Designing Form-Active Portable Shelters

Parametric Frameworks for Small-Scale Equilibrium Structures

MSc Architecture Thesis by Sarah J. Roberts

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Abstract

In a time of rapid population growth and climate change, temporary structures offer certain advantages over longer-lived architecture. Portable shelters, for instance, present a type of temporary architecture that is lightweight, easily assembled, and quickly relocated. Such a shelter whose shape is defined by its own figure of equilibrium under applied loads can be classified as a *form-active structure* [1].

Due to this trait, form-active structures are notably difficult to design and model; often their geometry must be *form-found*. Before computers, this required a laborious trial-and-error process with physical modeling [2]. Nonetheless, form-active structures are prevalent in vernacular and high-tech architecture due to their ability to conserve material by exploiting their own inherent bending and tensile properties.

This research aims to test computational parametric tools in aiding certain aspects of the design process for lightweight portable shelters. More specifically, it evaluates the capacities of a certain spring-based particle system *Kangaroo for Grasshopper* (a plug-in for Rhinoceros) in the design of small-scale form-active structures. A simplified two-pole tent provides a case study for the research.

The form-finding process is the primary focus; the fabrication process is the secondary focus, including possible methods for selecting materials and generating cutting patterns. Most methods can be implemented with basic knowledge of math, physics, or coding. Strengths and weaknesses of Kangaroo are identified, and inherent differences between idealized models and physical reality are noted. Alternative design methods are suggested where applicable. Finally, possibilities for further research are presented.

Key Words

Temporary Architecture, Portable Shelter, Equilibrium Structure, Form-Active System, Form-Finding, Spring-Based Particle System, Parametric Design, Kangaroo for Grasshopper, Materiality, Cutting Pattern.

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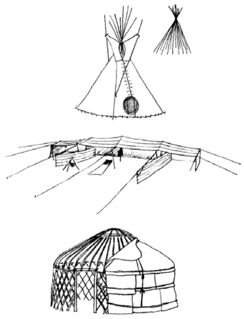

1.1.3.

1 Background

1.1 Introduction

1.1.1 Temporary Architecture

Successful architecture should accommodate humanity in all its evolutionary transformations. In a time of rapid population growth and climate change, the value of longer-lived architecture becomes questionable [3]. Humans have attempted to use architecture as a tool to attain immortality since antiquity. Monuments freeze legacies in travertine and bronze, aiming to commemorate public figures and legendary warriors (Fig. 1.1.1). Although monuments are engineered to counteract their inevitable disintegration, architectural permanence is an impossible undertaking.

This is because long-lived buildings see immense transformation of their social, political, and economic contexts. The environmental toll, high expense for construction and maintenance, and general dysfunction of long-lasting architecture all increase global demand for more transient designs. As more permanent architecture is increasingly demolished and abandoned, perhaps a turn to more temporary architecture is in order [4].

Due to its ability to flexibly handle environmental and social changes, temporary architecture periodically reemerges as a trend. Provisional architecture has been constructed since antiquity as makeshift shelter from climatic and predatory threats.

Today temporary architecture constitutes a relatively inexpensive, environmentally benign alternative to more lasting forms of new construction. Impermanent structures also provide opportunities to examine social behaviors, test new materials and technologies, and inform our future built environment (Fig. 1.1.2).

Figure 1.1.1. (2010) *Altare della Patria*. Monumento Nazionale a Vittorio Emanuele II.

Figure 1.1.2. Asal, Berk. (2010) *Spacebuster*. A mobile inflatable public space designed for New York City.

Figure 1.1.3. Renzo Piano Building Workshop. *Examples of Traditional Portable Shelters: North American Tipi, Bedouin Nomadic Tent, Asian Yurt.*

Introduction

Portable Shelters
Form-Active Systems

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1.1.2 Portable Shelters

Portable shelters are one type of temporary architecture built since the start of humankind. They are typically lightweight and deployable with a relatively short lifespan. They are also easily assembled, disassembled, and transported. Common vernacular portable shelters include tents, tipis, and yurts (Fig. 1.1.3).

These vernacular shelters resurface in contemporary architectural practice, especially when environmental, social, and economical circumstances demand alternatives for human survival (Fig. 1.1.4) [5].

Portable shelters also depart from their vernacular roots, appearing in high-tech modern forms. Contemporary deployable models are often flat packable and conserve material through prefabrication [6]. These makeshift structures are often used for recreational purposes.

They are also used to flexibly handle modern-day threats, including climatic fluctuations and extreme environments (Fig. 1.1.5). The common tent is a ubiquitous type of portable shelter; it provides a key case study for this research.

1.1.3 Form-Active Systems

Many portable shelters qualify as *form-active systems*, or systems in which the envelope has notable structural capacities. As stated by Moritz Fleischmann and Julian Lienhard, form-active structures enable a high level of integration in long-spanning and lightweight structures [1]. Many portable shelters made of stretched cloth, cords, and poles – such as tents – fall under the form-active class. Such shelters are the focus of this research (Fig. 1.1.6).

Bending-Active Systems

A class of form-active system whose geometry is based on the elastic deformation of initially planar elements can be classified as a *bending-active system* [7]. Bending-active structures rely on pre-stressed singly or doubly curved units for stability and strength. (Pre-stress involves the intentional introduction of stress into a structure to improve its performance [8]). Bending-active structures (including tents) have the power to integrate their geometry, structural system, and envelope in a single functioning entity (Fig. 1.1.7).

Figure 1.1.4. (2007) *Yurt with the Gurvansaikhan Mountains, Mongolia.*
Figure 1.1.5. (2014) *DRASH™ S Series Shelter.* Portable military tent.
Figure 1.1.6. Stuttgart ICD/ITKE. (2010) *Textile Hybrid M1.* Hybrid tension-active/bending-active (form-active) system.

Problem Statement

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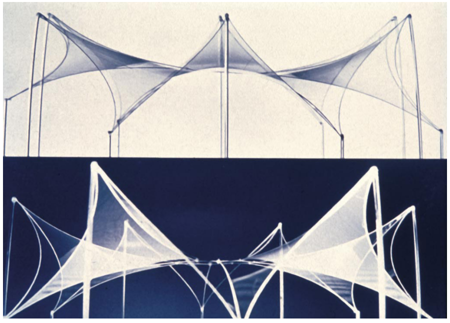


1.2.1.

Tension-Active Systems

Another class of form-active system whose tensile forces define its shape is known as a *tension-active system*. Structures in this class typically include a surface membrane exclusively carrying tensile forces [8]. The lightweight membrane is pre-stressed to eliminate compressive forces with supporting elements, such as masts or beams. Thus a stable state of equilibrium can be attained, despite outer loads (i.e. dead load, wind, or snow).

Tents often employ a tensile system, wherein ropes and rods provide pre-tension in the membrane. Membranes are usually fabricated from textiles, polymers, or foils, and they often derive their strength from a doubly curved geometry (Fig. 1.1.8).

1.2 Problem Statement

As previously stated, the design process for form-active structures is complex. The codependent interaction of geometry and force is a unique characteristic of membrane structures; it demands close collaboration between architect and engineer. This is unlike traditional design processes, wherein the architect largely conceptualizes the shape of a building before the engineer calculates how the structure can be built [9].

In the case of form-active structures, an optimal form using minimal materials can be determined through form-finding methods. Through these methods, a structure's form is defined by its own shape of *equilibrium* under applied loads [10]. The resultant rational form, therefore, is not a product of arbitrary aesthetic subjectivities.

Rudimentary approximations for the design of tension-active structures were first modeled in the 1970's with soap films (Fig. 1.2.1). A *minimal surface,* defined as a surface with the smallest possible area, is always formed by a soap-film within a set of defined boundaries. A uniformly pre-stressed membrane structure naturally follows the shape of a minimal surface [11].

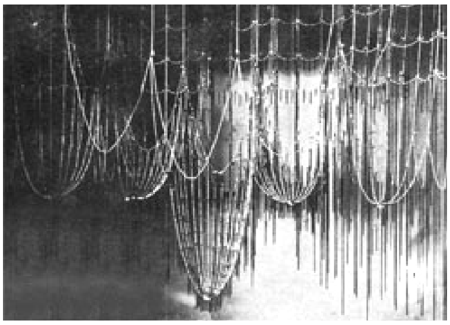
Before computers, designers constructed physical models to determine the shape of equilibrium structures. One such example is Gaudi's tension-only freely hanging catenary cables (Fig. 1.2.2). But the continuous construction and adjustment of physical models is an arduous and time-consuming process. The advancement of technology now allows for digital simulation and adjustment in real-time. Form-active systems are already designed using computational tools at larger scales, but the application of parametric methods in the design of smaller-scale structures (namely tents) until recently has been notably underdeveloped.

Figure 1.1.7 Halbe, Roland. (2010) *ICD/ITKE Research Pavilion 2010.*

Figure 1.1.8 Mojtahedi, Arad. *Munich Olympic Stadium, View from Olympic Tower.*

Figure 1.2.1. SL Rasch GmbH. *Soap Film Model as a Minimal Surface within a Defined Boundary Geometry.*

Research Questions and Objectives



1.2.2.

1.3 Research Questions

P**rimary research questions**:

1. How can computational parametric tools be used in the design process for small-scale form-active structures?
2. More specifically, what are the strengths and weaknesses of *Kangaroo for Grasshopper*, a plug-in for Rhinoceros, in the form-finding process?

S**econdary research questions**:

1. Once form-found, what are some possible methods for the fabrication of small-scale form-active structures?
2. More specifically, how might *Kangaroo* and *Rhinoceros* aid in the processes of selecting materials and generating cutting patterns? Which alternative methods are recommended?

1.4 Research Objectives

The goal of this research was to explore some possible techniques for the design of small-scale equilibrium structures. This comprised the implementation and evaluation of certain digital tools (namely *Kangaroo for Grasshopper*). Further, it involved the identification of key factors that should be considered in the design process, including the phases of form-finding, selecting materials, and generating cutting patterns. The output of this research would ideally be useful for designers and industry partners alike, to help guide the design and manufacture process of portable structures such as tents.

