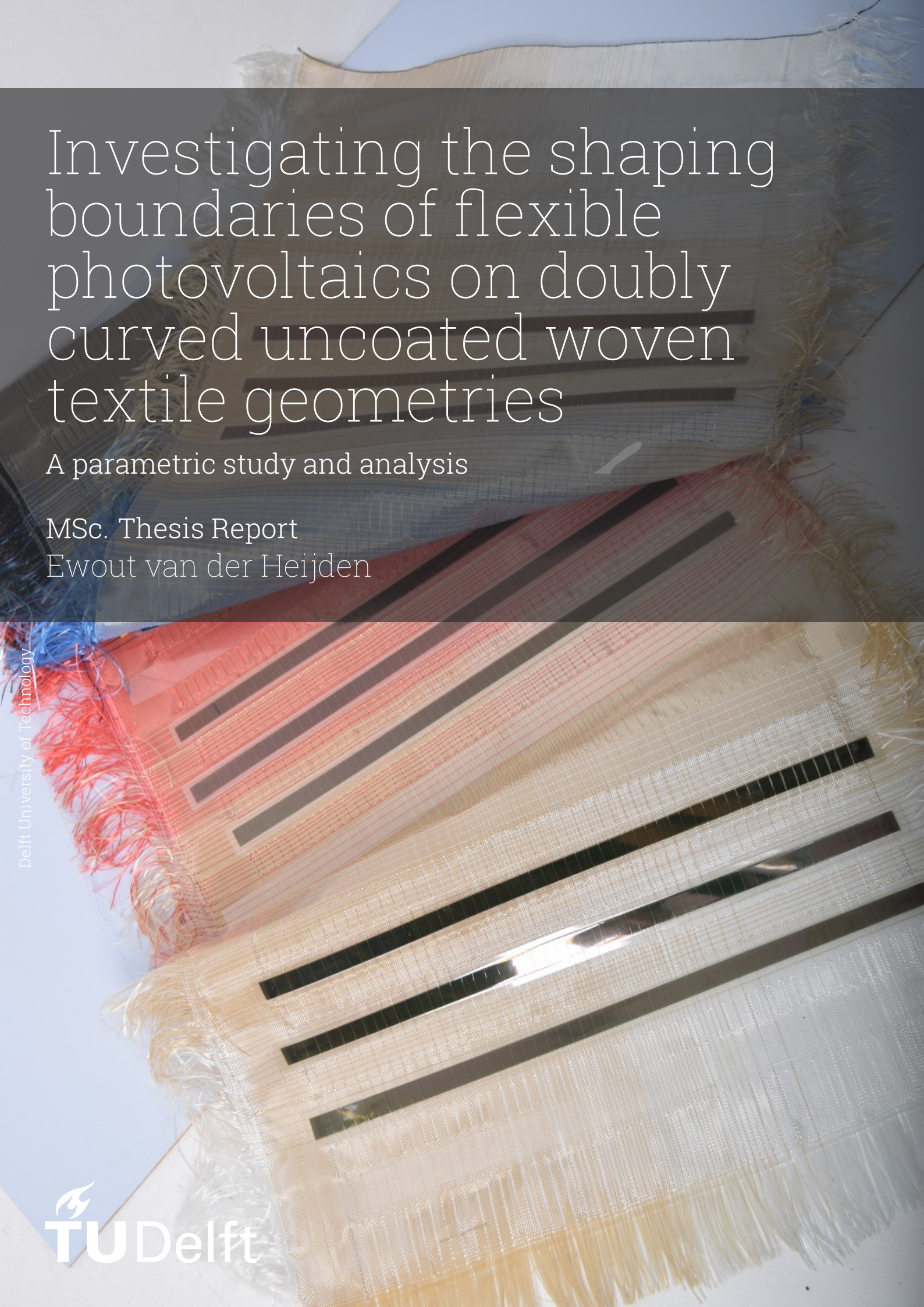




Investigating the shaping boundaries of flexible photovoltaics on doubly curved uncoated woven textile geometries

A parametric study and analysis

MSc. Thesis Report

Ewout van der Heijden

Investigating the shaping boundaries of flexible photovoltaics on doubly curved uncoated woven textile geometries

A parametric study and analysis

by

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This thesis is confidential and cannot be made public until July 1st, 2026.

Cover image: SUNTEX samples by Studio Pauline van Dongen

An electronic version of this thesis is available at <http://repository.tudelft.nl/>.

Preface

This thesis concludes my time as a Master student, and by extension my time as a student at the Delft University of Technology. Over the last year I've had the immense pleasure of developing myself academically, professionally and socially in an environment that encouraged me to explore the boundaries of what is possible. This has all culminated in my choice for a Master thesis with a subject that has been very scarcely studied before. Some might call it the road of most resistance, but my curiosity is what ultimately led me to take on this challenge. I will forever be grateful for the fact that I'm surrounded by people who have supported me in facing this challenge.

Firstly, I would like to thank my committee. Mariana Popescu, thank you for your insights and your example as an academic. Through our conversations and the examples of your own work, I have gained an enormous amount of knowledge and appreciation for what it takes to push boundaries. Secondly Rogier Houtman, thank you for all the grounded discussions we had on this topic, which were rooted in the practical outcomes while at the same time allowing plenty of space to explore freely. The tools that I gained from this experience will last me a long time. Thirdly to Stijn Brancart, thank you for your creative insights. Your independent view on this project from the perspective of Building Technology allowed me to keep looking back at what I was doing to ask questions. Throughout our conversations the emphasis remained on the 'why' more than the 'how', which was instrumental in placing the research into perspective. And lastly Roel Schipper. Thank you for your vast experience regarding the process itself. It was you who helped me in my search of a thesis topic, and you remained a constant source of support throughout the process, up to the very end. Your concise and clear feedback, both orally and written, kept the unknowns and uncertainties of the project within bounds. These insights will help me in my future career to keep even the most challenging projects tangible and manageable.

Apart from my direct supervisors, I want to express my gratitude towards the companies that took me under their wing. Firstly Tentech, where I worked and learned about the world of tensile structures properly for the first time. My thanks in particular go out to Daan and Laura for your insights on shaping, as well as your ideas about finding new methods to approach form finding with different tools. Thank you also to Jasper for your questions at my desk. These short conversations always provided me with interesting ideas, some of which planted seeds to improve the research in later stages. Secondly, I want to thank the team at Studio Pauline van Dongen. Thank you to Pauline for SUNTEX, the new pioneering project that allowed me to explore my boundaries as an engineer. Also Anna, for your fresh insights from an entirely different perspective. They have enriched my thinking and working immensely, and made me aware of the different perspectives that can be lost behind the numbers.

Lastly, I want to pay tribute to the people who have supported me from the sidelines. My family and friends, who showed endless interest in my pursuits, endless enthusiasm at my successes and endless support during the harder times. Sofia and Stephanie, thank you for the risotto and the talks, where I could always share freely. Jhalesh, merci monsieur for the talks, the walks and the energy to keep going, especially at the very end of the project. Raitis, thank you for challenging me and inspiring me to keep asking the bigger questions, and to say yes to the challenge ahead. Thank you to Amber, who has been with me since day one of the Bachelor. You were the constant factor throughout all of it. Lastly, thank you to the team, Natúúrljik. Your unconditional support is deeply cherished.

As this chapter closes, another opens. I look ahead with an insatiable curiosity around what will be out there in front of me. I look forward to putting my skills into practice, and hope to, some day, look back on what was a decade of personal development that I can be immensely proud of.

*Ewout van der Heijden
Delft, July 2024*

Abstract

The built environment faces the challenge of meeting the sustainable development goals of the Paris Agreement with regards to building emissions. One aspect of this challenge is the energy transition from fossil to more sustainable sources. A possible solution lies in the field of solar energy technology which, over the last decades, has become the main sustainable energy source globally. Various types of solar cells exist today, from large-scale solar parks to small strips of flexible organic photovoltaics, or OPV. In parallel, the field of tensile architecture provides answers to the materiality challenge of the same sustainable development goals. Tensile architecture is lightweight by nature, which reduces the material use. This reduction in turn limits the embodied carbon of the material.

The current body of knowledge regarding textile engineering shows a wide variety of different types of textiles in architecture. In parallel, the knowledge around the bending of semi-rigid elements such as the OPV strips supports their use in curved geometries. However, gaps remain relating to the use of uncoated textiles in tensile structures, as well as the non-adhesive integration of semi-rigid elements such as OPV strips.

Given the context, the main research question of this thesis was:

To what extent can an uncoated woven hybrid textile, using non-adhesively integrated solar cells, be applied in doubly curved tensile structures?.

SUNTEX, a newly developed hybrid textile consisting of rPET yarns and slender OPV strips, defined the scope of this research. A number of design parameters was established to determine the largest possible surface area, or maximum coverage, of OPV strips on a hyperbolic parabola and a saddle surface between arches, or barrel vault. To this end, a two-step computational analysis, using the Easy and Rhino Grasshopper software packages was performed. The analysis tool was designed to be compatible with current, conventional design workflows.

Results from the research showed an OPV strip coverage on the hyperbolic parabola of 23%. This best case scenario was produced on a shape which was divided into 5 cutting pattern segments. The barrel vault supported a maximum of 30% of the total surface area. This coverage was achieved on a shape which was divided into 5 cutting pattern segments. These results are global optima, as either increasing or decreasing the numerical design parameters results in a reduction of coverage on both shapes.

The conclusion of this thesis is that SUNTEX can be applied on doubly curved surfaces with a coverage up to 30%, depending on the type of shape that is used in the design, as well as the right combination of design parameters. Within a design sequence, the iterative analysis method that was researched in this thesis should therefore be applied twice. Once at the early design stages, and once at the detailed design stage.

It is recommended that the design parameters are further explored to better understand their influence on the coverage on various shapes. Apart from that, the analysis method itself should be evaluated to reduce the run time, and improve of the accuracy of the results.

Keywords: textile architecture, solar textiles, functional integration, developable surfaces, parametric modelling

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Nomenclature

Terms

Term	Definition
<i>Coverage</i>	The proportional surface area that can be covered by a specified volume or weight of a substance.
<i>Cutting pattern</i>	The representation of the components of a membrane structure when flattened into a 2D shape.
<i>Easy</i>	Software package that performs form finding, structural analysis and cutting pattern generation on membrane structures.
<i>Embodied carbon</i>	The carbon emissions associated with the mining and construction of materials.
<i>Fabric</i>	Cloth that is produced by knitting or weaving yarns in a given pattern.
<i>Force density</i>	Force per unit length that is applied to a shape in order to perform form finding.
<i>Functional integration</i>	The integration of a material into a textile structure with a specific functionality.
<i>Grasshopper</i>	Parametric tool within the Rhinoceros 3D modelling environment.
<i>Hybrid textile</i>	Fabric that contains multiple types of structural yarn.
<i>Membrane</i>	A flexible, thin surface that carries loads primarily through tension.
<i>Minimal surface</i>	Smallest possible surface area under uniform internal stresses.
<i>Radius of curvature</i>	The radius of a circle that best approximates a section of a curve at a specific point.
<i>Strain compensation factor</i>	Percentage by which cutting patterns are shrunk to ensure a fully tensioned surface.
<i>Sleeve</i>	Part of SUNTEX that keeps OPV strips in place.
<i>Surface</i>	Geometrical set of points that has a length and width but no thickness.
<i>Warp</i>	The longitudinally oriented yarns on a weaving loom.
<i>Weaving</i>	The act of interlacing warp and weft yarns to produce fabrics.
<i>Weft</i>	The transversely oriented yarns on a weaving loom, perpendicular to the warp.
<i>Yield</i>	The amount of energy that is harvested from the photovoltaic cells.

Abbreviations

Abbreviation	Definition
<i>BIPV</i>	Building integrated photovoltaics
<i>EFTE</i>	Ethylene Tetrafluoroethylene
<i>FPV</i>	Flexible photovoltaics
<i>IEA</i>	International Energy Agency
<i>OPV</i>	Organic Photovoltaics
<i>PTFE</i>	Polytetrafluoroethylene
<i>rPET</i>	recycled Polyethylene Terephthalate
<i>TE-FPV</i>	Textile envelope integrated flexible photovoltaics

Symbols

Symbol	Definition	Unit
E	Elasticity modulus	[Pa]
F_T	Tensile strength	[N]
G	Shear modulus	[Pa]
R	Radius of curvature	[m]
γ	Shear angle	[rad]
κ	Curvature	[m ⁻¹]
σ	Maximum membrane stress	[Pa]

Introduction

1.1. Problem context

Globally, buildings account for approximately 37% of all carbon emissions. The majority of these emissions, around 80%, come from the operational energy use by lighting and climate installations, to name a few examples [2]. In the Paris agreement, the goal was set to restrict the global average temperature increase to 2°C above pre-industrial levels, and "to limit the temperature increase to 1.5°C above pre-industrial levels" [36]. This goal was reiterated during the COP28 summit in Dubai in 2023, where the pledge was made to "keep the global temperature limit of 1.5°C within reach" [11]. In parallel to this, the Global Alliance for Buildings and Construction reports a steady increase in energy demand from buildings, with a 4% increase between 2020 and 2021 alone [2]. This presents a contrast which requires sustainable solutions that both keep up with demand and reduce carbon emissions.

One proven viable source of sustainable energy is solar power, which is becoming more common at an increasing rate [1]. The International Energy Agency reported that solar PV generation exceeded 1000TWh for the first time in 2021. This constitutes the second largest increase in renewable energy generation after wind energy. However, a 25% increase of PV energy generation is needed per year to follow the Net Zero Emissions by 2050 Scenario, at a value of 7000 TWh of solar power. As of 2022, solar energy power capacity is projected to surpass the capacity of coal by 2027. This forecast is displayed in figure 1.1. In order to maintain this projection the IEA argue that, along with more ambitious policy, the applications of solar power need to become even more widespread [1].

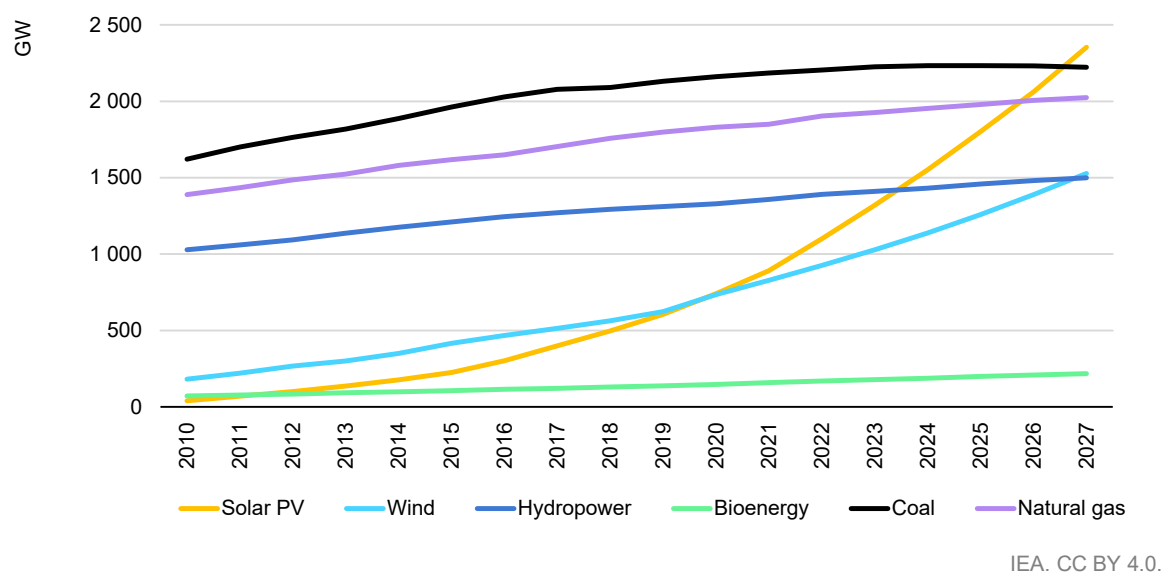


Figure 1.1: Share of cumulative power capacity by technology, 2010-2027 [1]

Currently, the most widely applied form of solar PV is crystalline silicon, which makes up 95% of the global market. Panels using this technology have been manufactured for around 50 years, and have been continuously developed since. For example, since 1990, the maximum achievable efficiency using crystalline silicon has doubled from 10% to around 20% [23][20].

The applications of solar PV technology mostly comprise the generation of electricity. To this end, the PV panels can be used in configurations of varying scale. In figure 1.2, one type of large-scale implementation of solar cells can be observed. The solar park in the image is made up of a plot of land on which the solar panels are placed in an orientation that maximises their electricity generation potential. Since solar parks are usually of large scale, they are placed at distance from the energy recipients. This solution will require additional infrastructure to transport the electricity from the park to recipients, or to an energy storage facility. These additional facilities will put extra strain on the electricity network, as well as result in extra operational and maintenance cost. An alternative could therefore be to place the solar cells closer to potential users.



Figure 1.2: Solar park overview [14]

In terms of eliminating additional infrastructure, the most economic solution is the harvesting of solar power on-site, which means that all energy generated is used by the user of the specific site. Examples of this strategy are the application of solar cells onto buildings at the roof, facade or elsewhere. They can simply be added on top of the existing structure, or used to replace certain building components. The latter option implicates the use of the solar cells as both an energy generating tool, as well as a building element. If this is the case, the solar cells are referred to as Building Integrated Photovoltaics, or BIPV. Two examples of BIPV can be found in figure 1.3 below.

Subfigure 1.3a shows the implementation of solar cells into a more secondary building function, as partial solar shading. Therefore they do not contribute to the structural function of the building. Subfigure 1.3b on the other hand, shows a more structural implementation of the solar cells into glass panels that form the outer shell of the facade. In this sense, the solar panels have both a structural and energy generating function. In both situations, the cells are placed on planar surfaces. Solar panels are most commonly produced this way, because their power production is highest when the cells are at a normal orientation to the sun's radiation vector [24].

Alternatively, solar panels can be combined with lighter structural supports in various ways. An example of this is new Google campus in Mountain View, California, shown in figure 1.4. This structure uses a curved grid of steel elements to support the roof, which is covered in solar cells. This curvature is retained by using a dragon scale-like configuration of the solar cells.

The examples in figures 1.3 and 1.4 show that the current uses of BIPV mostly have non-structural



(a) BIPV in a roof structure [37]



(b) BIPV in a facade structure [15]

Figure 1.3: BIPV examples



(a) Dragonscale solar cell overview [5]



(b) Dragonscale solar cell substructure [18]

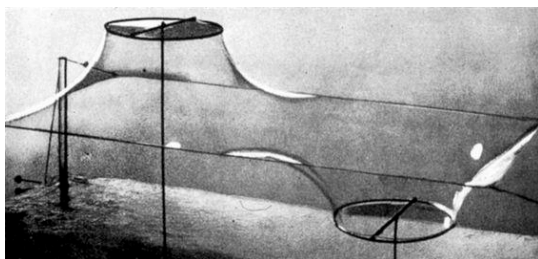
Figure 1.4: Curved roof with planar 'Dragonscale' solar cells

double functions, or require heavier core structures in order to function as a structural part of a building. With the aforementioned reduction of carbon emissions in mind, the question arises if there is a structural system that can provide large surface areas that can be covered in solar cells, while maintaining a low environmental impact.

