. 2.5 The platform.

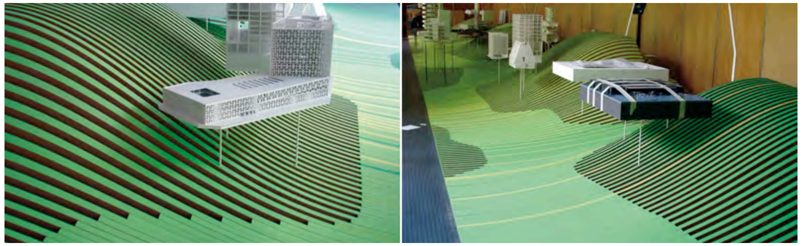


Fig. 2.6 Comb shape assembly.

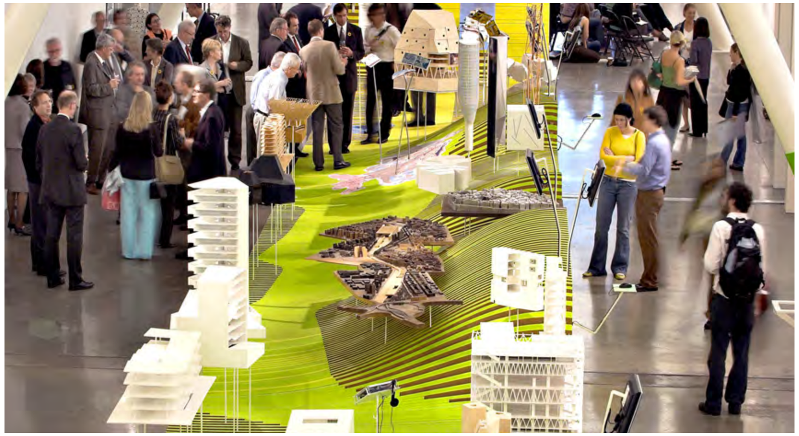


Fig. 2.7 Overall assembly of the exhibition.

Voussoir Cloud

IwamotoScott, Chris Chalmers, John Kim, Andrew Kudless, Buro Happold LA, Southern California Institute of Architechture gallery, Los Angeles, 2008

> Voussoir Cloud attempts to defamiliarize both structure and the wood material to create conflicted readings of normative architectural typologies. It is a light, porous surface made of compressive elements that creates atmosphere with these luminous wood pieces, and uses this to gain sensorial effects.
>
> (Iwamoto and Scott 2008)

The design of the Voussoir Cloud draws inspiration from the work hanging chain models of Antoni Gaudi and Frei Otto (Fig. 2.8). The architects use both a hanging chain computational model and form-finding programs to determine efficient vaulted geometries (Fig.2.9). Instead of using wedge-shaped vaulted blocks, a Delauney tessellation was used to develop petal-like components (cells) made out of wood laminate (Fig. 2.10).

Fig. 2.8 Overall assembly.

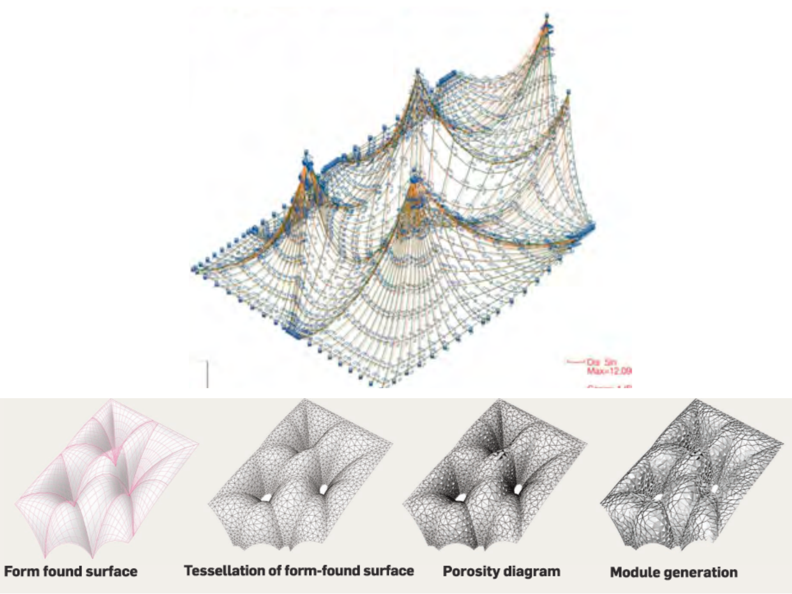


Fig. 2.9 Top: hanging chain computational model; bottom: analysis and tessellation diagram.

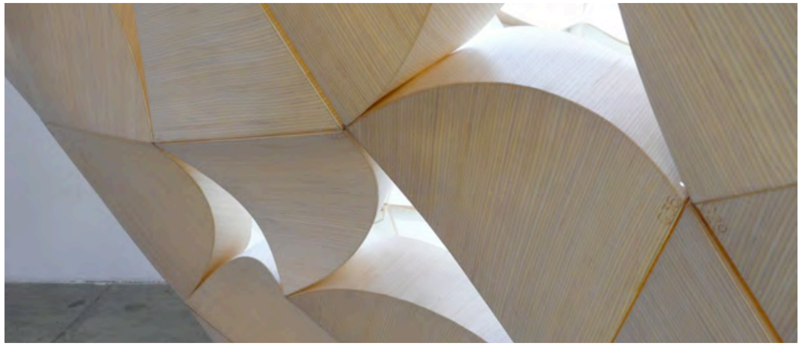


Fig. 2.10 Cells.

By folding the material, the cells rely on the internal surface of the wood and the folded geometry of the flanges to hold their shape. Because the flanges are under pressure, they bulge out along the curved edge. The individual components thus press against each other across the entire structure creating vaulted forms of compressive elements. There are four cell types in Voussoir Cloud with zero, one, two, or three curved edges (Fig. 2.12) and their behavior differs based on their size, edge conditions, and position relative to the overall form. The cells are flatter towards the base edges where they gain density and start gaining curvature and greater offset towards the top to create the voussoir. The design of the overall shape and that of the 2300 individual cells was done with the help of scripting. Each cell shape was than unfolded (Fig. 2.11) and laser-cut. Finally, the petals are reconstituted by folding along the score line and joining them together with plastic zip ties (Fig. 2.13).

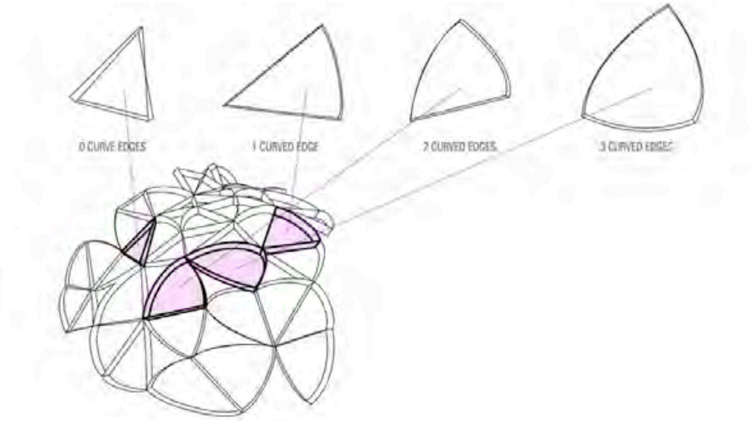


Fig. 2.12 The four types of cells used.

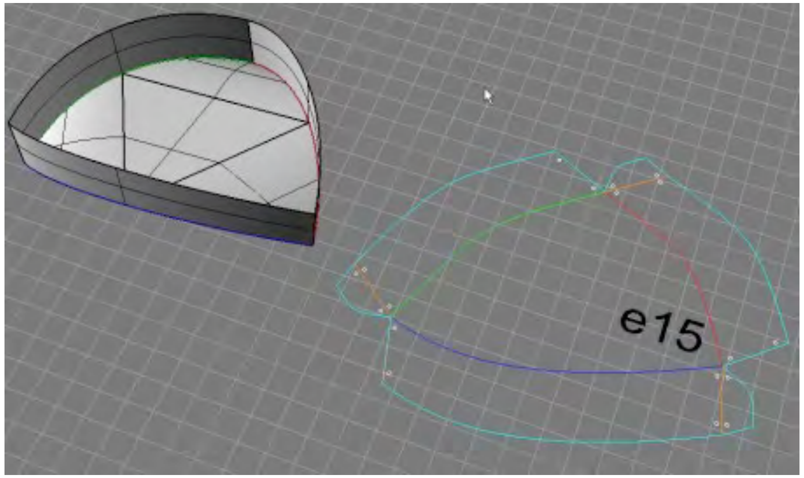


Fig. 2.11 One cell folded and unfolded.

Fig. 2.13 Three cells joined with a zip tie.

2.1.2 Composition method

Composition methods use a small number of different components to generate various shapes based on defining parameters (spatial, structural, formal, functional, etc).

White noise - Salzburg Music Pavilion

Soma, Bollinger Grohmann Schneider ZT GmbH, Salzburg, 2011

> For the development of non-regular structures with optimized load-bearing capacities, the applicability of existing, top-down design methods is limited. When architects and engineers successfully collaborate in defining the starting position and constraints for form-finding and structural design on a conceptual level, those methods can lead to emergence of shapes and structures that were not conceivable before.
>
> (Hoffmann, Scheuerer et al. 2007)

The temporary music pavilion for the city of Salzburg was erected for a period of three months and was meant to relocate in various places and house different artistic performances (Fig. 2.14). The pavilion is divided into five segments, and by combining these segments in various ways or by reducing some of them, the pavilion adapts both to its location and to its new function (Fig. 2.15). One segment of the pavilion is composed of 20 layers positioned at 20 cm distance from each other. One layer represents one contour curve on the reference surface. The reference surface is the textile climatic enclosure. The overall shape is obtained by arraying one simple element (a 2 m aluminum bar) along these layers based on a range of rules of aggregation and the definition of the architectural effects aimed at (Schinegger and Rutzinger 2011) which can be seen in Figure 2.16.

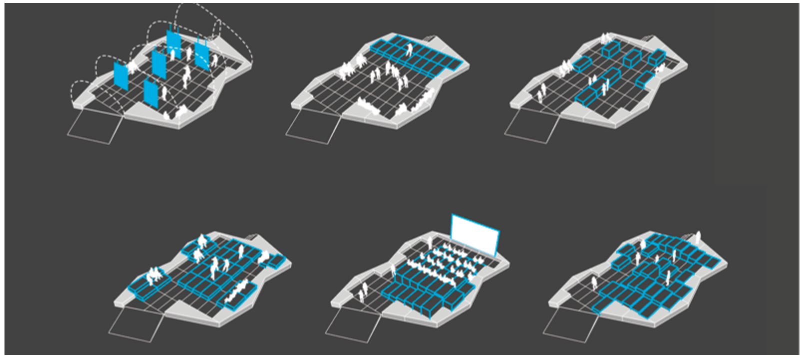


Fig. 2.14 Different configurations of the pavilion.

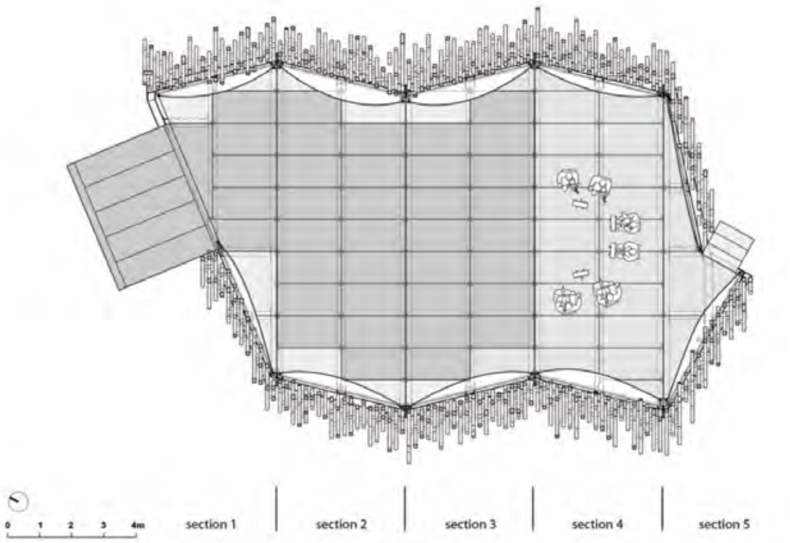


Fig. 2.15 The pavilion is divided into five segments.

The strategy of the pavilion is based on the aggregation of one single type of element to create a variation of spatial patterns. A series of different tests investigate simple base geometries and their potential as structures by evaluating the position of each bar in relationship to its neighboring members, taking into account the structural and geometrical edge conditions. To define the final shape, the tool Grasshopper had been used and a structurally optimized pattern was found with the help of the tool Karamba (Fig. 2.18). Furthermore, Karamba was combined with a genetic algorithm to extensively search for the right architectural and static solution.

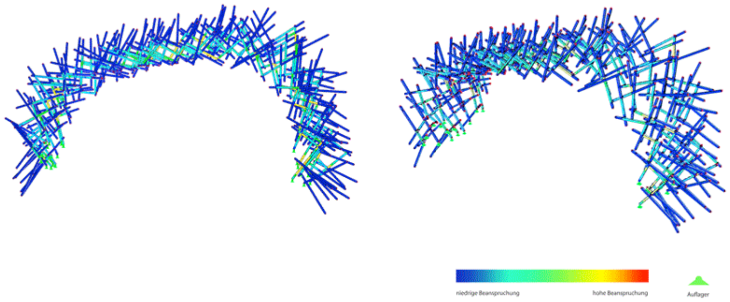


Fig. 2.17 Stress analysis in view and perspective.

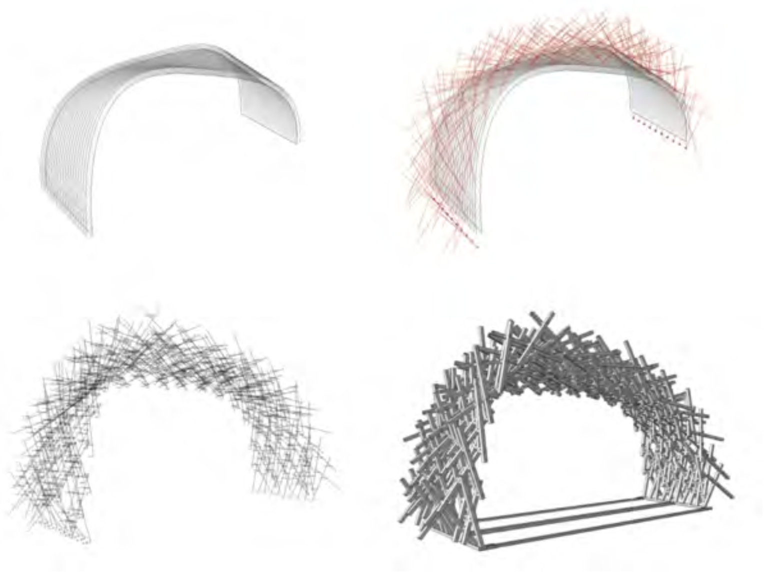


Fig. 2.16 Optimization of the structure.

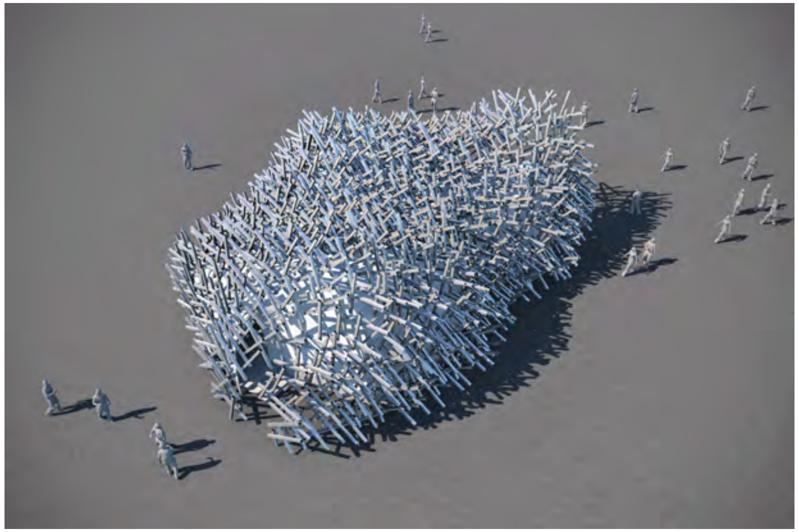


Fig. 2.18 Rendering of overall shape.

The programmed wall

Gramazio and Kohler, Architecture and Digital Fabrication, Architecture Department, ETH Zürich, 2006

With the help of a six axis industrial robot that reaches every point in a 3x3x8 m space, Fabio Gramazio and Matthias Kohler have developed an additive digital fabrication technique to create unique architectural elements. The component used in this additive process was the brick.

> A wall made of bricks is subject to the rules of mathematics, meaning the relationships (i.e connections) between the bricks, and can be described by an algorithm, and therefore "programmed". In turn, digital production allows direct translation of computer programs into physical artifacts.
>
> (Gramazio and Kohler 2008)

By using a common construction component, the design process concentrates mainly on the construction technique allowing students to design a constructive logic rather than a geometrical system (Fig. 2.19). The exercise was possible due to highly customized software and hardware tools. The design method was first developed in the Maya scripting software, followed by a post-processing script which was created for the translation of the output CAD models into a robotic specific procedural language. The robot was built with a custom made brick-gripper and later enhanced with a precise automated adhesive depositing applicator onto each brick (Guzik 2009) which can be seen in Figure 2.20. By accumulating materials precisely at the places where they are needed, the entire cross section of the wall can be manipulated, not just its surface. By waving both form and function into the building components, "architecture is 'informed' right down to the level of the material" (Gramazio and Kohler 2008).

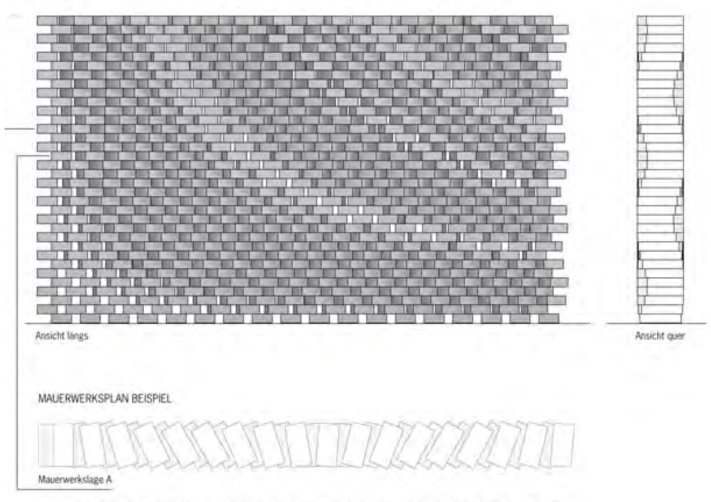


Fig. 2.19 Possible brick arrangement. View, plan and section.

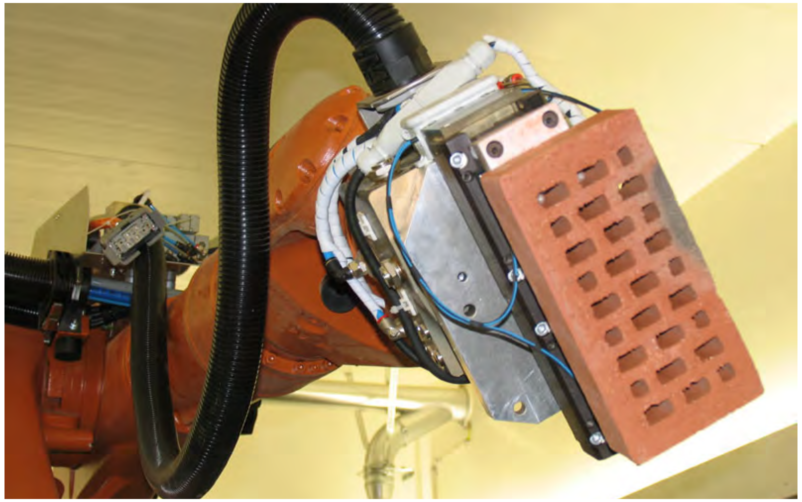


Fig. 2.20 The customized robot head.

The next step, “Flight Assembled Architecture”, made together with Raffaello D’Andrea works with stacking bricks which are assembled by flying robots (Quadrocopters). They pick up bricks and put them down exactly in the place and at the angle needed, reaching heights that the six axis robot cannot possibly reach. This type of production is closer to the economic efficiency ideal because there is almost no loss of material in the construction process, and the human involvement is reduced to simply programming the machine that stacks the bricks together.

SmartScrap

Ball State University, Indiana, 2008

SmartScrap is particularly interesting because it takes the flow of information from the fabrication back to the initial design decision-making and leads to an “applicable building component, while simultaneously reducing the waste generated during the fabrication” (Klinger 2008).

Composition methods can be implemented when designing with scrap materials. Unlike bricks and wooden slats, which require energy to be produced, scrap is already in its end-form. SmartScrap is a collaboration between the Institute of Digital Fabrication at Ball State University and the Indiana Limestone Industry aiming at testing ecological design strategies. With the help of a portable outdoor scanning technology system, the recording of heavy stone scrap objects into the digital space was made possible (Fig. 2.21). These pieces form a digital database of component pieces based on available sizes, shapes and quantities of stone scrap material. The catalogued information is introduced into a parametric design model. In SmartMosaic, a pilot project within SmartScrap, pieces with the same X and Y coordinates (but different Z heights) are used to create a parametric surface controlled by a b spline or an image data translation of pixels (Fig. 2.22).

Fig. 2.21 Scanning scrap with portable outdoor scanning technology.

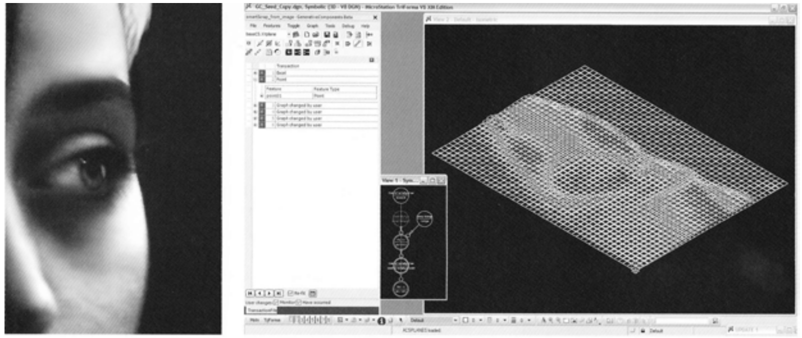


Fig. 2.22 Image data translation of pixels in the mosaic surface.

The model is supplied with information about the size, color and texture of each stone which allows the formal visualization of the design while the Visual Basic script questions the database for available pieces that could be plugged into the matrix. By deploying associative design and scripting capabilities, scraps of wasted limestone are reintroduced in the design process effectively.

Digital Origami

Chris Bosse, UTS master class students, Sydney, 2007

Taking advantage of the ability of folded paper to provide structure, Chris Bosse's project explores the material implications of structural surfaces.