More generally, this article aims to promote the creation of more structurally efficient, aesthetically beautiful, and financially economic shelters. The computational methods explored would ideally be paired with traditional analog techniques to create customized shelter typologies for a wide range of scenarios. This might include solutions serving the requirements of different programs, scales, and environmental contexts. Ultimately, these methods can support built solutions to flexibly handle modern-day threats, including climate fluctuations, environmental extremes, and social upheaval.

Figure 1.2.2. Tomlow, J. (1989) *Antoni Gaudis Hangemodell und seine Rekonstruktion.*

Research Framework

2.1.1.

2 Research Methods and Results

2.1 Research Framework

2.1.1 Overview

In order to identify the strengths and weaknesses of Kangaroo for the design of membrane shelters (and recommend alternatives), a framework should first be established. The content of this *Research Methods + Results* section is organized as follows. First, base conditions for the research are established (including the focus case study and the target design phases). Second, digital form-finding methods are explained and evaluated in parallel with analog methods. Third, a few methods for selecting materials and generating cutting patterns are briefly explained for possible further research and implementation.

2.1.2 Case Study: Tent

The case study selected for this research is a 2m x 2m tent consisting of a single tensioned membrane supported by two perpendicular bending poles. Based on a Sierra Designs model (Fig. 2.1.1), it is a simplified version of a classic two-pole tent. This typology was chosen for its classic dynamic of bending and tension forces present in many portable shelters. Its geometry forms the primitive basis of many popular tent models. For this study, the tent was modeled in abstract terms for basic simulation with the given functions of Kangaroo.

2.1.3 Research Scope and Limitations

The **form-finding** phase of the design process was the primary focus of this research. This phase, explained previously in section 1.2 *Problem Statement*, comprised the generation of various equilibrium geometries. Two additional phases of the design process were the secondary foci of this research: **selecting materials** and **generating cutting patterns.** The *selecting materials* process comprised various attempts to integrate specific material properties into the design. The *generating cutting patterns* process involved documenting possible methods for determining 2D cutting patterns from flat membrane material.

Figure 2.1.1. Roberts, Sarah. (2011) *Sierra Designs Tent.* Mom and Aunt Sarah camping at Beehive Lake, Idaho, USA.

2.2.1

2.2 Methods: Form-Finding

2.2.1 Introduction

2.2.1.1 Important Factors in Form-Finding

The following form-finding methods were attempted to generate various equilibrium geometries. Form-finding the basic shape of an equilibrium structure ultimately defines many of its **functional qualities** (Fig 2.2.1). For example, it designates the structure's dimensions, area, and volume, in addition to establishing the necessary construction, assembly, and deployment techniques. Further, the form-finding process also largely influences the **experiential qualities** of the final design. This includes how the space is perceived aesthetically, occupied, circulated, entered, and exited.

2.2.1.2 Methodology Framework

There exist many possible methods for form-finding. These techniques range from traditional physical prototyping to computational simulations. The methods attempted here require no extensive knowledge of math, physics, or coding. Instead, this approach focuses on the interactive advantages of parametric modeling. It aims to assist the designer in efficiently generating numerous iterations in a short time. The designer can thereby achieve distinct spatial qualities for their design with minimal effort required.

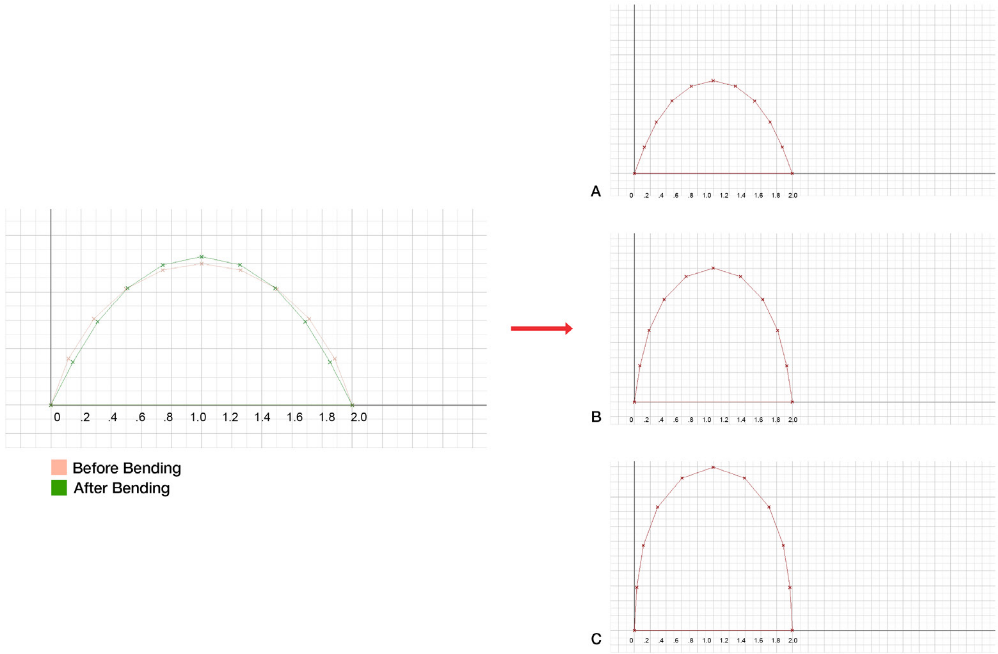
2.2.1.3 Kangaroo: A Spring-Based Particle System

This research evaluates *Kangaroo*, an add-on for the parametric design tool *Grasshopper*. Grasshopper works in parallel with the 3D modeling software Rhinoceros. Kangaroo allows geometries to be modeled and optimized in real time, simulating basic principles of physical behavior in the digital form-finding process [12]. The live simulation can be started and stopped at any specific moment for assessment and adjustment.

Figure 2.2.1. Simpson, Adam. (2013) *Tents.*

Methods: Form-Finding

Step 1: Construct Base Geometries



2.2.2.

Kangaroo is just one of several possible approaches using a *spring-based particle system* for simulation. (Processing, for example, can achieve identical results.) A particle system can be thought of as a network of independent objects, usually depicted as simple dots [13]. In Kangaroo, particles can be connected with damped springs to approximate real physical performance of non-rigid structures. More detailed information about spring-based particle systems can be found in the publications of Axel Kilian and John Ochsendorf [14].

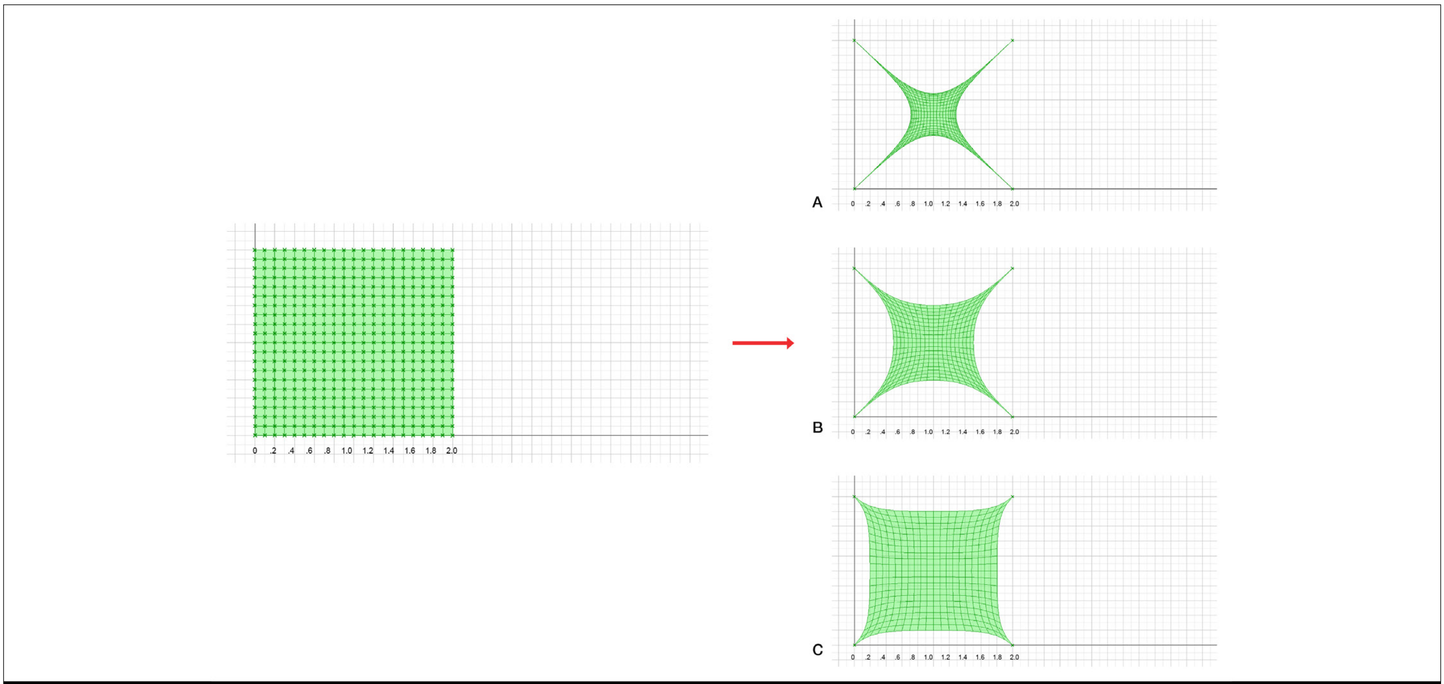
Kangaroo can simulate various forces (i.e. gravity and spring forces) affecting the particles in the system. Forces can originate from many different sources designated by the designer, such as geometric constraints or material elasticity [12]. All forces are represented with idealized force vectors, allowing for live interaction and negotiation between them. Spring force vectors, for example, are based on Hooke's law of linear elasticity [15, 16]. For this research, a Velocity Verlay solver was used. (The solver denotes the integration method used by Kangaroo to calculate new positions of particles [12]).

2.2.2 Form-Finding Methods

2.2.2.1 Step 1: Construct Base Geometries

In this step, the basic starting members of the case study were modeled prior to the simulation of forces. This included modeling **bending-active** members, **tension-active** members, and **anchor points** to be included in the spring-based simulation. This initial phase started to define the basic functional features and formal appearance of the structure. The choices made during this phase also inform possible manufacture techniques.