One solution to this question can be found in tensile architecture. Tensile architecture comprises the use of membrane-like materials to span surface areas of varying size. These membrane structures have a unique combination of properties. They are lightweight, highly flexible, pliable, translucent and have the ability to be used in architecturally expressive shapes. Since these structures are only loaded in tension and adjust their shape according to the force flow through the surface, they are considered optimal, meaning that a minimal amount of material is used to cover spaces [34].

Textile has been used in construction for millennia, but since the second half of the twentieth century, the field of textile engineering has been more thoroughly researched by pioneers such as Frei Otto and Buckminster Fuller. Frei Otto's work includes the research of shapes by using soap-film scale models, an example of which can be seen in figure 1.5. Buckminster Fuller incorporated mathematics into geometric design, most prominent for geodesic domes, which were sometimes covered with a membrane foil [13]. The developments that have followed since have allowed more complex designs to be executed in textile, see figure 1.6. Current developments focus on multiple aspects of the material and design methods, from generating composite materials for specific uses [30], to different methods to computationally model the structural behaviour of textiles [39].

If BIPV is to be applied to tensile architecture, more lightweight and flexible alternatives to the conventional solar panels have to be used. Over the last decades, the development of flexible photovoltaics has delivered various options for solar cells that can be shaped in a curved manner. Three different technologies have shown promising results in terms of performance. Those are amorphous silicon, which is also common in the conventional photovoltaic panels, organic photovoltaics and perovskites. All three technologies can be printed into flexible panels, offering efficiencies up to 18%. The use of flexible photovoltaics on a large scale has not been implemented frequently yet, but research is ongoing to improve the performance of the technology [40].

**Figure 1.5:** Frei Otto soap film model [41]**Figure 1.6:** Contemporary tensile architecture [10]

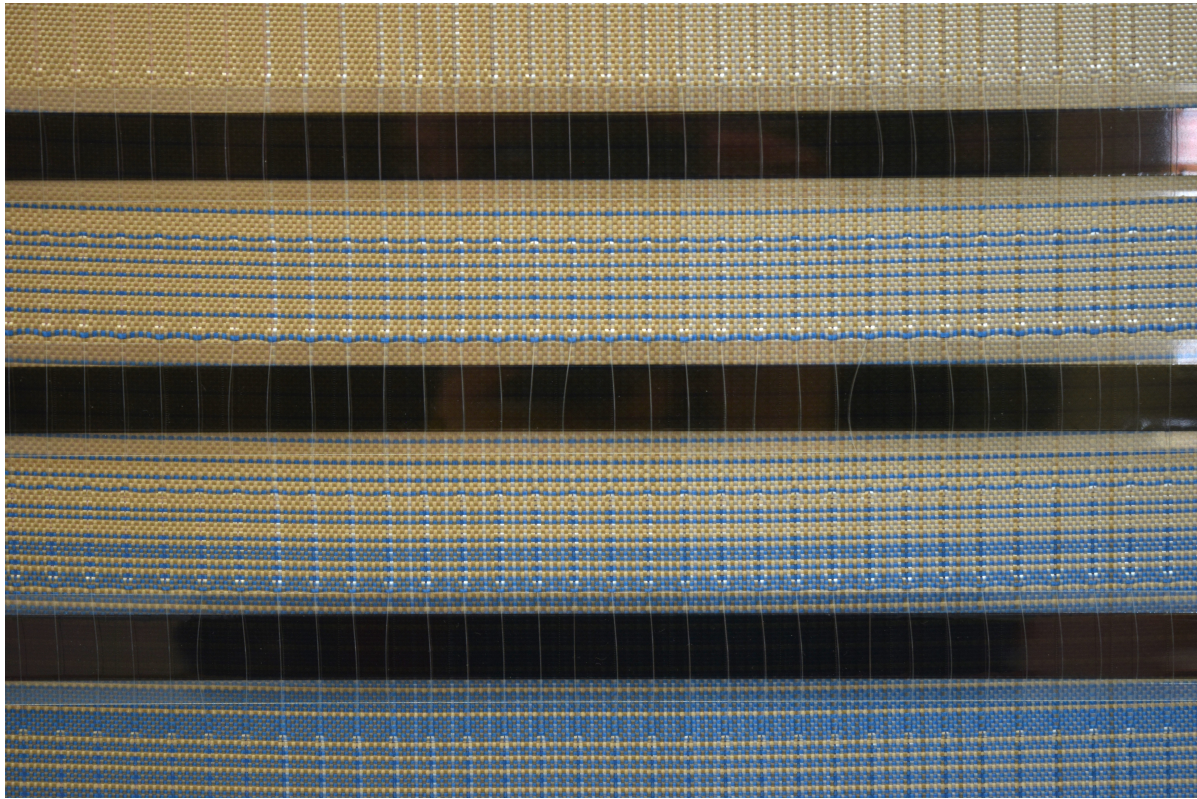


Figure 1.7: SUNTEX weaving pattern overview [19]

1.2. SUNTEX

The large spans of tensile architecture can provide a basis for new applications of flexible solar cells. The newly developed textile SUNTEX, conceptualised by Studio Pauline van Dongen, is an example of this very combination. The textile allows the textile to be applied both in conventional buildings, as well as tensile architecture [12].

The innovation in SUNTEX is most prominent in the method of integration of the solar cells. As opposed to more conventional methods, SUNTEX is woven in such a way that sleeves are formed in the fabric. These sleeves can be filled with strips of flexible Organic Photovoltaics, or OPV. The result of this is shown in figure 1.7.

The development of SUNTEX has seen two stages completed. In the first stage, the feasibility of the fabric was investigated by Bakr [4], whose research focused on the feasibility of the combination of textile and solar cells as a structural fabric. The final layout comprised a 50% coverage of the textile panel with PV strips, which is shown in figure 1.7 [4].

Woven fabrics respond to shear forces in a unique way, that determines the ability to be shaped in double curvature, a concept which will be explained in section 2.2.

In her research on the shear behaviour of SUNTEX, Ramos investigated the shear behaviour of the textile. This included the determination of the elastic modulus, the shear modulus and shear stiffness for angles up to 30 degrees. This was achieved through bi-axial shearing tests [29].

In this thesis, the material properties and existing knowledge on textile geometry are used to determine to what extent SUNTEX can be implemented into doubly curved tensile architecture. This is done to determine design boundaries for the textile in terms of its shaping. Apart from that, analysing the coverage will provide insights into the solar energy harvesting potential of the fabric in common textile geometries.

2

Literature review

This chapter outlines the current body of knowledge about textile and functional integration. Each research area relevant to the problem is explored and conclusions are drawn to form the framework for the setup and execution of the research, which will be described in later chapters.

2.1. Design principles

Within the scope of tensile architecture, most projects follow the same set of steps to go from initial ideas to a realised structure. These are:

- Form finding
- Static analysis
- Cutting pattern generation
- Construction engineering

The steps in this process have been researched and collected into a design guide by Mollaert et al, which has become an industry standard [25]. They will be explained in this section.

2.1.1. Form finding

The procedure to determine the shape of a tensile membrane where equilibrium is achieved is known as form finding, a term first described by Frei Otto [41]. This process relies primarily on how the boundaries are arranged and the levels of initial stress applied. Form finding starts by establishing the setup of all boundary conditions around the area where equilibrium is sought. The equilibrium is found by solving a set of equilibrium equations. Each distinct boundary condition results in a unique surface shape, and the variety of potential shapes corresponds to the different possible boundary and support configurations. The initial stress level doesn't dictate the surface shape; instead, it serves as a means to further modify the surface. A shape determined through form finding is one where the combination of support conditions and initial stress ratios together accomplish membrane equilibrium.



Figure 2.1: Fabric scale model [31]

Both physical and computational numerical techniques are employed for the form finding process and design development. In the past, physical models were used, involving soap films, elastic fabrics, or spring systems to mimic membrane behavior. An example of a form finding model using fabric is shown in figure 2.1. Before computer models, this was the most intuitive, iterative way to develop and change shapes [31]. Another alternative is the use of soap films, as displayed in figure 2.2. This method provides interesting insights into membrane shapes, as these models are relatively simple to create using rigid wires and thread supports, and provide a visualisation of a uniformly stressed surface with the smallest possible surface area [41]. Despite their short lifespan, photographs can be taken to extract relevant geometric data.

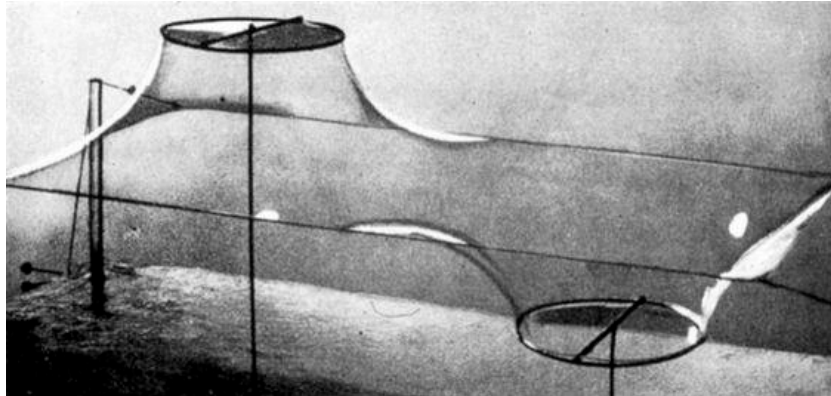


Figure 2.2: Soap film model by Frei Otto [41]

Nowadays, computational numerical models are most commonly used in practice. Their starting point comprises defining boundary conditions, followed by generating a 3D model using sets of non-linear equations. The core principle behind most computational systems is equilibrium modelling. One such method is the force density method, defined by Schek in 1974 [32]. The method applies a force per unit length, or force density to a geometry in order to linearize the equations for form finding. The force density method determines the equilibrium in a shape based on its topology and the force density ratios between the different cable network directions. In cases where textile is modelled, this cable network is aligned with the warp and weft directions in the fabric. If the force density is uniformly distributed and equal everywhere, a minimal surface is obtained. If fixed points and an edge geometry are also defined, a finite element mesh with approximate nodal coordinates can be constructed. Internal forces at these nodes can be assessed using various techniques. By applying external loads, the residual nodal forces that cause instability can be determined. The model then adjusts the mesh positioning until nodal equilibrium is achieved, resulting in a surface with uniform tensions and curvatures. Several methods, including force-density and dynamic relaxation, can be employed for form finding and comprehensive nonlinear analysis. All these methods divide the surface into a network of line elements or orthotropic mesh elements, allowing the incorporation of other structural elements like masts, beams, and slip elements into the model [25].

2.1.2. Structural analysis

The second step in the design process is the structural analysis that is performed on the form found shape. This requires a unique approach, since the assumptions of smaller deflections, as well as linear behaviour of material and structure, are not suitable for tensile structures. The mathematical models are therefore completely different, and use an iterative approach [6]. Load assumptions and material stiffnesses are applied to the textile, after which the analysis is performed. Since the form is closely linked to the structure, even a small change in the structural analysis phase might require changes to the form finding. This is another iterative process that continues until stability is reached and the shape matches relevant requirements [25]. This static analysis is commonly followed by a dynamic analysis, which can account for non-permanent loads. For tensile structures, these mostly comprise fluctuating wind loads. This is a crucial part of the design process, as under certain conditions, a slight change in wind pressure can cause the collapse of the whole structure [6].

2.1.3. Cutting pattern generation

Woven textiles are generally manufactured on fabric rolls in widths ranging from 2 to 5 metres. Consequently, to transform a flat fabric into a curved shape, the intended curved surface must be divided into individual cuttable shapes. These shapes are then either sewn or laminated together at their connecting seams. When dealing with doubly curved structures composed of two-dimensional panels featuring a perpendicular weave, shearing of the weave becomes necessary. The degree of shearing depends on factors like the flexibility of the coating (if present), the initial stress level, and the maximum width and length of the panel. Fabrics possess a limited ability to resist shearing forces. To counteract this, the warp and weft directions align with the primary stresses in the membrane, effectively minimizing shearing effects. This can be achieved by ensuring that the central lines of the panels follow geodesic paths across the curved surface. These geodesic paths are the shortest connection between two ends of the surface, and therefore have no sideways curvature. These paths can be followed by a flat piece of fabric without undergoing shearing. This practice not only caters to material efficiency but also enhances precision [25].

Another crucial factor in panel creation is determining the strain compensation factor. This involves reducing the size of the cut pattern by an amount that allows the panel to elongate during installation, achieving the desired initial stress and preventing wrinkling in critical areas.

Creating the patterns involves three key steps: breaking down a surface into separate fabric shapes, flattening the 3D structure onto a 2D plane, and calculating compensation values.



Figure 2.3: Cutting pattern generation [25]

The consideration of the cutting patterns is incorporated early in the design process, both during the form finding and structural analysis phases. The connection of adjacent panels requires selecting an appropriate seaming technique based on the type and composition of the membrane. Options include sewing, welding, and adhesive bonding. Sewing involves overlaps and stitches to mechanically interlock the panels, providing flexibility suitable for convertible roof structures. However, stitching diminishes the fabric's mechanical strength and water resistance. Welding, a favored alternative, fuses the coating material together in the case of coated fabrics. High-frequency welding is employed for PVC-coated polyester panels, while heat welding is used for PTFE-coated glass and ETFE foils. Vulcanization is specifically employed for silicon-coated fabrics, whereas adhesives are used otherwise. [25].

2.1.4. Construction engineering

Construction engineering is the final step in the design process, and comprises the detail design of boundaries, cable sleeves, and anything relating to the connection between the textile and the support structure. A plan is also drafted on how to transport and install the textile, which is often very large in area. The special attention that needs to be paid to this fact is also determined in this stage [25].

As shown in this section, the general design principles behind tensile architecture are at this point well researched and documented. A clear set of steps exists from initial ideas to construction. However, the design guides show no standardised design steps with regards to the integration of additional elements like solar cells. Particularly if those elements do not have a structural function. The current standard practice also heavily relies on coated materials to create the architecture, which leaves examples using uncoated fabrics scarce.

2.2. Geometry

The most efficient load transfer in structures occurs when shapes allow forces to transmit solely through compression or tension. Compression structures include shells, often made out of concrete, steel or timber. Tensile structures on the other hand are often executed as membranes, which use a variety of fabrics. These structures rely on tension forces within the membrane, achieved through prestressing and curvature, to establish structural stability. The unique design workflow of tensile structures involves the manipulation of boundary conditions and support geometries to achieve the optimal form for the intended purpose. This allows the surface to take on a wide variety of free-form shapes [26].

Structural stability in tensile membranes can be achieved by utilizing anticlastic forms, which are characterized by curvature in opposite directions along the axes of principal curvature. This concept is illustrated through cable mechanics. Stabilizing a point on a cable within a plane requires three tensile forces. Extending this stability into three-dimensional space requires a fourth force acting perpendicularly. Full stabilization of all cable points needs additional pairs of opposing forces. This process is akin to introducing extra sets of cables perpendicular to the main cable, resulting in a stabilized anticlastic surface. An overview of this logic is given in figure 2.4.

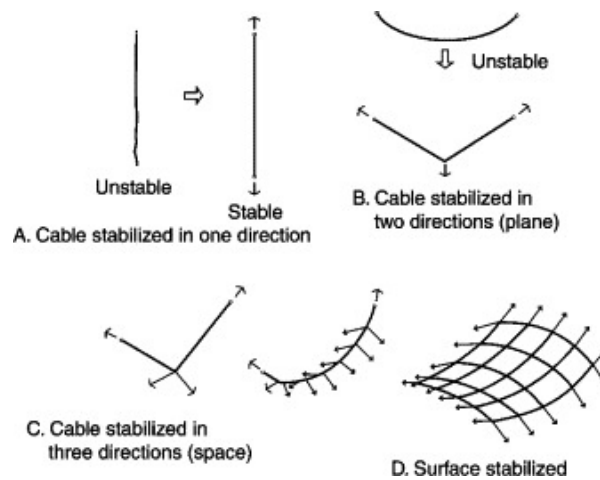


Figure 2.4: Cable mechanics in tensile structures [26]

Alternatively, synclastic membrane structures derive their shape and stability from variations in fluid or gas pressure across the membrane's surface. This requires a closed membrane in order to contain the pressure. The synclastic form finds applications in air-supported structures, air-inflated cushions, and to a lesser extent, hydrostatically shaped structures. Both the synclastic and anticlastic principles are displayed in figure 2.5.

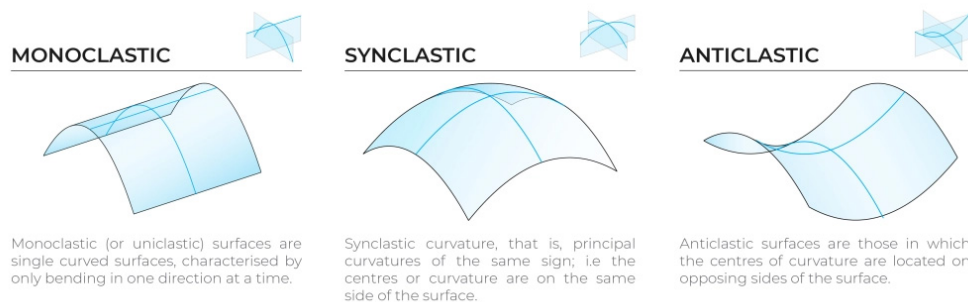


Figure 2.5: Types of geometric curvature and their curvature directions

Taking a closer look into the anticlastic principle, the warp and weft directions of the used fabric are aligned with load paths or principal curvature directions. These curvature directions are shown in figure 2.6. The equilibrium of the surface is maintained by edge reinforcements arranged spatially

using suspending and supporting elements. By manipulating the configuration of internal and external supports, designers can achieve distinctive anticlastic doubly-curved forms. For large-area anticlastic structures, it's preferable to construct them as grouped single structures. This approach is favored over expanding individual structures, as a significant increase in prestress load makes the prestressing process cumbersome and may necessitate the use of high-strength fabrics to manage elevated stresses [25].

Architectural textiles are in essence either coated woven fabrics or extruded plastic foils. This is why the term “membranes” is used to refer to them collectively. Typically, a coated fabric is composed of a woven textile which acts as the reinforcement compressed between two layers of coatings. The coatings provide protection against environmental influences, as well as fire. This makes the textiles suitable for use as a building envelope. In contrast, uncoated textiles rely on the properties of the yarns or fibres themselves for durability [8].

The characteristics of the woven fabric provide the stiffness and strength that are needed to withstand prestressing and any external loads. This prestressing and the geometrical shape are closely related, as stability with minimal prestressing is only possible when the radii of the double curvature are as small as possible. In order to achieve this in practice, the membrane is translated into cutting pieces or patterns with a curved geometry. These are then used to cut out pieces of fabric that can be put together to form the three-dimensional shape [9].