> The aim was to test the fitness of a particular module, copied from nature, to generate architectural space, with the assumption that the intelligence of the smallest unit dictates the intelligence of the overall system. Ecosystems such as reefs act as a metaphor for an architecture where the individual components interact in symbiosis to create an environment.
>
> (Bosse 2007)

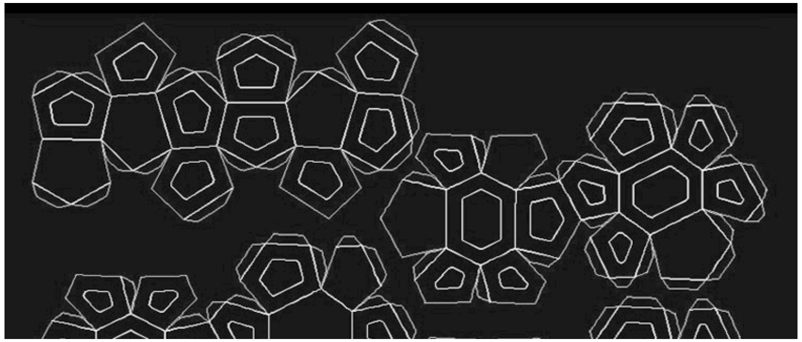


Fig. 2.23 Unfolded components.

"The bottom-up structural logic" (Iwamoto 2009) works with just two types of shapes in constructing 3500 modules out of recycled cardboard to create a reinterpretation of the traditional concept of space (Fig. 2.24). The building blocks are manufactured by laser-cutting the sheet of cardboard, and than folded into their desired shape (Fig.2.23). By adding the shapes to each other, a porous and open structure is formed. The outside fringes suggest a possible further growth and infinite reconfiguration in order to respond to different site conditions.

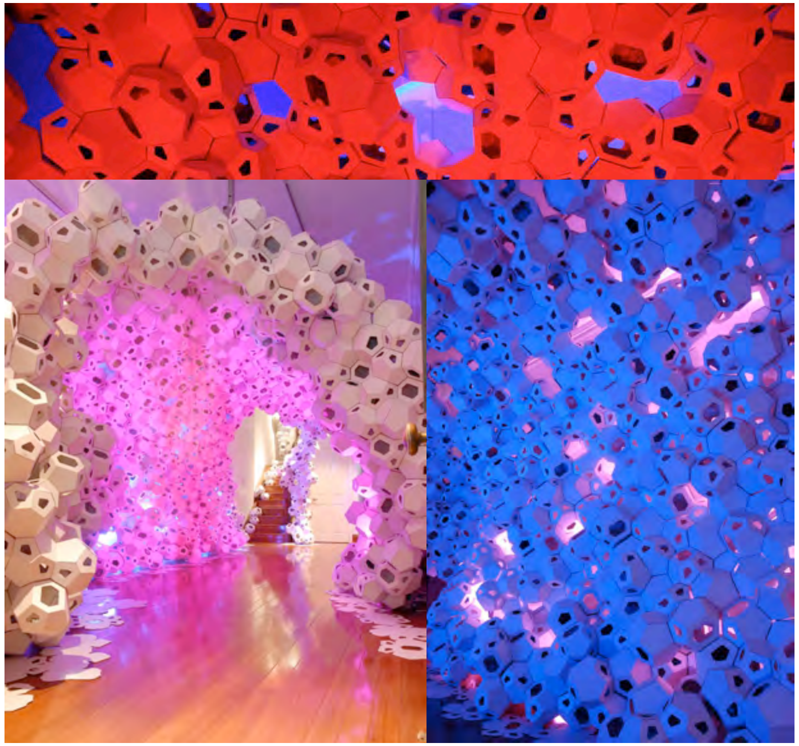


Fig. 2.24 Digital Origami installation.

2.2 Composite materials

> A material is efficient if its internal structure is optimally adapted to its purpose, thereby allowing the amount of material to be minimized.
>
> (Sauer 2010)

The materials of today are expected to be both sustainable and efficient. As the weight of a construction plays a significant role in saving energy and resources, increasing attention is given to materials which manage to combine ultra-light and high-tensile properties (Sauer 2010). Composite materials answer the the need of structural efficiency.

Composite materials couple a reinforcement material (fiber) and a matrix (lignin, cement, plastic, ceramics etc). One of the first material composites was the mixture of mud and straw seen in the Egyptian tomb bricks or the mixture of cementitious building material and animal hair (or plant fiber) developed by the Romans as one of the earliest forms of concrete.

Bio-composite materials combine natural plant fiber with a matrix of conventional or biodegradable polymers. One natural composite material is wood. Wood is made out of lignin (the natural polymer that fills the tree giving it compression strength) and countless cellulose fibers that transmit tensile forces. Because of that, wood can withstand both the compression forces coming from the branches and the tensile forces of a storm (Sauer 2010). Taking advantage of the internal structure of wood, Michael Thonet (1796-1871) developed a new style of furniture by softening the lignin with heat and water and subsequently bending the wood in the direction of the fiber. The fibers stabilize the shape and give it rigidity by keeping the cross section of the material to the minimum (Fig. 2.25).

Fig. 2.25 Thonet rocking chair No.1.

> Natural fiber reinforced polymers are up to 30% lighter than conventional fiber composites. The energy consumption required to manufacture renewable plant fiber is several times less than gloss or carbon fiber.
>
> (Sauer 2010)

Lightweight cars consume less fuel (Riedel 2007). As such, composite materials are of great interest to the automotive industry. However, since conventional plastics and fiber composites are harder to recycle, bio-composite materials have started to receive more attention. Biopolymers reinforced with natural flax fibers have been used by Four Motors to design the bodywork of BioConcept Car because they exhibit properties that are comparable to the fiber glass (Fig. 2.26). Additionally, the flax-cotton textile previously impregnated with linseed acrylate makes the car both stable and better at absorbing impacts.

Fig. 2.26 Four Motors BioConcept Car.

The award winning project for "environment and recycling" build by 3XN Danish architects as part of the Future Exhibition (2009) at the Louisiana Museum of Modern Art uses a flax fibers cast in a biological resin-based soybean oil and corn starch (Fig. 2.28). The inner core is made of cork sheets (Fig. 2.27).

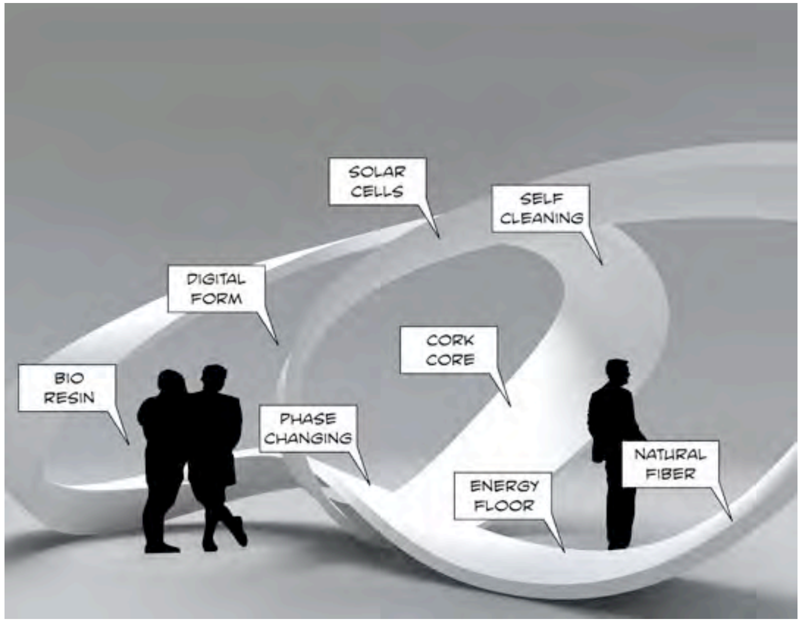


Fig. 2.27 Annotated rendering showing materials used for the pavilion.

Fig. 2.28 Pavilion at Louisiana Museum of Modern Art.

Both composition and decomposition methods explore a series of strategies in achieving efficiency in design and production. Soma and Gramazio and Kohler use scripting to create a variation of homogenous structures with one single type of element. Both Gramazio und Kohler's brick and Soma's aluminum bar are in their already established form or require minimal work to be finished which saving significant production energy in making the component itself. Moreover, Gramazio and Kohler use a robot to assemble their structure, thus reducing human input in assembling the structure and raising the speed and quality at which bricks walls are designed and built.

SmartScrap uses computation to put waste materials to new uses. Although the raw material does not need energy to be produced, scanning the stones requires time and manpower. However, with advances in scanning technology, this project has the potential to become economically feasible, as the building industry is still one of the largest waste producers (Sauer 2010).

Digital Origami is particularly interesting because it uses just two types of modules to create a structure that is flexible and can adapt to any kind of space.

Using a small number of different modules to generate various shapes based on different parameters (spatial, structural, formal, functional, etc) gives composition methods a high configuration flexibility with the same modules. Additionally, a classical component like a brick or a metal bar, will be much easier to replace should it be damaged than a uniquely shaped component.

Voussoir Cloud and Tesellion are two structural surfaces which use folding to obtain rigidity. Another efficient strategy for producing a structure is the use of sheet material instead of curved components because they need additional energy to be produced.

Inventioneering architecture is one project that manages to keep production costs very low by implementing a “continuous chain” in developing a series of scripts which translate the geometry in CNC machine milling code for each of the components. The assembly time is also reduced because the components are simply arrayed one after the other. The gradient surface makes arranging and cutting the components out of the MDF sheets very efficient because the gaps are minimized due to a tight arrangement.

In conclusion, building an efficient structure means taking care of both the production process and the possible use it might have. Knowing the material qualities, as well as the technological possibilities and limitations can determine very much how much time is spent in developing a quality object.

3.CASE STUDY

Although inspiring in their design, the projects in the previous chapter, offer limited information about the intelligence of the 3D models, the qualities of the material used and the design strategies that took them there. Even for design experts, replicating the projects would be very hard. The process model offered by Scheurer for example (2005), only explains the part between the design and production phases and it is useful only for decomposition methods. As information is even more limited about process models regarding composition methods, a case study was developed and documented in order to understand what the steps of a design and production process are, and what decisions need to be taken.

The case study has been developed during one semester and was realized by seven people:

Ana Maria Marcu - material testing, manufacturing of models, presentations, analysis of 3D model, design decisions and project management.

Kristof Retezar - construction and assembly of 1 mm and 2 mm cardboard modules, modules painting, paint testing, laser cutting 1mm cardboard sheet.

Dietmar Kolar - construction of 1 mm and 2 mm cardboard modules, modules painting, laser cut testing of 2mm cardboard, test irregular module, assembly of the final structure.

Daniel Wyrobal - test irregular module, construction of 1 mm and 2 mm cardboard modules, assembly of the final structure, logo design.

Niko Schwarz - test irregular module, joints development for 1mm and 2 mm cardboard structure, construction of 1 mm and 2 mm cardboard modules, assembly of the final structure.

Deniz Önengüt - Costs overview, sponsorship search.

Jan Pernecky - parametric 3D modeling, laser cutting of 1mm cardboard sheet.

The experiment is divided in five parts and can be followed in the Diagram 1. The first part describes the requirements which were important when developing the structure. The second part is about testing different materials and geometries to find the right combination between the two. The “Final shape” chapter portrays the selection process for the geometry type that suits the material and technique developed in the previous chapter. Starting with “Refining the final shape” chapter six other students were involved. Together, the structural attributes of the material in its end form were tested, and the final assembly system was developed. As 3D explorations have not been able to offer helpful information, a new way of creating variation within the modules was developed using the knowledge acquired by working with the material. The final chapter outlines the steps taken in fabricating and assembling the end structure.

Diagram 1


REQUIREMENTS
CONCEPT STUDY
FINAL SHAPE
REFINE AND TEST FINAL SHAPE
PRODUCTION
SELF-SUPPORTED STRUCTURE
FLEXIBILITY
EFFICIENCY
CURVED COMPONENTS
SPATIAL PARTITION
MATERIAL
GEOMETRY
IDENTIFY MATERIAL CANDIDATES
PLASTIC
CLAY
PLASTIFIED PAPER
PAPER
FOAM
COMPONENT - WORK WITH ALREADY EXISITING COMPONENTS AND DETERMINE VARIOUS WAYS TO ASSEMBLE THEM
WORK WITH STRIPS AND DETERMINE THE BASIC GEOMETRY OF THE COMPONENT
MODULE- TRIANGLE (3 STRIPES) AND TETRAHEDRON (36 STRIPES)
RESULTING SHAPE- AGGREGATION OF TETRAHEDRONS
TEST RIGIDITY - SCALE
PLASTIC
SOAK THICK TEXTILE IN TEXTILE HARDENER
SOAK THIN TEXTILE IN TEXTILE HARDENER
SOAK PAPER THIN
SOAK FOAM (1,5 mm) IN TEXTILE HARDNER
SOAK FOAM (5 mm) IN TEXTILE HARDENER
COMPONENT -KEEP BASIC SHAPE
MODULE - 12 NUMBER OF STRIPS PER TETRAHEDRON
TEST DIFFERENT WAYS TO COMBINE THE COMPONENT
RESULTING SHAPE- AGGREGATION OF TETRAHEDRONS
DETERMINE THE TYPE OF CARDBOARD
SOAK CARDBOARD LAYERD
SOAK CARDBOARD PRESSED (1mm)
COMPONENT -KEEP BASIC SHAPE
MODULE - TEST DIFFERENT WAYS TO COMBINE THE COMPONENT
COMPONENT -CHANGE BASIC SHAPE
MODULE - TETRAHEDRON. 12 NUMBER OF STRIPS PER TETRAHEDRON.
RESULTING SHAPE- AGGREGATION OF TETRAHEDRONS
DETERMINE THE SIZE AND PROPORTIONS OF A REGULAR MODULE
-WORK WITH 2mm CARDBOARD
- TEST DIFFERENT STRIP WIDTHS
- DETERMINE THICKNESS OF STRIP
-DETERMINE PROPORTIONS OF THE TRIANGULAR SHAPE IN RELATIONSHIP TO THE STRIP WIDTH
-DETERMINE THE TYPE / AMMOUNT OF JOINTS
-TEST PAINT
-DETERMINE MANUFACTURING STEPS AND MATERIAL NEEDED
DETERMINE THE RULES OF VARIATION
-TRIANGULAR SHAPE STAYS THE SAME
-LENGTHS OF STRIP VARIATE
TEST DISTORTED MODULE
PARAMETRIC 3D MODEL
-ONE TETRAHEDRON
-AGGREGATION OF DISTORTED TETRAHEDRONS
TEST LASER CUTTER
-INTENSITY/ SPEED OF BEAM
-WASTED MATERIAL
CUTTING
--CUT STRIPS 9/ 103 CM WITH THE PAPER CUTTING MACHINE
-CUT STRIPS IN 9 DIFFERENT LENGTHS
PRODUCTION AND ASSEMBLY
1. SOAK STRIPS
2. LET HALF DRY
3. GLUE
4. LET DRY
5. JOIN MODULES
6. PAINT
7. JOIN FINAL SHAPE

3.1 Requirements

The main requirements for building a lightweight self-supported structure were to make both a formally intricate and an economically feasible structure. That means achieving a degree of efficiency by obtaining maximum results with minimum cost, energy and resources. The structure should be flexible in the way the modules are combined with each other such that it can adapt to any kind of space. Another objective was to develop curved components that could be fabricated without molds. The structure was intended to be principally a space partition without any additional thermal or acoustical qualities.

3.2 Concept study

3.2.1 Identify material candidates

In order to understand how the composition design method works, the first experiments have been made with components of preexisting systems like the Rondi 25 Game (Simm 2010) and playing cards. Rondi 25 components are 2 mm thick plastic circles cut at 45 degree allowing the attachment of another piece only at angles of 45 and 90 degree angles (Fig. 3.1). The reason they were chosen is because the components are the result of a fabrication process that implies cutting standard sheets of material. In these two particular cases, all the component parts are the same offering a set of opportunities and limitations. The aim was to see whether creating space-filling polyhedrons or tessellations with them would result in a self-supporting system. Another goal was to see if achieving a curved surface would be possible with a limited type of components (Fig 3.4). As a result of various tests, it can be concluded that the flexibility of the material (Fig. 3.2) compensates for certain irregularities which is hard to perceive without working with the material (Fig. 3.5).

> A polyhedron is a 3D shape that consists of planar faces, straight edges and vertices. Each edge is shared by exactly 2 faces and at each vertex at least three faces and three edges meet.
>
> (Pottmann, Asperl et al. 2007)
>
> A space-filling polyhedron, is a polyhedron which can be used to generate a tessellation of space.
>
> (Weisstein 2002)

> A tiling of regular polygons (in two dimensions), polyhedra (three dimensions), or polytopes (n dimensions) is called a tessellation.
>
> (Weisstein 2002)

Fig. 3.1 Basic component of Rondi (left); basic component of Playing cards (right).

Fig. 3.2 Rondi elements illustrating the flexibility of the material together with the joints.

Fig. 3.3 Rondi pieces joined at 45 degree angles creating a tessellation of space.

Fig. 3.4 Tests of curved modules.

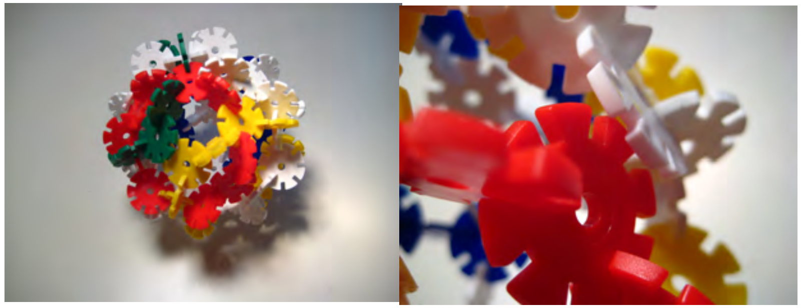


Fig. 3.5 Left: one polyhedron; right: overlapping of the components.

Fig. 3.6 Different types of modules.

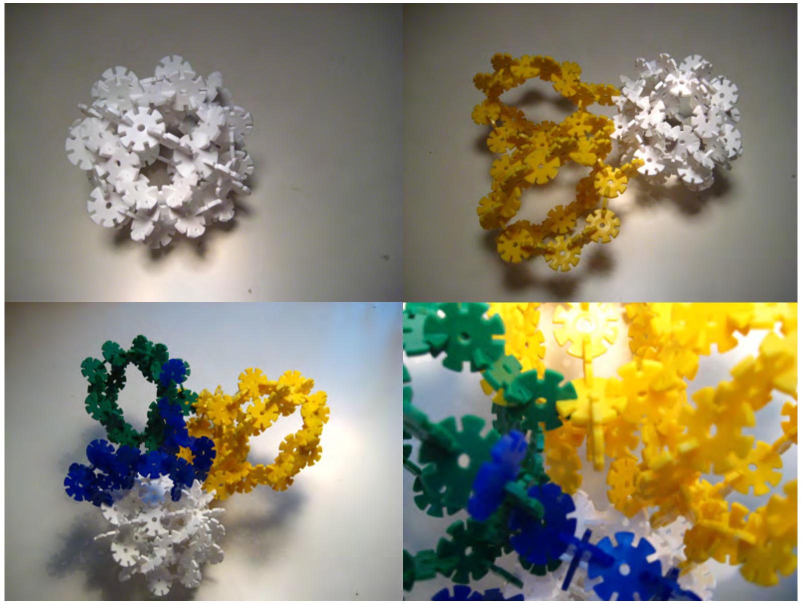


Fig. 3.7 One module (top left); three modules (top right); four connected modules (bottom left); detail of the connection of the four modules (bottom right).

In Fig. 3.7 the tests made in finding a system of connecting the modules can be seen. Three particular formal qualities looked at were density in relationship to light and colors.

The fixed 45 degree angles do not allow for other space filling polyhedrons beyond the cube and the prism (Fig. 3.3). Additional to that, adding more parts in the system, result in more stress added in the joints. The agglomeration of modules create a homogenous kind of surface (Fig. 3.6).

The second material tested was plastified paper, the composing material of playing cards (Fig 3.1). Playing cards have the geometric shape of a rectangle which is easy to arrange on a standard sheet of paper and therefore, the loss of raw material required to manufacture them is very low. Using the joining technique of the IQ lamp (Strom 2012) and applying solely geometric principles and material properties to join its components, a rhombic dodecahedron shaped module was achieved (Fig. 3.9 and Fig 3.10). A rhombic dodecahedron is a space-filling polyhedron with 12 rhombic faces (Fig. 3.8). The idea to make a polyhedron out of playing cards is not original. Other designers have tried it as well (Hart 2001). The aim was however, to test the material possibilities in achieving a system of connecting modules.

As a result of these tests, it was concluded that a planar sheet of paper can achieve curvature and become three-dimensional if it is stressed and kept in that position in certain points. Furthermore, a tessellation of space cannot be achieved if the faces of the polyhedron are rising out of their plane because too much stress would be added to the joints. Because the joints are too fragile and tight, they are not able to hold too many corners. Adding other modules resulted in torn components. Should the joints become bigger, the curvature of the playing card is almost unrecognizable.

Fig. 3.8 Left: one rhombic dodecahedron; right: a tessellation of space of rhombic dodecahedrons.

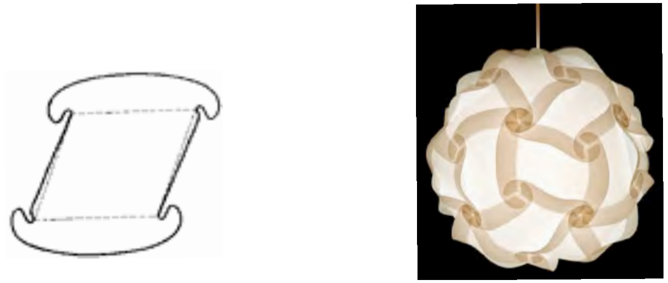


Fig. 3.9 Left: one IQ lamp component overlapped on a rhombic dodecahedron's face; right: the IQ lamp with 30 components.

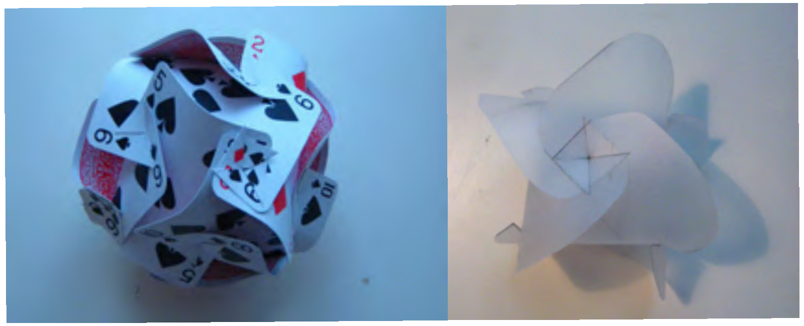


Fig. 3.10 Left: A rhombic dodecahedron made out of playing cards; right: a pyramid made out of semi-transparent paper.

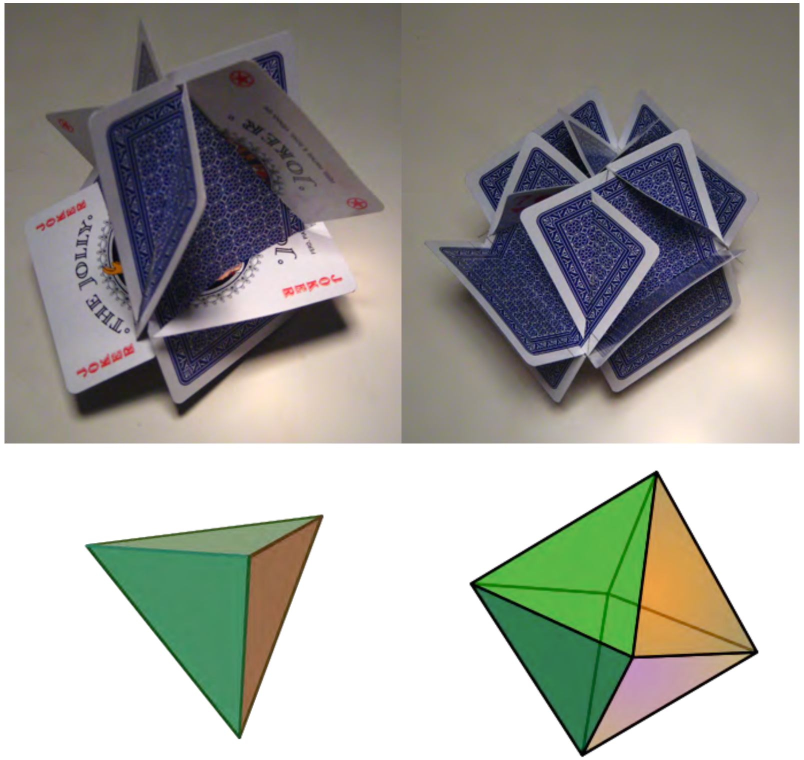


Fig. 3.11 Top: a tetrahedron (left) and an octahedron (right) made out of playing cards. Bottom: left - a tetrahedron and right - an octahedron.