Figure 2.2.2. Left: Geometry of Rods: Before and After Bending Force. **Right:** Variations in Parameter: Spring Rest Length.



2.2.3.

2.2.2.1.1 Base Geometries – Digital Model

1. Bending-Active Rods

Two bending-active rods composed the support structure for the tensile membrane. In Kangaroo, a spring is represented as a line segment connecting two points (particles). Therefore, in order to approximate the behavior of a flexible member, the overall shape must be broken into smaller line segments and modeled as a series of separate springs.

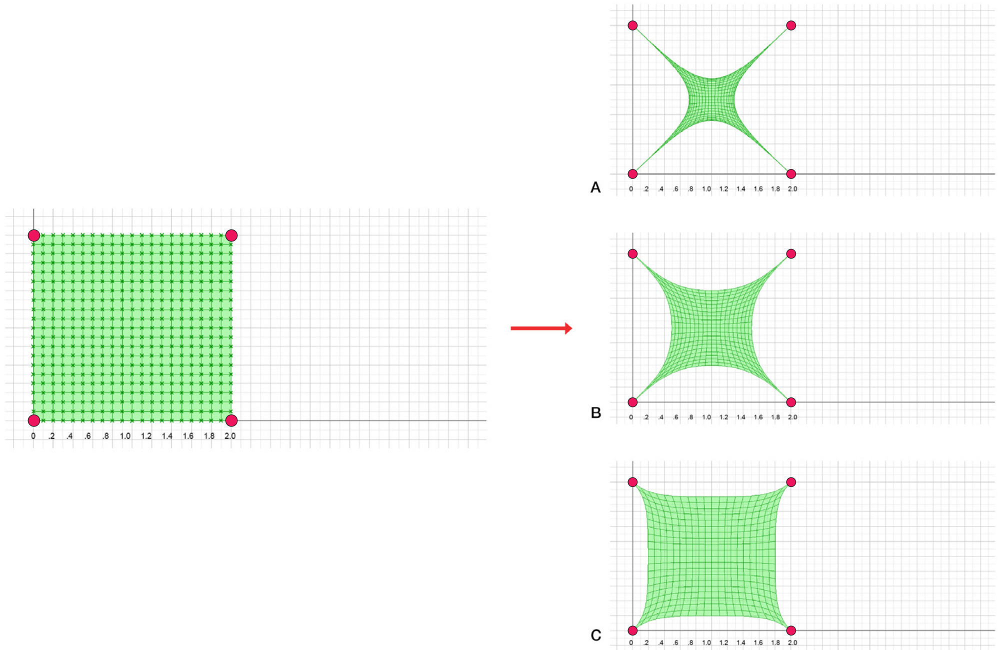
Here, the arcs that resemble the tent poles were subdivided into smaller line segments. Each segment acted as one spring (Fig. 2.2.2). It should be noted that in reality the rod's mass would have been distributed throughout its length, instead of at the endpoints of each line segment [12]. While this configuration was not accurate in terms of continuum mechanics, it still provided a formidable estimation of real behavior.

Base geometries can be modeled in Rhinoceros or in Grasshopper. As a parametric design tool, Grasshopper offers the possibility to quickly alter the definition. Of course, Rhinoceros also has its own advantages for modeling, especially for those not yet proficient in Grasshopper.

Figure 2.2.3. Left: Planar Mesh Before Tension Force. **Right**: Variations in Parameter: Spring Rest Length.

Methods: Form-Finding

Step 1: Construct Base Geometries



2.2.4

2. Tension-Active Membrane

A single planar mesh represented a simplified textile membrane for the tent. In order to behave like a sheet material, the mesh was modeled as a grid of many springs. The *Weaverbird* add-on (Giulio Piacentino) was used to set each mesh edge as an individual curve.

Next, an appropriate method for mesh subdivision was determined. Here, a simple quadrangular subdivision was used (Fig. 2.2.3). In addition to Weaverbird, Grasshopper's *MeshEdit* tool and Kangaroo's *Refine* and *QuadDivide* functions can assist in quadrangular, triangular, and other subdivision strategies to achieve different results. Topology is essential in defining tensioned membranes. Rearranging springs not only changes the overall geometry, it also rearranges forces. Optimal mesh resolution is a fine balance between curvature and geometry [15, 16]. Further, the chosen subdivision strategy later informs seam patterns for the manufacture process [8].

3. Anchor Points

Next, the boundary conditions for the structure were determined. Anchor points were used to fix the structure; within Kangaroo these points do not move when forces are applied. But once these points are *baked* into Rhinoceros geometry, they can be moved even while the simulation is running. This allows for real-time adjustment.

Figure 2.2.4. Left: Anchor Points, Pre-Simulation. **Right:** Anchor Points, Post-Simulation

2.2.5

In reality, anchor points are often used for lightweight tent membranes to resist upward wind loads. These points are usually located at high points, low points, and along the perimeter of the structure. They also largely determine the membrane's equilibrium shape. (Fig. 2.2.4)

2.2.2.1.2 Base Geometries – Physical Model

A physical model of the case study tent (scale 1:10) was fabricated to measure the accuracy of the digital simulation (Fig. 2.2.5). This included the accuracy of the behavior of the bending-active rods and the tension-active membrane. In this step, the basic starting components of the physical model were constructed, prior to the application of forces. Dimensions were exported directly from the digital model.

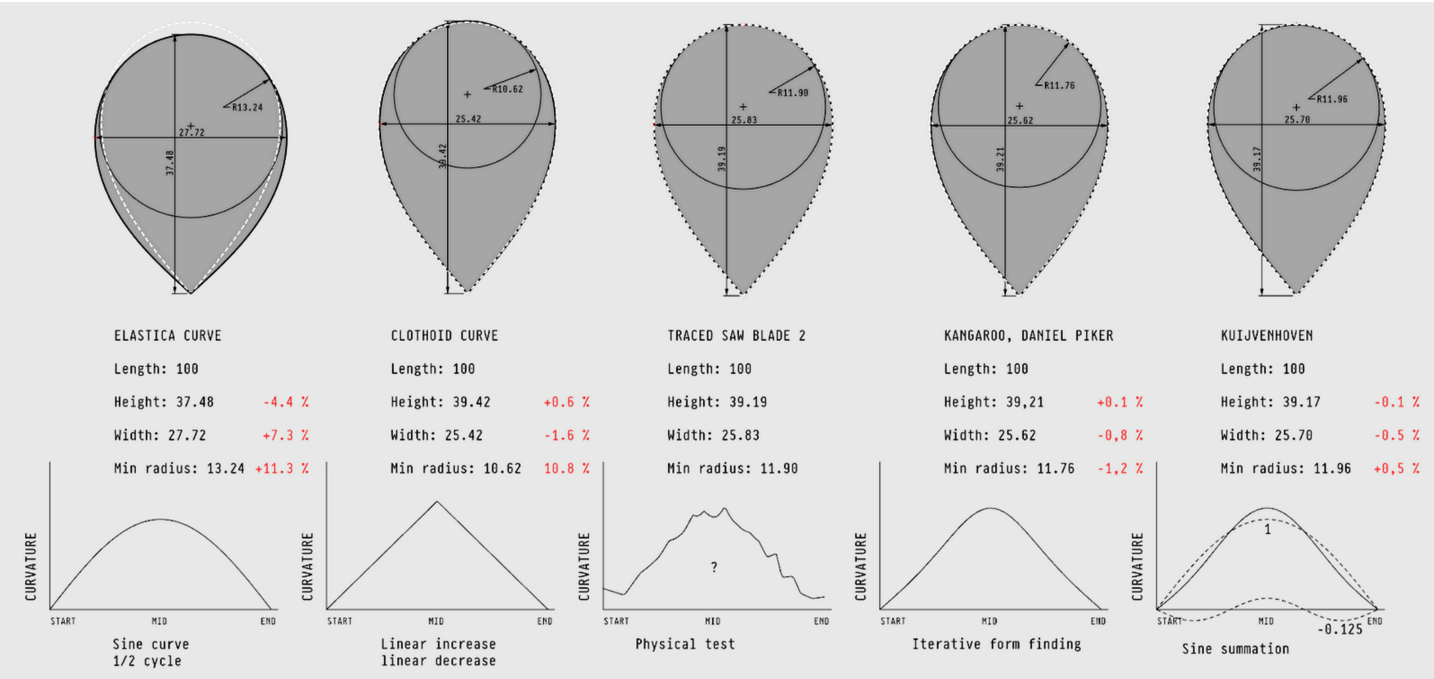
1.**Bending-Active Rods**

The two bending rods were constructed from 1mm diameter tempered high-carbon steel. While typical tent poles consist of multiple smaller segments connected together, the two single rods used in this scale model approximated the same bending geometry.

Figure 2.2.5. Analog (Physical) Model of the Tent Case Study (Scale 1:10)

Methods: Form-Finding

Step 2: Implement Forces



2.2.6

2. Tension-Active Membrane

The fabric for the scale model membrane was made of polyamide nylon. Many elastic fabrics share the same general properties of this highly elastic material; Kangaroo should therefore be capable of making an elementary approximation of its behavior.