To conclude, geometrical principles allow textiles to be applied in structures of varying curvature. However, the notion that curvature and prestress are closely related currently does not provide insights into how the fabric behaves on a detailed level, such as the PV sleeve edges. Knowledge about a method to model and analyse the behaviour of such a detail, as well as the interaction between fabric and PV strip does exist, but has so far not been used on full-scale geometries.

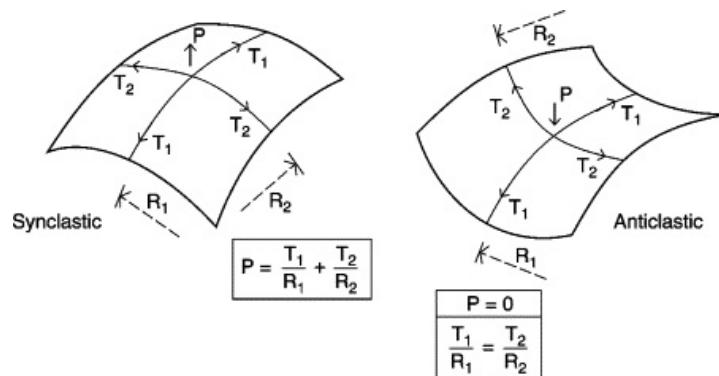


Figure 2.6: Synclastic and anticlastic: principal curvature directions

2.3. Functional integration in tensile structures

The integration of solar cells into, in this case, textile, falls under a category of tensile architecture that relies on so-called functional integration. In order to provide a scope for functional integration, the following definition by Sennewald et al is used: “Functional integration refers to the creation of an additional functionality beyond the original function of the woven fabric.” [33]. They elaborate by stating that the additional functionality can be achieved by applying other distinct materials that have one or multiple specific properties to the fabric, under the condition that the combination remains functional [33].

A review by Li et al [22] shows a small variety of textiles with integrated PV cells that have been manufactured to this day to form so-called hybrid textiles. Buildings that are realised with functional integration are shown to be constructed using a different process, so no two examples are the same in any respect. Textiles includes EFTE foil, PTFE coated woven glassfiber and PVC coated woven polyester. Different types of flexible photovoltaics, or FPV, exist that have been used to integrate the solar energy functionality onto the textiles above. The types considered are amorphous silicon solar cells, CIGS solar cells and organic solar cells or OPV. Various methods were used to integrate the FPV into the various textile types, as shown in figure 2.7. The first method comprises the mechanical

integration of the FPV by welding the edges of the FPV base, or substrate, to the textile. Using the second method, the FPV is laminated onto the textile. The last method involves the direct printing of the FPV onto the textile which serves as a substrate.

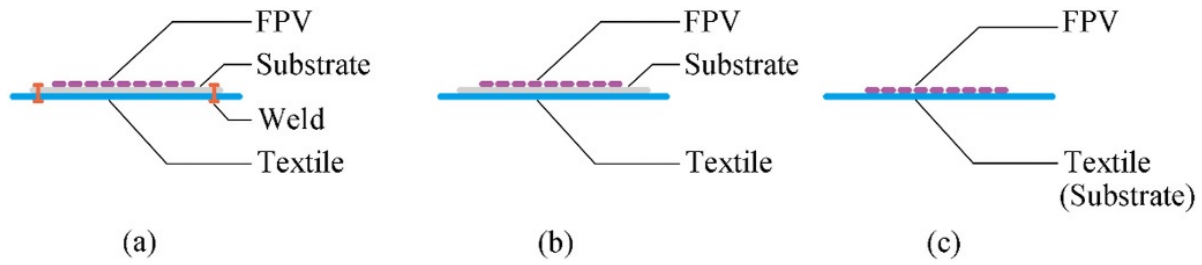


Figure 2.7: Integration methods for FPV. a: Mechanical integration; b: Lamination; c: Printing [22]

Integration is referred to as a textile envelope with integrated flexible photovoltaics, or TE-FPV. Various examples have been realised, all using unique combinations of PV and textiles. One example to look at is the Japanese pavilion for the 2010 Shanghai World Expo, as shown in figure 2.8a. This project, with the name 'Breathing Organism', was made up of two-layer EFTE cushions, which create a clear separation between the inside and the outside. The amorphous silicon solar cells were placed on the inner layer of EFTE, in order to generate electricity to power the LED lighting. The air inside the cushions, apart from maintaining the cushion shapes, was used as thermal energy storage.

Another example is possibly the first experiment with TE-FPV in 1998, shown in figure 2.8b. This project, named 'Under the Sun', consisted of a PVC canopy with flexible amorphous solar cells laminated onto its surface. The structure was designed as a solar shading structure that could demonstrate the potential for off-grid power generation for temporary or permanent structures [17].

A third example, shown in figure 2.8c, was the German Pavilion for the Milan 2015 Expo. This structure was meant to show the potential of using flexible OPV in tensile architecture. It used OPV which was laminated between two sheets of EFTE foil and hung in a cable net structure between the canopies to create the esthetic of seedlings [7]. This cable net was not just a structural component, but also served to transport the generated power to the lighting in the structure [22].

These three examples show that the integration of FPV in tensile geometries is viable. However, the review by Li et al shows that projects like these have very unique requirements and therefore a unique design process. This makes standardisation difficult. Another point to note is that all textiles make use of either EFTE or coated woven textiles in order to comply with structural regulations. In this sense, uncoated woven textiles remain unexplored as an alternative, due to their general lack of weather tightness and fire retardancy. This knowledge gap is in part filled by research done by Bakr [4] and Ramos [29]. However, these theses focus on more fundamental and mechanical aspects of the textile itself, and do not focus on the shaping aspects of the uncoated textile.

Another important observation from the examples is that all types of FPV are placed onto the textiles using some form of adhesive method, or they are placed in a configuration next to the textile, like the example in figure 2.8c. This limits the demountability and therefore recyclability of the materials. Li et al call for more investigation in terms of the performance prediction by computational analysis and simulation, as it is proposed as a cost-efficient and fast way to design TE-FPV applications [22].

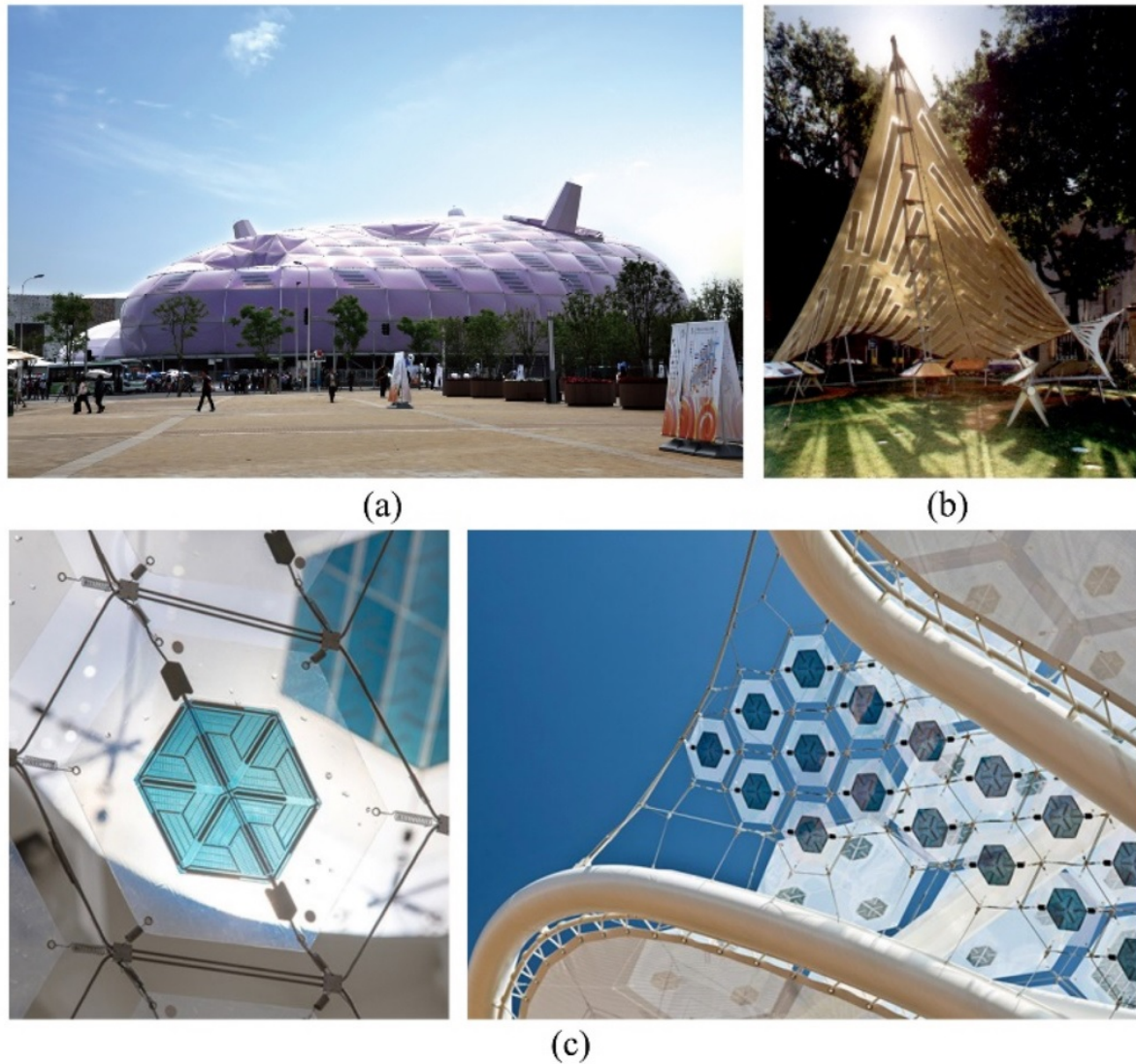


Figure 2.8: Application examples of TE-FPV. a: Japanese pavilion for the Shanghai expo; b: Under the Sun; c: German Pavilion at the Milan Expo [22]

2.4. Developable surface modelling

When applying strips of PV on a curved textile, special attention needs to be paid to the shaping of those cells, and more importantly the limitations of shaping. Given the geometry of most FPV, which has very limited thickness compared to its length and width, they can be regarded as developable surfaces. In order to understand developable surfaces, its geodesic property needs to be known. Wallner et al provide an explanation for this property in their research into the discretisation of surfaces into curved timber panels. They consider long and thin panels to have a weak and strong axis. The weak axis allows for relatively large amounts of bending, as well as twisting. The strong axis allows little to no bending [38].

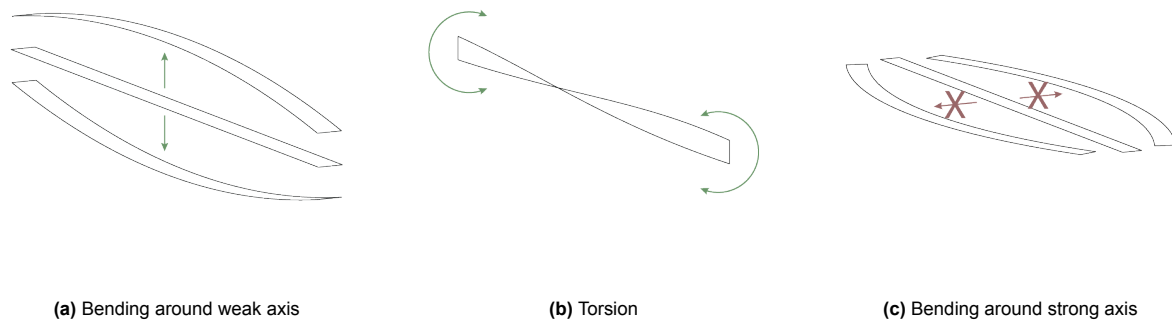


Figure 2.9: The geodesic property of panels

If these panels are flattened out, they follow a geodesic curve. A geodesic curve in turn is defined as the shortest distance between two points on a surface. This is shown in figure 2.10. In case of a flat surface, this means that a straight line is formed, or a line with zero geodesic or sideways curvature. With this in mind, taking a rectangular developable surface and bringing it into space, the element will retain a constant width. In other words there will be no stretching or tearing [38].

This geodesic property of an element with constant width provides the backbone of various methods to populate surfaces with geodesic curves, and subsequently decompose the surfaces into developable strips. The insights from these methods help to determine how and to what extent these curves can be placed on surfaces at all. When applying curves onto surfaces computationally, shapes are often represented using triangulated meshes. This means that the geodesic curves will be represented by polylines, which form the shortest connections between the mesh corners. This can lead to certain ambiguities. Polthier et al solve this by introducing the concept of so-called straightest geodesics [27]. The application of straightest geodesics uses distance fields, the algorithms for which have been researched extensively for various cases.

In other words, important insights can be taken from the state-of-the-art in terms of how geodesic curves and developable surfaces can be employed in curved geometries. An important takeaway is the distinction between the strong and weak bending axes, and the use and limitations of using geodesic curves on curved surfaces as the base for panels. This is important to note because it differs from textile modelling on one crucial aspect, namely the use of bending stiffness of a material. One limiting aspect of the current body of knowledge is that the research focuses mostly on discretising a surface into panels, as opposed to having the panels and surfaces interact with one another. Another limitation is that all the previous research makes use of materials that are well-researched and serve the purpose of being a structural element. This changes the nature of the questions and assumptions that are done with respect to the amount of curvature, location and orientation of the panels onto the target surfaces. Also, the surfaces are merely used as a reference, and not as a base which the developable surfaces must follow to within a limited tolerance.

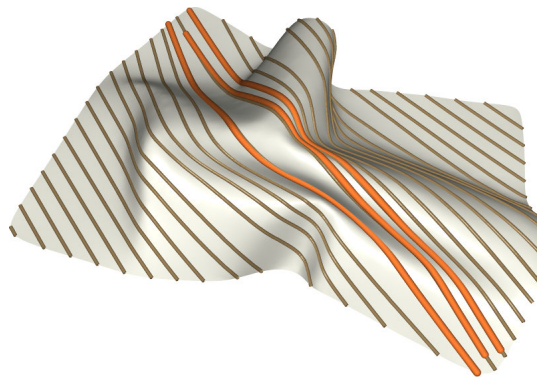


Figure 2.10: Geodesic curves as the shortest path between two points [28]

2.5. Problem statement

Assessing the state of the art as described in this chapter, various research gaps can be identified. Firstly, there are unanswered questions when it comes to the place that non-adhesive functional integration will take within the design process. The examples from section 2.3 show that each project has a unique design process. Consequently, apart from the design steps as described in section 2.1, no overarching principles are present. As described before, the design process is an iterative process within each step and between various steps, so a clear definition of the integration of the additional elements is vital for the success of any project.

Secondly, although functional integration using OPV is already seen in practice, no peer-reviewed examples exist of non-adhesive integration of any type. Apart from that, all adhesive methods rely on coated fabrics.

Lastly, the understanding around the modelling of OPV as developable surfaces requires further research. This is due to the fact that most research done on this topic considers the developable surfaces as structural elements that will approximate a base surface. The interaction between straight OPV strips and a curved textile sleeve requires specific assumptions and tolerances for which the current body of knowledge provides a starting point, but insufficient answers.

The aforementioned gaps come together in the research regarding the shaping capabilities of SUNTEX. In order to understand how SUNTEX works and how it can be used, the design process needs to be explored, so that any additional requirements might become clear. In terms of the geometrical limitations of SUNTEX, the material needs to be analysed while used in common anticlastic shapes. In addition, the interaction between the OPV cells and the fabric sleeves needs to be explored in order to define boundaries for the shaping of the fabric.

3

Research design

Chapters 1 and 2 have established the relevance and context to this thesis, as well as a state of the art regarding the relevant research areas. This chapter builds on this foundation by determining the goal of this research, as well as the questions that need to be answered to this end. These are described in section 3.1. They are followed up by the scope of the project in section 3.2, where the relevant parts and boundaries of the project are stated. The last section, section 3.3, contains a description of the methods that were applied in this thesis.

3.1. Research goal and questions

The objective of this thesis is to investigate the extent to which hybrid textile using non-adhesive integrated PV strips can be shaped in double curvature under static loading. The main question that follows from this goal is therefore:

To what extent can an uncoated woven hybrid textile, using non-adhesively integrated solar cells, be applied in doubly curved tensile structures?

In order to answer this question, the following sub-questions have to be answered:

1. Which design parameters are important to consider when covering textile with OPV strips?
2. How can the coverage of a textile shape with OPV strips be modelled computationally?
3. Where does functional integration fit in the general design workflow for hybrid textiles?

3.2. Scope

To answer these research questions as posed in section 3.1, the scope of this research is defined with regards to three elements, being the material, the geometries and the computational methods.

Firstly, the material used in this research is SUNTEX. Due to the lack of a case study in this thesis, only the self weight of the fabric will be taken into consideration when constructing the shape. Dynamic, temporary loads are not included in the structural analysis. In addition, the target coverage and yield of SUNTEX are listed below [4]:

- An OPV to fabric proportional coverage of 50%
- An energy generation yield of around 6.8 watts per m²

Secondly, a geometrical constraint is defined for the modelling of SUNTEX. Based on its material properties and the fact that the material is uncoated, anticlastic shapes were the only shapes considered. Within this category, two basic shapes can be distinguished, of which all other occurring shapes are either a variation or a combination. These two shapes are saddle surfaces and barrel vaults.

Lastly, the method for shaping and analysing SUNTEX is determined. The initial form finding and static analyses were performed in Easy GmbH, an industry-standard tensile architecture program. The parameter study and analysis of the textile on the basic shapes will be performed in Rhino Grasshopper.

3.3. Methodology

Based on the scope as described before, the methodology for the research is established (figure 3.1). Each sub-question, as described in section 3.1, requires a separate approach to draw the final conclusions. Sub-questions 1 and 3 are answered largely by the outcomes of the literature review, described in chapter 2. Sub-question 2 is answered by performing a parametric design study, which is set out in chapter 4. This study is performed in two steps, which have been already introduced in section 3.2. Firstly, the Easy GmbH software is used to construct the shapes that are analysed. Secondly, Rhino Grasshopper is used to calibrate the Easy results, and analyse the shapes for the placement of solar cells. A detailed overview of these steps is shown in figure 3.2.