Tests of building polyhedrons with straight faces were made in order to test whether it would be easier to combine them without the added stress from curving the paper (Fig 3.11). The joints however, were far too fragile and could not hold many components. Continuing with paper, this time not plastified, because it is a cheap and available material, an experiment was made using a tessellating pattern (Butterfly, tessellation 70) from one of the paintings of M.C. Escher (1898 - 1972).

The reason his drawing was chosen is because he found a solution of arranging components on a plane which is one step that most professionals in digital manufacturing deal with: arranging components on a sheet of material such that only very limited amount of material is lost when they are cut (Fig 3.12). If arranging the components and determining a way of assembly could be done at the same time, this could result in both a formally interesting and efficient structure. In Escher's drawing, a group of three butterflies create a triangular shape. Four connected triangular shapes build a tetrahedron. However, as the triangles do not have straight edges, conflicts appear when joining the parts. More work on the shape and joints needs to be done in order for a coherent system to grow out of it.

Fig. 3.12 Left: Butterfly, tessellation 70 (M.C. Escher); right: one tetrahedron composed out of four triangular shapes cut out of the tessellation.

Clay was chosen because it offers the possibility to create curved components when it is soft, and once it is dry, it becomes rigid (Fig. 3.13). This could contribute to a self-supported system. Unfortunately, the material is very soft and it is difficult to hold it in the desired shape without a mold, which goes against the pre-established requirements.

Fig. 3.13 Curved components made of clay.

The last material tested at this phase was foam rubber. It is 1.5 mm thick and it comes in A4 and A3 sizes. The material is soft and although very malleable, it is very resistant to stretching. Taking Escher's example, the components were realized by subdividing a sheet of material. Equal sized strips were cut out of an A4 sheet. The strips were than made into a loop and stapled together. What was noticed is that if the loop is rotated once and than joined, the whole structure would have an added resistance (Fig. 3.14). Developing the component, the strip is bent into a loop and stapled. This loop is bent once towards the inside as well (Fig. 3.15).

With this component, several experiments were made to test gradience, rigidity and various ways of assembling them in a module (Fig. 3.16).

Fig. 3.14 An agglomeration of twisted strips of foam.

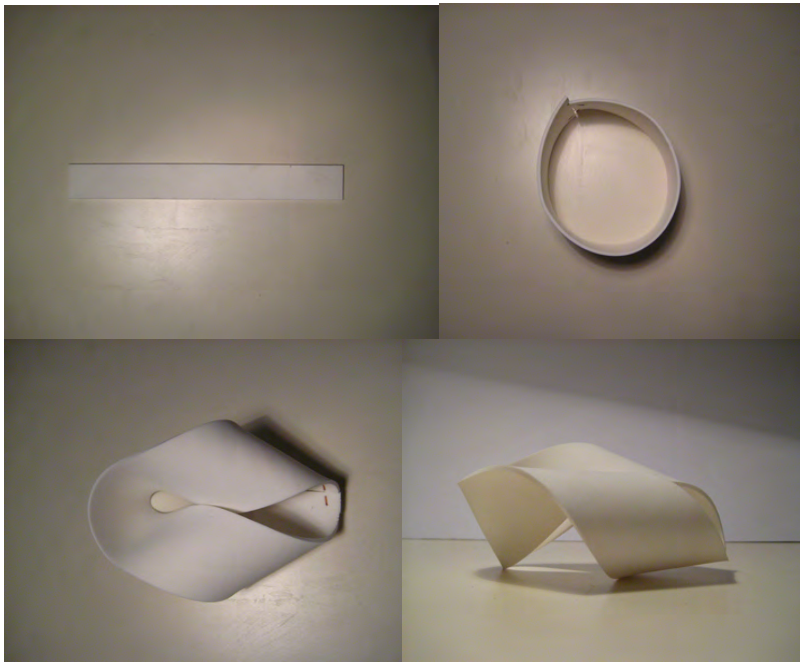


Fig. 3.15 One strip of foam, bent once to make a loop and stapled at the ends (top). Basic component: one stapled loop bent once (bottom).

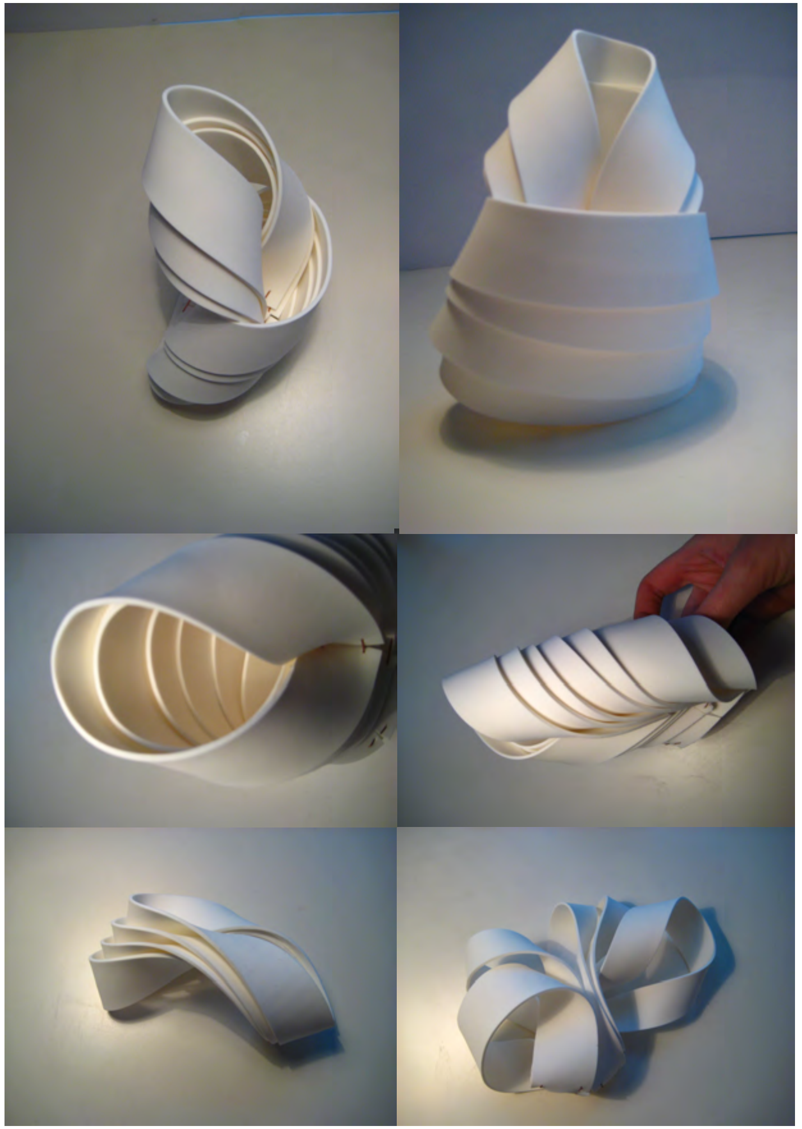


Fig. 3.16 First tests of gradience, lightness and rigidity.

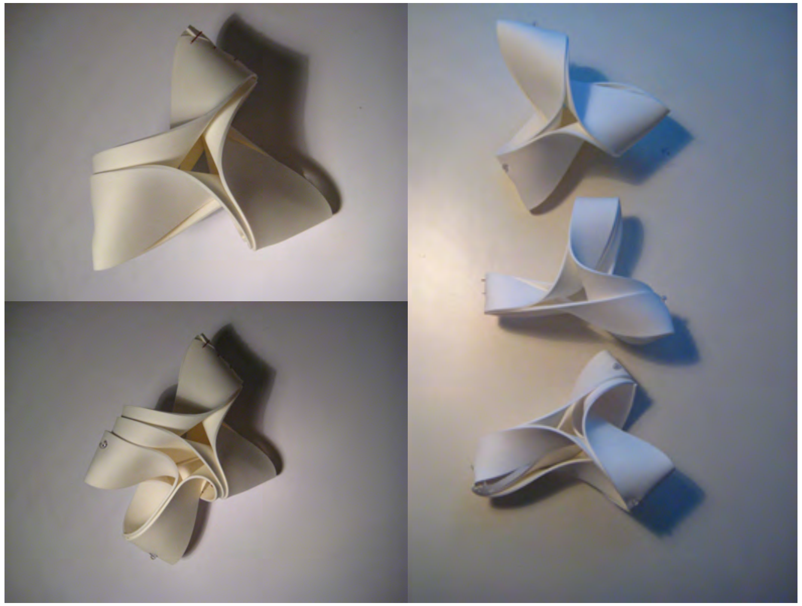


Fig. 3.17 The module (top left); different types of modules (right); two interlocked modules (bottom).

Interlocking three components within each other, one rigid self-supported module is realized. Different component lengths and widths can create modules of different sizes but they can also make the module loose and unstable. It was determined that the proportion between the length and width of the strip which creates the component needs to be established such that the right rigidity is achieved (Fig. 3.17). Further tests have been made with the module realized out of three components in order to determine a logical way of combining them (Fig. 3.18).

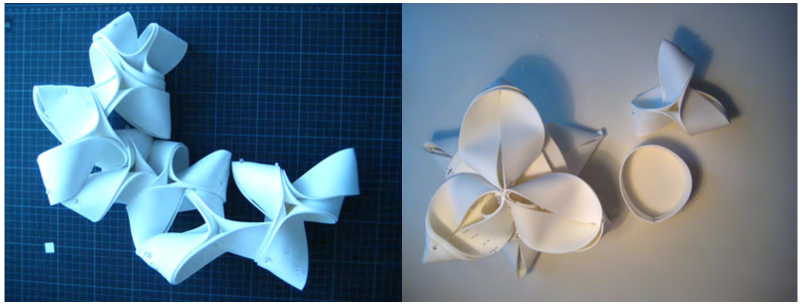


Fig. 3.18 First experiments with the module (left). Bent loop, module and a structure made by interlocking modules on the side (right).

By using geometric principles, three modules were joined at the side which made one triangular shape between their most extreme points. Four of these triangular shapes create one tetrahedron shaped module (Fig. 3.19). Adding several tetrahedrons together however, makes the material bulge between the triangular shapes (faces of tetrahedrons) and adds stress to the joints (Fig. 3.20). As a result, working with a more rigid material and developing a new joining strategy was needed.

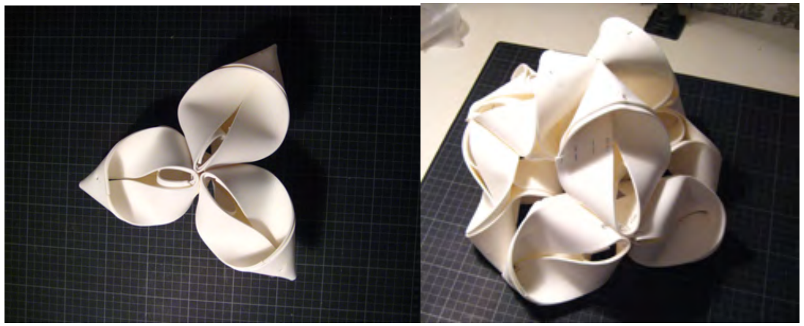


Fig. 3.19 Three modules joined on the side (left); one tetrahedron (right).

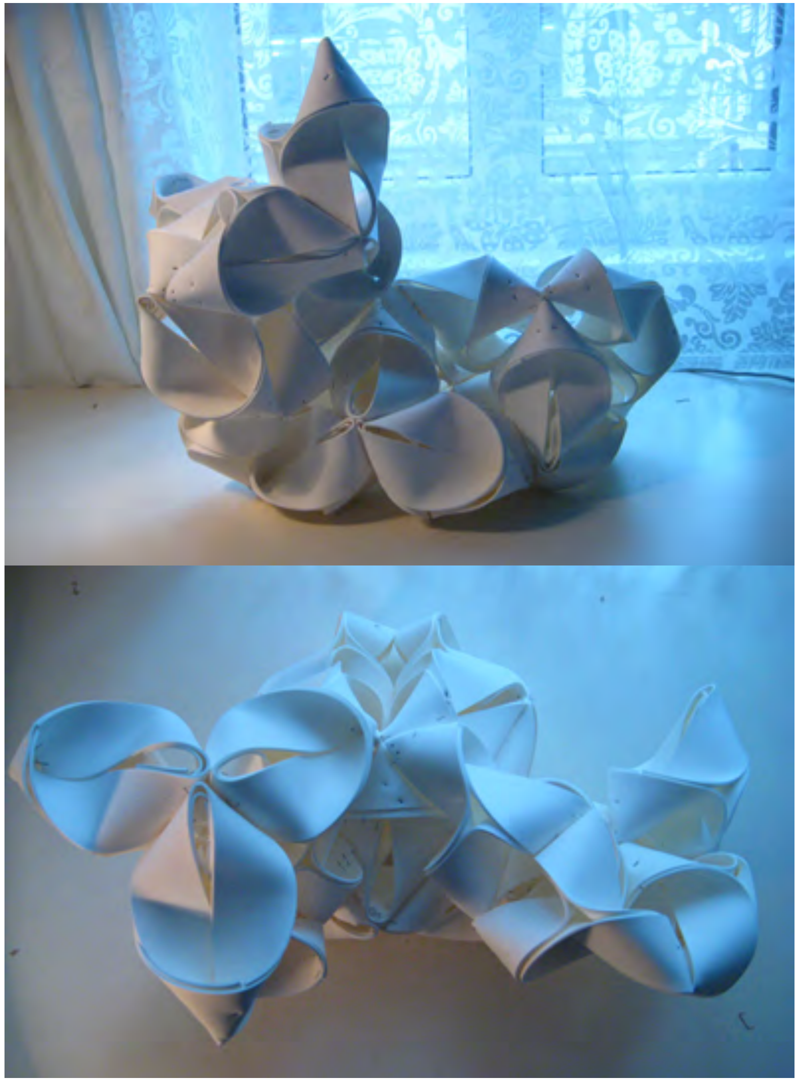


Fig. 3.20 Four incomplete modules inscribed in regular tetrahedrons joined together. Front view (top); top view (bottom).

3.2.2 Test rigidity and scale

The aim of this step was to maintain the wavy component of the previous model while achieving rigidity and a larger scale model. As such, experiments with other materials were made. The fabric hardener, Powertex was used to solidify thick textiles, foam and paper. Working with other materials, means taking advantage of other qualities, which changes the overall shape, the way to assemble the components, and the type of joints.

> Powertex is a fabric hardener, an environmentally friendly water-based alternative to polyester. Powertex is a hardener for all absorbent and preferably natural materials such as textiles, paper, cardboard, leather, plush and fiberglass. Items can be dipped directly into Powertex or brushed on. Once applied, Powertex begins to dry but will remain flexible for hours, depending on room temperature. Powertex is weather resistant and suitable for use outdoors. Powertex is environmentally friendly and cleans up with soap and water.
>
> (Powertex 2008)

Once the various materials are soaked in the fabric hardener, the main problem that appeared was keeping the components made from them in a certain shape, which can only be done with the help of molds (Fig. 3.21). Casting molds is very expensive especially if the components of the structure are numerous and different from one another. Therefore, the main challenge was to create curved components without molds which is why the previous bent loop idea was kept.

Fig. 3.21 Powertex bottle (left). Basin of water with textile hardener solution in which different paper, foam and textile materials are soaked.

Fig. 3.22 Painted rubber foam with textile hardener in pure state.

First from the experiments involving soaking in textile hardener, was the foam rubber material (1.5 mm and 5 mm), which did not absorb any liquids, leaving the textile hardener as a superficial layer that cracked the moment the material was in any way pulled or twisted (Fig. 3.22).

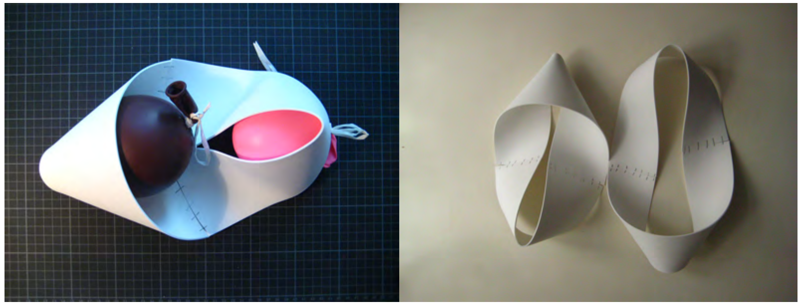


Fig. 3.23 Larger component made from 1.5 mm thick rubber foam held by balloon molds (left); different component sizes made from 1.5 mm rubber foam (right).

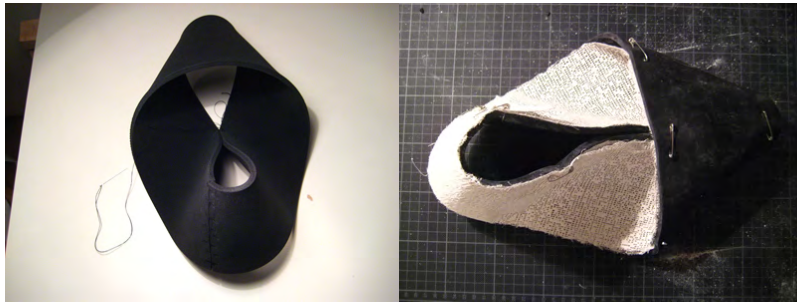


Fig. 3.24 Larger component made out of thick foam material (5mm) used afterwards as a mold for a light textile material (right).

Following the previous tests, larger components were made. This was done by stapling two strips of foam together as the sheets of foam only come in maximum A3 sizes. One challenge was to hide the stapled joints but also, to keep the shape intact after soaking the foam in textile hardener. The solution for that was to use a standard, flexible and inexpensive mold - a balloon (Fig. 3.23). As results did not turn out as expected, a thicker foam material was tested by soaking it into water with textile hardener (Fig. 3.24). The thicker foam behaved similarly to the thin one by keeping its previous properties intact.

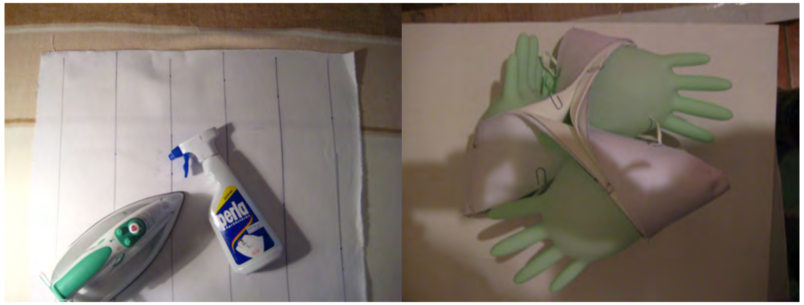


Fig. 3.25 Textile sprayed with a textile strengthening solution used for shirts (left). Textile soaked in hardener held by foam rubber molds and balloons (right).

Fig. 3.26 Three conical shaped molds for keeping the cement shape in place (left); one conical shape in production (right).

The next experiment was with textiles (Fig. 3.25). As the textile hardener is a very thick and heavy liquid, the textile had to be stretched on a fixed mold. First, the textile was prepared by being sprayed with a starch solution that strengthens the textile. After soaking it into pure textile hardener, the textile was places on the previously prepared foam shaped components. The foam components were used as molds and the textile was fixed on the mold with paper clips. Aiming for cheap molds, balloons (inflated gloves) kept the shape intact (Fig. 3.25). Once dried, it was impossible to remove the paper clips. The textile was indeed stiff, but still very fragile for a construction. Neither the use of molds nor the amount of textile hardener needed were plausible solutions for a construction.

Another possibility was to work with fiber cement sponsored by a cement factory in Germany (Rieder 2004). As cement is very heavy, designing easy to transport molds which can hold a cement shape intact was desirable. As a result, three conical inflatable shapes made out of 0.5 mm PVC were developed (Fig. 3.26). However, cement is not a lightweight material and working with it would imply a different range of safety measurements, testing and detailing. Also testing cement would mean traveling to the cement factory in Germany several times which was not cost effective.

Looking for a rigid, but cost effective material, thick paper was tested. Paper and cardboard are two very common materials used in architecture and design schools. They are easy to find and manipulate, and the university provides all the machines needed in cutting them. Cardboard is a rigid material, which will not allow many changes to its original shape without folding or breaking. Therefore, soaking the paper (and subsequently cardboard) in water mixed with textile hardener was an interesting option worth exploring. When wet, paper changes its properties and becomes easily malleable. Due to the textile hardener, once it is dry, it remains in the shape it was left when it was wet. About 0.33 liter of textile hardener was used for all the experiments. The textile hardener (Powertex) and water solution is so strong that the mixture could have continued being used for many more parts just by adding more water. First experiments were with thin folded paper. Although the material has an added rigidity, it was still too soft and therefore, the next tests were made with thick paper.

Fig. 3.27 Folded paper (left); soaking folded paper (right).

Fig. 3.28 Stapled loops out of thick paper strips (top left). Component kept intact after drying with the help of tea cups (top right). Components drying (bottom left). Shape of components after drying (bottom right).

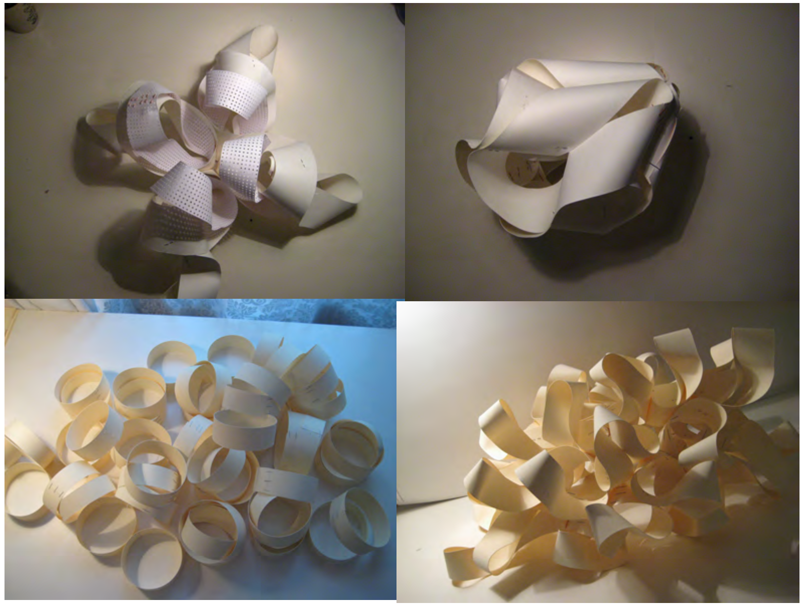


Fig. 3.29 Combining the components into modules (top). Small paper loops (bottom left). Random combination of loops (bottom right).

The thick paper tests were made by cutting various colors of A3 paper sheets along their width such that they are divided in equal parts. The next challenge was to keep the curves of paper components in place without the use of additional molds. After leaving them on the table to dry, it was observed that the wet paper follows gravity and the wavy initial shape tends to replicate the surface of the table. Thus efforts were made to keep the curves in shape with the help of tea-cups (molds) but that was not an answer for the set requirements. However, if gravity can be used to keep the curves of the components intact, that would make the system more efficient. Hanging the parts with the curved side down provided an easy way of keeping the curvature of the components without having to fabricate molds as well (Fig. 3.28).