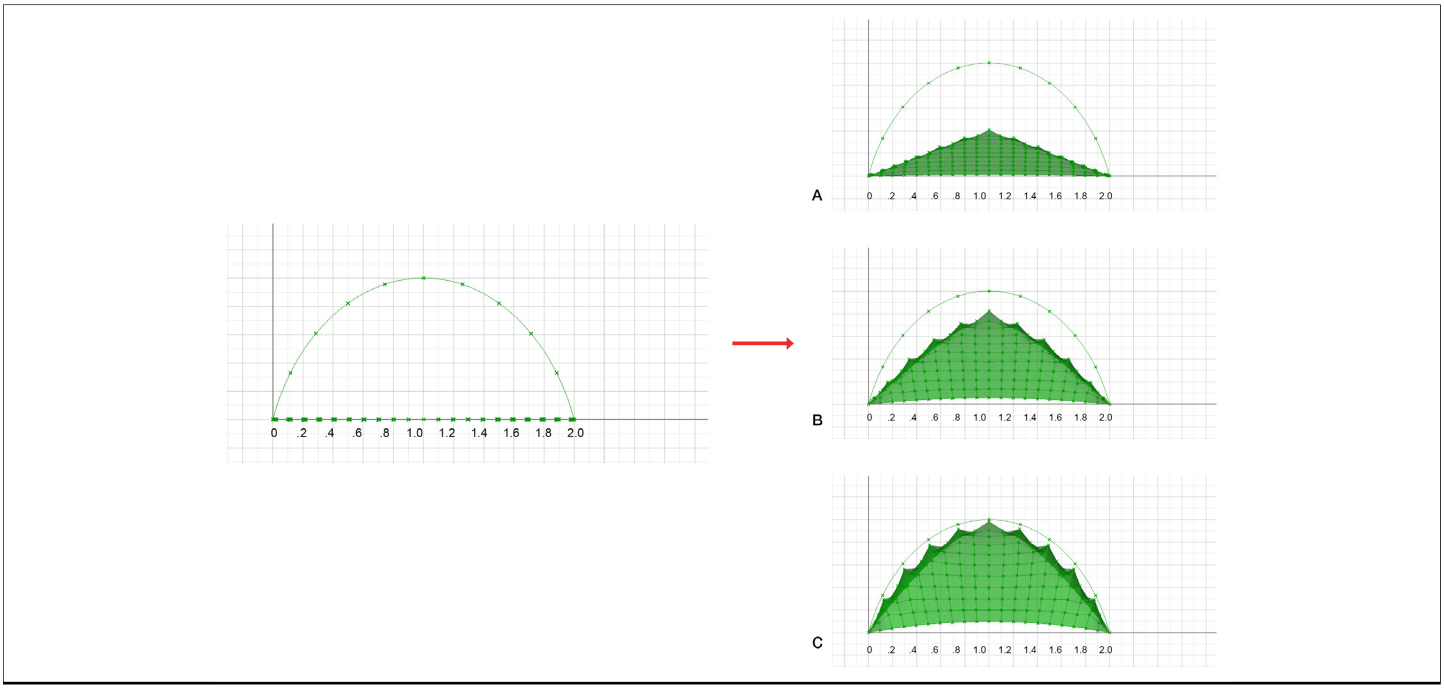
3. Anchor Points

In the physical model, anchor points were positioned at the four corners of the membrane and the end points of the bending rods. Spring connections between rods and membrane were modeled as static members in the physical study using .25mm diameter steel wire. The positions of all anchor points were exported directly from the digital model.

2.2.2.2 Step 2: Implement Forces

This section describes the application of a few essential force types on the case study tent. This includes the implementation of **bending**, **spring**, and **unary** forces. In the digital simulation of such forces with Kangaroo, an equilibrium state is eventually reached through application of damping to the particle system. (Damping eventually ceases the movement of the system.) The physical model provided a comparison study.

Figure 2.2.6 Nettelbladt, Mårten. (2011) *Comparing 5 Curves.*



2.2.7

2.2.2.2.1 Implement Forces – Digital Model:

Kangaroo uses Newton's second law to approximate particle movement. The law states: *The change of momentum of a body is proportional to the impulse impressed on the body, and happens along the straight line on which that impulse is impressed.* This law is also known as $F = ma$. Forces are simulated in Kangaroo by calculating the total force vector F for each particle as a sum of all forces acting upon it [12]. When the net forces acting upon each particle sum to zero, the system stops in a position of equilibrium.

2.2.2.2.1.1 Bending Force

Bending force was applied to the two tent rods. The rods experienced elastic deformation. Therefore, when the bending force was eliminated, the rods returned to their original state. In Grasshopper, the rods were represented as segmented polylines. In Kangaroo, bending resistance works in sets of three points [12]. Elastic bending is simulated for each set of three consecutive points along the polyline. (For example: node 1, 2, and 3; node 2, 3, and 4; node 3, 4, and 5; etc.) (Fig. 2.2.2).

As explored by Mårten Nettelbladt, the geometries formed when bending different materials within their elastic limits (before plastic deformation occurs) share related qualities [17]. (Fig. 2.2.6) shows Nettelbladt's comparison of five versions of a bending curve, including (1) an elastic curve, (2) a clothoid curve, (3) a traced saw blade, (4) a curve made with Kangaroo, and (5) a curve made of Sine curves. The last curve (5) was drawn by Maarten Kuijvenhoven (a 2009 TU Delft MSc Civil Engineering graduate) as a combination of two sine waves with different amplitudes.

Figure 2.2.7. Spring Force: Rod-Membrane Connections. **Left**: Base Geometry Pre-Simulation: Flat Membrane and Rods. **Right**: Variations in Parameter: Spring Stiffness.

Methods: Form-Finding

Step 2: Implement Forces

While simulating the bending force in Kangaroo, variations in certain parameters were tested in real-time. (Fig. 2.2.2) shows variations in the spring rest length parameter, which triggered changes in tent height: (A) Rest Length = 400mm, (B) Rest Length = 500mm, (C) Rest Length = 580mm. Further information about the bending force in Kangaroo can be found in the work of S.M.L. Adriaenssens and M.R. Barnes [18].

2.2.2.2.1.2 Spring Force

Introduction: Spring Force

As previously explained, Kangaroo uses springs to simulate the behavior of non-rigid structures. This is possible because all materials, even relatively stiff ones, can stretch and compress in reaction to the forces exerted upon them [12]. In Kangaroo, springs behave in tension or compression according to Hooke's law $F = kx$. This law states that the force F needed to extend or compress a spring by a distance x is proportional to that distance. Various basic spring forces applied to the tent in the digital simulation are explained below.

Spring Force: Mesh Relaxation

Here, springs were used to model the textile membrane of the tent. The starting mesh of interconnected springs and particles was "relaxed" to form-find its initial shape, given the assigned anchor points. While the simulation ran, particles moved relative to each other. Thus the sum of forces acting upon each particle was in constant flux [13].

Tensile membranes carry loads only through tension force. Pre-stress in the membrane eliminates compressive forces. This type of system can be extremely lightweight and achieve a significant degree of transparency, if desired [8]. Pre-stress also gives the structure stability given external loads such as wind and snow.

In Kangaroo, springs can be ascribed certain rudimentary parameters, including *rest length* and *stiffness*. These parameters were changed in real-time to allow for optimization. (Fig. 2.2.3) shows variations in spring rest length, which induced changes in tent surface area, elasticity, and transparency: (A) Rest Length = 0mm, (B) Rest Length = 40mm, (C) Rest Length = 80mm. In variation (A), the area of the mesh was minimized, much like the behavior of a soap film.

Spring Force: Rod-Membrane Connections

Springs were also used to model the connections between the textile membrane and the two rods (Fig. 2.2.7). The end points of each line segment subdivided from each rod were connected to corresponding points on the mesh. These springs were crucial; they acted on both rods and membrane. They maintained tension in the membrane by providing the required level of pre-stress.

The stiffness parameter for each spring is one of many which can be adjusted to the preferences of the designer. (Fig. 2.2.7) shows variations in spring stiffness that changed membrane stability and tent height: (A) Stiffness = 10, (B) Stiffness = 500, (C) Stiffness = 1000. If the connection points are not satisfactory, their positions can be tweaked until membrane behavior is in-line with the designer's intentions.

Spring Force: Edge Cables

In certain cases, it might be advantageous to integrate more robust edge cables along the periphery of a tent membrane. Such cables are used in reality to give tents extra stability and maintain the bending forces acting upon the elastic rods. In order to accomplish this, the stiffness of the springs along the mesh edges was increased. As previously explained, each spring acts depending on its ascribed properties. (Fig. 2.2.8) shows variations in spring stiffness that induced changes in membrane stability and distance off the ground: (A) Stiffness = 0, (B) Stiffness = 5000, (C) Stiffness = 10000.

These edge cables, in combination with the relaxed mesh and rod-membrane connections, simulated an entire network of spring forces. This network provided a simplified visualization of force distribution, including different classes and magnitudes of neighboring interactions that influenced global geometry and structural behavior [15, 16].

2.2.2.2.1.3 Unary Force

In order to simulate the effects of gravity in Kangaroo and assign specific weights to particles in the system, a unary force can be incorporated. Unary forces can also be used to represent forces not reliant on the distances between particles (wind, for example). This force acts under the premises of Newton's third law, which states: *To every action there is always an equal and opposite reaction.*

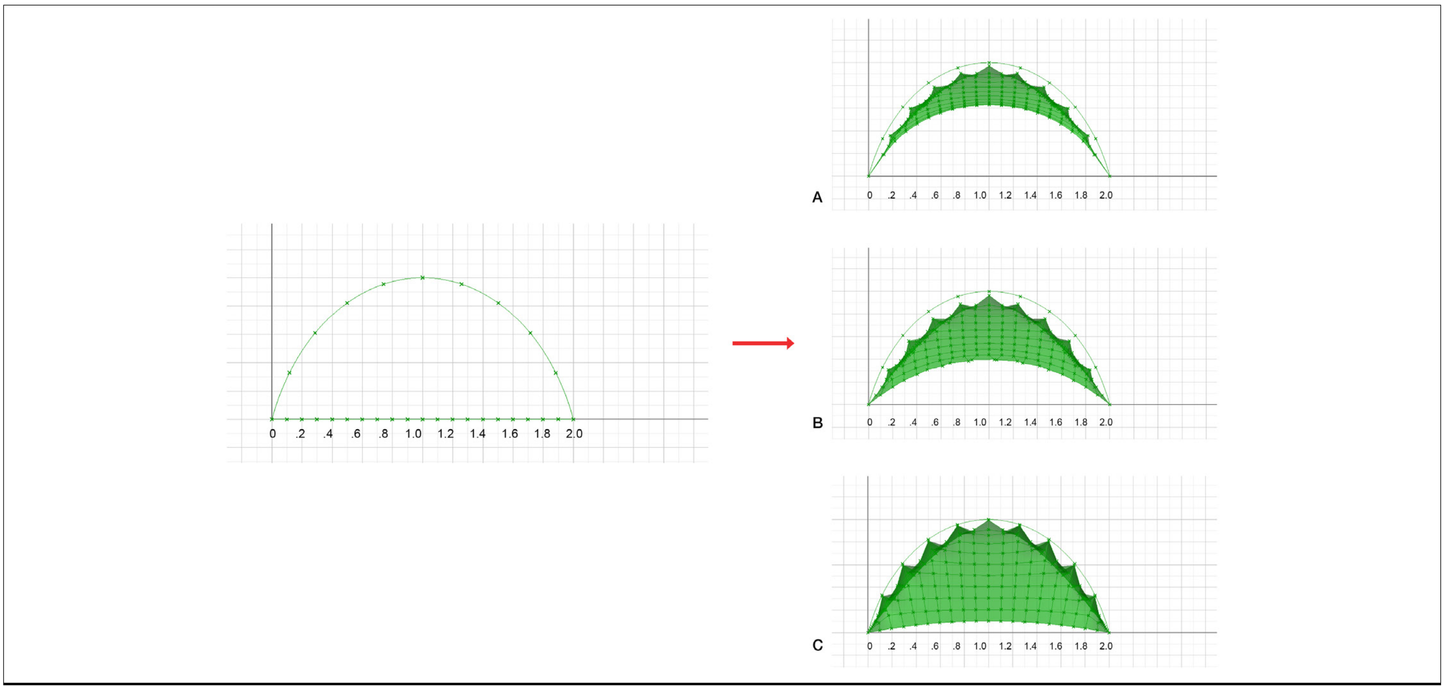
Whereas spring forces in Kangaroo are simulated with interactions between pairs of particles, unary forces only apply to single particles [12]. So instead of subtracting a force from one particle and adding it to another, unary forces are represented by linking particles to another infinitely distant and massive particle [12, 13].