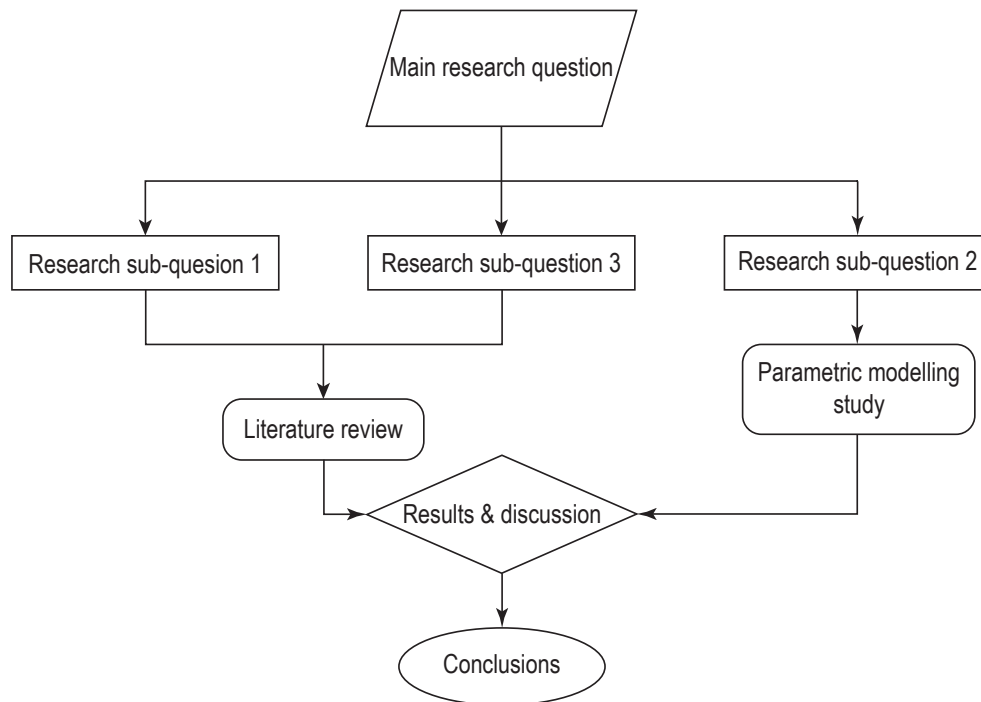


Figure 3.1: Overview of the methods to answer the research questions as listed above

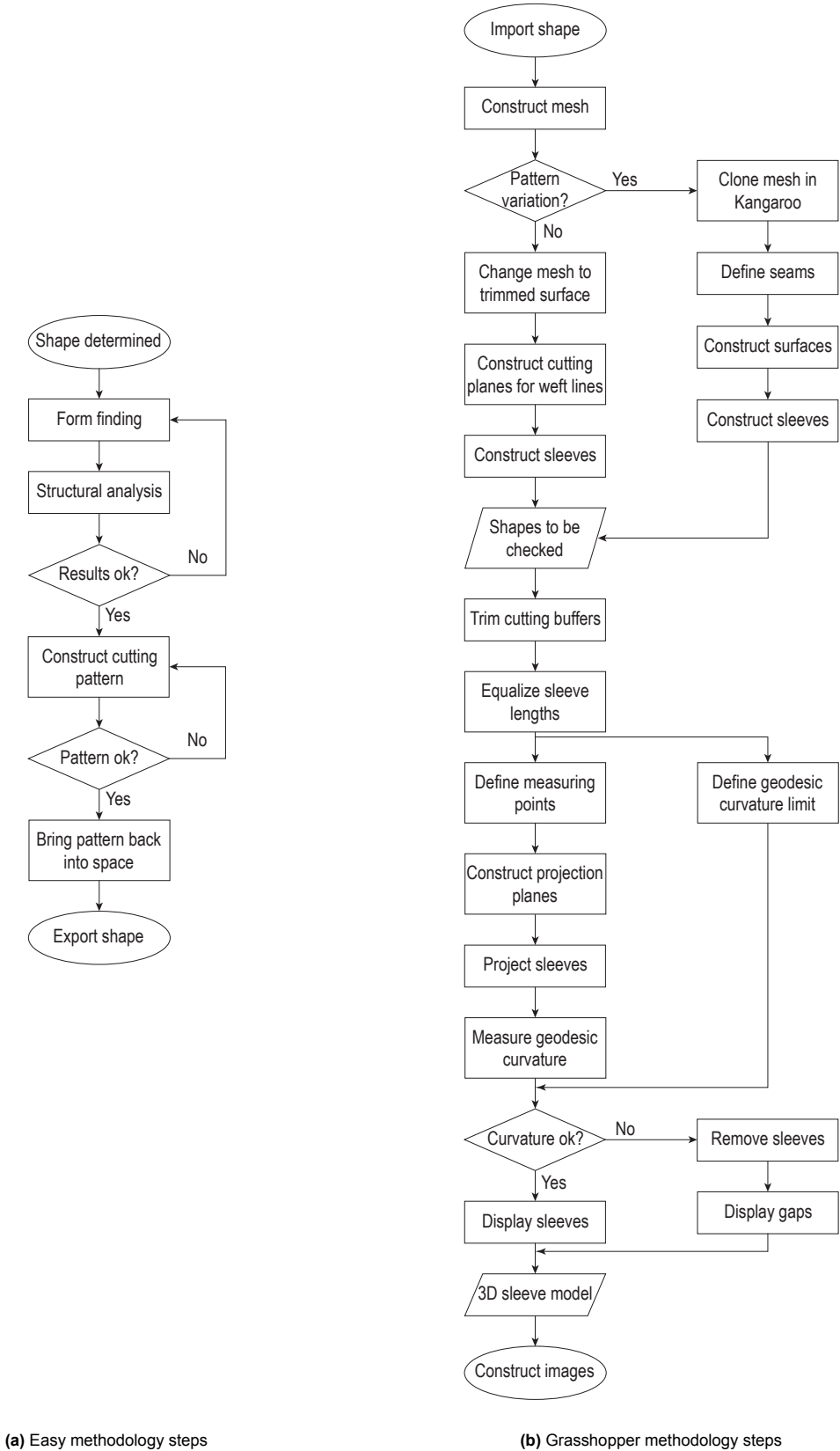


Figure 3.2: Detailed overview of the two steps of the parametric modelling study

4

Shape generation and analysis

This chapter describes the computational program that was set up in order to answer the research questions. This program comprises three main steps. The first is a number of physical trials that was set up in order to gain insights into the behaviour of textile under loading, see appendix A. The second step is the construction of a form finding workflow in order to generate shapes. The third step is the analysis of the shapes in terms of both their curvature, and their OPV coverage.

The first step to get to the analysis of the shapes is the determination of the material properties, as well as the shaping boundaries that are applied to the geometries. Afterwards, the computational software is briefly discussed to determine the use cases and limitations. This is then followed by the previously described research workflow and its validation.

4.1. Material properties

In chapter 1, the material SUNTEX was introduced as a hybrid textile, composed of rPET fabric and OPV strips. One aspect that determines the coverage is the production layout of the textile. The layout as adopted from previous research comprises a 50% coverage of the fabric with sleeves to fit OPV strips. This is achieved by weaving 30mm wide sleeves into the textile using monofilaments in the warp direction. This results in sleeves that are oriented in the transverse, or weft direction. These sleeves are then filled with 25mm wide OPV strips while weaving. An example of an OPV strip is shown in figure 4.1. In order to achieve the 50% coverage, the sleeves are placed at 60mm intervals. In this configuration, which is shown in figure 4.2, textile failure was shown to occur at the ends of the solar cells. This is due to high contact stresses that develop under extreme loading. Previous research recommends that the OPV should not be designed to carry load. Another important observation from his research is that the so-called active area of the strips, meaning the area where sunlight is actually converted to electricity, does not encompass 100% of the strip surface area, but only 52,8% [4]. This influences the final solar power yield, but has no influence on the geometrical challenges which are discussed in this thesis.



Figure 4.1: OPV strip overview, sample size 25x500 mm [4]

Having established the aforementioned, the next stage of the SUNTEX project comprised experimental research, which established the material properties of SUNTEX. These properties are needed for the form finding stage of the research. The properties are listed in the tables below. In table 4.1, the tensile strength, maximum membrane stress and modulus of elasticity are given for both the warp and weft directions. In table 4.2, the shear stiffnesses of the material is shown. Her research found two distinct values, one for shear angles below 2.5 degrees and one for shear angles between 2.5 and 27 degrees [29].

	F_T	σ_{max}	E
Warp	56	11.2	62
Weft	68	13.6	58

Table 4.1: rPET fabric material properties, unit [kN/m] [29]

	G
$0 \leq \gamma \leq 2.5$	42
$2.5 \leq \gamma \leq 27$	17

Table 4.2: rPET fabric shear stiffness, unit [kN/m] [29]

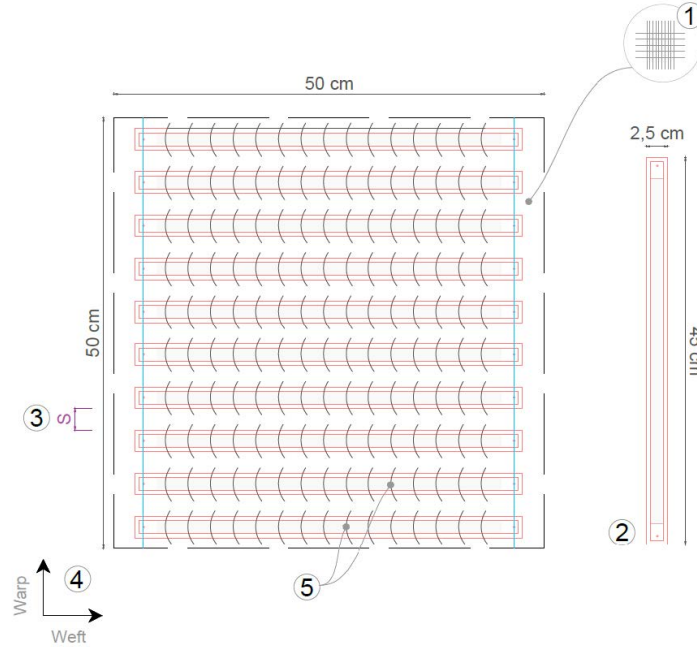


Figure 4.2: Schematic SUNTEX layout [4]

4.2. Shaping boundaries

In order to define a limit of curvature for SUNTEX, the interaction between the OPV strips and textile sleeves is looked into in more detail. As established in section 4.1, the SUNTEX layout remains unchanged. This means that the sleeves are modelled with a width of 30mm for OPV strips of 25mm, leaving a 5mm gap. This results in room for geodesic curvature in the textile. This phenomenon is shown in figure 4.3.

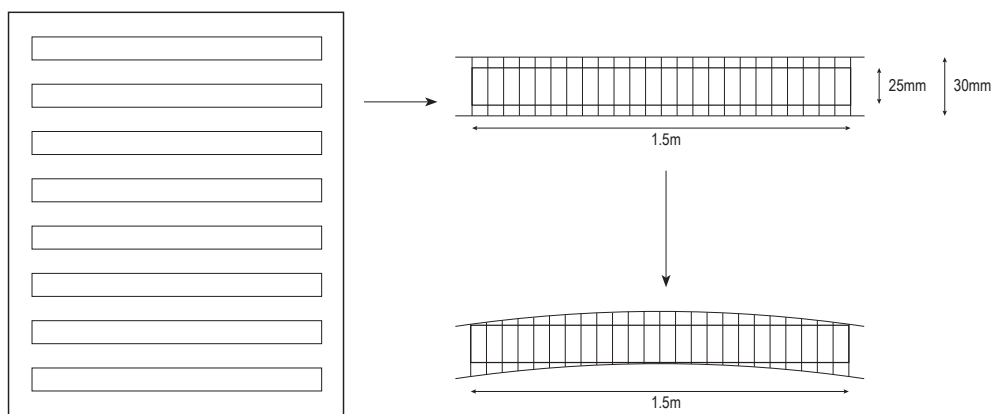


Figure 4.3: Detail of geodesic bending in SUNTEX OPV sleeves

As was also described in section 4.1, previous research showed that the OPV should not be designed to carry loads. This means that the edges of the OPV strips cannot come into contact with the edges of the sleeves. Since the sleeves are 5 mm wider than the OPV strips, there is limited room for geodesic curvature in the textile. This curvature limit needs to be known in order to provide a design space for curving the textile after the production of the cutting patterns. Within this design space, no contact stresses are expected between the OPV strips and the sleeves when the structure is erected.

The situation in figure 4.3 shows the limit state for curvature, as the top corners and bottom edge are just about to make contact with the edges of the sleeve. This limit state is used in order to define the largest allowable curvature, or the smallest radius of curvature in the sideways direction. This process involves a simple hand calculation based on the Pythagorean principle. The necessary parameters are displayed in figure 4.4.

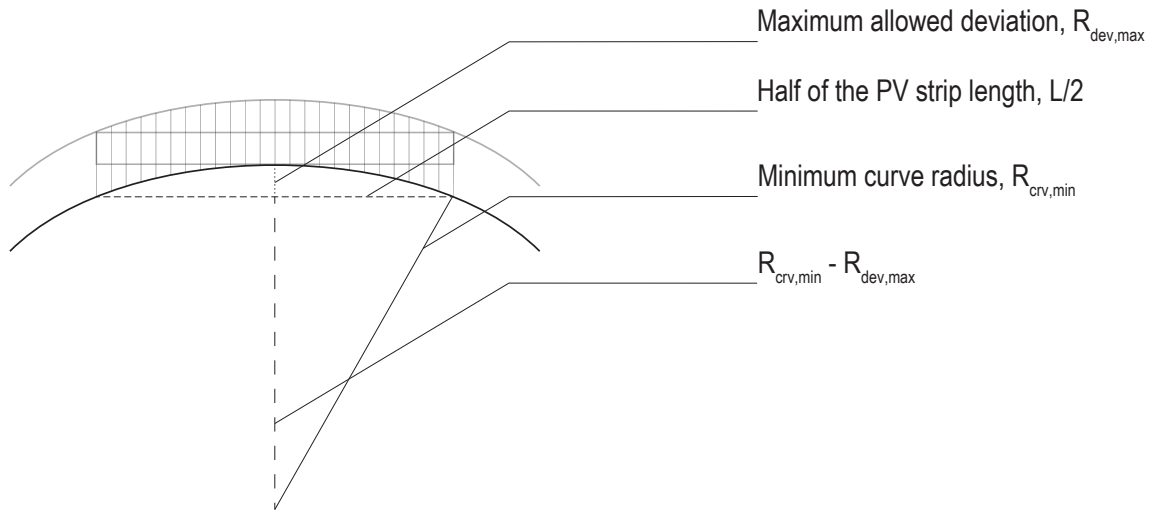


Figure 4.4: Calculation parameters for the determination of the minimum radius of curvature

The maximum allowed deviation is a set value of 5mm, but the other parameters are left free to manipulate. The final equation to establish the curvature boundary is therefore found to be:

$$A^2 + B^2 = C^2 \Rightarrow \frac{L^2}{8 * R_{dev,max}} + \frac{R_{dev,max}}{2} = R_{crv,min} \quad (4.1)$$

Where the inverse of the radius of curvature equals the curvature in the sleeve, or:

$$\frac{1}{R} = \kappa \quad (4.2)$$

From the state of the art, which was established in chapter 2, anticlastic geometries are known to have a common basis, which can be roughly divided into three shape categories. These categories are depicted in figure 4.5. Two of these, the cones and conoids, have a radial ground plane, whereas the saddle shapes have a cartesian ground plane. Within the scope of this research, two saddle shapes are modelled. One shape is modelled as a simple saddle surface or hyperbolic parabola. The other shape is modelled as a saddle surface between arches, otherwise known as a barrel vault. Representations for these shapes can be seen in figure 4.5 at the bottom left and right respectively.

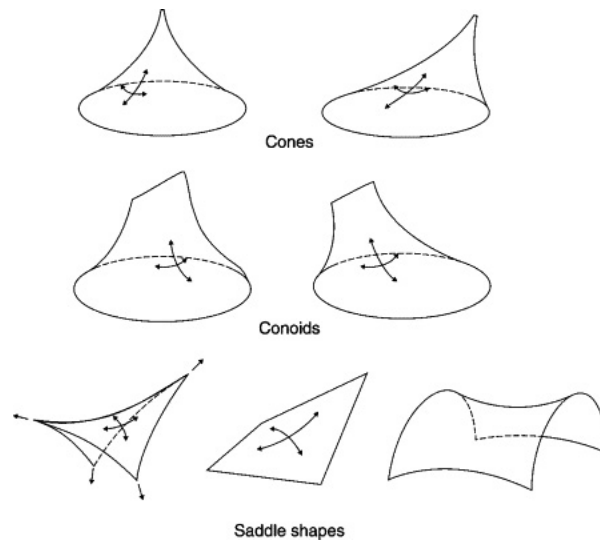


Figure 4.5: Tensile structure shapes [26]

For this research, the orientation of the warp and weft directions of SUNTEX are set to follow the principle directions of curvature on the shapes. These directions are drawn into the shapes of figure 4.5. This is done in accordance with conventional design techniques as described in section 2.1, in order to ease the process of integrating the research steps into more conventional design workflows if the research were to be used in industry.

4.3. Computational software

For the first computational step, the technet GmbH software package Easy is used. It is made up of several modules, each of which forms a step in the process of form finding, statical analysis and cutting pattern generation. Each individual step returns a text file, containing all information about the geometry and its properties. Alternatively, the produced shapes can be exported as digital drawing files. This method is used in the scope of this research. The workflow in Easy is depicted in figure 4.6. The method of form finding in Easy is the force density method, which requires an assigned initial mesh length, force density, and stiffness in order to determine the final shape of the geometry.

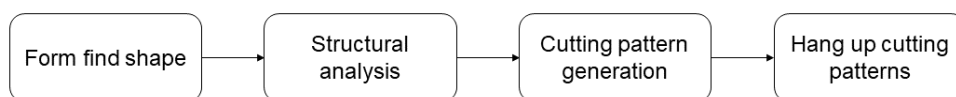


Figure 4.6: Easy workflow

The first step in the form finding process is the definition of a shape. This is done by defining boundary conditions such as fixed boundary points, boundary curvature, force density and mesh size. The program then constructs the closed boundary, as well as the internal net that will represent the geometry. The next step is the application of the force density onto the net, which will pull it into shape. An example of a finished geometry is shown in figure 4.7.

For the generation of the cutting patterns, the form found geometry from the previous step serves as the input. Geodesic curves are drawn onto the surface, either manually or automatically. For the automatic drawing, the desired amount or width of the patterns, as well as the orientation of the geometry is used as input boundary condition. The geometry is then cut along the curves and flattened to reveal the shape of the cutting patterns. A visual representation is given in figure 4.8 [35].

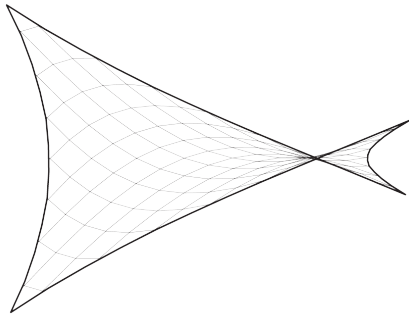


Figure 4.7: Form found shape, initial mesh length: 0.5m; force density: 1N/m; stiffness: 1000N/m

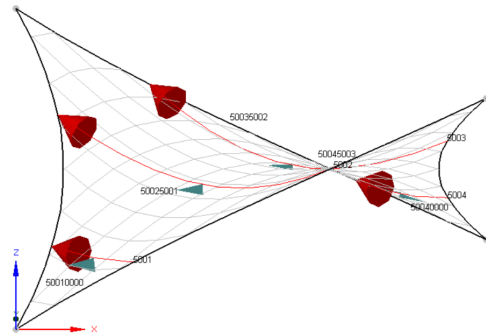


Figure 4.8: Cutting pattern generation through geodesic curve placement

The last step comprises the re-tensioning of the cutting patterns from the last step in order to form the initially form found shape. This gave the most accurate representation of how the patterns and seams will act in reality. This process is visualised in figure 4.9.