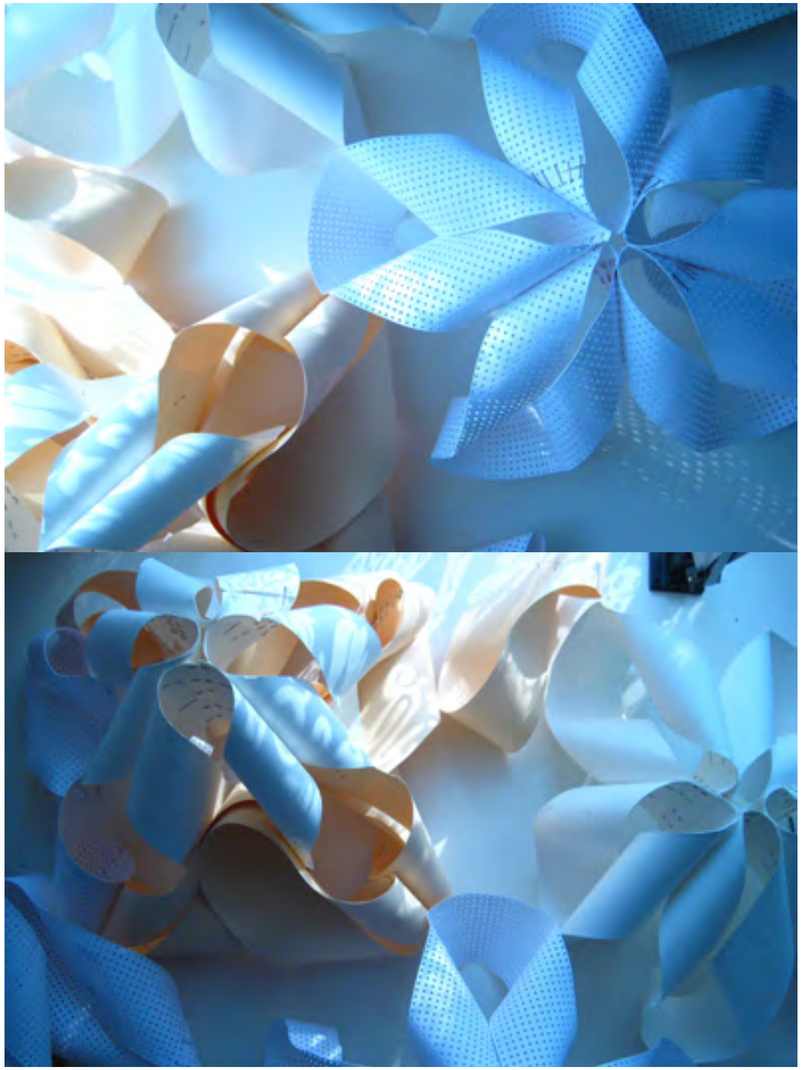


Fig. 3.30 Various modules.

Once the components were ready, different ways of combining them were tested. The behavior of the joints, stiffness, density, colors and transparency of the overall model were looked at. The joints used are staples, which were not resistant when many components were joined together. First tests were to create modules, which can be seen in Figure 3.29 and figure 3.30 but could not be developed into growing system. The following tests were executed to create a surface by joining the components on the side (Fig. 3.31 and Fig. 3.32). However, the location of the staples was imprecise and the surface lacked rigidity.

Fig. 3.31 Components joint on the side.

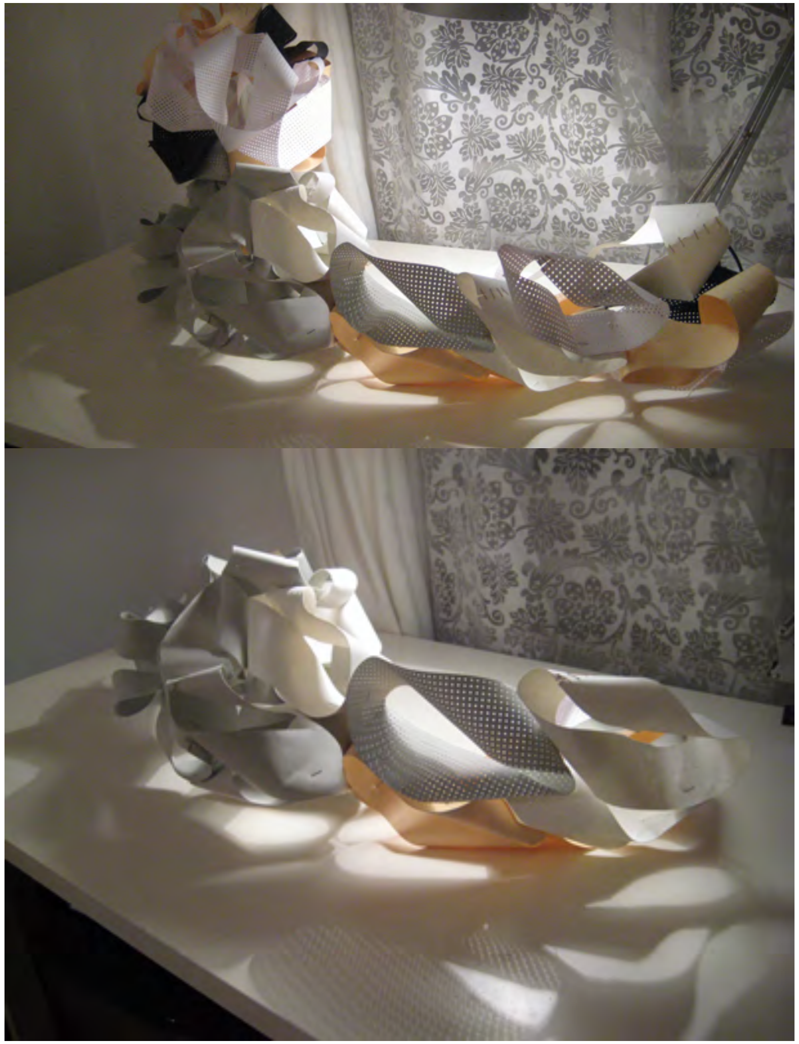


Fig. 3.32 Light, color and vertical growth tests.

Coming back to the last idea of creating a structure out of adjacent tetrahedrons, the triangular face of a tetrahedron was redesigned with the help of only three components rotated at 120 degrees from each other and joined in the middle by inserting them into one another (Fig. 3.33). One tetrahedron is composed of four such triangular shapes. The tetrahedrons have been simplified from thirty-six components (from the foam model) to twelve. The components were joined with staples but the joints were very fragile and the paper broke easily. The position of the joints was imprecise and the overall system was soft which would not resist well to added weight from attaching more modules. Similar to previous tests, observations of color, light, and density were made (Fig. 3.34).

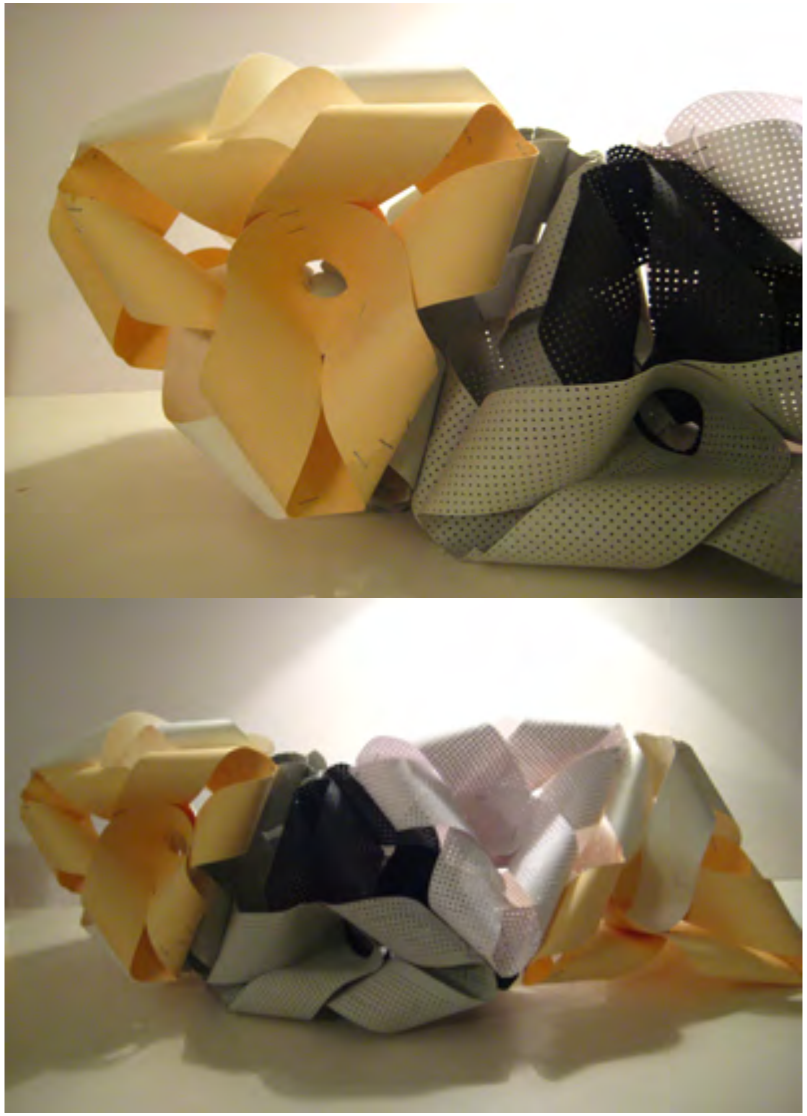


Fig. 3.33 The triangular face of a tetrahedron (top); four joined tetrahedrons frontal view (bottom).

Fig. 3.34 Four joined tetrahedrons top view.

3.2.3 Determine cardboard type

Once paper had been established as a working material, two principle explorations were made: one looking for the right type of cardboard, the other for a coherent way to assemble the component. Starting with this phase, solely for the manufacturing and assembly of the 1 mm and 2 mm cardboard structures and developing the 3D model, six other students joined the project.

After testing various types of cardboard, it was determined that certain types behave better than others (Fig. 3.36). Layered cardboard behaves badly because the layers tend to stand apart from each other when in contact with water (Fig. 3.35). The best behaviors were exhibited by gray pressed cardboard and timber based cardboard which absorbed the solution evenly, remained intact, and showed a high rigidity level once dry. By continuing to make curved components without molds, it was established that between the two types of cardboard, the gray pressed cardboard had the additional advantages that it did not break if the curves were very tight and it was also considerably cheaper than the timber based cardboard.

There is a direct relationship between the type of cardboard, its thickness, the temperature of the water and the amount of textile hardener in the water. The hotter the water, the easier it is to change the properties of the cardboard, especially if it is a very thick reflecting directly on the amount of time needed to make the cardboard flexible enough to bend. The stiffness of the material depends on the material thickness and the amount of textile hardener in the water. A normal piece of paper will not be much stiffer if the hardener content is increased. A 2 mm carton-board will show a big difference.

Fig. 3.35 Layered cardboard soaked in water and textile hardener solution.

Fig. 3.36 Components made from various types of thick paper (left); components made from timber cardboard bent without molds (right).

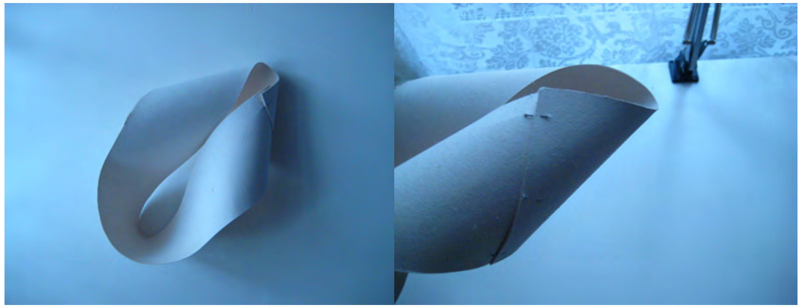


Fig. 3.37 Staples positioning on the component.

The aim was to change the properties of the material such that it becomes stiffer but also to allow it to be a little elastic as to permit certain construction inequalities that may appear during assembly. By manufacturing the component in different scales and with different cardboard thicknesses, the material limitations were tested. While thin paper is very elastic and allows for adjustments to be made, cardboard is quite inflexible once it has dried and therefore, it needed not only stronger joints but also precise positioning. Particular attention was given to hiding the staple holding the component, such that they would be noticeable as little as possible inside the construction (Fig. 3.37).

The tests continued by keeping the shape of the component but raising the scale (50 cm long) using a 1mm thick cardboard. The strips were cut out of A0 sheets of cardboard (80/100 cm) in sizes of 10/100cm. The scope was to fully use the sheet of cardboard. After soaking, the components were again hanged on one of their sides. It was observed that there is a direct relationship between the size of component, its thickness and the amount of textile hardener used. For example, a 20 cm component made out of 2 mm cardboard would be more rigid than a 50 cm component (Fig. 3.38).

Fig. 3.38 Soaked components drying (left); work process (right).

The components realized were large, covering a lot of space but far too soft under pressure. Slightly shorter strips would have generated stiffer components. Difficulties were also noticed at finding a system of combining the parts. The first experiment was to realize a module that would replicate the shape of a tetrahedron, but because it lacked stiffness, additional side components were needed (Fig. 3.39). Difficulties were also noticed when trying to join several such modules. A vertex point joint was developed but it proved unstable (Fig. 3.40). As a result, different types of modules were tested (Fig. 3.42). The main problem was that the shape of the component was such that it would not permit the addition of other modules to it. Also the lack of a wireframe guiding a precise geometrical combination of these modules was an obstacle in building a structure (Fig. 3.43). The joints used at this phase were rivets and zip ties (Fig. 3.41) which proved to hold very well.

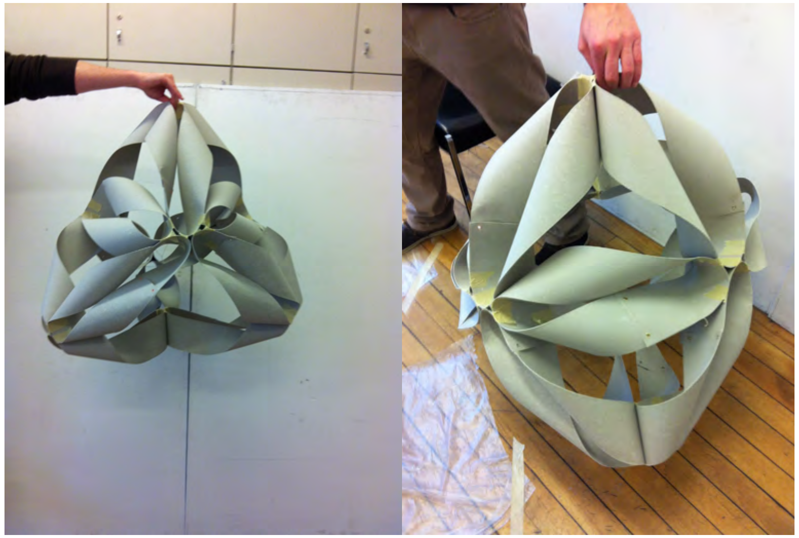


Fig. 3.39 The module inscribed in a tetrahedron.

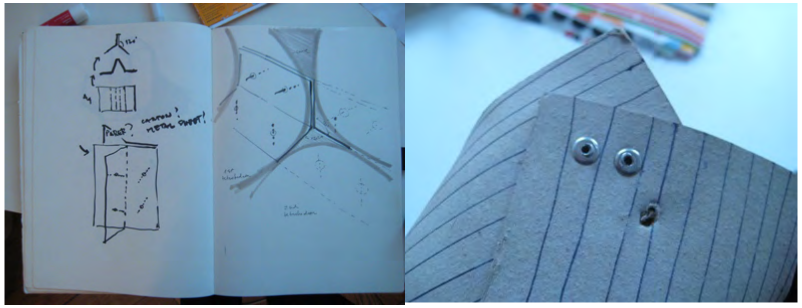


Fig. 3.40 Detail design for the module inscribed in a tetrahedron (left); testing rivets on cardboard (right).

Fig. 3.41 Joint components with plastic zip ties.

Fig. 3.42 Different modules tested.

Fig. 3.43 Agglomeration of modules.

3.3 Final shape

Due to the difficulties the component was creating, its redesign in relationship to the module was needed, such that the module would allow the possibility to connect with other modules easily, and it would suit the cut/ soak/ glue process developed until than. The initial design idea of making an agglomeration of tetrahedrons was renewed. The module therefore, was inscribed in the shape of a tetrahedron and the flaps of three components are glued together in the shape of an equilateral triangle to create one triangular shape (Fig. 3.44).

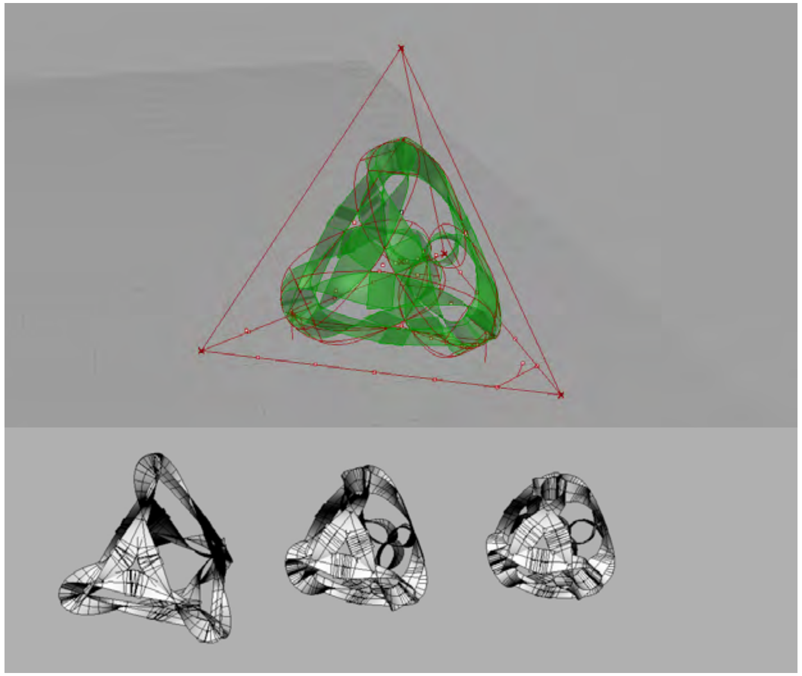


Fig. 3.44 Module inscribed in a tetrahedron (top); different sizes of modules created by pulling the vertices of the tetrahedron (bottom).

The idea behind it, is to have a planar triangular shape on all the faces of the module (and consequently tetrahedron), which will than easily connect to the planar shape of another module and therefore, it would result in a system of aggregation of modules. One face of the module is created by crisscrossing the flaps of three components at 120 degrees angle resulting into a regular triangle between their arms (Fig. 3.46). Twelve components recreate the module inscribed in a tetrahedron. Initially experiments with small paper modules were made by cutting on the length of colored A4 paper and assemble the strips with staples. Together with the shape, studies of color and modules variation based on strip width have also been made (Fig. 3.45).

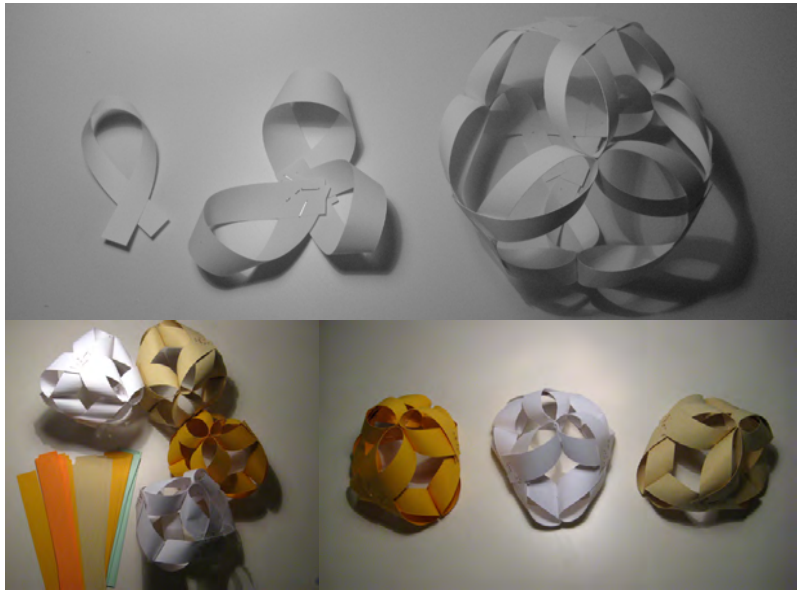


Fig. 3.45 The new component, one face of the module (three components), the module (up). Different colored modules (bottom).

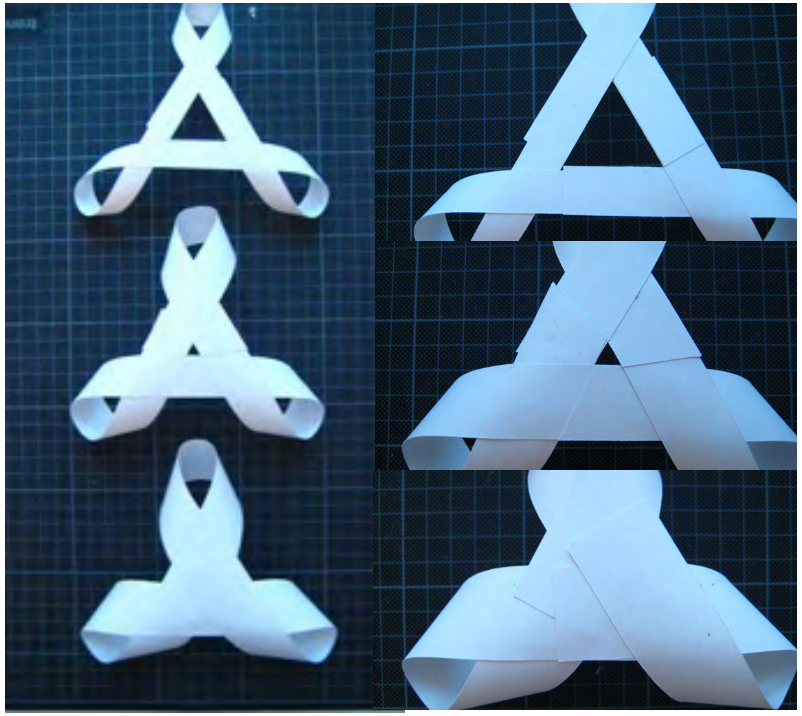


Fig. 3.46 Module faces made of different strip widths (left); the triangular shape of these faces (right).

The difficulty in working with strips of different widths was to keep the contour of the triangular planar shape joining the components in the middle equal. The reason was that esthetically, triangular shapes of different sizes did not look good. Also, considering that the modules would be produced by hand, keeping the contour of the triangular shape equal would be very challenging. Structurally, different strip widths would also add more problems. If thin strips could compose the triangular shape easily, the thick strips added on top of each other with no coherent connection between the components of the face or to the other modules (Fig. 3.46).

Two challenges that presented themselves at this point were:

1. The modules created from thin strip components turned out to have a large triangular shapes, in comparison to their curved side (Fig. 3.47).
2. The thick strip modules were hard to realize once the triangular shape became very small (Fig. 3.46).

A middle solution had to be found by determining the right proportion between the length and width of the strip such that the components could be added to each other and the ratio between the triangular shape and the remaining curve would be both beautiful and structurally stable.

Fig. 3.47 The component fixed on a stencil, its two flaps facing downwards (left); two module faces made of components of different widths (right).