2.2.2.2.2 Implement Forces – Physical Model

The physical model of the tent (scale 1:10) was built to test the accuracy of the digital simulation (Fig. 2.2.5). In comparison to the physical model, Kangaroo's approximation of bending force was formidably accurate. Both digital and analog bending curves shared very closely related geometry (Fig. 2.2.9).

Kangaroo's simulation of the tensioned membrane with various spring forces was also reasonable, but could have diverged significantly for different types of materials. The polyamide nylon used in the physical model is a highly elastic material; it would be interesting to see how Kangaroo would have performed in modeling more rigid materials, like those used for many tents. Possible methods for addressing specific materiality are discussed in further detail in the *Methods: Fabrication* section below.

Methods: Fabrication



2.2.8

2.3 Methods: Fabrication

2.3.1 Introduction

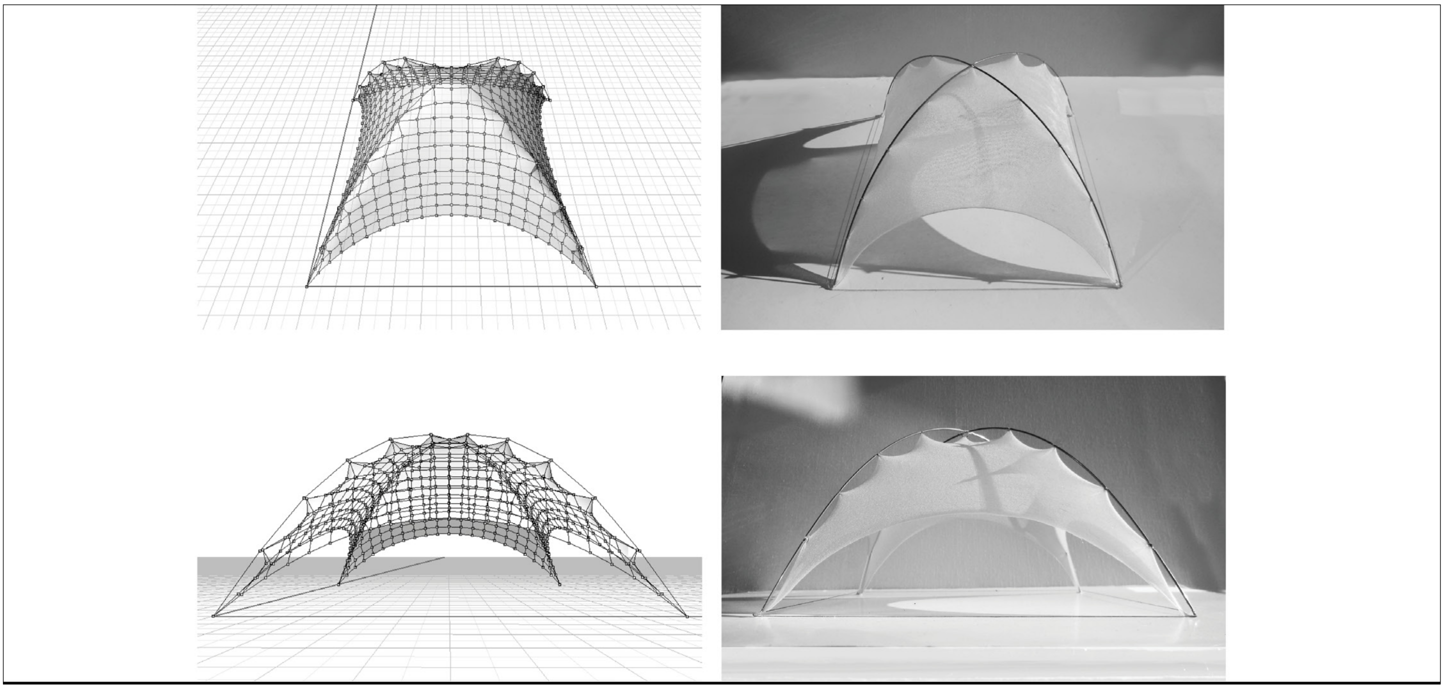
The processes of form-finding and fabricating form-active structures are inherently linked. While the form-finding phase largely determines the base geometry of a design, the fabrication phase departs from the abstract realm of springs and particles, leading into preparation for manufacture. This section is divided into two key processes for fabrication: *selecting materials* and *generating cutting patterns*. The material selection process involves the selection, simulation, and application of different materials. The pattern generation process involves defining the proper 2D cutting patterns for the chosen material. This section provides a brief overview of some possible fabrication methods for implementation. Kangaroo and Rhinoceros were used where possible; alternative techniques are recommended where necessary.

2.3.2 Possible Methods: Material Selection

2.3.2.1 Introduction

Selecting specific materials for form-active shelters and simulating their behavior can be challenging. This is because each material has its own set of characteristics that influence its shape under given forces. A material's internal structure provides key limitations that guide the design process. Often, selecting materials for small-scale tents is done through trial-and-error with physical models (i.e. cutting, fitting, re-cutting, re-fitting, etc.)

Figure 2.2.8. Spring Force: Edge Cables. **Left**: Base Geometry Pre-Simulation: Flat Membrane and Rods. **Right**: Variations in Parameter: Spring Stiffness.



2.2.9

The following introduces some possible computational strategies to approach the material selection process more efficiently. Some key factors for consideration when selecting materials include the design's function (i.e. overnight shelter, sun/rain canopy), geometry (i.e. dimensions, curvature, subdivision/seam pattern), and environmental conditions (i.e. temperature, precipitation, wind, ground quality). These factors play an important role in determining optimal material properties (i.e. weight, durability, and resistance to stretching and compression) (Fig. 2.3.1) [19].

2.3.2.2 Possible Methods: Grasshopper and Rhinoceros

Materials: Bending-Active Rods

As concluded in the case study, Kangaroo's simulation of elastic bending was sufficiently accurate. This is because a truly elastic bend shares related geometry, regardless of material [17]. While bending behavior stays constant, the forces required to bend a component into a certain shape (and the stresses in the component itself) differ depending on the material used. Some common materials used for tent poles include carbon fiber, glass-reinforced plastic (GRP), steel, and aluminum alloy.

Materials: Tension-Active Membrane

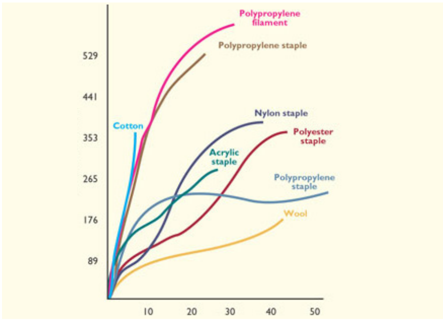
Kangaroo's simulation of the generic behavior of high-elasticity materials was also sufficient, to a certain extent. When classified, a sampling of highly elastic materials reveals many products with similar material compositions [20]. But in order to model the precise behavioral differences between specific materials, it's not as simple as directly inputting numbers into the spring *stiffness* or *rest length* parameters.

Figure 2.2.9. Left: Digital Tent Model. **Right:** Analog Tent Model (Scale 1:10).

Methods: Fabrication

Possible Methods: Material Selection

2.3.1.



2.3.2.

Kangaroo does not currently simulate the actual physical properties of materials; it is not possible to feed explicit material values into Kangaroo, only numerical values. The *stiffness* input in Kangaroo does not directly link to a physical material property; rather it uses Newton's second law $F = ma$ for approximation. The difference between external loads L and internal resistance I defines a resultant force F for each particle.

However, certain basic steps can first be taken using the given features of Kangaroo to more accurately model the generic behavior of fabric. For instance, *shear springs* – diagonals that can prevent each mesh face from deforming – can be added. Different stiffness values can also be applied for the normal springs and the shear springs to simulate various fabric properties [19].

Proposal: Simulating Real Material Behavior in Kangaroo

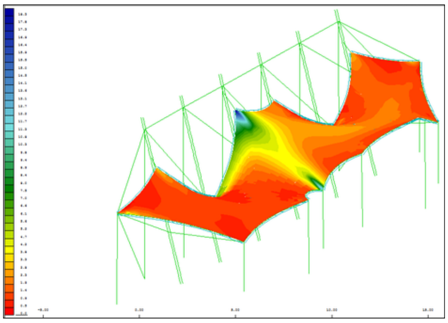
The following rough proposal describes a possible method for simulating specific material properties in Kangaroo, using its given components, components of other add-ons (i.e. *Karamba*), or by coding new custom components. The latter involves more in-depth knowledge of programming, math, and physics.

Common materials used for tent fabric include polyester coated with PVC and nylon coated with acrylic, polyurethane (PU) or silicone. Many materials used for tensile membranes fall under the *non-linear* class. Such materials have a non-linear stress v. strain graph (Fig. 2.3.2). The *Young's modulus* (or the elastic modulus) of materials can be defined as a local ratio of stress over strain. Physical experiments performed with a material can determine values of a local Young's modulus from the slope of its stress/strain curve. Alternatively, values from such physical experiments can be numerically interpolated to determine a material's Young's modulus for specific stresses.