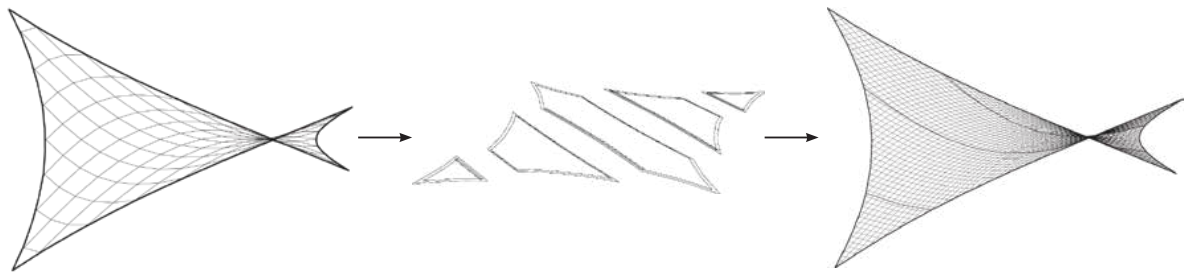


Figure 4.9: Full Easy workflow overview

The Easy software provides the ability to alter the workflow steps because of the fact that they are split up. The main limitation of this is that, while iterating design decisions, changes have to be made manually and automation is limited. This is mitigated by replicating the shapes in Rhino Grasshopper and performing the parametric study on those shapes.

From Easy, the final patterned shape can be exported to Grasshopper. This program is used for the analysis of the geometries for curvature. Within Grasshopper, the end goal is to produce a compliance check to see whether the curvature of the cutting patterns remains within the bounds of extreme curvature of the solar cells, using equation 4.1. The main steps for this workflow are shown in figure 4.10.

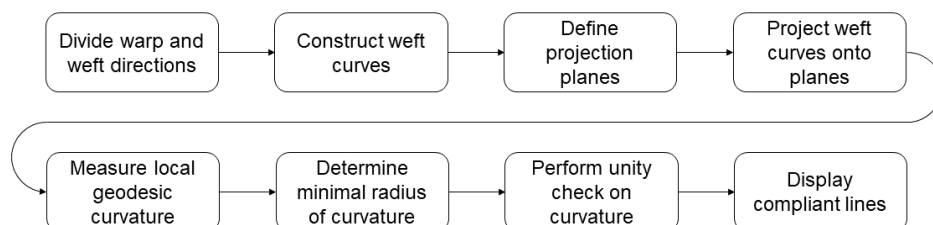


Figure 4.10: Grasshopper workflow

Grasshopper provides the ability to handle various parameters simultaneously. This means that parameter studies can be performed on multiple pattern segments within the geometries at once. One drawback of the program is its linear workflow. A set of input parameters is defined, which are taken through a script to produce a set of outputs. Iterative processes are not standard practice in this workflow. Therefore, a plugin by the name of Galapagos is used to create an iterative maximisation tool to determine the maximum amount of OPV strips on each geometry.

4.4. Sleeve placement and analysis

Using the material and shaping data as established in the previous sections, the sleeve placement workflow can be set up. The first step in the process is the construction of a hypar and a barrel vault in Easy. They are both designed on a rectangular ground plan. The design space for the hypar comprises a box of 5 by 5 by 2.5 metres. For the barrel vault, a design space of 4 by 6 by 2.5 metres is used. The difference in size allows for a similar free height under both structures while the same force density is applied. Both shapes are assigned a mesh of 0.06 by 0.06 metres in order to replicate the distance between the OPV sleeves. The design spaces for the shapes are shown in figure 4.11.

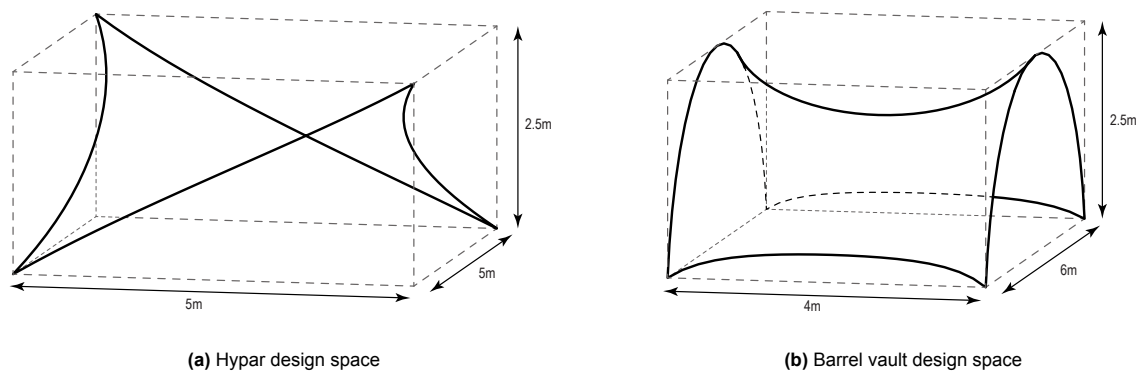


Figure 4.11: Design space overview for the evaluated shapes

The form found shapes provide the basis for the static analysis. This step serves as a check to see whether the shape, fabric orientation and force density work together to keep the membrane fully in tension. Both the membrane and edge cable stresses can be viewed and used to perform extra form finding iterations as needed. The results are visualised, which is shown in figure 4.12.

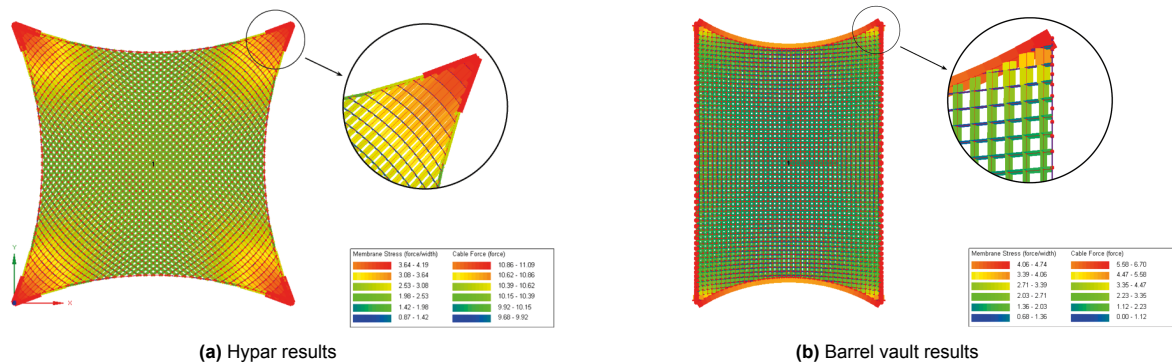


Figure 4.12: Visual static analysis results following form finding

The following step is the construction of the cutting patterns, as shown in figure 4.13. In this step, the maximum allowable width of the produced fabric has to be taken into consideration, in order to account for the width of the weaving loom. Therefore, a target segment width of 1.75 metres is used. Another factor that is determined in this step is the stretch compensation factor. As the main fabric directions are aligned with the two principle axes of curvature, this factor was set empirically at 2%. This factor ensures the absence of negative tensile forces in the digital model in later stages.

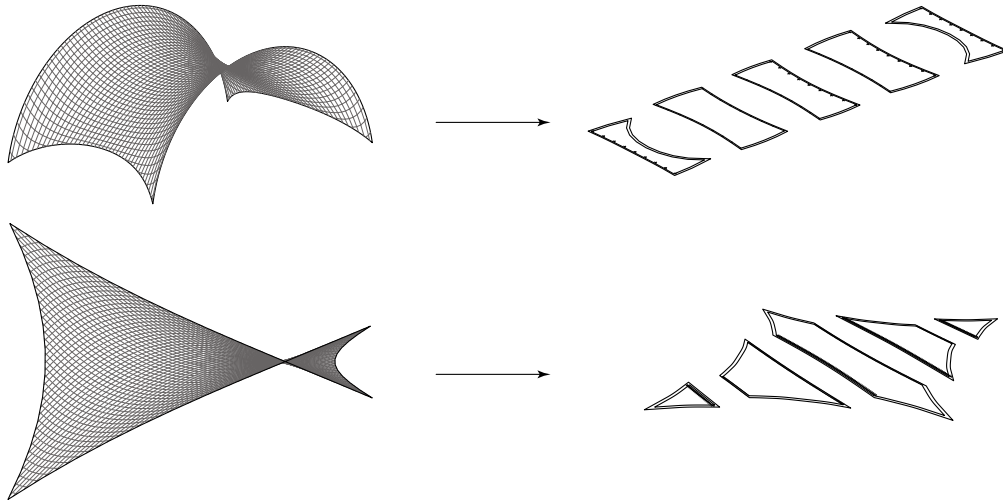
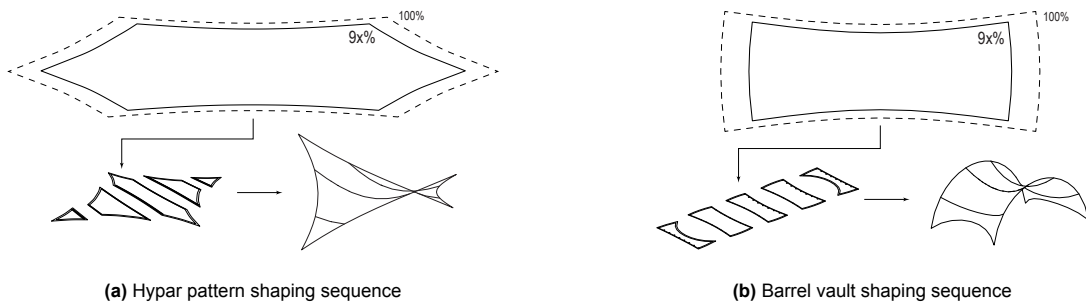


Figure 4.13: Cutting pattern generation

With the cutting patterns constructed and compensated, the last step involves the hanging up of the cutting patterns according to the original form found shape. This process is shown in figure 4.14. This step allows the perpendicular mesh on the patterns to be curved along the geometry. These curved lines will later be used for the validation of the curvature analysis.



(a) Hypar pattern shaping sequence

(b) Barrel vault shaping sequence

Figure 4.14: Cutting pattern compensation and reshaping sequence

With this step complete, the first phase of the research is done, and the shapes are taken into Grasshopper in order to place and analyse the OPV sleeves. The first step in the Grasshopper workflow is the calibration of the form found Easy meshes. In order to do this, the shapes are replicated using the built-in form finding tool in Grasshopper, called Kangaroo2. This method makes use of the dynamic relaxation method, which requires inputs slightly different from the force density in Easy. The result of this form finding is then used to find out which parameters are needed in Grasshopper in order to replicate the Easy form most closely. This includes the parameters for the initial form finding as described before, but also the manual drawing of geodesic lines in order to replicate the cutting pattern segments.

Since the Kangaroo2 shape does not have a mesh pattern representing the warp and weft directions, the weft lines have to be constructed on the mesh. This is done through a local analysis of the curvature of the shape, which results in a number of base points, on which the curves can be placed and projected. This process is shown in figure 4.15. Firstly, the orientations of all pattern segments have to be aligned. In order to achieve this, the center line for each segment is drawn. At each base point on this line, the tangent and normal vectors are extracted, shown in figure 4.15 a, and the cross product is taken to find the sleeve curve direction. From the normal vector and the curve direction vector, a local alignment plane is formed, as seen in figure 4.15 b. The third step comprises the projection of the local vector of the U-direction of the segment onto the plane, as shown in figure 4.15 c. When this is done, the curve

direction vector is rotated around its base point in order to align with the U-direction. This is depicted in figure 4.15 d. This rotated vector is then used to draw the sleeve lines and pull them onto the surface, as seen in figure 4.15 e. Lastly, a buffer needs to be placed at both end of the sleeve lines to allow room for detailing and connections between the OPV strips. The final result is shown in figure 4.15 f.

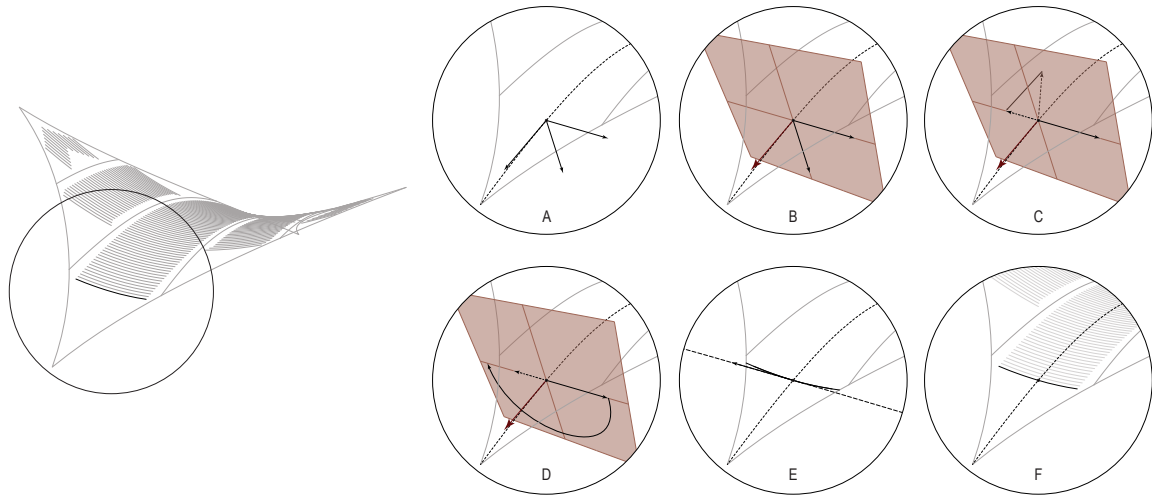


Figure 4.15: Placement of weft curves on the Kangaroo2 mesh

The base vectors as displayed in figure 4.15 a are used for the next step, which is the placement of projection planes on the midpoint of each weft curve. These planes are used to project the weft curves onto, which eliminates normal curvature and allows for the geodesic curvature to be measured on each curve locally. This time, the middle curve tangent and the cross product vector serve as the local x and y axes, and the normal vector, in blue, is normal to each plane. This can be observed in figures 4.16 a and b respectively. This local projection method was chosen because of the curved nature of the shapes. Projecting downwards globally is no longer representative for geodesic curvature if the surface stands at an angle to the horizontal floor plan.

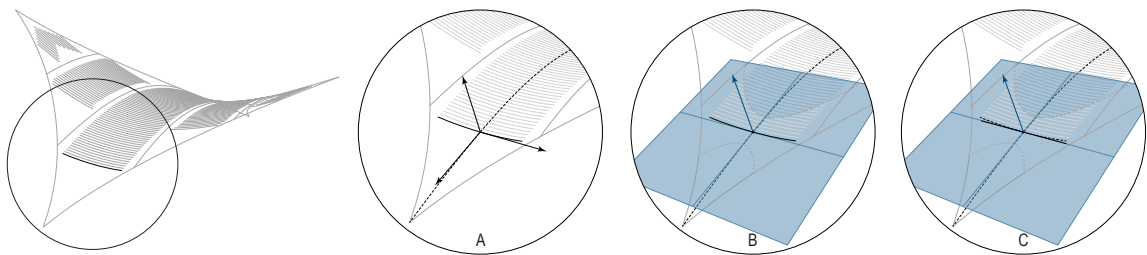


Figure 4.16: Projection plane construction for each individual sleeve curve

The projected curves are then given six equally distributed measuring points and subjected to a curvature analysis component, which measures the curvature of the projected curves on their planes. This results in a curvature vector for each measuring point, the inverse of which is the radius of curvature (see equation 4.2). These radii of curvature are subsequently averaged, after which a unity check is performed using the minimum radius of curvature as determined using equation 4.1. Any sleeve curves that do not meet the required radius length, are taken out of the database. The remaining curves are displayed on the analysed shape. For the shapes that are analysed within the scope of this thesis, an example is given in figure 4.17.

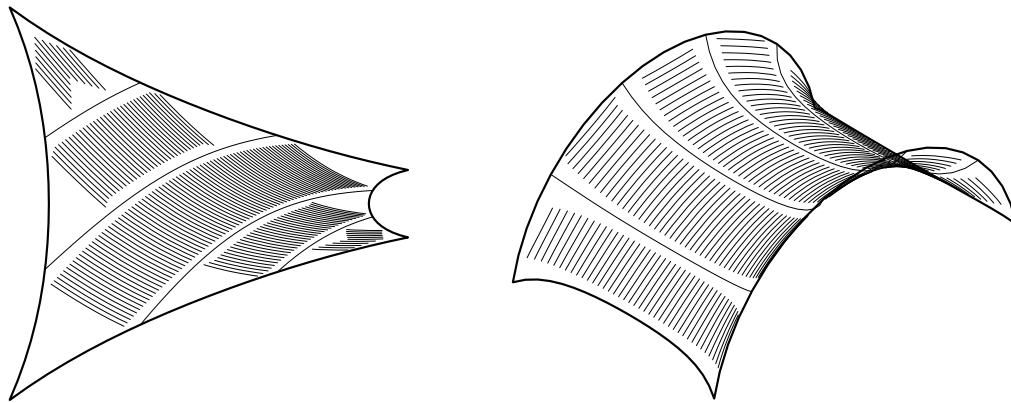


Figure 4.17: Visualisation of the compliant curves on the analysed shapes

4.5. Validation

In order to draw conclusions from the digital Grasshopper model, the results have to be validated. As stated earlier, the models as produced in Easy are considered accurate representations of reality due to the ability of Easy to model the warp and weft directions similar to the geometry's physical form. Therefore, the models have to be subjected to a similar curvature analysis to be able to compare these results. The models that are imported from Easy are line clouds, or groups of lines, that can be sorted into warp and weft lines. These lines, as shown on the right in figure 4.18, are not continuous, but rather short, ordered, line segments. These can be joined and then broken in order to reveal points at the ends of each segment. These points can be isolated and sorted per weft line. The next step involves the fitting of a plane through each set of lines, which is used to cut the surface. The resulting lines are continuous curves, which can be analysed equally to the Grasshopper weft lines as explained in the previous section.

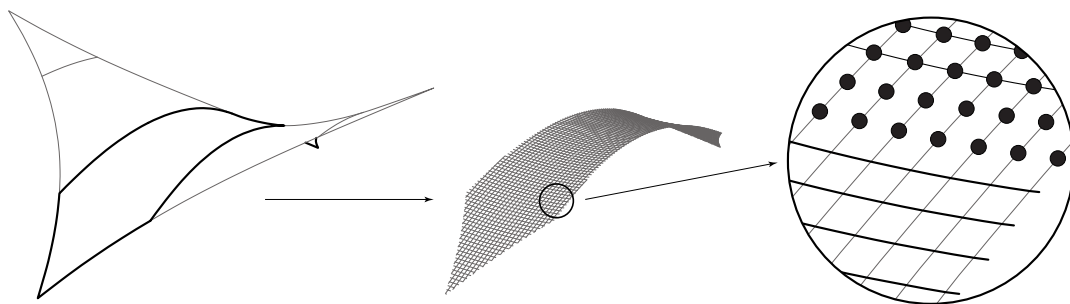


Figure 4.18: Overview of the workflow steps to extract the control points per weft line, fit planes through each set and produce continuous weft curves.