3.4 Refine and test final shape

3.4.1 Determine the proportions of a regular module

The tests with the 2 mm cardboard have focused in particular on the joints. For further comprehension of the text, the two “arms” of the component were called the “flaps” (Fig. 3.47). The first experiments have started with twelve screws per triangular shape, which proved to make the face of the module not only heavy but also inefficient because adding screws such that another module would be added to that face, would make the module unstable (Fig. 3.48). Since the screws were added in groups of two for the increased stability, it was established that the smallest width of the strip that would accommodate the two rivets without jeopardizing the stability of the module would be 9 cm.

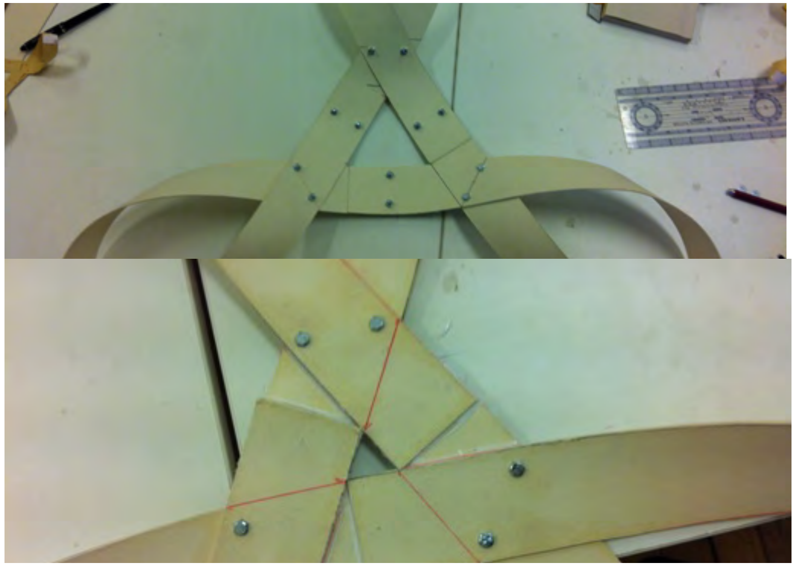


Fig. 3.48 A triangular shape fixed with twelve screws (top); a triangular shape fixed with six screws and glue (bottom).

To reduce production costs and weight of the overall structure, the triangular shape of the module was fixed in place with the help of glue and screws were used only when joining different modules together. By having the width and the length of the strip, the dimensions of the triangular shape were established such that it would be both structurally stable and visually interesting. To produce one face of the module, three strips (components) were needed. A right triangle having the short cathetus of 5 cm is cut out of each side of the strip such that the triangular shape has constant width on its entire surface. The markings for the overlapping are drawn, resulting in an equilateral triangle having 3 cm on one side being achieved in the middle. The strips are than soaked, left to dry for a while and glued together. The three components criss-cross their flaps such that the inner flap of one component always overlaps the outer flap of the next component for added structural stability (Fig. 3.49).

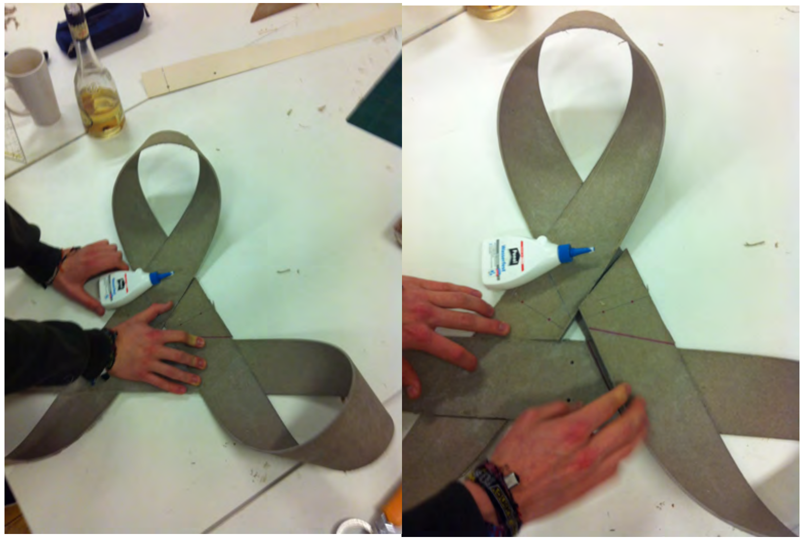


Fig. 3.49 A triangular shape marked and perforated in 2mm gray cardboard.

Fig. 3.50 The face of the module done with strips of non-constant width (top left); broken module (bottom left); tools used at this stage (top right); testing rivets (bottom right).

Drying the components this time did not involve hanging anymore, they were simply left to dry on the floor (Fig. 3.52). Objects found in the working space were used to keep the flaps crossed such that the components would dry in the position they would than be joined. Initially, the holes for the screws were made at this phase but because it was difficult to overlap the flaps exactly where the holes met (because they were made by hand), it was decided that the holes should be made with the drill after glueing (Fig. 3.53). Tests of paint and color were also made at this phase using sprays and acrylic colors (Fig. 3.54 and Fig. 3.51). After drying, the faces of the module are joined together in groups of four. Screws were chose for the final assembly instead of rivets because they proved to be more resistant and faster to assemble. The tests made with strips of variable width along their length proved to be unstable and broke. The width had to remain equal on the entire length of the strip and a ratio between the size of the triangular shape and the size of a component had to be established such that the strips are not too stressed and can work together without breaking (Fig. 3.50).

Fig. 3.51 Module joined with rivets and painted with spray paint.

Fig. 3.52 Components (left) and faces of the module (right) drying on the floor.

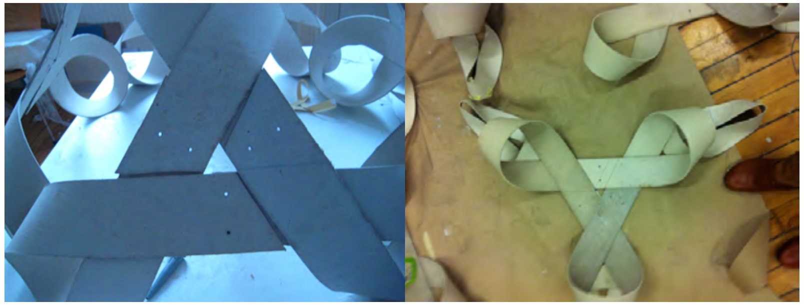


Fig. 3.53 Imprecise overlapping of the flaps due to priorly made holes (left); old components used to hold new components in shape when drying (right).

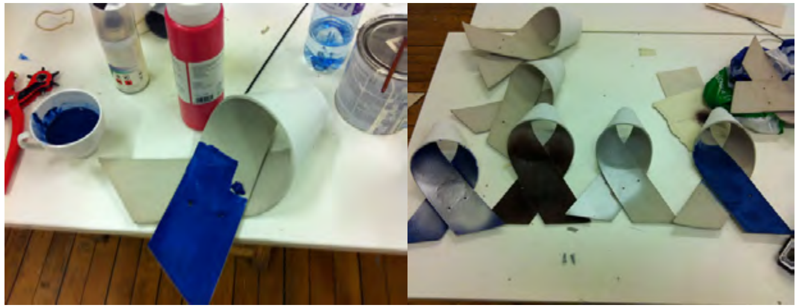


Fig. 3.54 Tests of paint on components.

Fig. 3.55 First 1:1 faces of modules leaning on each other (left); the module inscribed in a tetrahedron (right).

One module inscribed in a tetrahedron and one inscribed in an octahedron were produced by six people in ten hours (Fig. 3.55). The one inscribed in a tetrahedron needs twelve strips which means 1.5 sheets of cardboard and twelve screws to join the faces. Painting it with the spray took around 20 minutes and 200 ml of paint mixed with water. Since one module inscribed in an octahedron has eight faces, it is easy to assume that producing one octahedron requires double the materials needed for one inscribed in a tetrahedron (Fig. 3.56). At this phase, estimations about the amount of material and costs needed to create one relatively large structure were made. It was therefore concluded, that a structure of 23 agglomerated modules would be enough to prove the concept and get done in the required time.

Fig. 3.56 Assembling one octahedron (top); the first two joined modules, one inscribed in a tetrahedron and the other one in an octahedron (bottom).

3.4.2 Test distorted module

Parametric 3D Modeling

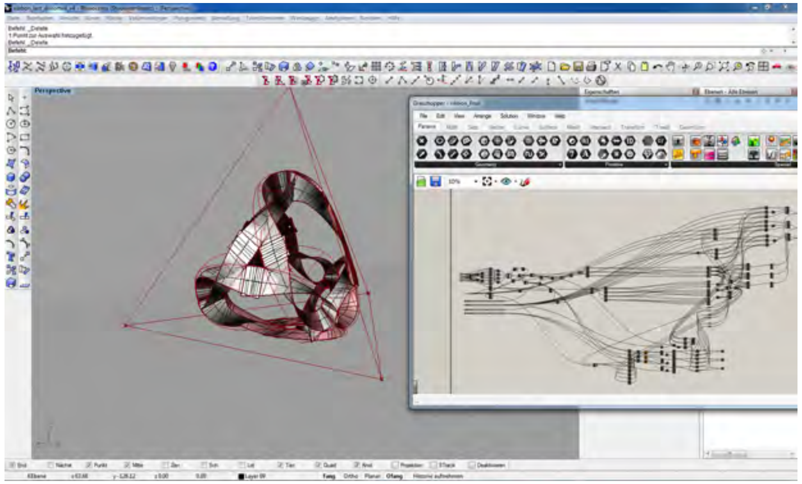


Fig. 3.57 One module inscribed in a regular tetrahedron.

The module inscribed in one tetrahedron was modeled with the help of the plug-in for Rhino, Grasshopper. First the points in space defining the tetrahedron are created than the edges, the faces, the center points of the faces and the center point of the tetrahedron. Than one triangle is created around the center point of each face. The size of the triangle can be modified by a slider. Each vertex of the triangle has two perpendicular lines going to its defining edges. Their length, and the length of each strip is also defined by a slider (Fig. 3.57).

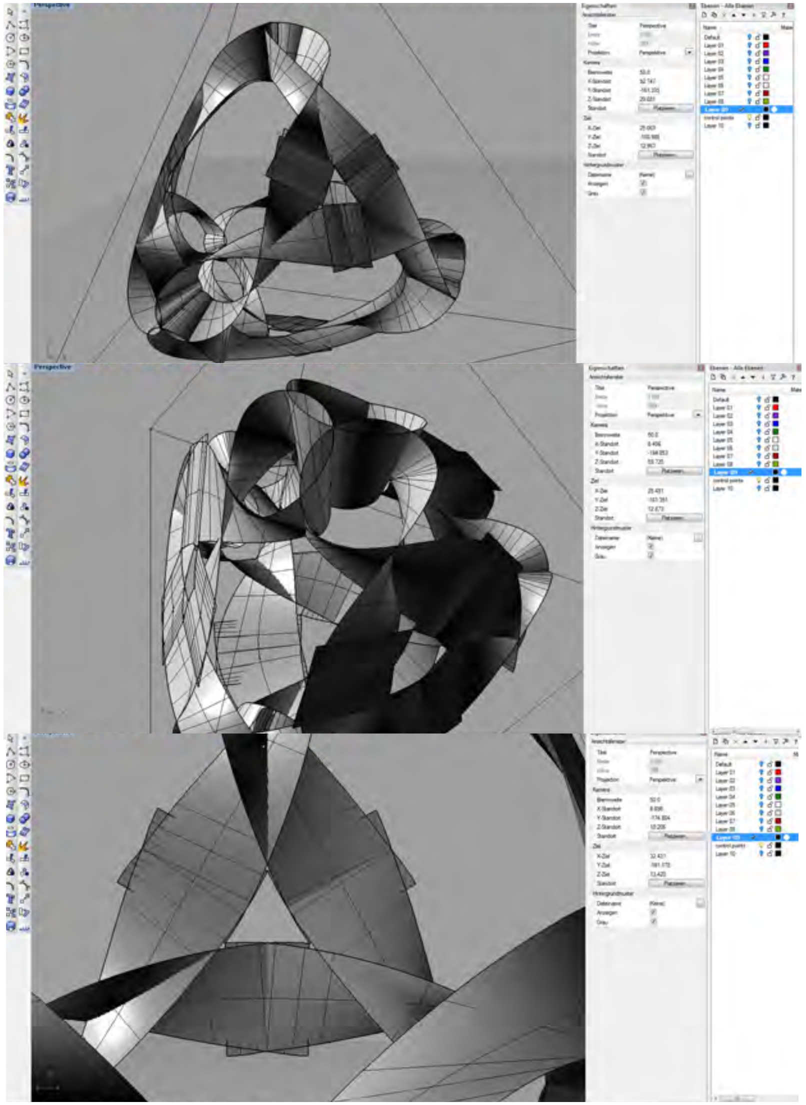


Fig. 3.58 Close up of the module (top). The vertex intersection of three components (middle). View from behind the triangular shape (bottom).

The model developed, although similar was not really replicating the physical model. The flaps of each strip were intersecting, not overlapping (Fig. 3.58 up). They ended in the predefined perpendicular lines and not in the flap of the other component, which was not providing the correct information about the length of strip. By prolonging the strips, they would eventually exit the triangular shape, which was not the case of the physical model whose stability was depending on the exact overlapping of the strips (Fig. 3.58 low). The components intersect at vertex point instead of being tangent (Fig. 3.58 middle). By modifying the strip width it was observed that the middle triangular shape tends to become round and not straight, like the one in the physical model (Fig. 3.59). Also the kind of curve the components are making is that of a thin paper strip and not that of a cardboard strip. Here the material specific elasticity makes a difference. The next step was therefore, to map the exact curvature of the cardboard components with the help of the digitizing system MicroScribe G2x (fig. 3.60).

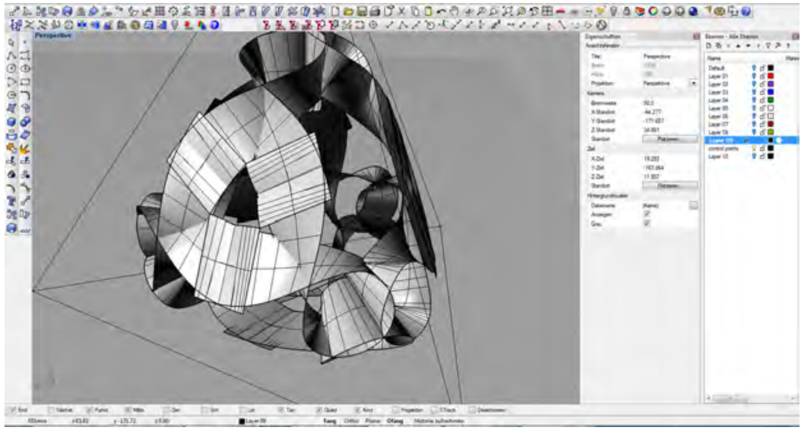


Fig. 3.59 Thicker strip width. Additional modification of the curvature.

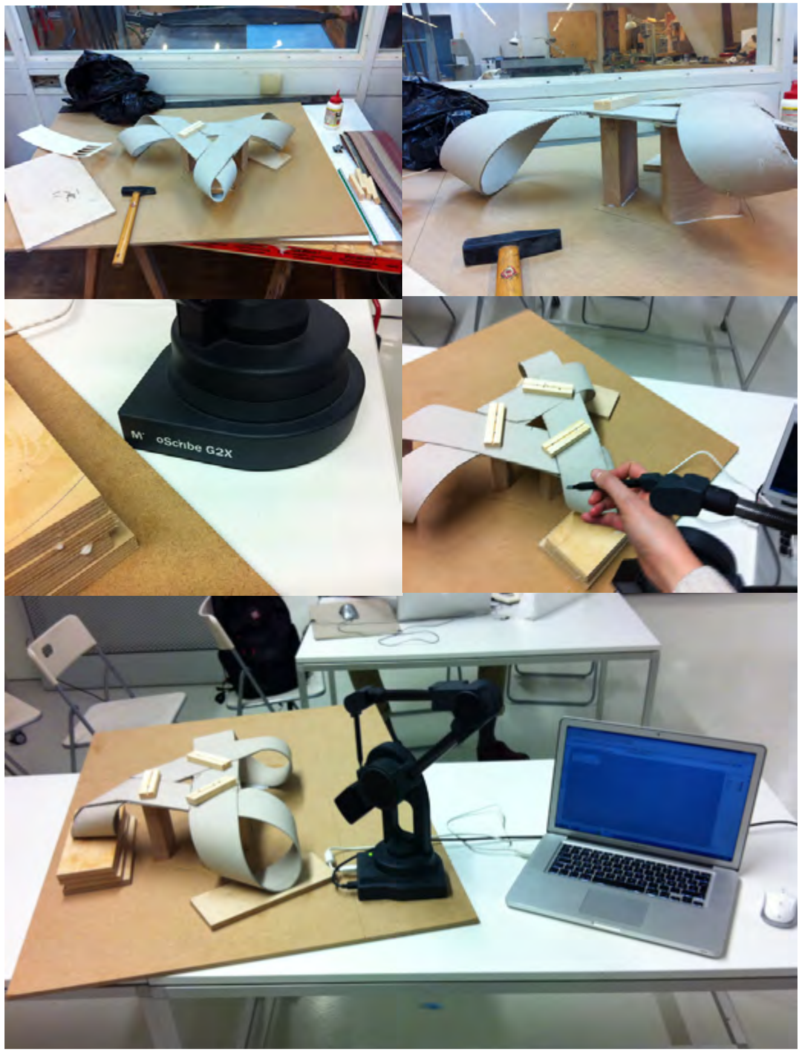


Fig. 3.60 One face of a module fixed on a wooden board (top). Digitizing the exact curvature of the strips (middle and bottom).

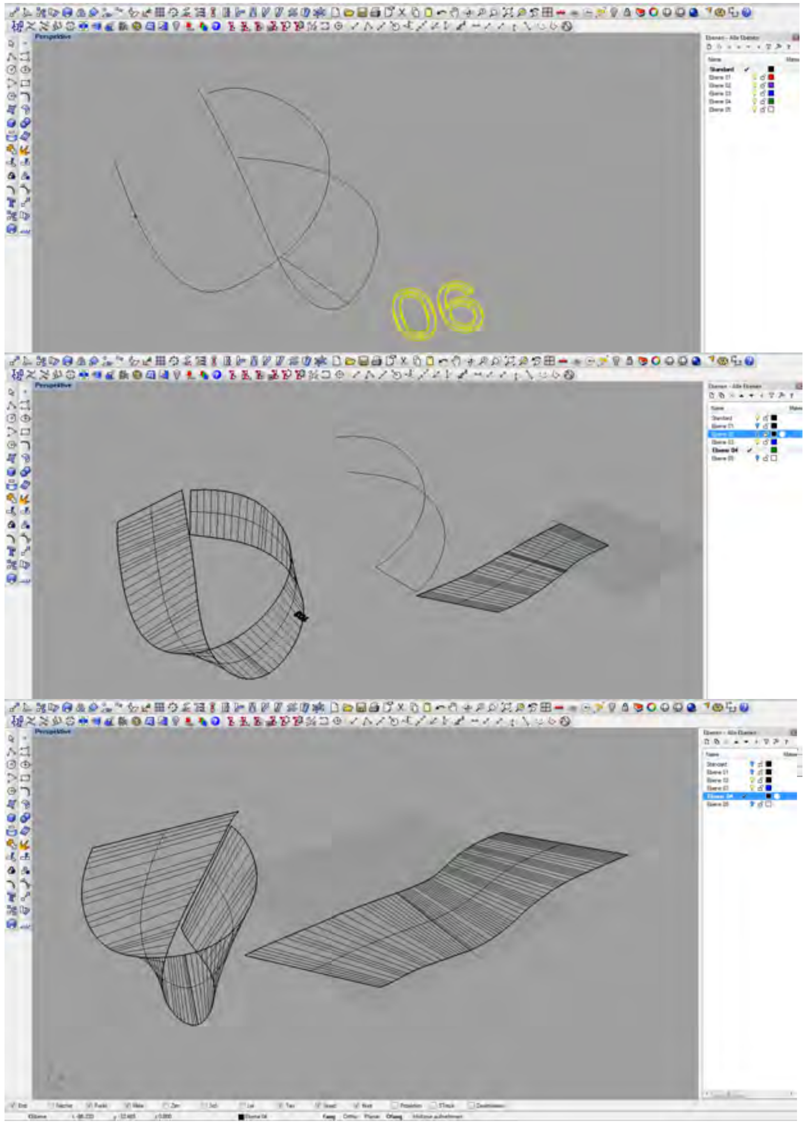


Fig. 3.61 A mapped 90 cm (top), 103 cm (middle) and 70 cm (bottom) component.

> Micro Scribe G2x is an accurate 3D digitizing system. It captures the physical properties of three-dimensional objects and accurately translate them into complete 3D models. Its accuracy is of 0.009.
>
> (MicroScribe 2002)

MicroScribe has a head in the shape of a pen and by placing the tip of the “pen” onto a surface, it records a point. Once the head is moved to record a second point, it draws a line between the two points. By means of “rebuild” and “sweep” command the exact curvature of the model in 3D can be rebuild. However, by unrolling the surface on a plane, it was observed that the strip is not straight but deformed in spite that the original cardboard strip is straight. If the actual physical strip is mapped deformed after curving it, unwrapping an exact 3D model to straight strips would be even more difficult to do (Fig. 3.61).

What was missing so far was an overall shape and therefore, the existing Grasshopper script developed was to be applied to a shape composed of 23 modules. As tetrahedrons are not space filling polyhedrons and the structure needed a planar surface on which to stand, the tetrahedrons had to be modified. Afterwards the script was applied to the shape (Fig. 3.62). Selecting one modified tetrahedron out of the structure, many script errors were observed. The strips create additional loops both on their lengths and at vertex points (Fig. 3.63). For a better view of the overall shape see Appendix A.3 Renderings, Fig. A3-1.

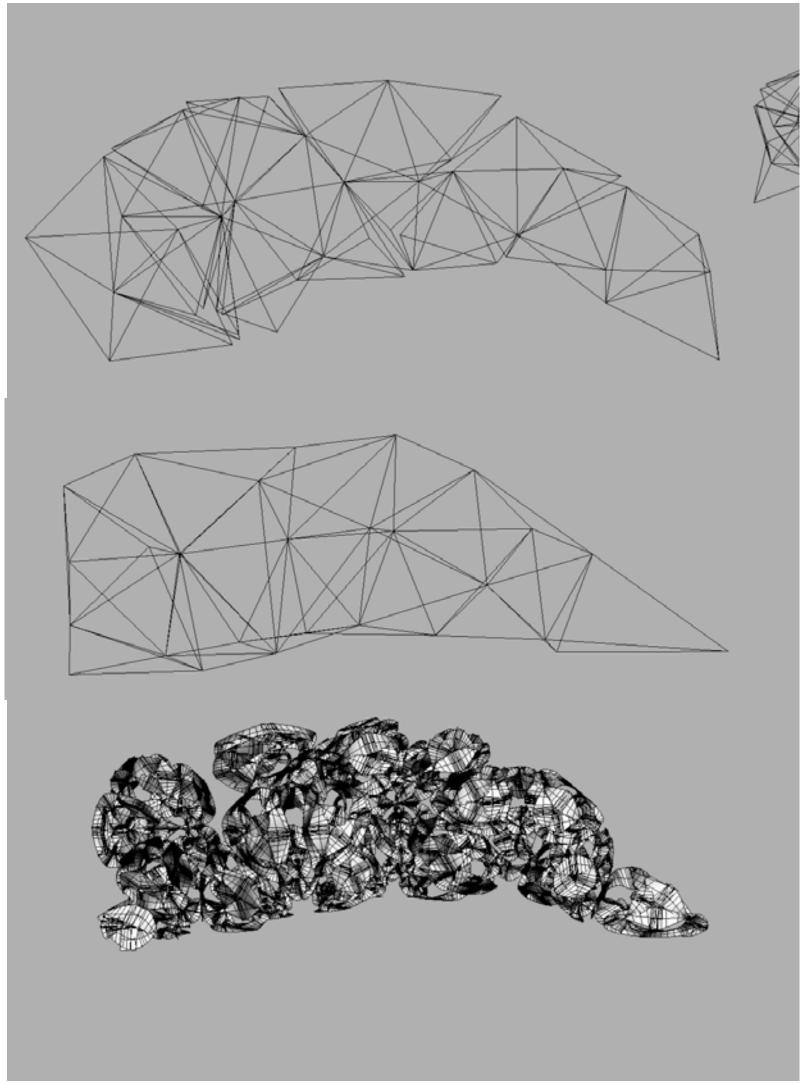


Fig. 3.62 Structure made out of 23 regular tetrahedrons (top); modified tetrahedrons (middle); final shape (bottom).