It might be possible to use local values of Young's modulus to calculate a numerical difference in behavior between various materials. Thibault Clar, an engineering student at TU Delft, proposed the creation of a certain algorithm to work in parallel with Kangaroo. This proposal comprised modifying the particle system code by linking the varying stiffness of a certain material (due to its non-linearity) to the behavior of the particle spring system. Mesh subdivision (seam patterns) and spring properties could therefore be assigned based on the stress/strain ratios derived from the material tests.

Figure 2.3.1. SL-Rasch, Sefar Architecture, Buro Happold. (2010) *Courtyard of the Al-Masjid al-Nabawi*, Medina, Saudi Arabia.
250 deployable sun umbrellas (each 306m^2) composed of steel structures with PTFE membranes.

Figure 2.3.2. (2014) *Load-Elongating Curves for Select Fibers.* Stress/Strain Curves: Comparison of tensile properties of man-made and natural fibers.



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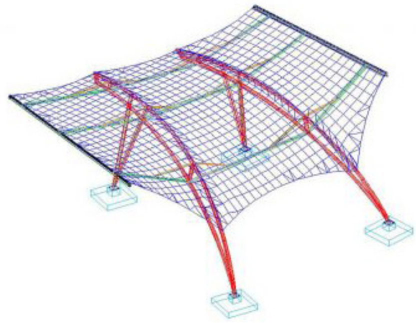


2.3.4.

This proposal can be attempted using Grasshopper's existing *math* and *list* functions. The Python code *PyFEM* could also be implemented, as it can handle non-linear material behavior. As stated by Clemens Preisinger, developer of the *Karamba* plug-in, currently Karamba cannot handle material non-linearity.

2.3.2.3 Possible Methods: Alternative Software

It may be more efficient (and effective) to address materiality not within Kangaroo, but using alternative software. Large-scale form-active structures are already largely designed with specialized software incorporating specific material properties. Of course, different scales require different topologies, materials, and structural detailing.

But such software can also be used for the design of small-scale shelters such as tents. While different physical systems and materials are at play, the same approach still holds valid at different scales.

Multimedia Engineering Pte. Ltd. produces *WinFabric,* software that integrates the properties of commonly used fabrics obtained from biaxial testing (Fig. 2.3.2). WinFabric also facilitates the tasks of form-finding, nonlinear finite element load analysis, patterning, connection detailing, fabrication, and assembly. German-based company Sofistik AG produces software that allows users to define stress-strain curves for materials and spring elements (Fig. 2.3.3).

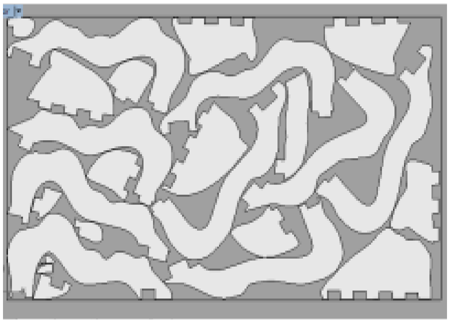
GSA Fabric, developed by Oasys, provides analysis of non-linear fabrics in dynamic relaxation. *Maya* is comparable to Kangaroo as it uses a spring-based particle system for simulation. But it also provides the option to select from a handful of common membrane materials.

Figure 2.3.3. Multimedia Engineering Pte. Ltd. (2014) *WinFabric Software.* Setting Fabric Properties.

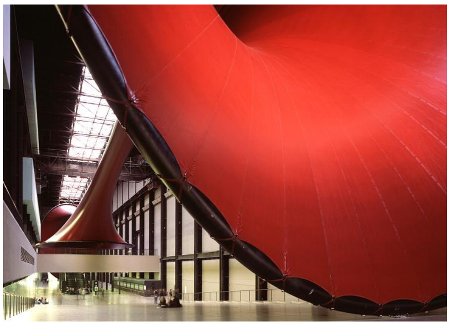
Figure 2.3.4. Sofistik. (2014) *Sofistik Software: Measuring Maximum Principal Tension Stress.*

Methods: Fabrication

Possible Methods: Cutting Patterns



2.3.5.



2.3.6.

2.3.3 Possible Methods: Cutting Patterns

2.3.3.1 Introduction

The process of generating cutting patterns for tensile membranes requires translation of the form-found 3D geometry into 2D shapes. These shapes can then be *nested,* meaning their position and orientation in relation to each other can be optimized to minimize fabric waste. The final shapes can then be cut from the appropriate flat material by the manufacturer and fabricated together. This process can be difficult because the necessary pre-stress in the membrane must be accounted for.

In the design of form-active structures, different materials (i.e. a very stretchy nylon versus a more rigid polyester) affect structural behavior. This behavior affects the structure's equilibrium shape, which in turn affects cutting patterns in the manufacture process. Traditionally, cutting patterns for different materials were determined by manually disassembling physical prototypes. The following overview provides some possible digital techniques to approach the patterning process.

2.3.3.2 Possible Methods: Grasshopper and Rhinoceros

Generating cutting patterns can be challenging because tensile structures assume their equilibrium shape under a certain degree of prestress. While a rigid panel can be *unrolled* in Rhinoceros, a doubly curved membrane is a different animal.

Rhinoceros and Grasshopper indeed offer some features and plug-ins that facilitate patterning for membrane structures. For example, the plug-in *Rhino Nest* (Rafael del Molino) optimizes the position and orientation of parts on a flat surface for cutting. It also allows the designer to assign priorities to objects and identification tags (Fig. 2.3.4).

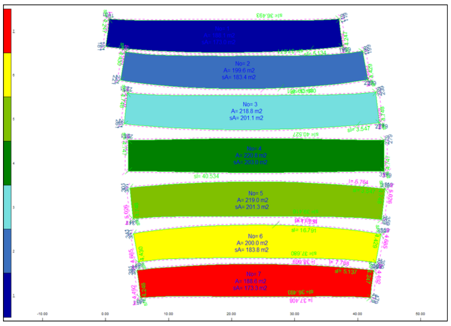
The Shrinking Method

One approach to generating cutting patterns in Rhinoceros is to deliberately *shrink* the fabric membrane by intentionally cutting its parts too small [21]. First, the membrane seam layout is defined by its mesh subdivision pattern. Optimal subdivision can be attained by evaluating stress in the membrane for adequate distribution. As a general rule, seams should trace the zones of greatest stress. And regardless of scale, designs of the same shape, material, and pre-stress typically require the same number of panels.

Once the final form-found geometry is *baked* out of Kangaroo into Rhinoceros geometry, the anti-clastic shape can be converted to flat panels derived from the mesh

Figure 2.3.5. Del Molino, Rafael. (2014) *RhinoNest Patterns.*

Figure 2.3.6. Kapoor, Anish. (2002) *Marsyas.*



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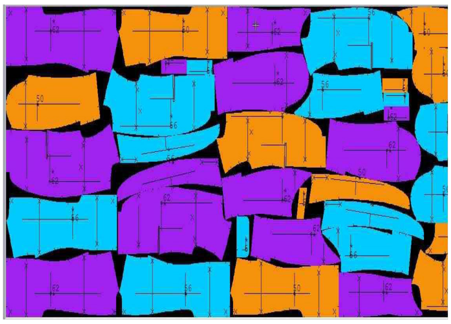


2.3.8.

faces. These panels can be downsized according to their material type. Thus the necessary pre-stress is present when the membrane pieces are welded together along its seams, ensuring stability and strength in the assembled structure. This method was used by Anish Kapoor and Arup for the construction of *Marsyas*, an immense elliptical membrane structure installed in the Turbine Hall of the Tate Modern in 2002 (Fig. 2.3.5).

Since non-linear material behavior depends on the quality of applied stresses, compensation values are often determined from experience (and physical material tests) instead of calculation. Values around 1% *warp* (the direction of the fabric's long threads, generally stronger) and *weft* (the direction of the cross-threads, generally weaker) are typical for common membrane fabrics.

2.3.3.3 Possible Method 3: Alternative Software

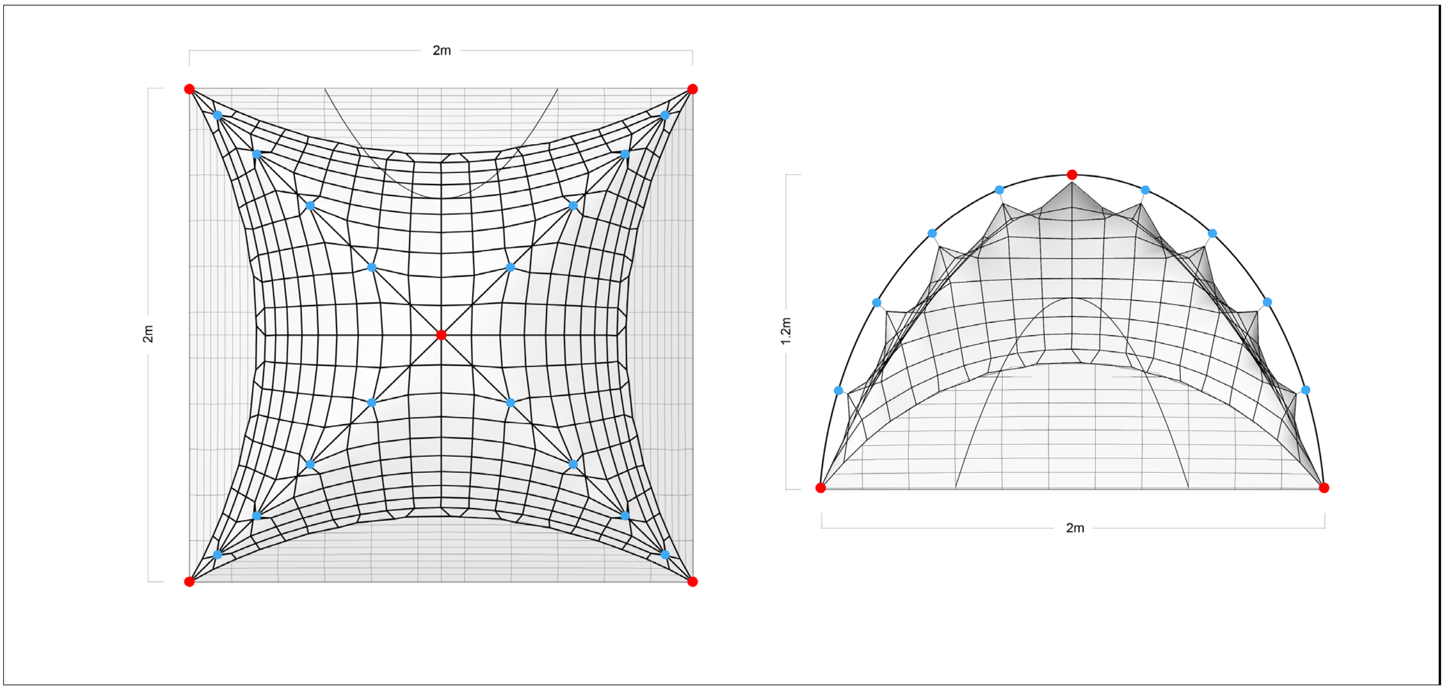
For cutting patterns, *MPanel-R* can be used as a plug-in for Rhinoceros to facilitate basic form-finding, seam allowance, and nesting. Alternatively, the final form-found geometry can be exported out of Kangaroo and Rhinoceros and into different software to address issues of patterning and nesting. *Compad* by Tentnology and Sofistik AG's software (introduced in *Possible Methods: Material Selection*) can output cutting patterns (Fig. 2.3.6).