Since the Grasshopper logic makes use of continuous surfaces to curve and display the sleeve curves, the Easy models have to be transformed into surfaces as well. This is done using the weft line points, that can be used to create patch surfaces between the cutting pattern segments. To check the accuracy of this construction method, the surfaces are overlaid on the line and point grids, and the distance between the surfaces and the points is measured, as is shown in figure 4.19. The boundary conditions can be altered in order to improve the accuracy.

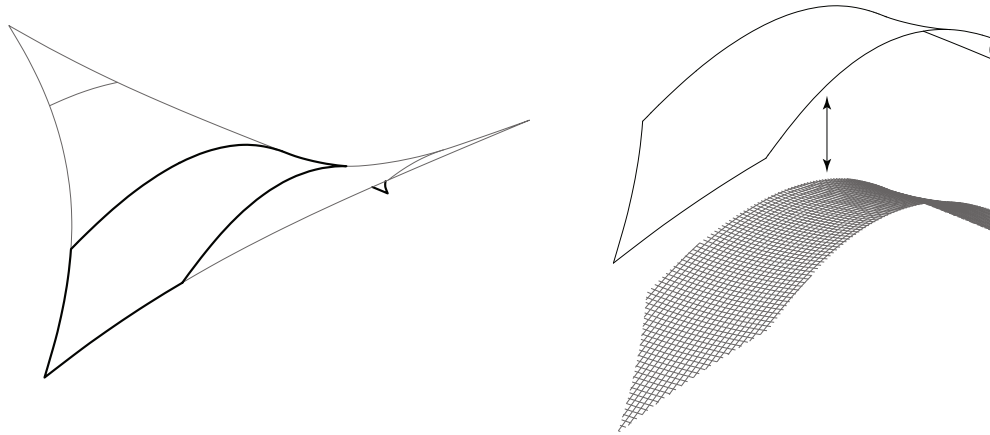


Figure 4.19: Measuring the accuracy of the constructed surfaces against the Easy input line model, using the vertical distance between the shapes.

After sorting and surface accuracy measuring, the points are used to interpolate curves through. These curves are smooth, in contrast to the joined segments that were described earlier. This smoothness enables the Grasshopper model to apply the same curvature measurement. These results can then be extracted and displayed in the same way as the results from the Grasshopper shapes.

5

Results

This chapter outlines the results that were obtained from the research workflows as described in chapter 4. They have been divided into two parts, relating to the analysed shapes. The most significant results are displayed in this chapter using images and tables, while any additional results can be found in Appendix B.

5.1. Hypar

The Hypar construction in Easy, as explained previously in section 4.4, results in a shape of 5 by 5 by 2,5 metres with a total surface area of 19,61 m², as shown in figure 5.1 below.

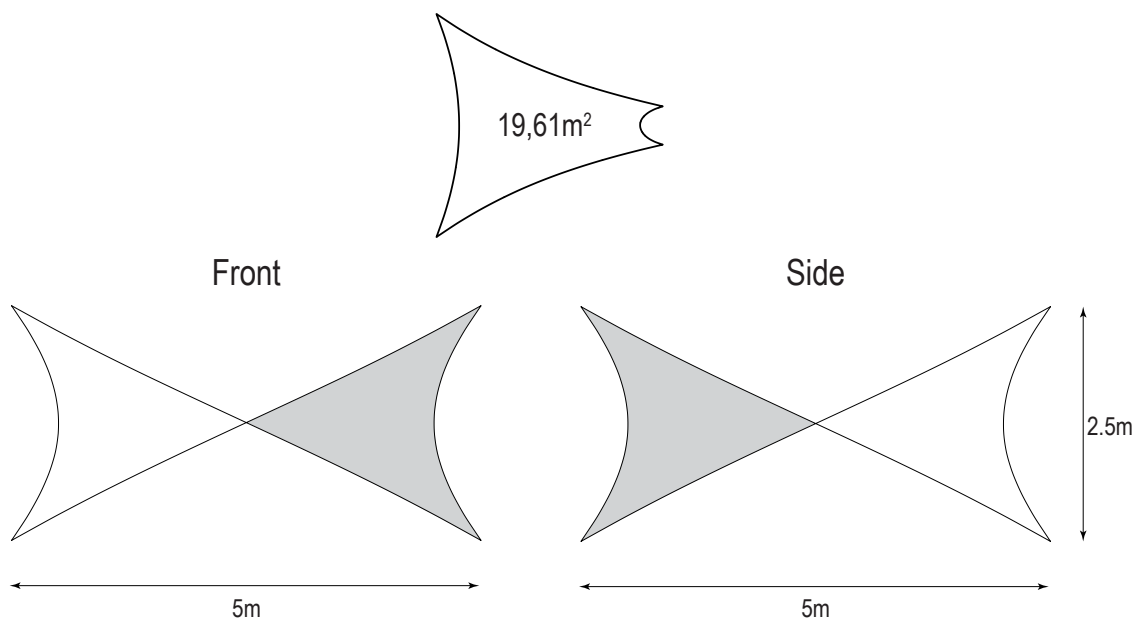


Figure 5.1: Overview of the hypar layout as constructed in Easy. The shape is constructed on a 5 by 5 ground plan, with a total height of 2,5 metres. The resulting surface area is 19,61 m²

Using this shape, a first study is done to determine the influence of seam locations on the total coverage of the surface with OPV. The results are shown below in table 5.3.

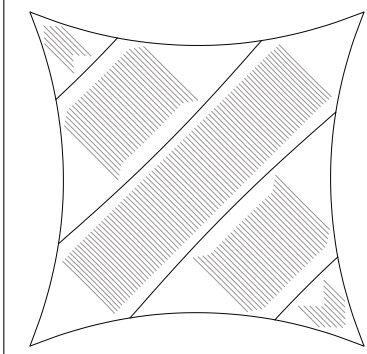
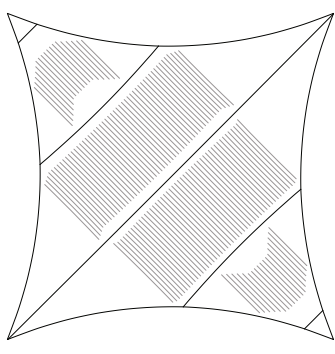
		
OPV coverage [%]	21,5	19,4
OPV total area [m ²]	4,2	3,8
OPV strip length per segment [m]	0,7 1,3 1,1 1,2 0,5	- 0,9 1,2 1,3 0,9 -

Table 5.1: Hypar seam positioning

The numerical results of this first parameter study are shown in figure 5.2 as well, ranging between 19,4% and 21,5% relative coverage. The total surface area ranges between 3,8 and 4,2 m². In the figure, the surface area covered in OPV strips, as well as the percentage of the total surface that is covered are shown.

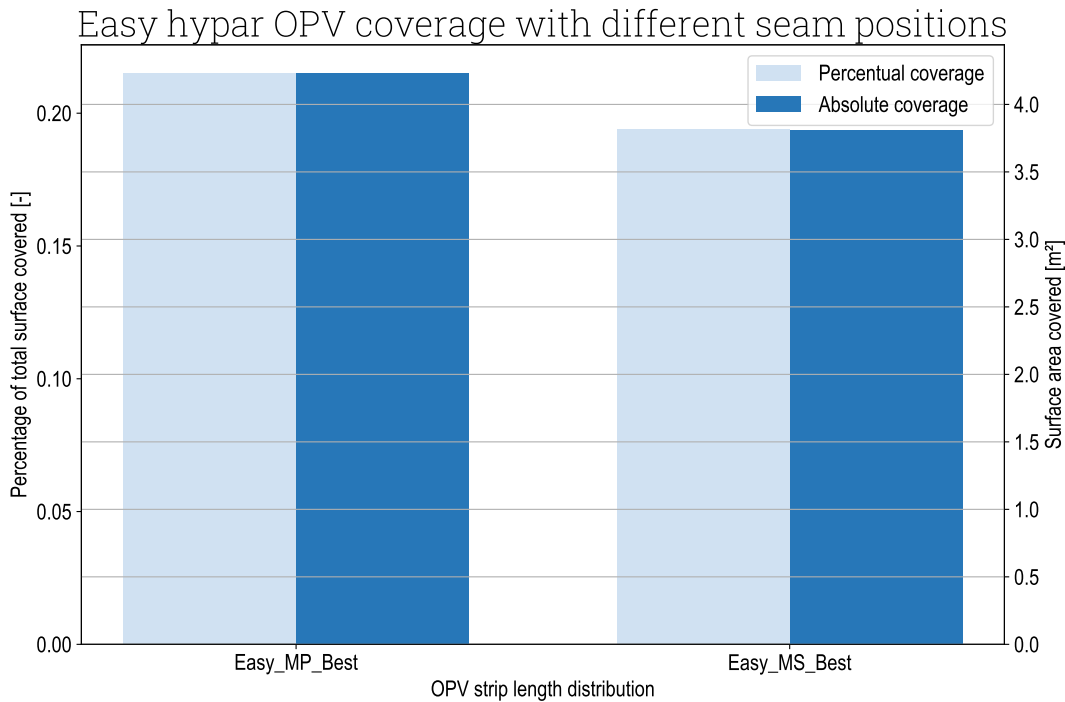


Figure 5.2: Overview of the relative coverage of PV in light blue, as well as the total area covered by said PV in dark blue. The two bars on the left represent the left hand image in table 5.1. The two rightmost bars represent the right hand figure.

Another parameter that was varied is the PV length on the pattern segments. Table 5.2 shows the variation of PV length in two scenarios. Three cases have been given one length of OPV strip for the whole surface, while the case displayed between the double lines has a setup where each pattern segment is given it's own PV length.

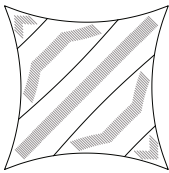
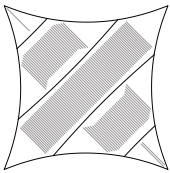
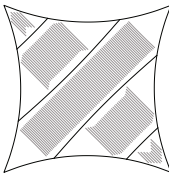
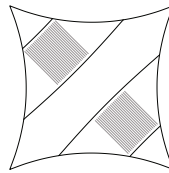
				
OPV coverage [%]	11,6	20,5	21,5	8,6
OPV total area [m ²]	2,3	4,0	4,2	1,7
OPV strip length [m]	0,4	1,1	0,7 1,3 1,1 1,2 0,5	1,5

Table 5.2: Overview of the hypar shape with varying length of PV, from 0,4m on the left to 1,5 on the right. In between the double lines, each pattern segment has been given its own PV length.

The numerical results are displayed below in figure 5.3, with a minimum coverage of 8,6% and a maximum of 21,5%. Similar to figure 5.2, this figure shows the surface area covered in OPV strips in dark blue, as well as the percentage of the total surface that is covered in light blue. The cases titled '1L' received one length of OPV strip for the whole surface, and the third set of bars from the left displays the case between the double lines in table 5.2.

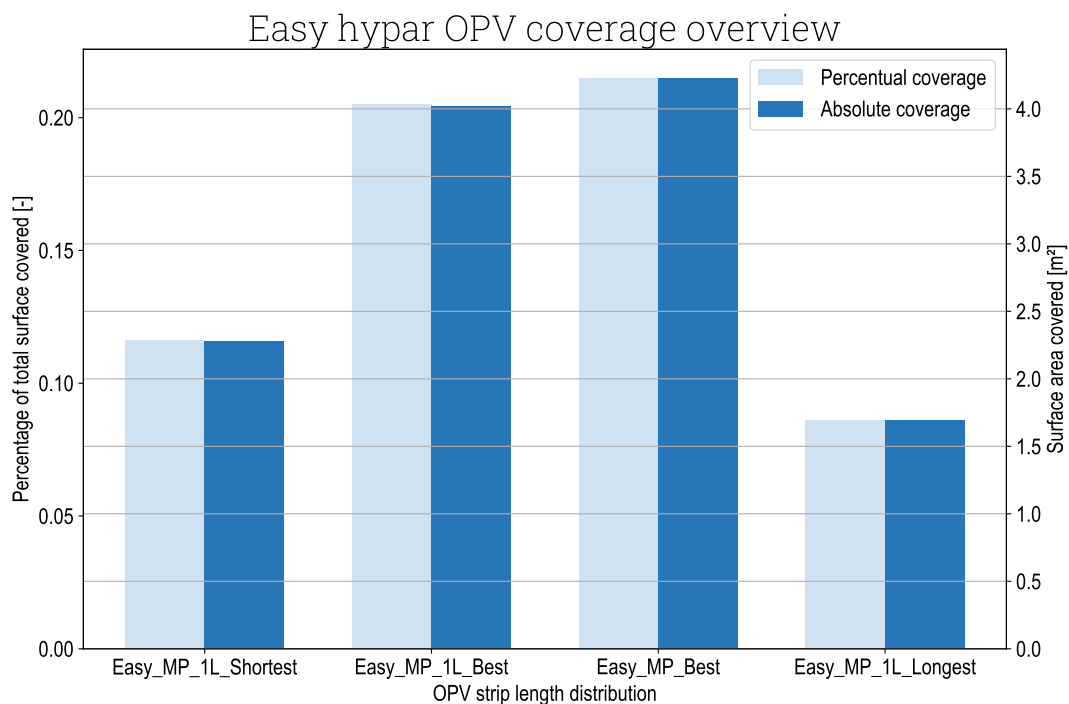


Figure 5.3: Overview of the percentual and actual coverage of the hypar shape using varying lengths of OPV strips, ranging from 0,4m to 1,5m. The order of the bars corresponds to the order of the topviews as shown in table 5.2.

The third parameter that was investigated is the amount of cutting pattern segments in the overall geometry. For this study, the Kangaroo2 shape was used. This shape is shown below in figure 5.4. For an equal design space to the Easy shape, and under equal tension, this shape has a surface area of 19,54 m².

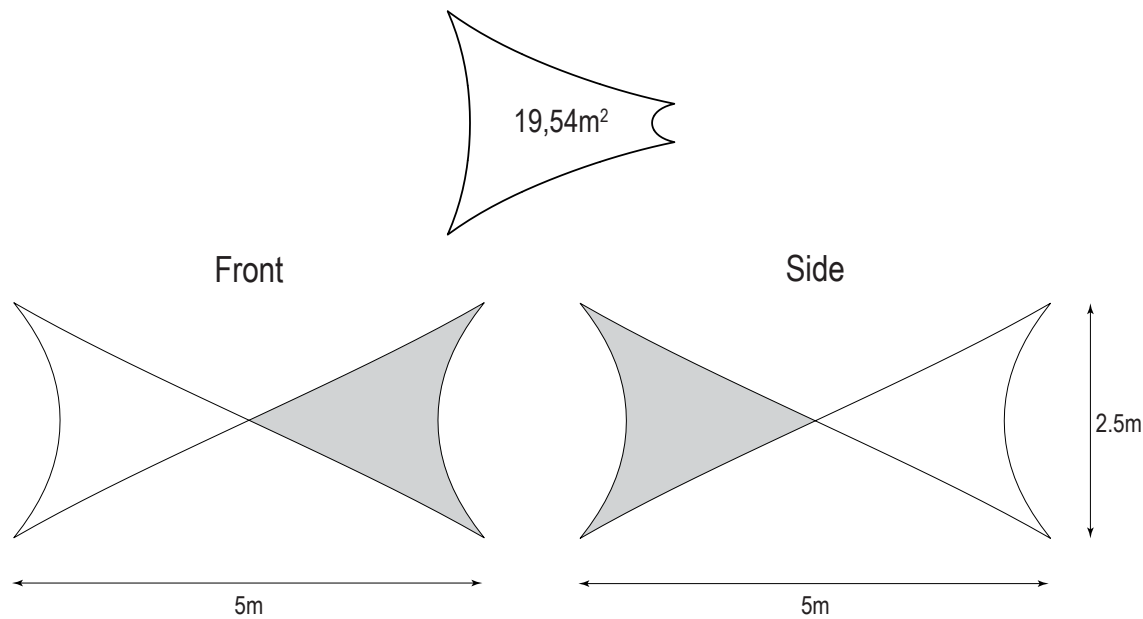


Figure 5.4: Overview of the hypar layout as constructed in Kangaroo2. The shape is constructed on a 5 by 5 ground plan, with a total height of 2,5 metres. The resulting surface area is 19,54 m²

In table 5.3, top views are given of the hypar shape with varying amounts of cutting pattern segments, ranging from 3 to 9. For these cases, the OPV strip lengths were adjusted per segment to maximise the coverage on each pattern.

OPV coverage [%]	20,5	22,9	22,7	21,2
OPV total area [m ²]	4,0	4,5	4,4	4,1

Table 5.3: Overview of the hypar shape with varying numbers of cutting segments. The variation ran between 3 and 9 segments at uneven intervals.

The numerical results from table 5.3 are visualised in figure 5.5, again displaying the percentual and actual coverage. In this figure, these parameters are related to the varying amount of cutting pattern segments, with the percentage on the left axis, and the square metres on the right axis.

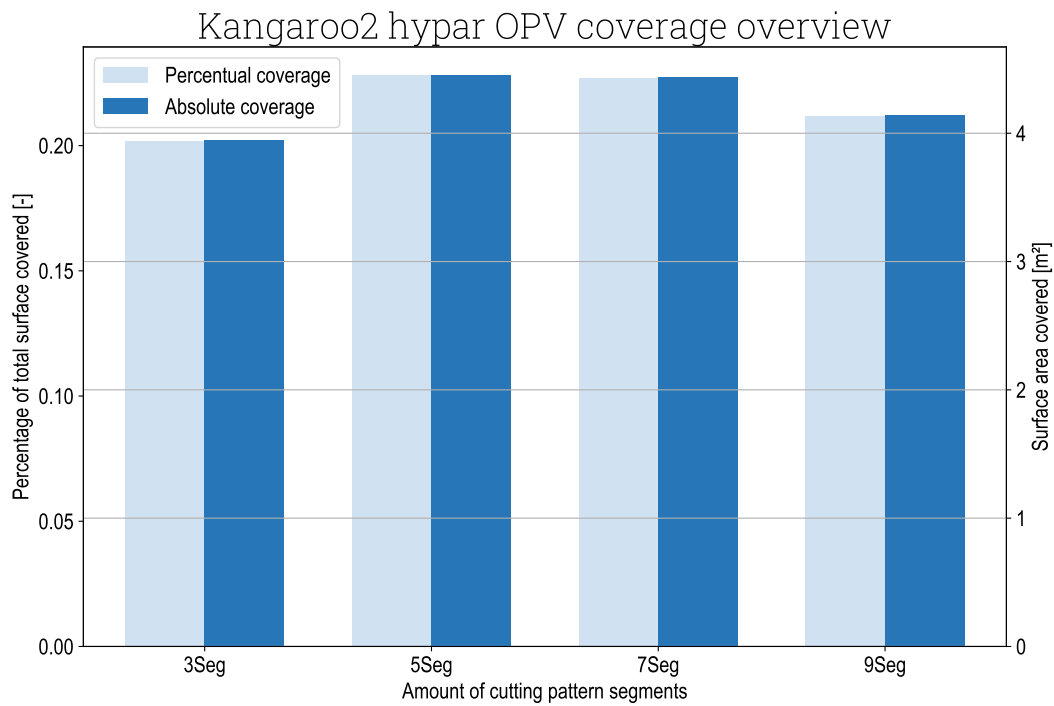


Figure 5.5: Comparison in percentage and square metres for the highest coverage using on length OPV for varying counts of cutting pattern segments in uneven intervals.