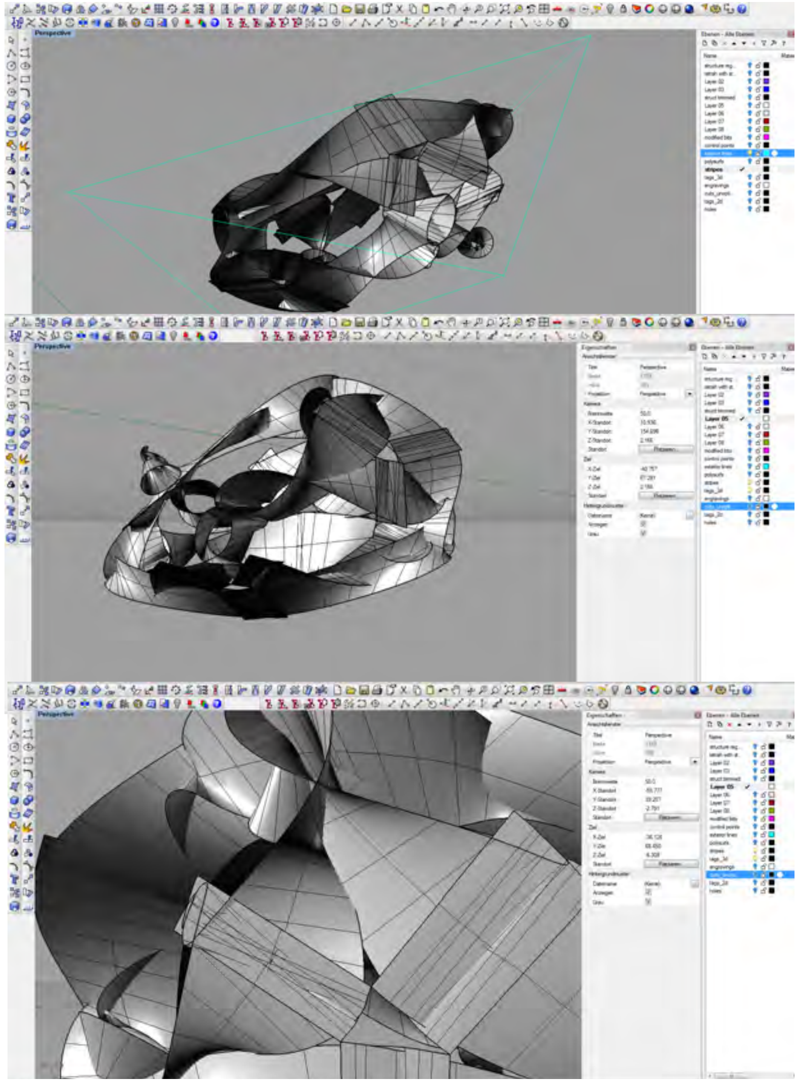


Fig. 3.63 The script applied to one modified tetrahedron.

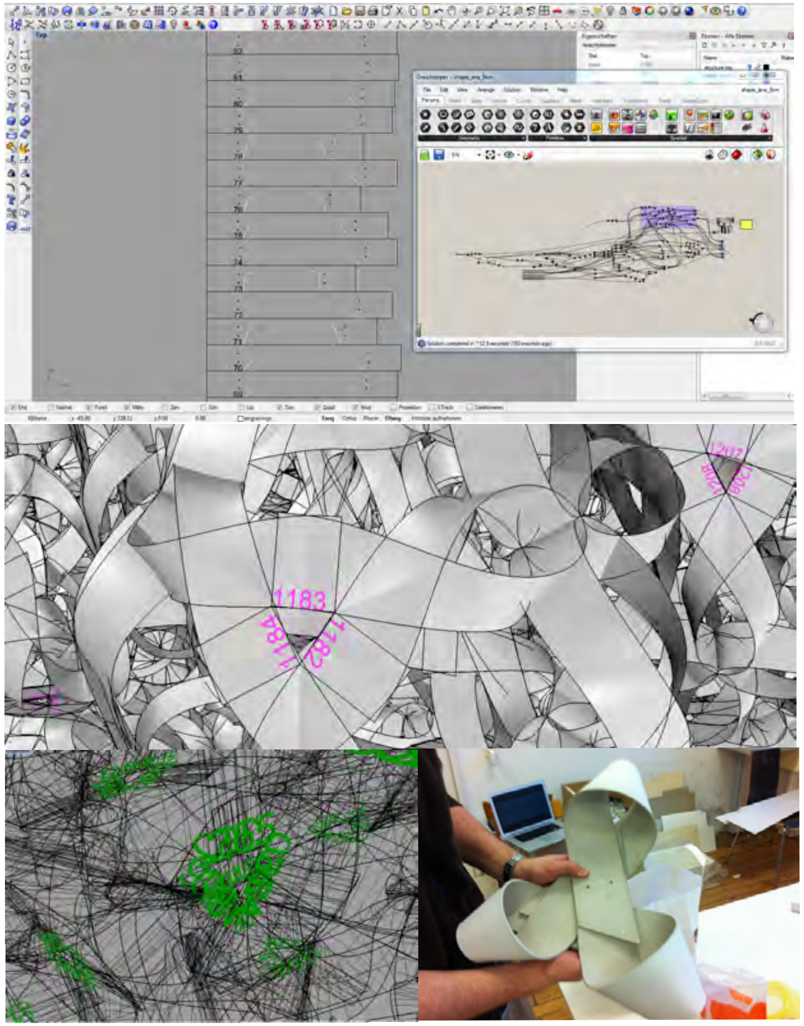


Fig. 3.64 The unrolled strips (top); the labeled strips (middle photo); overlapping of the labeling (bottom left); cardboard test model, trying to figure out the angles with the help of the holes (bottom right).

Because introducing the elastic material properties was difficult, the model need a lot more time to be developed and the information it had to offer was not enough to produce a structure, for the following reasons:

1. The markings where the overlapping should take place were distorted (Fig.3.64 top and Fig. 3.66).

2. The different angles between the flaps of the components were without additional help really hard to replicate on site as there was nothing to measure them with or molds to keep them fixed in a certain position. A test to determine the angles between the flaps with the help of the holes as guide was made. The holes proved to be too far into the strip and therefore not helpful.

3. The labels of each strip were overlapping and not baking in the Rhino model which made them impossible to distinguish from each other (Fig.3.64 bottom left).

4. The model was also lacking a maximum and minimum length of strip. A minimum because the 2mm cardboard would not bend below the length of 66 cm and strips longer than103 cm could not be produced (the maximum length of the standard sheet of cardboard).

5. The behavior of the model does not replicate reality. In the 3D model, the longest strip components tend to look the most like tetrahedrons, while the modules made of short strip components tend to look like balls. In the physical model, it is the other way around. The components with the longest strip components push each other out, and due to the length of the strip they tend to look more like balls, while the short strip modules look more like tetrahedrons (Fig. 3.65).

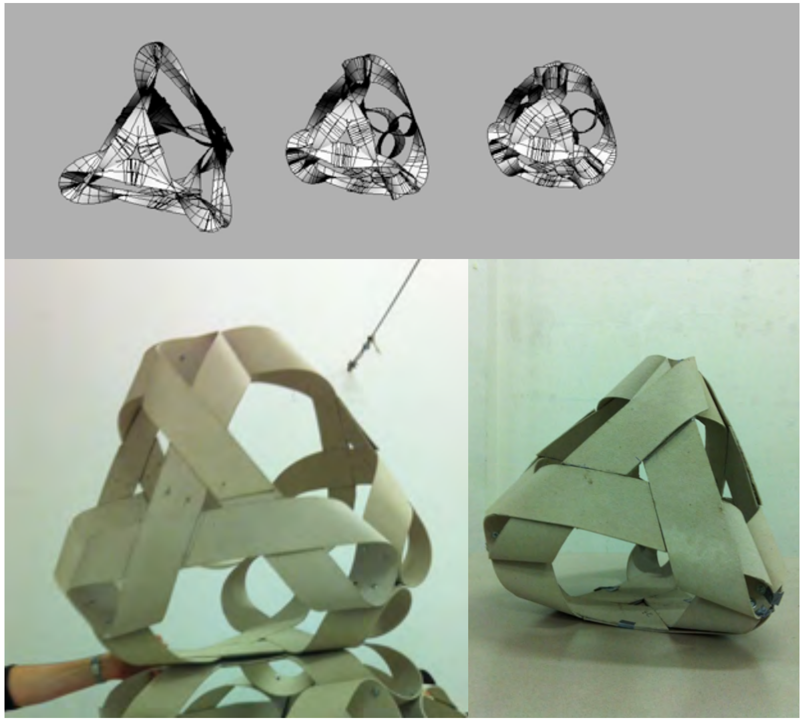


Fig. 3.65 3D modules with maximum and minimum length of strip from left to right (top); a module inscribed in a regular tetrahedron with the maximum length of strip (bottom left); and minimum length of strip (bottom right).

Testing the laser-cutter

The strips of one parametrically designed distorted module were tested on the laser-cutter using both 1 mm and 2 mm cardboard. The laser cutter works with dxf format files. Because the laser-cutter cuts in the order the layers are arranged in, the layers have to be ordered. The intensity of the beam, also needs to be set for each layer. The dxf file was set up such that there would be engraving layers for the markings where the strips had to be overlapped and cutting layers for the strips themselves. If a test layer is prepared, the laser cutter starts cutting on the side of the paper and there the intensity of the beam can be established (Fig. 3.67). Than the laser-cutter goes on to do the engraving. Once it is done with the engraving layer, it continues with the cutting layer. In the 1 mm cardboard test, the sheet was not cut (Fig. 3.66) but engraved because the intensity of the beam was set at a low level and therefore needed additional cutting by hand after the laser cutter was done (Fig. 3.68). To cut properly, a good relationship between the speed of the laser cutter and the intensity of the beam needs to be established. If the beam is too fast it may not cut the cardboard, and if it is too slow it may burn the cardboard, which happened to the 2 mm test sheet. It took the cutter half an hour to go over the entire sheet of 2 mm cardboard, however although it engraved the surface, it did not cut through.

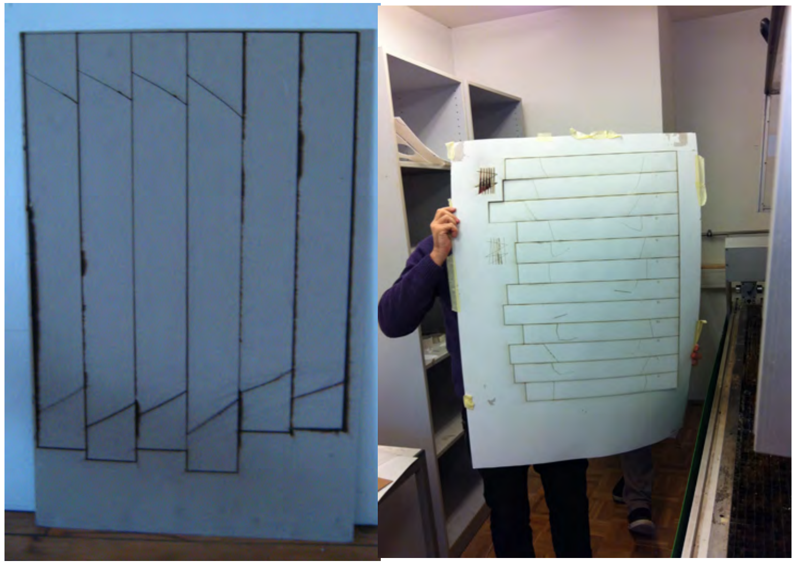


Fig. 3.66 A 2 mm sheet of cardboard sheet engraved (left); a 1mm sheet of cardboard laser-cut (right).

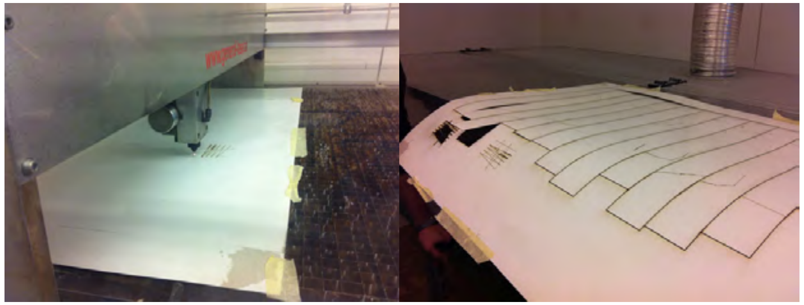


Fig. 3.67 The laser cutter engraving the test layer (left); the laser-cut sheet of cardboard (right).

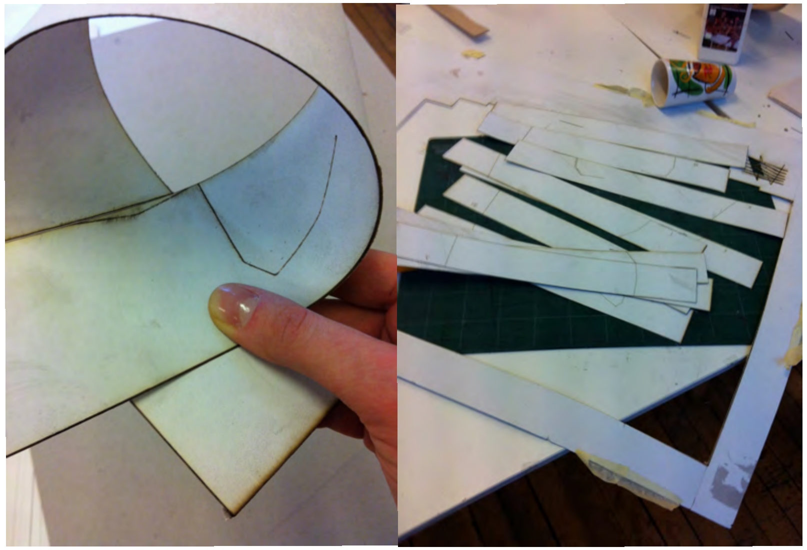


Fig. 3.68 Markings as guide for the overlapping (left); the laser-cut strips, cut one more time by hand (right).

This meant that the cutter would have had to go over the entire sheet twice, which would have burned the sheet fairly badly and would have brought the cutting time to one hour which (at seven strips per cardboard sheet) was not at all efficient. Also by using the laser-cutter, margins had to be left so that the sheet can be glued onto the cutting surface which added to the amount of the wasted material. An alternative cutting tool was needed.

3.4.3 Determine the rules of variation

Because the 3D model needed more time to be properly developed, a new solution to achieve distorted modules was needed, one that would use the knowledge acquired until than. The idea behind it was to keep the triangular shape intact, and because the strip length would variate, so would the shape of the modules. Three components meeting in one vertex of the tetrahedron would always have to have the same length so that the stress in the modules would stay low. After a certain amount of testing, it was determined that very large components combined with very small ones do add a certain stress and deformation to the module. It was important that the difference between the components of each module would not be too big. Initially, foam test models were made to test the theory. In order for the assembly to go smoother, the components were positioned on the floor such that the same length components would always meet in one vertex (Fig. 3.69).

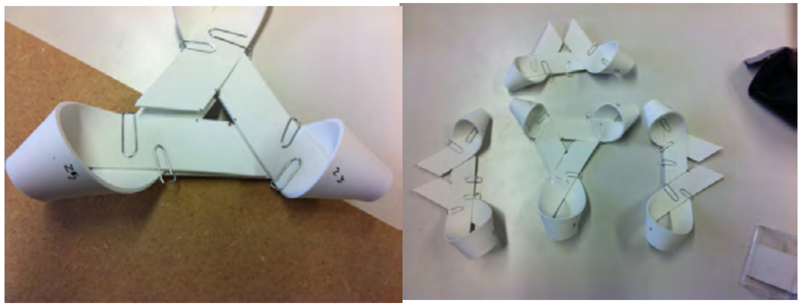


Fig. 3.69 Foam test models. Three same length components facing each other.

3.5 Production

3.5.1 Cutting

The laser cutter was too slow and was wasting material, and therefore, a new tool was needed. As a result, a paper cutting machine Perfecta Sey 115-1 was chosen (Fig. 3.70). The knife is driven by a hydraulic system and it cut 40 sheets of cardboard in 15 minutes which saved five days of intensive laser cutting. Once the strips were cut, the manufacturing of the components was done manually with the use of stencils (templates). First by cutting one corner (a right triangle with a the short cathetus of 5 cm) and than by using the nine different stencils to cut the strips in different lengths of: 66 cm, 70 cm, 73 cm, 75 cm, 80 cm, 85 cm, 90 cm, 95 cm 103 cm (Fig. 3.71). Because a production process had already been established, the workflow went smoothly.

Fig. 3.70 The paper cutting machine programmed to cut strips of 9 cm and capable to cut six sheets of cardboard at a time.

Fig. 3.71 Strips cut by the paper cutting machine (top left); cutting the strips at different lengths (top right). Helping templates for cutting the strips (bottom).

3.5.2 Production and assembly

After cutting, each strip was labeled with its length on the right side such that the length of strip would still be visible after glueing. Than the strips were marked at the points where the strip flaps should overlap. Following tagging and marking, the strips were soaked in water and 1/3 l textile hardener solution. To make the soaking time short, hot water was repeatedly added to the solution. Once soaked, the two flaps of the strip were crossed at 60 degrees angles from each other and fixed in place with the help of heavy objects (in this case iron bars found in working the space). The iron bars held the strips in place and lifted the components up so they would dry in the exact position they would be joined such that no additional tension would be added to the modules (Fig. 3.72).

Fig. 3.72 Soaking the strips and criss-crossing the flaps (left); components drying (right).

Fig. 3.73 Components drying (top); holding the components up with strips of cardboard (bottom left); glueing process (bottom right).

The components should not dry completely, otherwise they would become too rigid. Glueing would than be difficult but the components are glued when they are still moist, the overlapping of the flaps is easier. To prevent the component heads from flattening, rests of cardboard strips were used to hold the component's "heads" up. As in the previous tests, the "heads" of the components had to be parallel with the floor, so that the later joining would be easier. Bags of water were used to keep the components together and make them glue evenly (Fig. 3.73).

Fig. 3.74 Triangular faces of the module with different size components arranged on the floor in groups of four.

Fig. 3.75 First modules put together (top); tape was used to keep the components together until they were fixed with screws and washers (bottom).

Letting the bags of water in the same place for too long however, would keep the humidity and drying would not take place. The faces of the module were always made together such that keeping track of the components meant be joined would be easy. For the same purpose they were arranged on the floor in groups of four (Fig. 3.74). Afterwards, the faces of the module were held together with tape. Holes were made with the drilling machine and one screw with two washers was used for joining two component “heads” (Fig. 3.75). By variating the length of components, the modules resulted in unique shapes and sizes (Fig. 3. 76).

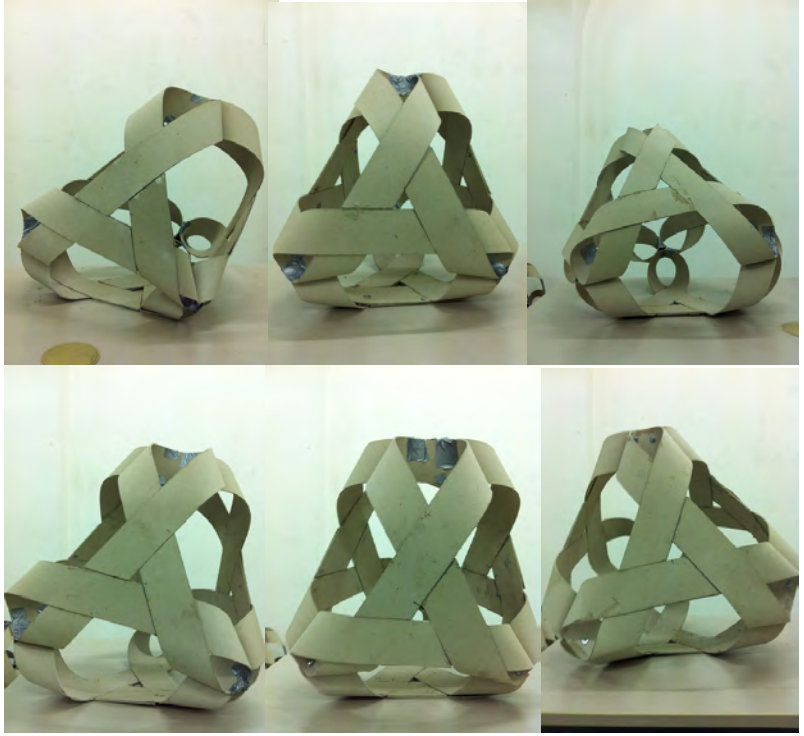


Fig. 3.76 Different size modules.

After the first modules were made, the first assembly was also tested. The weight of the modules in relationship to each other and the tension in the joints resulted was observed (Fig. 3.77). Afterwards, the modules were brought to the painting room in the university. Spray painting each module took around 15-40 minutes, depending on its size and paint consistency. Acrylic paint was mixed with water and for the overall structure about 3.5 l of paint were used (Fig. 3.78). The modules were joined on site by making the holes with a drill. Six screws (5 mm diameter, 15-25 mm length) were used per face and two washers per rivet.

Fig. 3.77 The first module assembly test.

Fig. 3.78 Spray-painting of modules.

Fig. 3.79 Site assembly. Detail of two modules fixed with six screws (top right).

Fig. 3.80 Assembly.

The biggest modules were first added: the one module inscribed in an octahedron and attached to it, the modules made from components having the longest length of strip. Afterwards they were raised on chairs and smaller, stiffer modules were added at the bottom. Because attaching tetrahedrons together tends to geometrically make a circle rather than a line, the structure didn't become that high even with 23 modules. In the end it covered a surface of about 8-9 sq. m and had a hight of about 1.6 m. Also because the modules weren't touching the ground with their faces, additional modules for structural support were needed on the ground. The assembly took three people seven hours. Photo shooting at the end took two more hours (Fig. 3.79 and Fig. 3.80). The end structure, was exhibited at the University of Applied Arts Vienna in February 2012 (Fig. 3.81). For more photos, see Appendix A.4 Photos.

Fig. 3.81 Final built structure.

3.5.3 Material use

Saving material when producing digitally can be difficult. The following cases are meant to depict the problems in optimally arranging components on the standard sheet of material and how this could result in large material waste.

Student project

Martina Hatzenbichler, Technical University Vienna, 2010

The project was made out of 1 mm cardboard for the Advances in Architectural Geometry conference held at TU Vienna (Fig.3.82). The structure was hanged not self supported and it was cut with the laser cutter. Material wasted: 49.16% (Appendix A.2, Table A2-1).