German company Technet GmbH produces *EasyNT*, software that aids in the comprehensive membrane structure design process, including form-finding, non-linear load analysis, cutting pattern generation, and nesting. *K3-Tent* by GeoS can subdivide doubly curved surfaces and approximate their flat state by mapping them onto a plane. As a rule, the mapping results in a pattern with dimensions 1-2% less than those of the final surface. K3-Tent can also define appropriate margins for cutting and implement algorithms for nesting. These cutting lines become prospective seams for the final design.

ExactFlat can convert a 3D model into a 2D pattern, including necessary compensation for material stretching. It can also nest patterns on a cutting template to optimize yield. Further, ExactFlat allows the designer to make adjustments to material type and dimensions while simultaneously providing cost information. *Lectra* and *Gerber* can also aid in patterning and nesting processes (Fig. 2.3.7).

Figure 2.3.7. Sofistik. (2014) *Sofistik Software: Contour of 2D Cutting Patterns.*

Figure 2.3.8. Lectra. (2011) *Lectra Screenshot: Cutting Patterns.*



3.2.1.

3 Conclusions

3.1 Main Conclusions

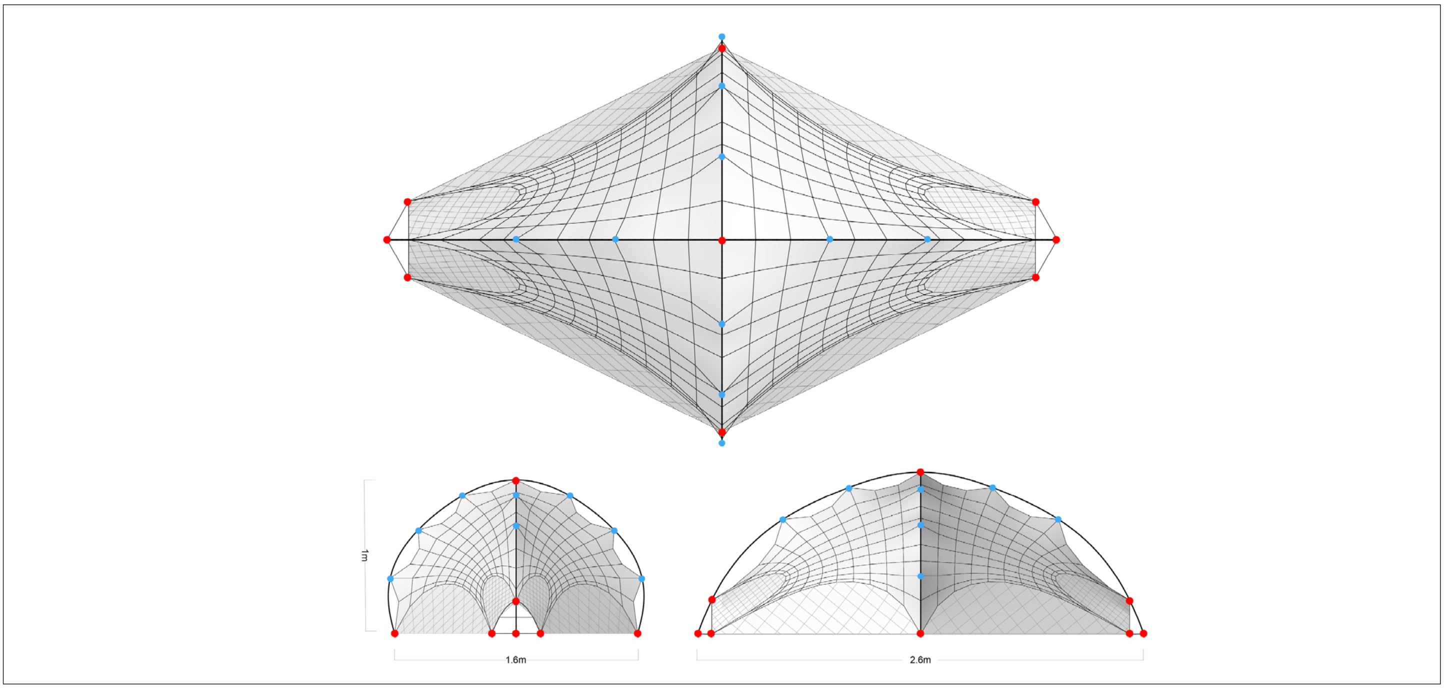
3.1.1 Parametric Tools

In retrospect, parametric computational tools proved to be useful for aiding certain aspects of the design process for small-scale equilibrium structures, particularly for form-finding. The primary advantage of parametric modeling lies in its ability to test several iterations in a short time period, demanding minimal effort from the designer. Further, the interface of Grasshopper and Kangaroo is visually intuitive, allowing direct manipulation of the design without a high level of specialized knowledge or technical skill.

3.1.2 Form-Finding

Kangaroo proved to be an effective tool for approximating real-life physics in the form-finding process. But Kangaroo is just one of many spring-based particle systems which can facilitate form-finding. Like its comparable tools, Kangaroo has its own strengths and weaknesses. *Processing*, *RhinoVault,* and Karsten Schmidt's *Toxiclibs* (based on *Java* and *Processing*) can all achieve nearly identical results. *RhinoMembrane*, a plug-in for Rhinoceros, uses FEM-based algorithms and can estimate specific pre-stress levels. The *ixForten* software can support a wide range of processes beyond form-finding, including engineering and production phases (i.e. structural non-linear analysis and pattern layouts).

Figure 3.2.1. Roberts, Sarah. (2014) *Tent Typology 1*. Scale: 4 m^2, Capacity: 4 people, System: bending-active + tension-active. Form-found in Kangaroo.



3.2.2.

3.1.3 Materiality, Cutting Patterns, and Nesting

While its strengths in form-finding are formidable, Kangaroo's inability to link efficiently to real material properties suggests alternative methods. Kangaroo acts primarily as an abstraction; material-specific behavior is not in the nature of the tool. Yet, while Kangaroo does not currently simulate specific materials, its generic approximation for highly elastic materials comes close enough to reality to help guide the manufacture and construction of form-active structures like tents.

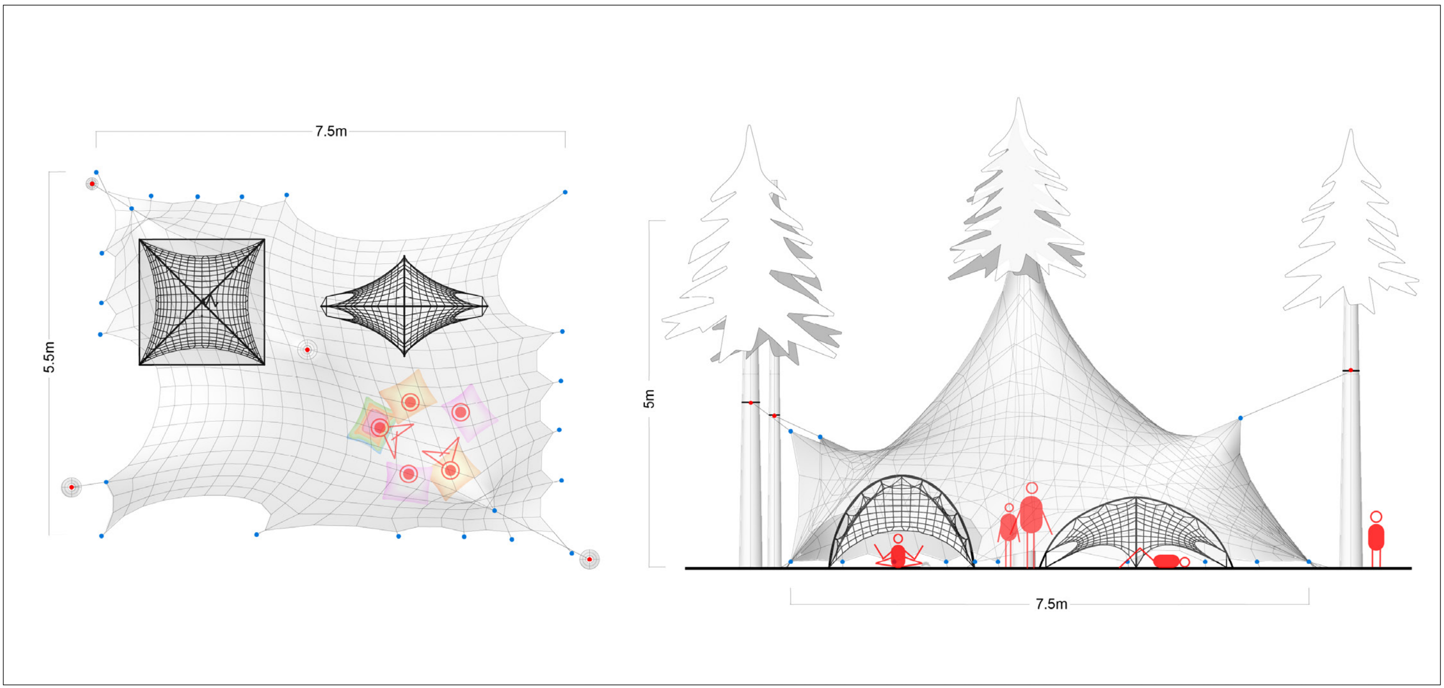
For the tasks of generating cutting patterns and nesting, there certainly exist strong possibilities within Grasshopper and Rhinoceros. And where these tools fall short, there exist numerous other digital methods to efficiently approach these tasks. (These methods were discussed in detail in the *Methods: Fabrication* section.)