Since the primary determinant of curvature placement is their geodesic curvature, a closer look is needed into the exact curvature of the lines that are placed onto the surface. Below in table 5.4, the extreme curvature values for the shapes with the highest coverage are given.

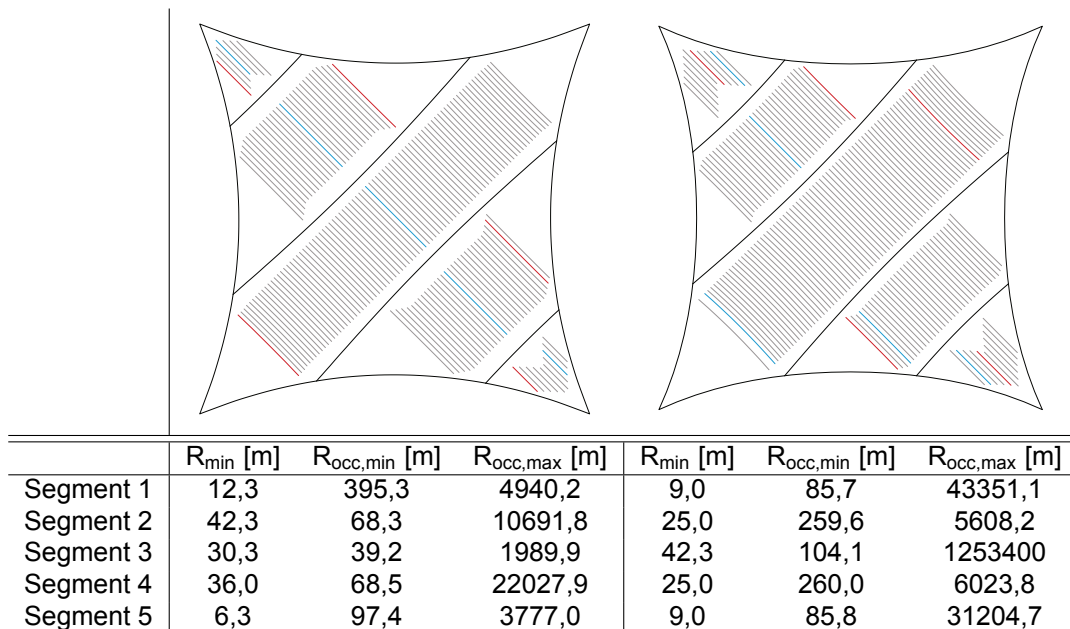


Table 5.4: Overview of the minimum sleeve curvature radii of the hypar (leftmost value), as well as the smallest (in red) and largest (in blue) occurring curvature radii on each cutting pattern segment, counted 1 to 5 from left to right, shown in the middle and right columns respectively.

5.2. Barrel vault

The barrel vault modelling workflow in Easy resulted in a shape with a design space of 4 by 6 by 2,5 metres, with a total surface area of 27,55 m², as shown in figure 5.6 below.

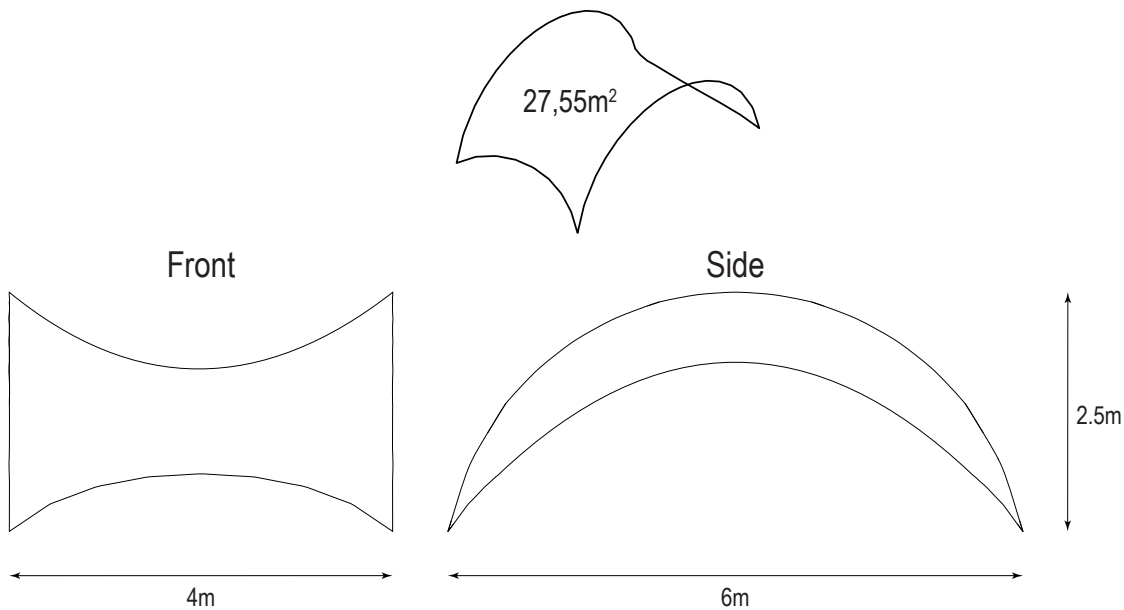


Figure 5.6: Overview of the barrel vault layout as constructed in Easy. The shape is constructed on a 4 by 6 ground plan, with a total height of 2,5 metres. The resulting surface area is 27,55 m²

For this shape, variation of the location of the seams is linked to the pattern segment count, and therefore they are seen as one parameter. This is contrary to the hypar as described in section 5.1.1. As with the hypar, the first parameter that was varied was the OPV strip length on the pattern segments. Table 5.5 shows the variation of OPV strip length with one set of pattern segments. Three cases have one length of OPV strip overall, and one case, between the double lines, has been given a different OPV strip length for each segment.

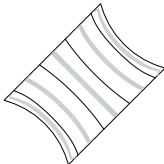
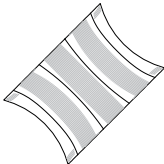
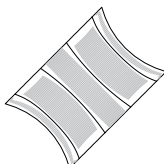
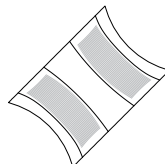
				
OPV coverage [%]	6,5	21,1	26,0	14,6
OPV total area [m ²]	1,8	5,9	7,1	4,2
OPV strip length [m]	0,2	1,0	0,3 1,4 1,0 1,4 0,3	1,4

Table 5.5: Overview of the barrel vault shape with varying length of PV, from 0,2m on the left to 1,4 on the right. In the case between the double lines, each pattern segment has been given its own PV length.

The numerical results are displayed below in figure 5.7, ranging from a minimum coverage of 6,5% to a maximum of 26%. The order of the bars again corresponds to the order of the images in table 5.5 and shows the resulting coverage of the barrel vault with OPV strips, both relatively in light green and in terms of the actual surface area in dark green.

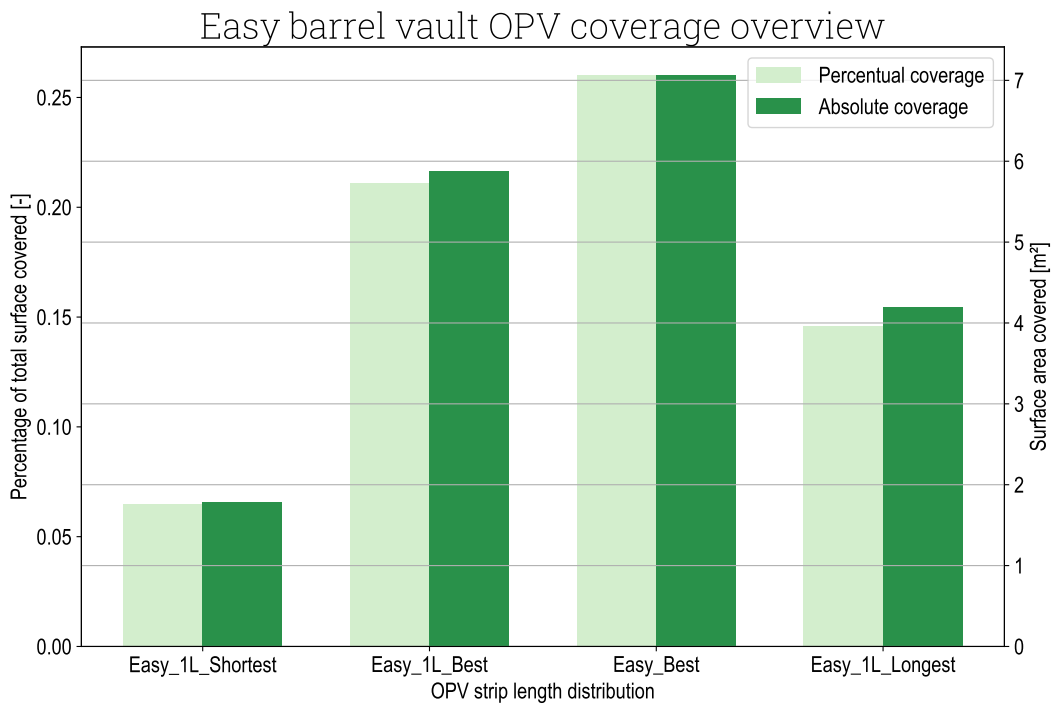


Figure 5.7: Overview of the percentual and actual coverage of the barrel vault shape using varying lengths of OPV strips, ranging from 0,2m to 1,4m. The order of the bars corresponds to the order of the top views as shown in table 5.5.

The other parameter that was investigated, similar to the hypar, is the amount and size of the cutting pattern segments. For this, the Kangaroo2 clone of the Easy shape was used. This shape has an equal design space and force density. The resulting shape has a surface area of 29,58 m², which is shown below in figure 5.8

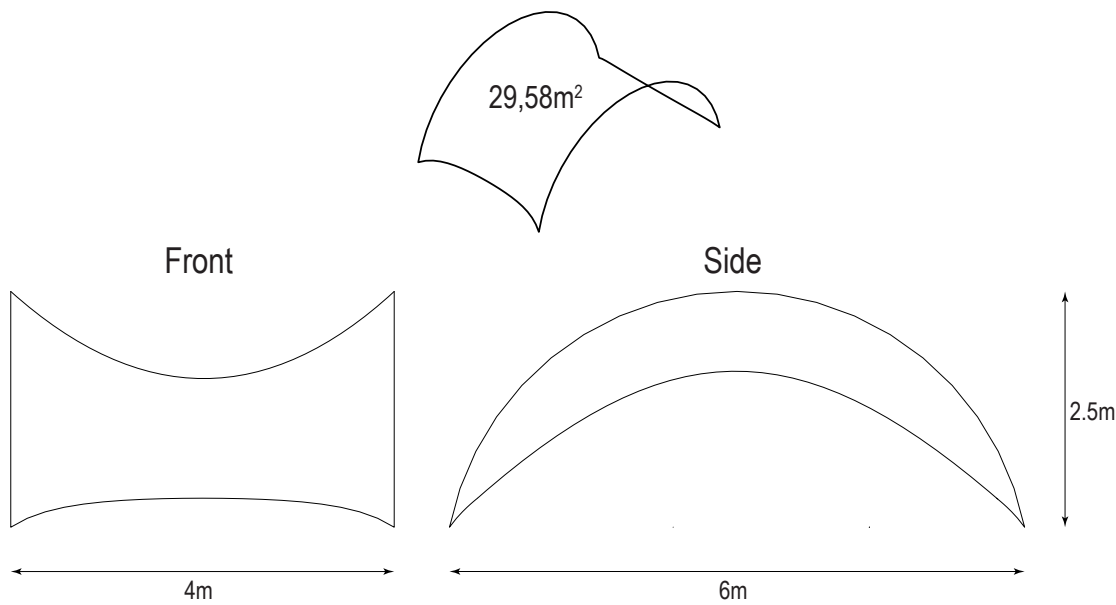


Figure 5.8: Overview of the hypar layout as constructed in Easy. The shape is constructed on a 5 by 5 ground plan, with a total height of 2,5 metres. The resulting surface area is 19,61 m²

In table 5.6, a top view is given of the barrel vault shapes, as well as the variation of the amount of cutting pattern segments.

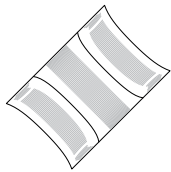
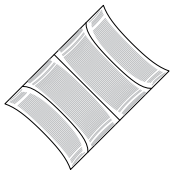
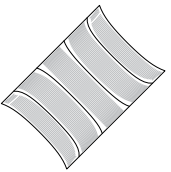
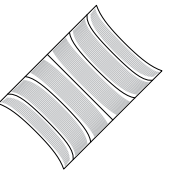
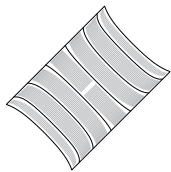
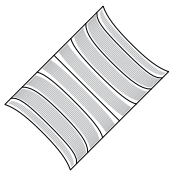
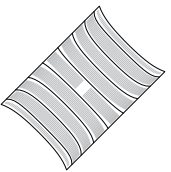
				
PV coverage [%]	19,5	27,6	29,6	27,4
PV total area [m ²]	5,8	8,2	8,8	8,0
				
PV coverage [%]	26,7	25,1	24,2	
PV total area [m ²]	7,9	7,4	7,2	

Table 5.6: Overview of the barrel vault shape with varying numbers of cutting segments. The variation ran between 3 and 9 segments.

The numerical results from table 5.6 are again shown in figure 5.9, ranging from a minimum coverage of 19,5% to a maximum of 29,6%. They display the coverage relating to the varying amount of cutting pattern segments, both in percentage on the left axis, and in square metres on the right axis.

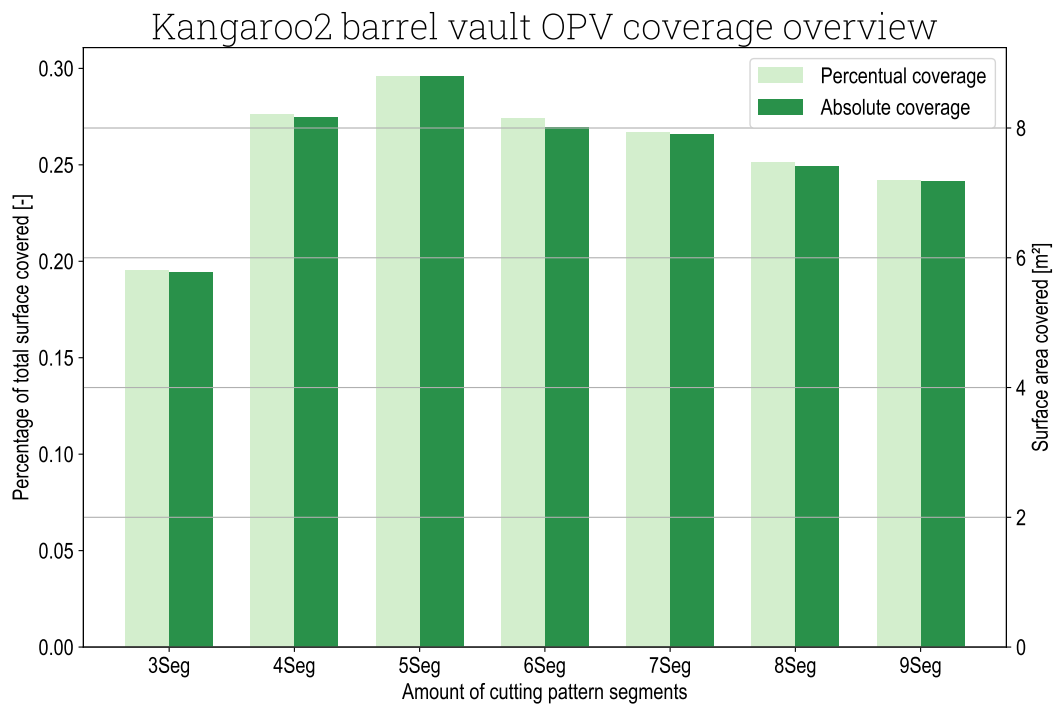
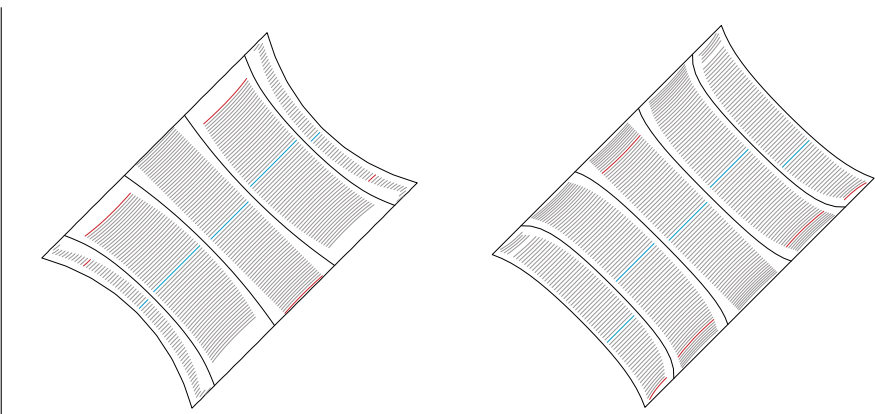


Figure 5.9: Comparison in percentage and square metres for the highest coverage using on length OPV for the whole shape on the left, and per pattern segment on the right

Since the primary determinant of curvature placement is their geodesic curvature, a closer look is

needed into the exact curvature of the lines that are placed onto the surface. Below in table 5.7, the extreme curvature values for the shapes with the highest coverage are given.



	$R_{\min}$ [m]	$R_{\text{occ},\min}$ [m]	$R_{\text{occ},\max}$ [m]	$R_{\min}$ [m]	$R_{\text{occ},\min}$ [m]	$R_{\text{occ},\max}$ [m]
Segment 1	2,3	47,1	21279,5	20,3	31,5	13733,2
Segment 2	49,0	50,2	28455,4	30,3	118,9	104139,8
Segment 3	25,0	32,2	122601,7	25,0	53,6	7942,3
Segment 4	49,0	49,1	15048,4	30,3	119,0	103225,1
Segment 5	2,3	47,1	23452,9	20,3	31,5	13733,7

Table 5.7: Overview of the minimum sleeve curvature radii of the barrel vault (leftmost value), as well as the smallest (in red) and largest (in blue) occurring curvature radii on each cutting pattern segment, counted 1 to 5 from left to right, shown in the middle and right columns respectively.

6

Discussion

The results of the research, which were discussed in chapter 5, provided the first insights into the outcomes of the analysis. From these insights, different trends and behaviours of the models can be observed. In parallel, the methodology itself can be evaluated in order to provide possibilities for improvement. This chapter combines these observations and evaluations. The discussion is structured according to the research sub-questions, and each paragraph will deal with observations and interpretations that are relevant to their respective sub-question.