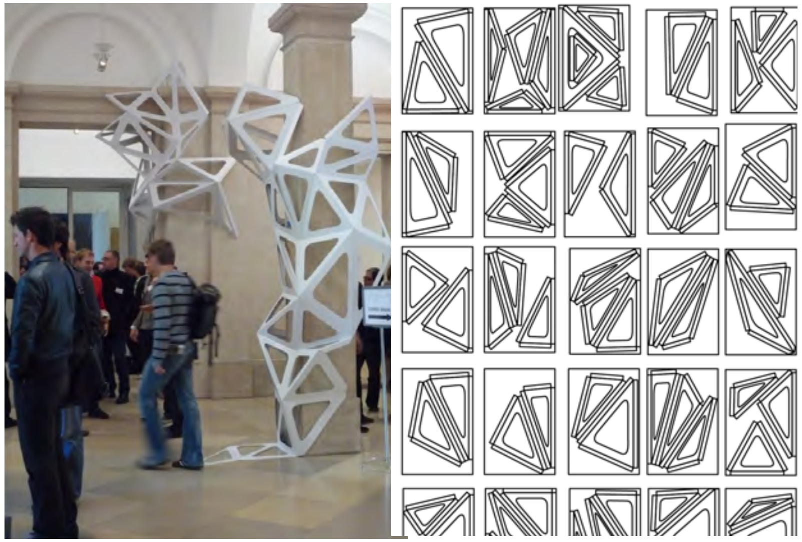


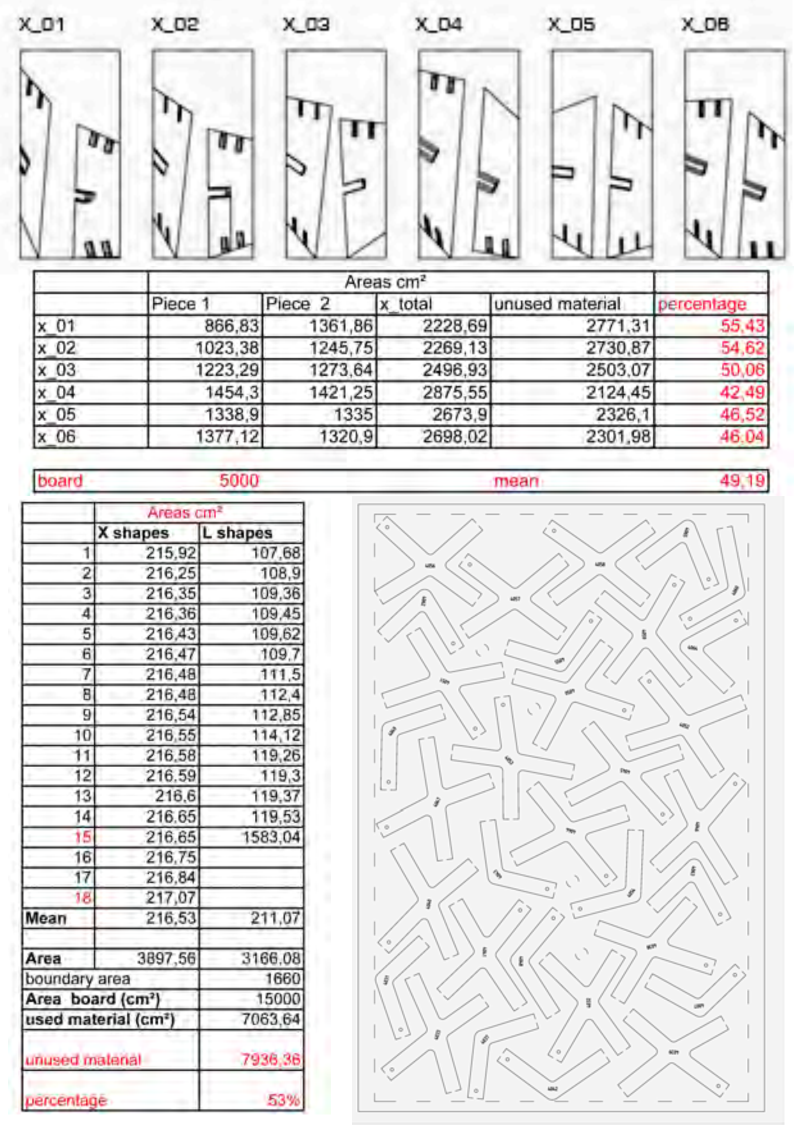
Fig. 3.82 Project view (left). Arranged shapes on cardboard for cutting (right).

X-Blur

Markus Stürzenbacher and Hannes Tallafuss, Technical University Vienna, 2010

The project was designed for the presentation of the architectural diploma 2010 and it was made out of XPS boards held by wooden connectors (Fig. 3.83). The structure is hanged not self supported. As depicted in figure 3.84 the average material lost was: wooden connection pieces 53% (average based on one sample sheet material), XPS boards 49% (average based on six samples).

Fig. 3.83 X Blur project.



	Areas cm²				
	Piece 1	Piece 2	x_total	unused material	percentage
x_01	866,83	1361,86	2228,69	2771,31	55,43
x_02	1023,38	1245,75	2269,13	2730,87	54,62
x_03	1223,29	1273,64	2496,93	2503,07	50,06
x_04	1454,3	1421,25	2875,55	2124,45	42,49
x_05	1338,9	1335	2673,9	2326,1	46,52
x_06	1377,12	1320,9	2698,02	2301,98	46,04

board	5000	mean	49,19

	Areas cm²	
	X shapes	L shapes
1	215,92	107,68
2	216,25	108,9
3	216,35	109,36
4	216,36	109,45
5	216,43	109,62
6	216,47	109,7
7	216,48	111,5
8	216,48	112,4
9	216,54	112,85
10	216,55	114,12
11	216,58	119,26
12	216,59	119,3
13	216,6	119,37
14	216,65	119,53
15	216,65	1583,04
16	216,75	
17	216,84	
18	217,07	
Mean	216,53	211,07
Area	3897,56	3166,08
boundary area		1660
Area board (cm²)		15000
used material (cm²)		7063,64
unused material		7936,36
percentage		53%

Fig. 3.84 Calculation of material waste: XPS (top), wood (bottom).

Hexigloo

Tudor Cosmatu, Irina Bogdan, Andrei Raducanu, and guest tutuors Andrei Gheorge (Angewandte, Vienna) Alexander Kalachev (DIA, Dessau) and Bence Pap (Zaha Hadid Architects London), Bucharest, 2011

The workshop took place during one week at Bucharest and 55 students participated. It taught the basic of parametric design and software with the task that a spatial self supported structure would be build at the end (Fig 3.85). It is based on a honeycomb structure and it's applied on an igloo surface typology. The material used was 6 mm cardboard. Amount of material wasted: 53%. The calculation is based on nine samples (Fig. 3.86).

	area used	total area	% used	% wasted
Sample 1	2357,18	5400	43,65	56,35
Sample 2	2622,95	5400	48,57	51,43
Sample 3	2712,18	5400	50,23	49,77
Sample 4	2517,64	5400	46,62	53,38
Sample 5	2378,8	5400	44,05	55,95
Sample 6	2772,97	5400	51,35	48,65
Sample 7	2571,96	5400	47,63	52,37
Sample 8	2407,02	5400	44,57	55,43
Sample 9	2534,82	5400	46,94	53,06
		mean	47,07	52,93

Fig. 3.85 Hexigloo overview (top). Calculation of wasted area based on nine samples of cutting files (bottom).

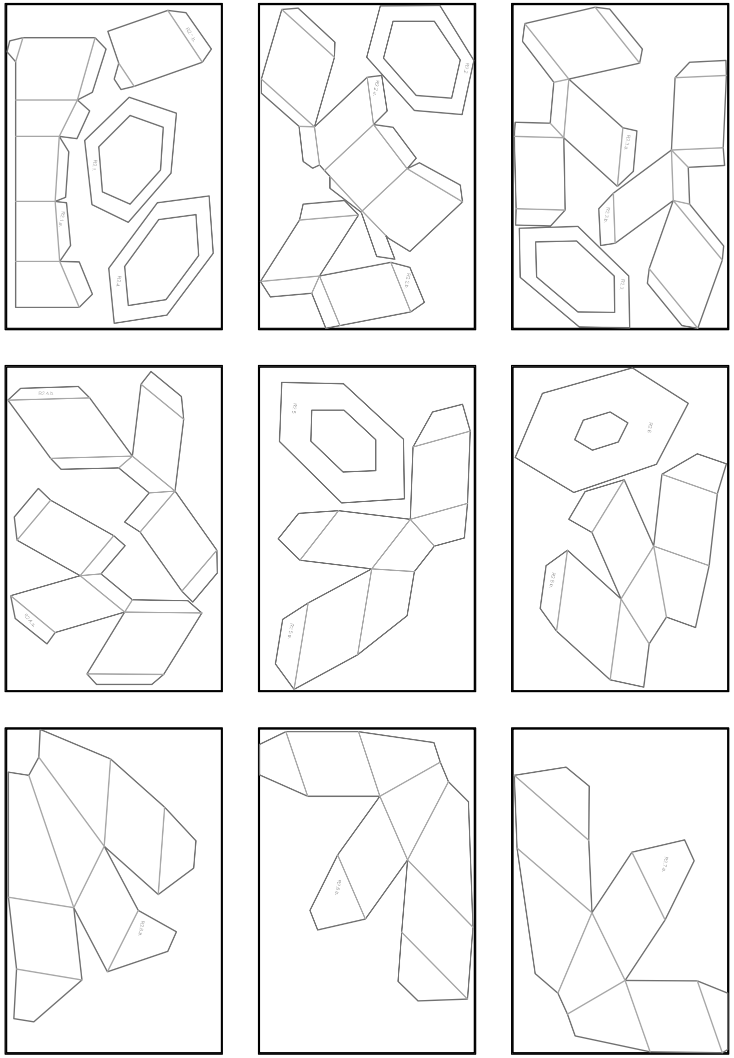


Fig. 3.86 Nine cutting files arrangements from Hexigloo.

Case study

In the case study, there were 23 modules used, out of which one octahedron (containing double the faces of one tetrahedron). There were nine types of components used with lengths of strip from 103 to 66 cm (66 cm being the smallest strip possible to bend and 103 the maximum length of the standard cardboard sheet). In black color is the wasted material, while in red is the shape of the standard sheet of cardboard used (103/72 cm). Exactly eight strips of 9 cm width fit on one sheet (Fig. 3.87).

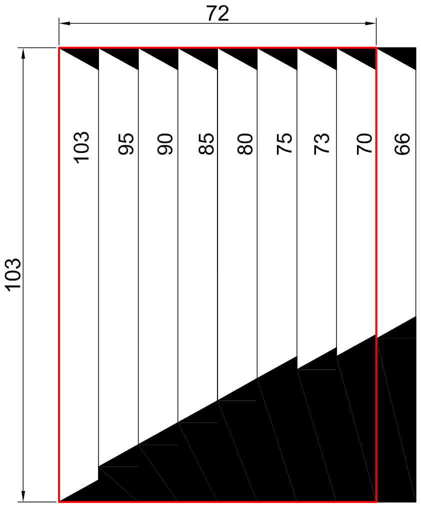


Fig. 3.87 Nine different strip (component) lengths.

In the project, almost half of the components were based on the longest strip (103 cm) and the second shortest strip (70 cm) and the rest based on the spectrum of lengths in between. Because the strips of 66 cm were very tight and the cardboard was very stressed, 70 cm strips were preferred when making smaller modules (Fig. 3.88).

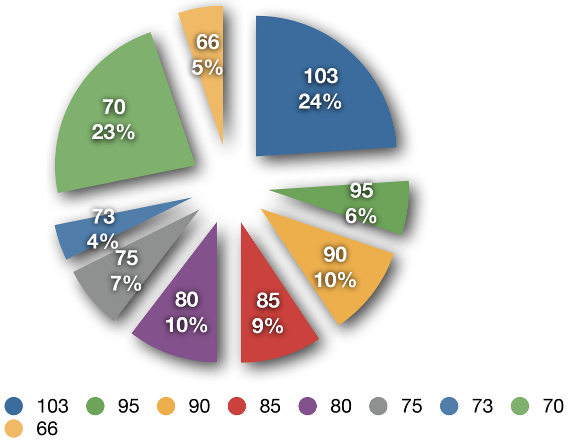


Fig. 3.88 Percent of components (length of strip) used in the structure.

Wasting material can also depend on the machine used for cutting. For many irregular shapes, the laser-cutter is indeed useful, however in the case study explored in this paper the cutting-machine was faster and it saved more material. With the paper machine, for 23 modules, 36 sheets of cardboard were needed for 15 min cutting time and 23% of area wasted (Table 1). To cut with the laser cutter, additional margins need to be left in order for the sheet to be fixed on the laser-cutter surface (4.5 cm left and right and 1 cm top and bottom) which would reduce the size of the longest strip to 101 cm. Additionally, 41 sheets of cardboard are needed and the cutting time would be five days (Fig. 3.89). If the area of one cardboard sheet is 7416 sq. cm and the margins area wasted is 1053 sq. cm than the overall area wasted using the laser cutter is:

=(0,23x36x7.416) + (1.053x40) + (1.053+45+101x9x6) = 110.076 sq. cm

110.076/ (41x7.416) x100= 36,20%

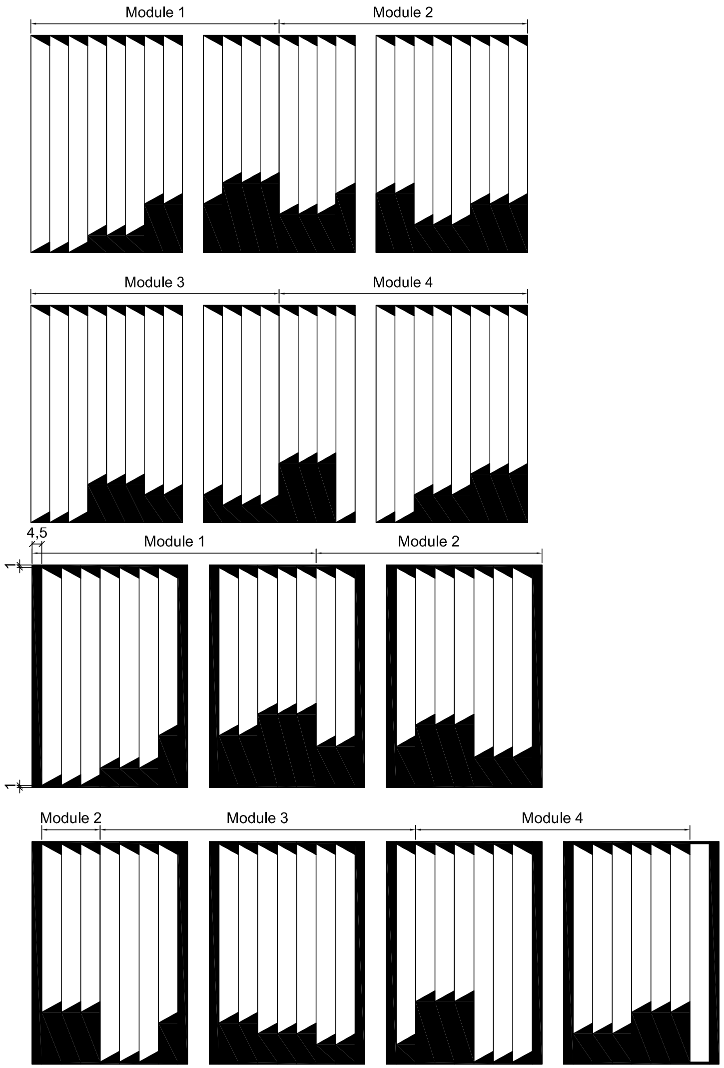


Fig. 3.89 Material wasted cutting with the paper cutting machine (top) versus the laser cutter (bottom).

Table 1: Average area wasted for the project.

lengths of strip used versus lengths of strip wasted for each module in centimeters																										
	face 1						face 2						face 3						face 4							
	1		2		3		4		5		6		7		8		9		10		11		12		sum lw	%
	lu	lw	lu	lw	lu	lw	lu	lw	lu	lw	lu	lw	lu	lw	lu	lw	lu	lw	lu	lw	lu	lw	lu	lw		
module 1	103	5	103	5	103	5	95	13	95	13	95	13	80	28	80	28	80	28	70	38	70	38	70	38	252	20.39
module 2	85	23	85	23	85	23	75	33	75	33	75	33	90	18	90	18	90	18	80	28	80	28	80	28	306	24.76
module 3	103	5	103	5	103	5	85	23	85	23	85	23	90	18	90	18	90	18	95	13	95	13	95	13	177	14.32
module 4	75	33	75	33	75	33	103	5	103	5	103	5	90	18	90	18	90	18	80	28	80	28	80	28	252	20.39
module 5	70	38	70	38	70	38	80	28	80	28	80	28	103	5	103	5	103	5	75	33	75	33	75	33	312	25.24
module 6	103	5	103	5	103	5	70	38	70	38	70	38	80	28	80	28	80	28	95	13	95	13	95	13	252	20.39
module 7	73	35	73	35	73	35	66	42	66	42	66	42	73	35	73	35	73	35	73	35	73	35	73	35	441	35.68
module 8	95	13	95	13	95	13	85	23	85	23	85	23	103	5	103	5	103	5	85	23	85	23	85	23	192	15.53
module 9	103	5	103	5	103	5	70	38	70	38	70	38	90	18	90	18	90	18	70	38	70	38	70	38	297	24.03
module 10	103	5	103	5	103	5	90	18	90	18	90	18	75	33	75	33	75	33	85	23	85	23	85	23	237	19.17
module 11	75	33	75	33	75	33	85	23	85	23	85	23	90	18	90	18	90	18	80	28	80	28	80	28	306	24.76
module 12	75	33	75	33	75	33	90	18	90	18	90	18	95	13	95	13	95	13	80	28	80	28	80	28	276	22.33
module 13	70	38	70	38	70	38	70	38	70	38	70	38	70	38	70	38	70	38	80	28	80	28	80	28	426	34.47
module 14	103	5	103	5	103	5	90	18	90	18	90	18	73	35	73	35	73	35	70	38	70	38	70	38	288	23.30
module 15	103	5	103	5	103	5	85	23	85	23	85	23	85	23	85	23	85	23	70	38	70	38	70	38	267	21.60
module 16	66	42	66	42	66	42	90	18	90	18	90	18	103	5	103	5	103	5	85	23	85	23	85	23	264	21.36
module 17	90	18	90	18	90	18	80	28	80	28	80	28	75	33	75	33	75	33	103	5	103	5	103	5	252	20.39
module 18	66	42	66	42	66	42	66	42	66	42	66	42	66	42	66	42	66	42	70	38	70	38	70	38	492	39.81
module 19	103	5	103	5	103	5	103	5	103	5	103	5	103	5	103	5	103	5	95	13	95	13	95	13	84	6.80
module 20	70	38	70	38	70	38	70	38	70	38	70	38	70	38	70	38	70	38	70	38	70	38	70	38	456	36.89
module 21	70	38	70	38	70	38	70	38	70	38	70	38	70	38	70	38	70	38	70	38	70	38	70	38	456	36.89
module 22	70	38	70	38	70	38	70	38	70	38	70	38	70	38	70	38	70	38	80	28	80	28	80	28	426	34.47
module 23 a	103	5	103	5	103	5	103	5	103	5	103	5	103	5	103	5	103	5	103	5	103	5	103	5	60	4.85
module 23b	103	5	103	5	103	5	103	5	103	5	103	5	103	5	103	5	103	5	103	5	103	5	103	5	60	4.85

12 strips x103 =	1236
% material wasted	23

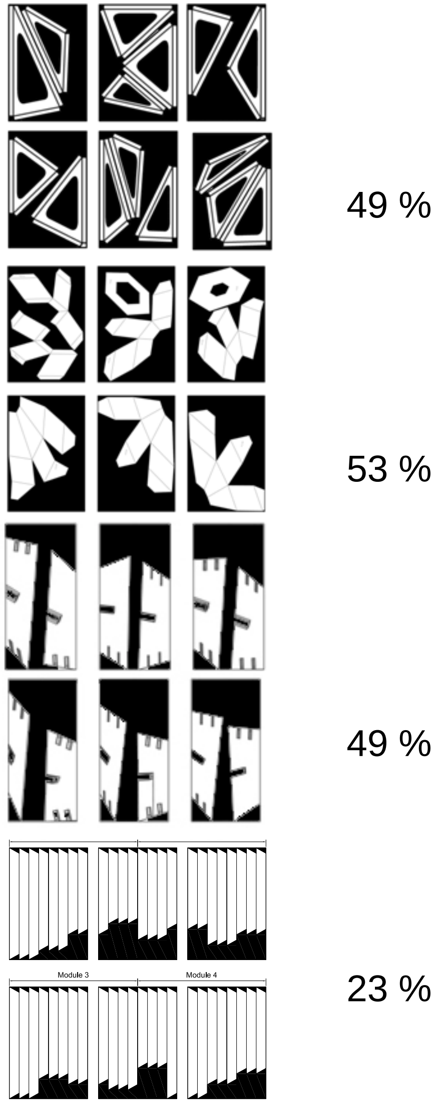


Fig. 3.90 Overview of the wasted material in the four projects.

The projects explained are all university projects and workshops meant for learning not economic use. Wether the material is sponsored or not makes a big difference in saving material which could be an explanation why it may not have been a priority for the other projects (Fig. 3.90).

Saving material in this project depended on a the following criteria:

1. The geometrical shape of the component in relationship to the shape of the standard sheet of cardboard. Using rectangular strips for the components resulted in a compact arrangement on the cardboard sheets.

2. The size of the component in relationship to the standard sheet. Because the component was created such that eight components would fit on a sheet made a big difference on keeping material waste low.

3. Type of cutting machine used. As explained, with the paper cutting machine only 23% of material was wasted, while with the laser cutter an additional 13% of material would have been wasted.

4. Because the raw material was sponsored by the people involved in the project, it pushed for early questions about how to save material.

5. The composition design method used, allowed for the construction of 1:1 mock-ups which gave a clear overview early on about how to save materials and how to optimize the components.

> When a design saves materials, it not only makes the product less expensive but also uses fewer resources in manufacturing and logistics.
>
> (Roth and Uphaus 2008)

4. DISCUSSION

Achieving the main requirements for building a lightweight self- supported structure, has been challenging but nonetheless possible. Choosing between a composition or decomposition design method depends on the requirements, however, using a composition method, has given the case study explained in this paper two advantages:

The first one is that by working with an aggregation of modules, the structure remains “open”. It can always be continued by adding more modules to it or by interchanging the modules between them with the condition that, for structural purposes, the stiffer modules (the smaller ones) remain on the bottom and the larger ones towards the top. This quality gives the structure the flexibility to adapt to any new space.

The second one is that once the first 1:1 scale module was produced, an exact estimation of how much cardboard, textile hardener and joints needed for the final structure was made. At the end of the assembly we’ve had: no cardboard left-overs, no paint left overs, no glue, just half a bottle of textile hardener and a few screws. Doing a 1:1 model (mock up) is also a very good way to detect problems joints problems early in the design process.

The project is characterized by an economy of method. By using folding, large volumes of space can be covered with little material, making the weight to volume ratio very efficient. Also, using a stiffening agent to solidify cheap materials, was a much more economical decision than anything else available that could have reached the same result. Bending wood, heating plastics, curving metal or cement would have been far more expensive. With a bucket of water and half a bottle of textile hardener the final components were produced and many more could have followed using the same solution.