3.2 Reflection

Hopefully the methods explored in this research can help inspire the creation of more structurally efficient (and aesthetically beautiful) form-active structures. The ultimate goal of this research was to create a design technique applicable for many different scenarios. This included different requirements such as function, scale, or environment.

Figure 3.2.2. Roberts, Sarah. (2014) *Tent Typology 2.* Scale: 3 m^2, Capacity: 1 person, System: bending-active + tension-active. Form-found in Kangaroo.

Reflection



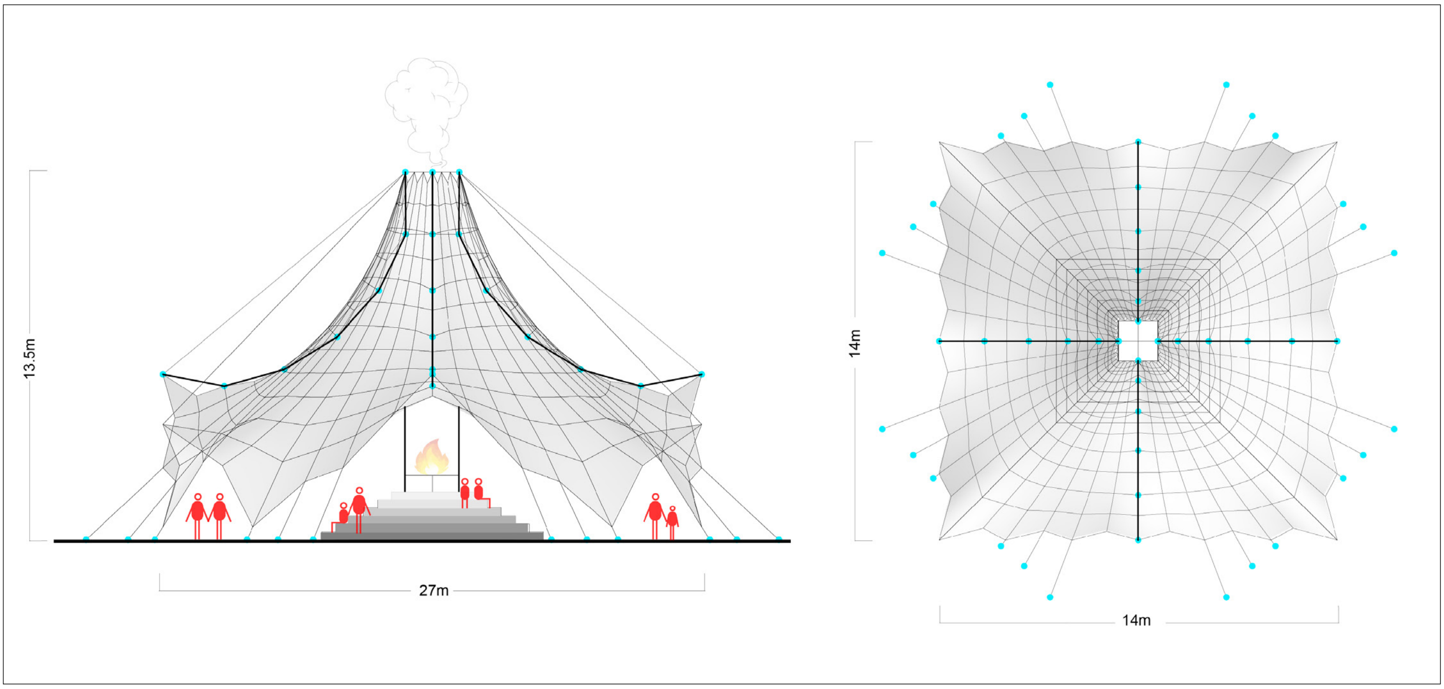
3.2.3.

While the case study selected for this research was a simple small-scale tent, many other form-active typologies can be created with similar techniques. For example, canopies, hammocks, and kites all support different functions but share some related geometric and physical systems. Kangaroo is flexible enough to roughly model these typologies and output customized models for specific situations. (Fig. 3.2.1, 3.2.2, 3.2.3, 3.2.4, 3.2.5, 3.2.6) show some example typologies all form-found in Kangaroo.

Please note that the digital methods deemed effective in this research are still most effective when paired with physical tests. Simulations are abstractions that provide a basic understanding of real-world physics. An idealized computational model, no matter how precise, cannot account for all the complex conditions that exist in reality.

Figure 3.2.3. Roberts, Sarah. (2014) *Tent Typology 3*. Scale: 40 m^2, Capacity: 5 people, System: tension-active. Form-found in Kangaroo.

Further Research



3.2.4.

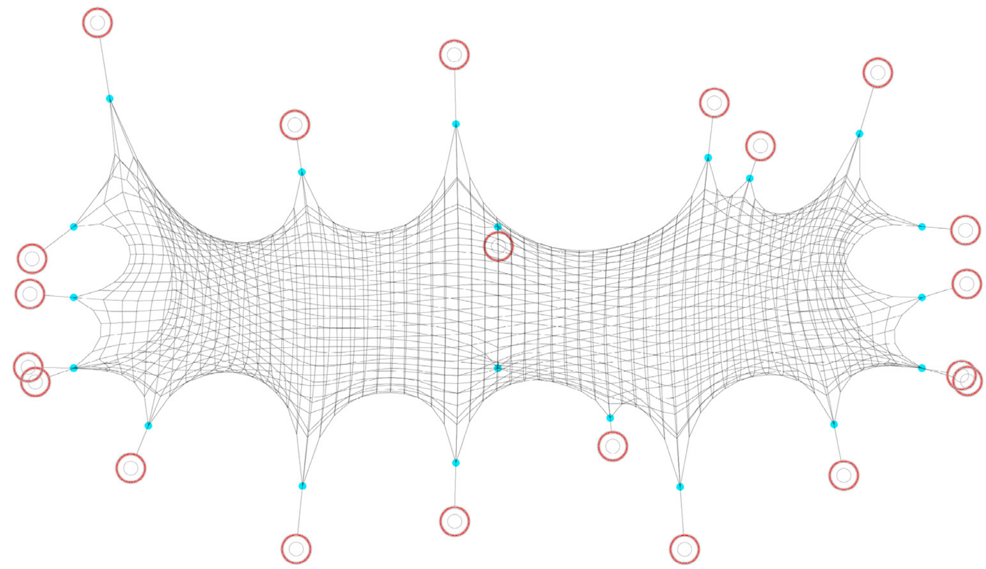
3.3 Further Research

Possibilities for further research could involve further testing and evaluation of the alternative methods introduced in the *Methods: Fabrication* section. Additionally, these methods could be compared to physical models to evaluate how they measure up to reality. Further, techniques could be explored to simulate the impact of site-specific environmental conditions. This could include temperature, wind, rain, and snow loads. Environmental feedback from actual contexts could thereby be integrated into the design model.

This research may also prove relevant for larger social and scientific questions beyond temporary architecture. Cultivation of similar computational methods could even provide solutions for non-architectural functions. Some examples might include military, space, or ad venture sports applications such as sailing, parachuting, or kite surfing. Additionally, further research into materials could yield new information for the fabrication of higher-caliber textiles, foils, and polymers.

Figure 3.2.4. Roberts, Sarah. (2014) *Canopy Typology*. Scale: 200 m^2, Capacity: 50-100 people, System: tension-active. Form-found in Kangaroo.

Further Research



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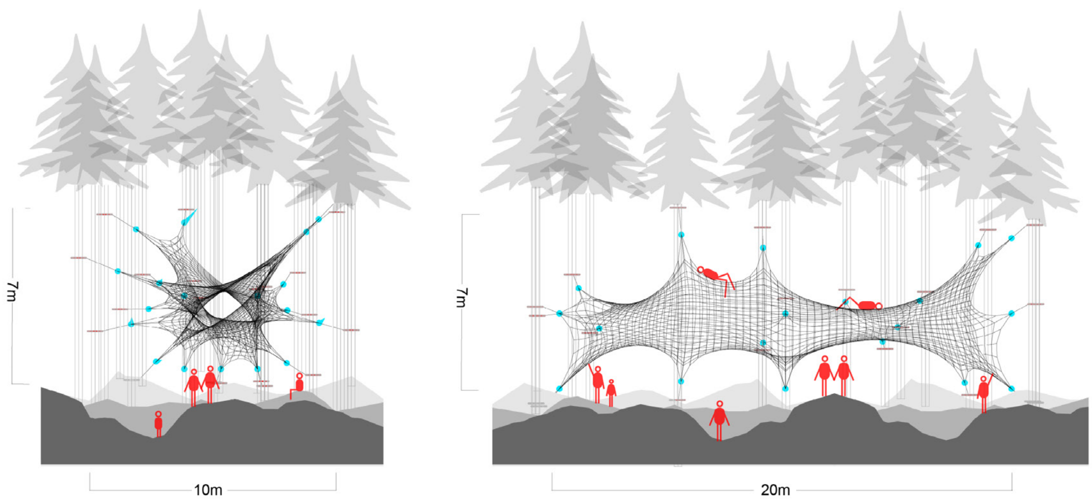

3.2.6.

Figure 3.2.5. Roberts, Sarah. (2014) *Installation Typology*. Scale: 200 m², Capacity: N/A, System: tension-active. Form-found in Kangaroo.
Figure 3.2.6. Ibid.

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