Making curved components without molds has been easy once the system of soaking the strips of paper into water and textile hardener solution was developed. Cardboard was used as basic material for the structure because it was cheap, available and recyclable. The textile hardener is also environmentally friendly. Cardboard is mainly made of old paper. It is realized not only out of recyclable material but it is recyclable in its end form. The cardboard manufacturing process is quite simple: before the old paper is mixed into a pulp, it is first checked for fiber length. If these fibers are too short (because it has gone through too many recycling processes), new cellulose fibers are added to the composition thus making the material flexible but rigid. When soaking the cardboard strips, using the fiber in the cardboard, is of great importance. The wet strips are held in place by fiber until dried. Once the paper has dried, the strips receive wood-like qualities. The waving of strips creates a light filtering, porous composition which can be adjusted by adding more or tighter modules in the areas where more shade or privacy is needed.

Working with paper, has offered the possibility to work with tools that are easy to find and replace, and with machines made available by the university. When cutting the sheets of cardboard, wasting as little material as possible was one high priority. The width of the strips have been not only proportional to the their length (for structural rigidity) but they have also been dimensioned such that exactly eight strips of cardboard can be cut out of one sheet. In the end just 23% of the cardboard was wasted, the reason being of the variation in length of the strips (between 66 cm the smallest length bendable and 103 the longest). These 23% could have been recycled, however they were used for heating the house of one of the students in the project, which put our waste to good use. Cutting exactly eight strips out of the cardboard sheet was possible with the paper-cutting machine, however it would have never been possible with the laser-cutter which always needs a couple of centimeters on the side of the sheet for it to be glued onto the surface of the laser-cutter, bringing the final estimation to 41 sheets of cardboard, 36% material waste and five more days of cutting.

Replicating the modules after the shape of a tetrahedron made each module a rigid assembly in itself. The combination of modules in various ways would always result in a rigid self-supported structures. Only one single type of connection detail was used, such that it would not only limit the assembly time but allow the modules to be disassembled easily and separate materials such that they can be easily recycled.

During the exercise, there were a lot of lessons learned about material properties, manufacturing constraints, technological constraints and assembly logic. Knowing this beforehand makes a big difference in the quality of the design and the time invested. Therefore, integrating expert consultancy early on in the design phase could save a lot of time and energy wasted later on production problems. People with carpentry skills, with already acquired laser-cutter skills would have saved many days of experimenting in the early design phases.

The soaking/ drying/ glueing technique developed in the project, although efficient for an university case experiment, still needs development should it become economically feasible. At this point, there is still far too much handwork to be made which would definitely raise the costs of the structure. There are two ways this could be improved:

First, it could be developed such that it would involve the “end-user” contribution, the way a company like Ikea or IQ lamp would do. Delivering just the strips of cardboard (or material) to the end user, such that the end user can put it together, would be much more efficient than to transport the modules which cover a lot of space.

The second option would be to automate the fabrication process. Having produced the structure by hand, is something quite visible in how the structure looks which would make the product uncompetitive in an economical environment. Changing the material and bending it in an automized environment, could raise the quality of the product but most likely the cost as well. Automation plus end-user involvement could be an efficient way to further produce the structure.

Working with a parameterized digital model which allows for fast explorations of various designs can be indeed of great use and with the right computer simulations, large amount of material used for testing can be saved. However, introducing material elastic behavior in the parametrical model is still in development. One add-on for the Grasshopper parametrical plugin for Rhino that could improve the quality of the result of the 3D model is Kangaroo, which embeds physical behavior directly in the 3D model allowing for the interaction with it 'live' as the simulation is running. The warning of the developers is however, that Kangaroo is not developed or funded by any institution, it’s still a work in progress and that the accuracy of the results is not guaranteed. Another software worth exploring would be a light analysis (simulation) software to determine the size of the modules or regional agglomeration of the modules based on the space requirements. Once a correct 3D model is made, implementing “a continuous digital chain” (Scheurer, Schindler et al. 2005) from generating the geometry of every single part to generating the production code, would be the following step.

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List of Figures

Appendices

A.1 Glossary

Geometry glossary

Polyhedron - a 3D shape that consists of planar faces, straight edges and vertices. Each edge is shared by exactly 2 faces and at each vertex at least three faces and three edges meet (Pottmann, Asperl et al. 2007).

Space-filling polyhedron - a polyhedron which can be used to generate a tessellation of space (Weisstein 2002).

Tessellation - a tiling of regular polygons (in two dimensions), polyhedra (three dimensions), or polytopes (n dimensions) (Weisstein 2002).

Octahedron - a Platonic solid with six polyhedron vertices, twelve polyhedron edges, and eight equilateral triangular faces (Weisstein 2002).

Regular tetrahedron - the Platonic solid with four vertices, six edges and four equivalent triangular faces. A tetrahedron does not form a tessellation (Weisstein 2002).

Rhombic dodecahedron - a convex polyhedron with twelve congruent rhombic faces (Wikipedia 2012).

Equilateral triangle - a triangle in which all three sides are equal and all triangles are congruent to each other and are each 60 degrees (Wikipedia 2001).

Right triangle - has one of its angles measuring 90 degrees (Wikipedia 2001).

Project-specific glossary

Strip - a long narrow band of material, having the same width throughout its length cut from a standard sheet of material (A4, A3, A0 foam, paper or cardboard).

Component - typically 1 strip of material bent into a loop, stapled and bent one more time (Chapter 3.2) or soaked and bent (Chapter 3.3, 3.4, 3.5). It can also refer to one Rondi plastic piece or one playing card.

Module – a group of components which form a closed shape. In most tests, inscribed in the space frame of a tetrahedron.

Aggregation of modules – a loose form composed of a group of regular or/and irregular modules joined by a common face.

Face of a module (triangular) – three components glued together at 120 degrees angle from each other having a triangular shape in the same plane.

Flaps - the two “arms” of the component (Starting with chapter 3.3).

Triangular shape – the place where the flaps of three components are glued together in the shape of an equilateral triangle.

A.2 Tables

Table A2-1: Average area wasted for the project designed by Martina Hatzenbichler.

cutting boards	area cm²									
	triangle 1	triangle 2	triangle 3	triangle 4	used material	hole 1	hole 2	hole 3	hole 4	unused material
1	2249	1025	1802		5076	693	263	487		1443
2	2415	2196			4611	735	658			1393
3	1273	1107	3642	842	6864	346	301	409	201	1257
4	1685	1649	925	1376	5635	322	212	465	213	1212
5	3445	2483			5928	1150	781			1931
6	2370	2444			4814	403	598			1001
7	1773	2025	1395		5193	471	573	395		1439
8	2263	2097			4360	631	629			1260
9	2365	2000	1150		5515	620	757	296		1673
10	1724	3073			4797	472	987			1459
11	1415	2444			3859	403	553			956
12	1797	2289			4086	398	605			1003
13	2031	1584	1173		4788	610	426	165		1201
14	1673	1465	1752		4890	473	377	453		1303
15	2482	1995			4477	795	617			1412
16	2044	1913	1084		5041	607	594	269		1470
17	1595	1836	1913		5344	414	488	511		1413
18	3220	1638			4858	1085	455			1540
19	1811	2235			4046	498	700			1198
20	2417	2255			4672	742	685			1427
21	954	3471	958		5383	230	1194	146		1570
22	993	4046	1257		6296	237	1421	339		1997
23	1912	1229	1372		4513	272	288	572		1132
24	2075	1491	2075		5641	639	354	639		1632
25	1236	3407	1146		5789	334	1159	304		1797
26	1866	1834	1790		5490	540	568	536		1644
27	586	3894	1838	790	7108	105	564	544	157	1370
28	2229	2253			4482	713	718			1431
29	1725	3773			5498	515	1275			1790
30	1923	1855	2670		6448	600	544	848		1992
31	2733	1385	1289		5407	880	271	281		1432
32	1789	1708	2157		5654	514	459	681		1654
33	987	3183	2058		6228	246	1076	621		1943
34	3439	2079			5518	1198	616			1814
35	2401	2381	1060		5842	735	787	167		1689
36	2026	1809	2085		5920	666	555	606		1827
37	2305	2669			4974	699	843			1542
38	1618	1092	1897		4607	372	252	425		1049
39	2958	2102			5060	1025	641			1666
40	2048	2678			4726	656	838			1494
41	2824	1938			4762	923	587			1510
42	2686	2239			4925	885	685			1570
43	2084	1230	2040		5354	643	165	625		1433
44	2425	3048			5473	1010	790			1800
45	1662	2110	1907		5679	475	652	569		1696

					235631					67465
1 board area	7350	all boards	330750	total used	168166				total unused	162584
				percentage	50,84				percentage	49,16

A.3 Renderings

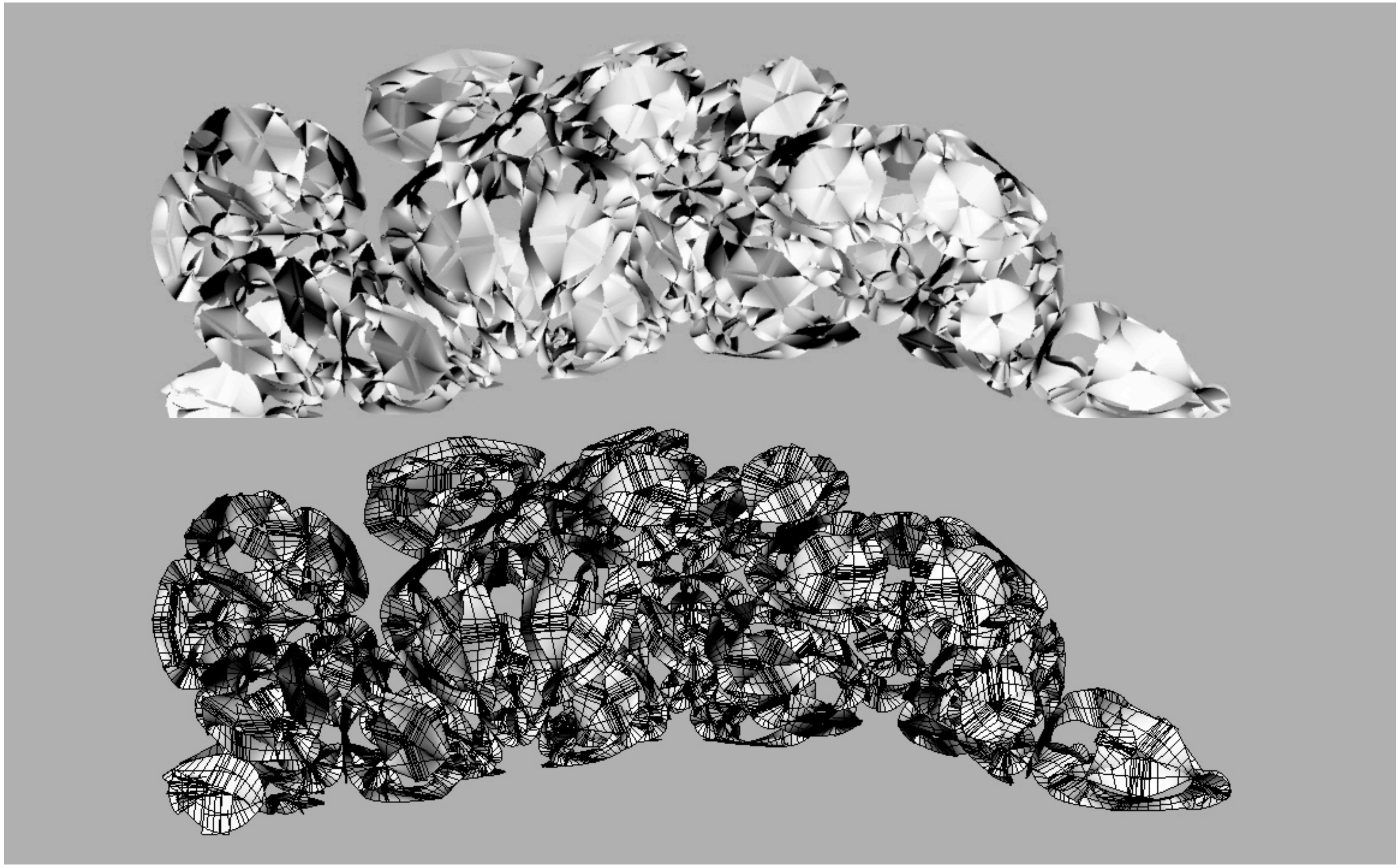

Fig. A3-1 Structure composed out of 23 modified modules inscribed in tetrahedrons.

A.4 Photos

Fig. A4-1 Final built structure.

Fig. A4-2 Final built structure in relationship to human scale.

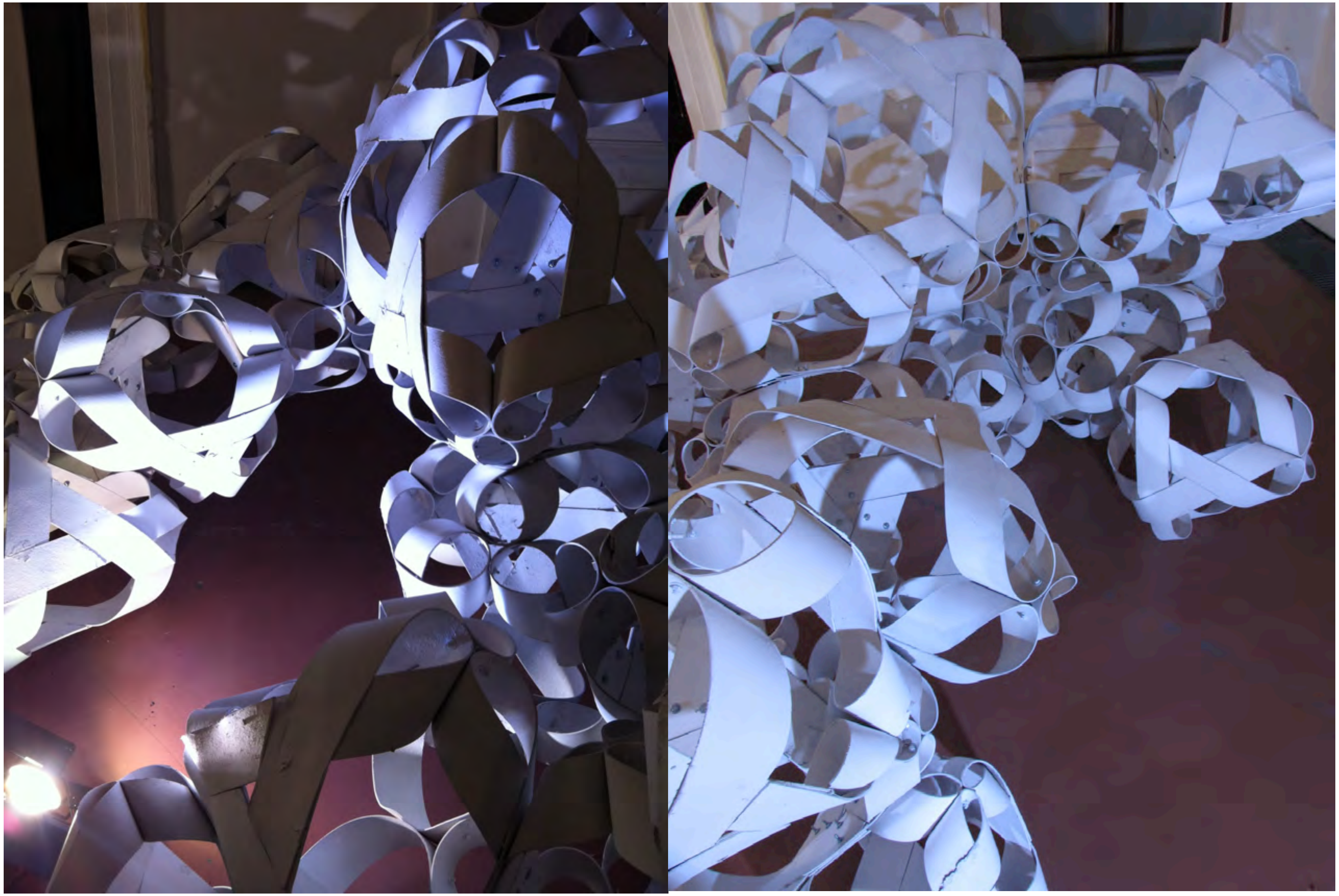

Fig. A4-3 Close up on the structure. Light - shadow tests.

Fig. A4-4 Detailed view of connecting modules.

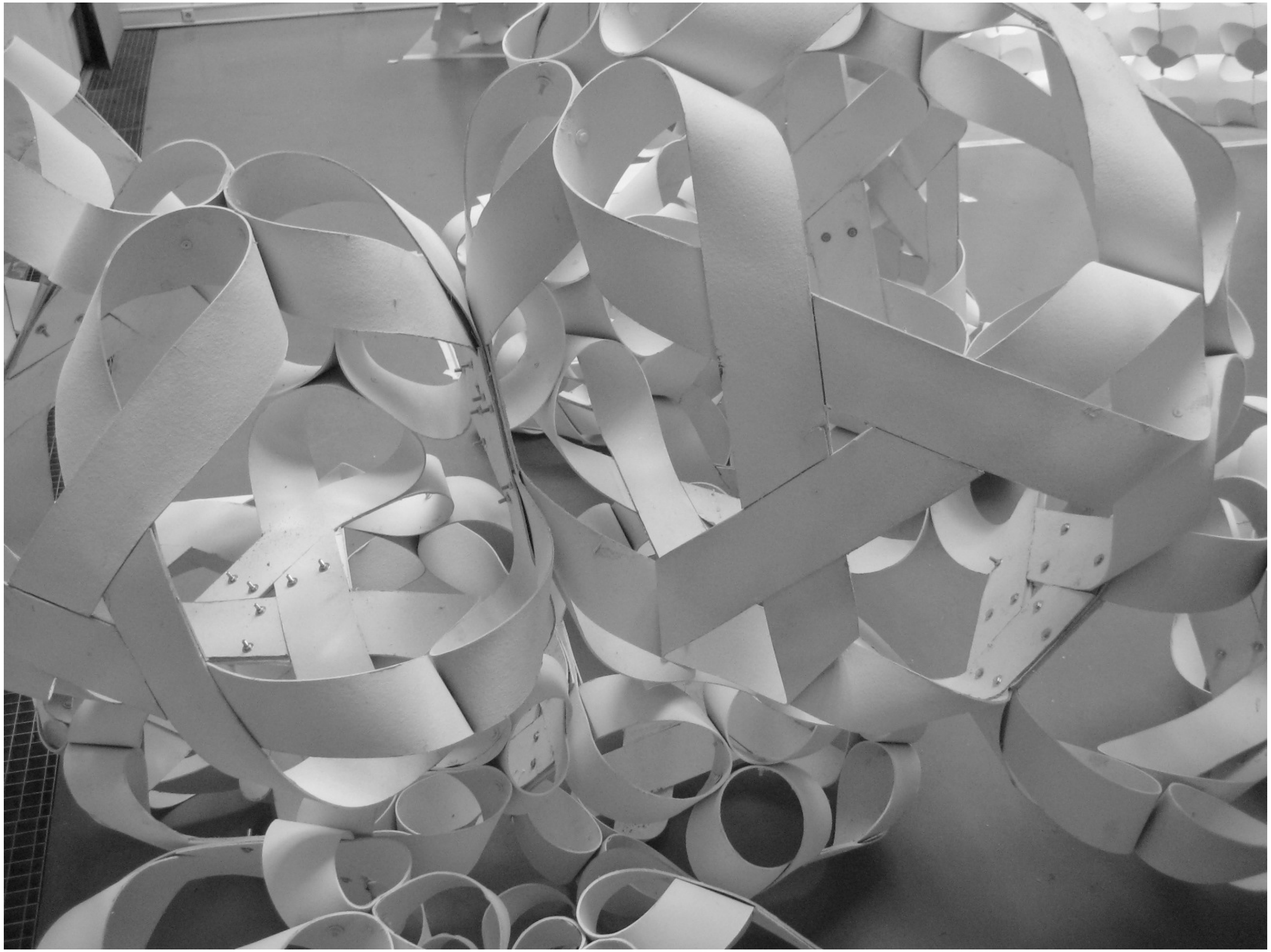

Fig. A4-5 Detailed view of connecting modules.

Fig. A4-6 Detailed view of connecting components.

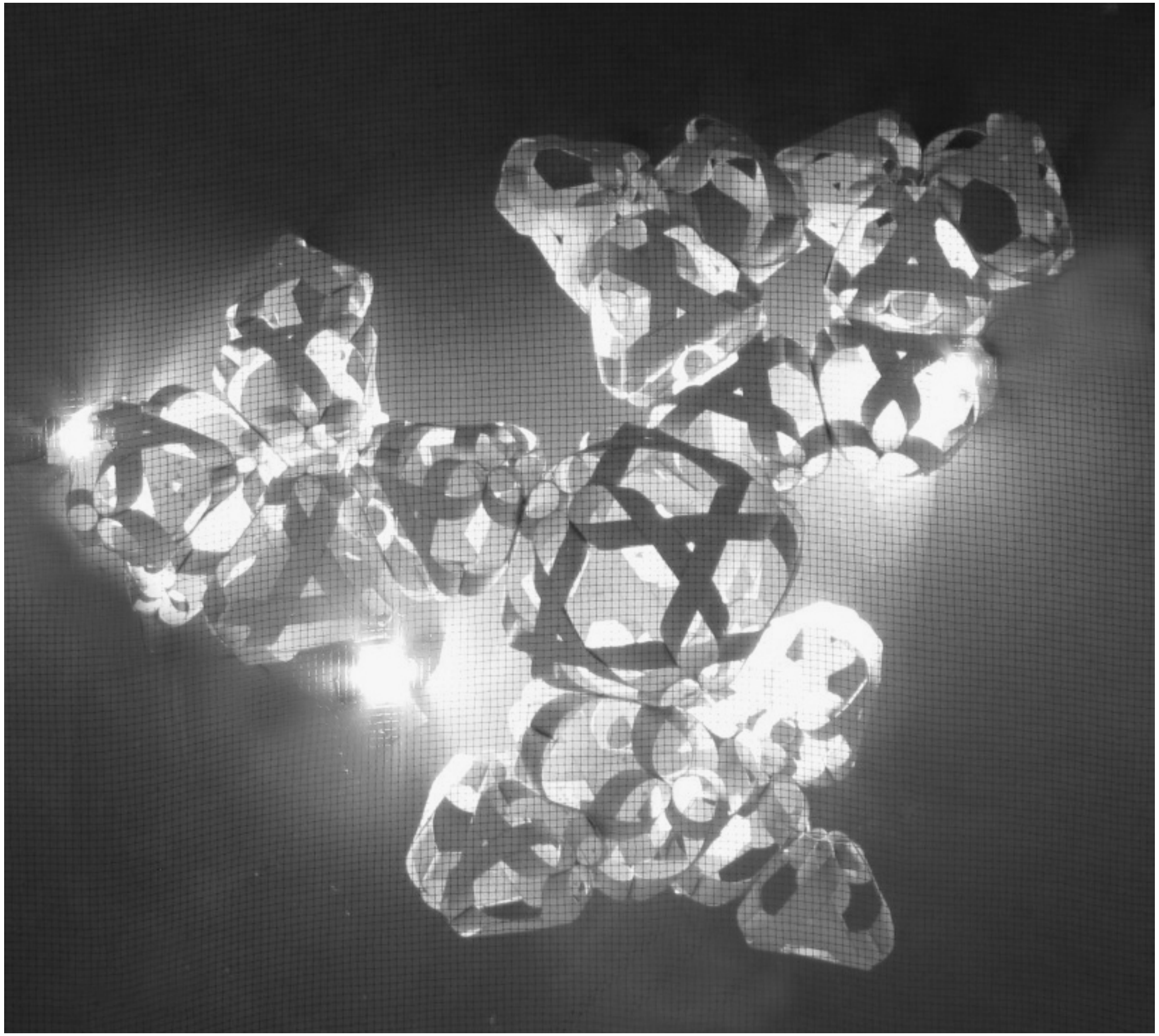

Fig. A4-7 Top view of the structure.