6.1. Design parameters

The design parameters as described in chapter 4 have provided the results that were described in chapter 5. Although the two shapes were constructed under different boundary conditions, they both show the coverage potential of SUNTEX. They can be compared in terms of their proportional coverage, which illustrates the efficiency of the shapes. This is done in table 6.1 below for the best case on the hypar (left) and the barrel vault (right).

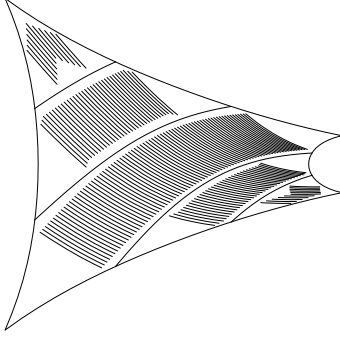
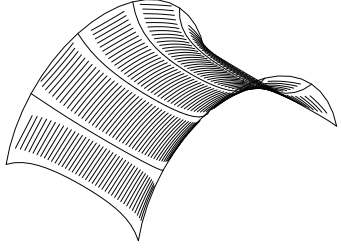
		
OPV strip coverage [%]	22,8	29,6
OPV strip total area [m ²]	4,5	8,8
OPV active area [m ²]	2,4	4,6

Table 6.1: Shape coverage comparison between the hypar on the left and the barrel vault on the right

The table displays both the total surface area of the OPV strips, as well as the active area. This is the area of the strips that actually generates energy, covering only 52,8% of the strips. This difference drives the effective coverage further away from the goal of obtaining 50% coverage on a flat piece of SUNTEX, as established in section 4.1. The buffer at the edges of the strips is needed for weather proofing and sealing, so increasing the width of the strips can provide a more efficient active surface area. This is connected to the fact that the occurrence of monofilaments in the fabric reduces the

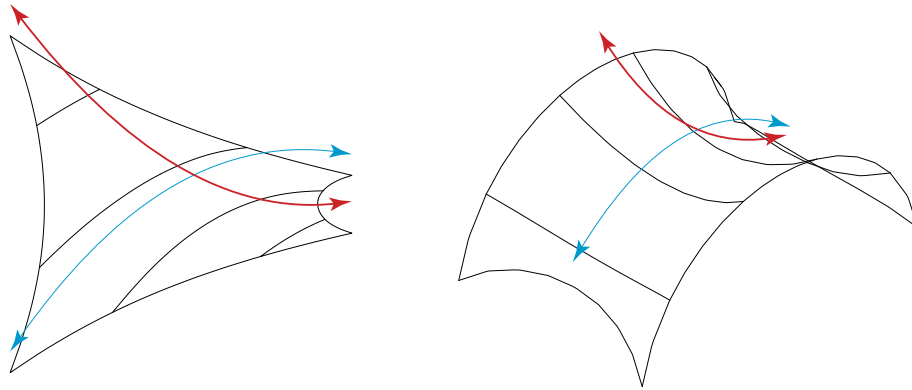


Figure 6.1: Overview of the axes of principle curvature for the hypar and barrel vault. The load bearing curvature is shown in red, and the stabilising curvature in blue.

tensile strength in warp direction [29]. Therefore, increasing the sizes of the sleeves can positively influence the structural properties of the material, while also increasing the OPV effective area. With this in mind, since the geometrical properties were leading for the curvature analysis, the total surface area will be displayed in consequent results. The best cases show that the barrel vault has a higher coverage, which can be attributed to a number of factors. Firstly, the principle load bearing curvature axis is parallel to the short sides of the barrel vault, and the principle stabilising curvature axis lies parallel to the long sides. This enables the placement of the OPV strips more efficiently. On the hypar however, both principle axes of curvature run from corner to corner, and therefore at a 45 degree angle relative to the borders of the shape. This orientation leaves triangular shaped patches of textile devoid of OPV. An overview of both sets of axes of principle curvature is given below in figure 6.1.

This observation can be made for all barrel vault and hypar layouts, irrespective of the amount of cutting patterns. This is displayed in tables 5.3 and 5.6 for the hypar and barrel vault respectively. Additionally, figure 6.2 shows the efficiency of the shapes for increasing pattern segment counts.

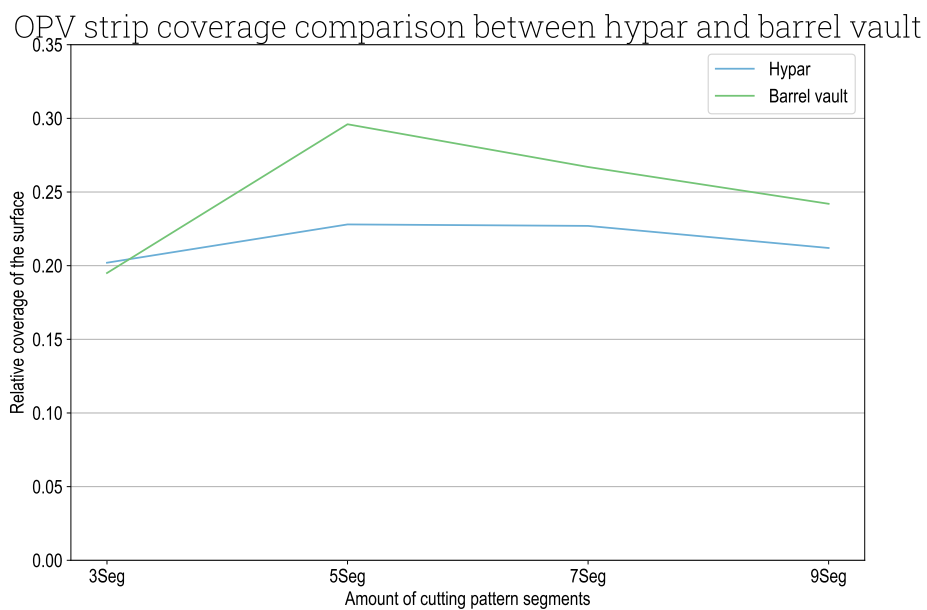


Figure 6.2: Comparison of the relative coverage of the hypar and barrel vault shapes

The lines follow the same trend as shown in graphs 5.5 and 5.9, but the comparison in figure 6.2 clearly shows the difference between the two shapes. Based on these results, the barrel vault is a more efficient shapes for the placement of OPV strips, in the best case by around 10%. In terms of the cutting pattern segment count, the hypar performs more consistently, with a difference of a few percent between the best and worst cases. The barrel vault shows more variation in efficiency based on the amount of segments.

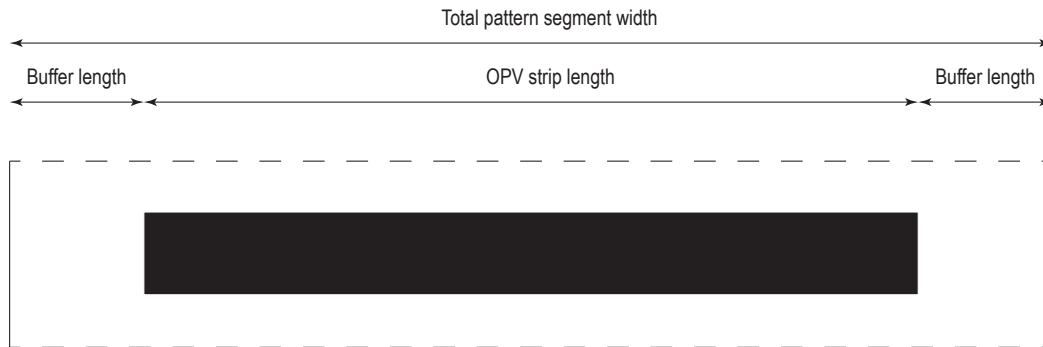


Figure 6.3: Construction buffer as part of the total cutting pattern segment width.

The downward trend, as seen in figure 6.2 for the increasing amount of pattern segments can be correlated to the presence of a construction buffer on each end of the segments. This buffer, shown in figure 6.3, is in place to accommodate tolerances when combining the segments, as well as to leave room for the electrical connections between the solar cells. The minimum buffer was fixed at 10cm on each end of the OPV strips at the narrowest point on the segments, as was introduced in chapter 4. Its influence can be observed when observing the fraction of the segment width that is attributed to this buffer. this is displayed for the hypar below in figure 6.4.

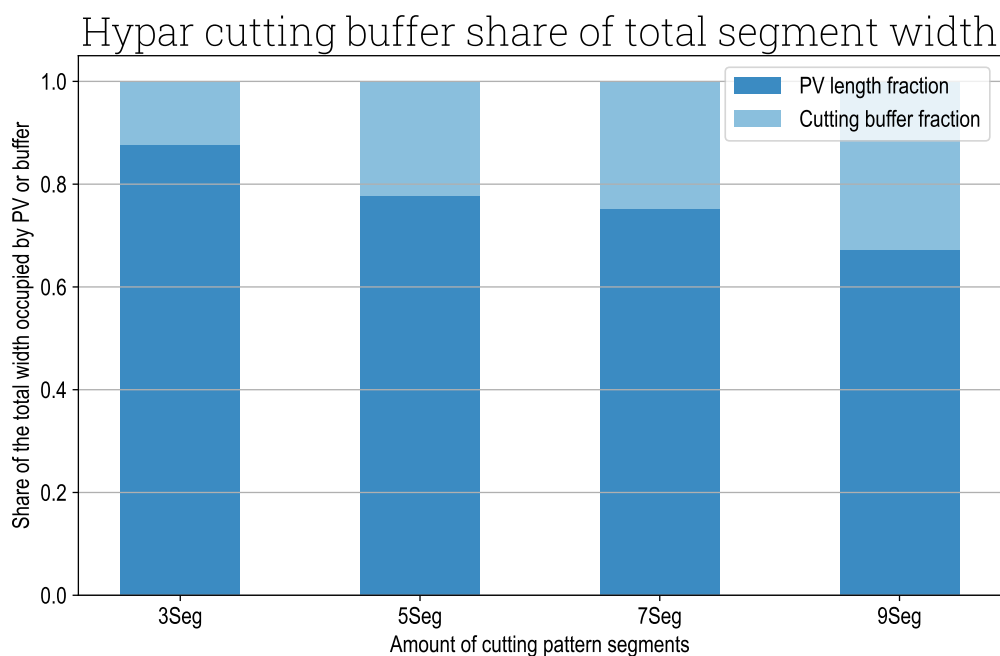


Figure 6.4: Hypar shape of segment width assigned to cutting buffers

The first observation in the graph is the fact that the share of the total width of the segments that is occupied by the buffers, shown in light blue, increases as the amount of segments increases. This is an expected outcome, as the buffer is 10cm on each side, regardless of segment width. Therefore, in narrow segments especially, less room remains to place OPV strips. However, the near-linear relation between pattern segment count and buffer influence implies a best case at the lowest pattern count. As was established previously, the 3-segment shape does not provide the best coverage case for the hypar, so the buffer cannot be seen as solely indicative of best coverage. An explanation for this lies in the orientation of the OPV strips on the segments. The triangular ends of the segments significantly influence the amount of OPV that can be placed there, and in the case of a uniform strip length, larger areas at the ends will remain uncovered.

Contrary to the hypar, the barrel vault shows a buffer fraction that is more closely related to the total coverage of the shape with OPV strips, as seen in figure 6.5. This can be explained by the fact that the pattern segments of the barrel vault are of a more rectangular nature. This allows for more efficient placement of OPV strips at the ends of the segments. An increase in buffer space will therefore be less influential with respect to the coverage.

Barrel vault cutting buffer share of total segment width

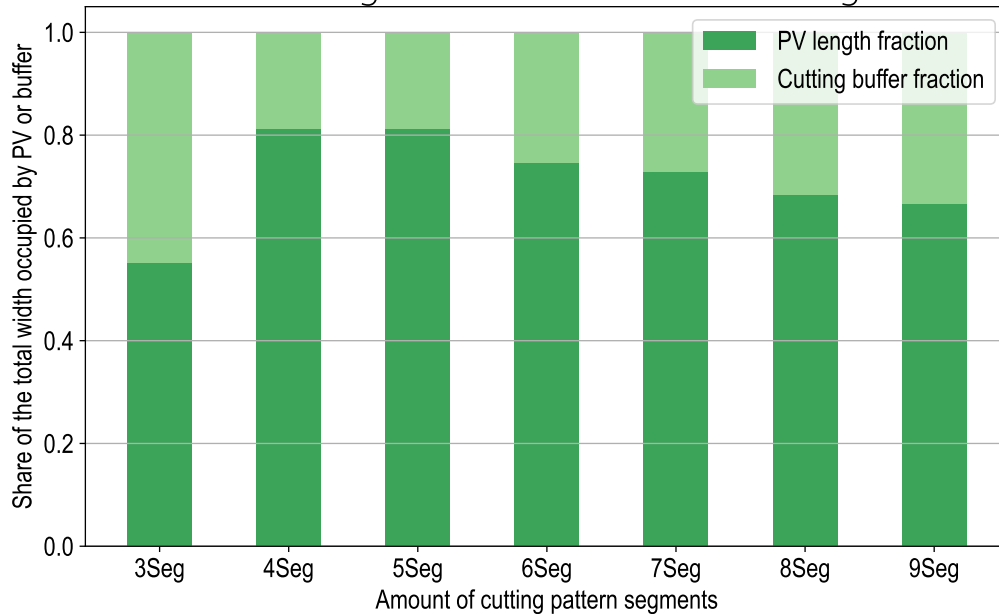


Figure 6.5: Barrel vault shape of segment width assigned to cutting buffers

When looking at the sleeves that are discarded, various observations can be made. Firstly, only in shapes with 3 to 5 pattern segments, sleeves have been discarded based on the curvature constraint at all. This is displayed for the hypar below in table 6.2. Secondly, the OPV strips are laid out over the whole width of each segment, as the buffer space is stable at around 10cm on either side.

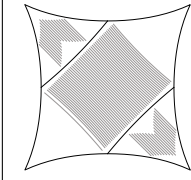
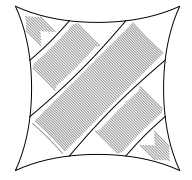
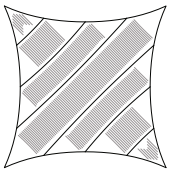
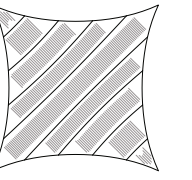
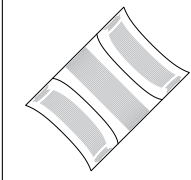
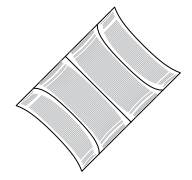
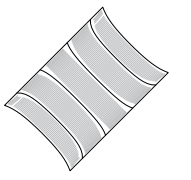
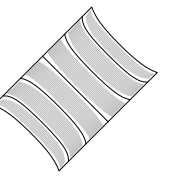
				
Shortest strip [m]	1,0	0,6	0,5	0,4
Longest strip [m]	2,5	1,3	0,9	0,7
Average buffer [m]	0,2	0,3	0,2	0,3
Discarded sleeves [-]	1	1	0	0

Table 6.2: Overview of the hypar OPV strip lengths, buffer lengths, and amount of discarded sleeves based on curvature over varying numbers of cutting segments. The variation ran between 3 and 9 segments at uneven intervals.

The barrel vault shows a similar trend of discarding more sleeves as the number of cutting pattern segments is lower, although the highest amount of discarded lines is found on the 4-segment shape, as shown below in table 6.3. Two more observations are made from this table. The first is the fact that in two cases, being the 7-segment and 9-segment layouts, gaps are left in the strip layout that do not seem to exist due to excessive curvature. Secondly, contrary to the OPV strip length on the 3-segment hypar, the strips on the 3-segment barrel vault do not cover the full width of the segments.

				
Shortest strip [m]	1,1	1,1	0,9	0,6
Longest strip [m]	1,2	1,4	1,1	0,9
Average buffer [m]	0,9	0,2	0,2	0,3
Discarded sleeves [-]	8	22	2	0

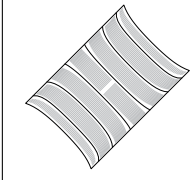
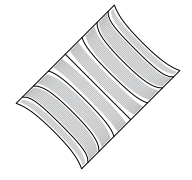
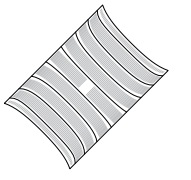
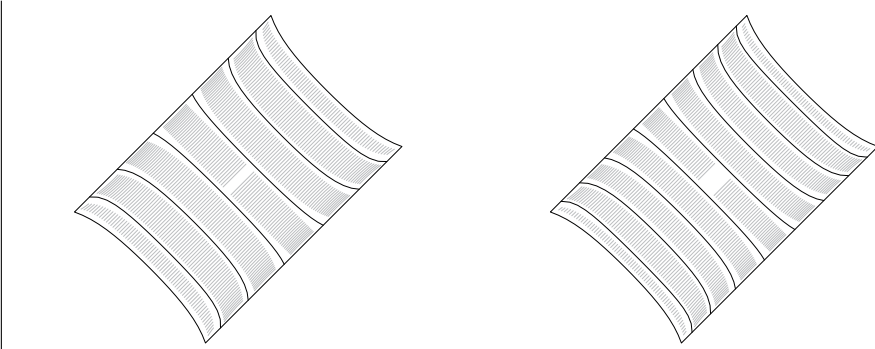
				
Shortest strip [m]	0,4	0,3	0,2	
Longest strip [m]	0,8	0,7	0,6	
Average buffer [m]	0,2	0,2	0,2	
Discarded sleeves [-]	0	0	0	

Table 6.3: Overview of the barrel vault OPV strip lengths, buffer lengths, and amount of discarded sleeves based on curvature over varying numbers of cutting segments. The variation ran between 3 and 9 segments.

The anomalies in the 7-segment and 9-segment layouts can be explained by the fact that the chosen OPV strip length is too large to allow a 10cm buffer on each side at the centers of the central segments. In these cases, a shorter OPV strip length does not seem to provide higher coverage, even if the gaps are filled. This is shown numerically in table 6.4. As the numbers show, the difference is small, but carries implications for the look of the fabric. One alternative to remedy this gap is the reduction of the buffer space from 10 to 9cm on each side. This closes the gap and increases the total coverage marginally.



	OPV strip length [m]	OPV area [m ²]	OPV strip length [m]	OPV area [m ²]
Gap	0,7	1,2	0,5	0,8
Short OPV	0,6	1,1	0,4	0,7
Short buffer	0,7	1,3	0,5	0,9

Table 6.4: Design alternatives for the closure of gaps in the barrel vault OPV strip layout.

Another observation relating to the buffer zones is the fact that the OPV strip length variety on the hypar is much larger than on the barrel vault, ranging from 0,4 to 2,5 metres, see also table 6.2. In this sense, the buffer space on the segments of the hypar is more constant than the buffer space on the barrel vault. This is most apparent for the cases with lower segment counts. The lengths of the OPV strips for all the segment distributions are shown in figure 6.6 for the hypar. This shows the decrease of the length of the OPV strips as the number of segments increases.

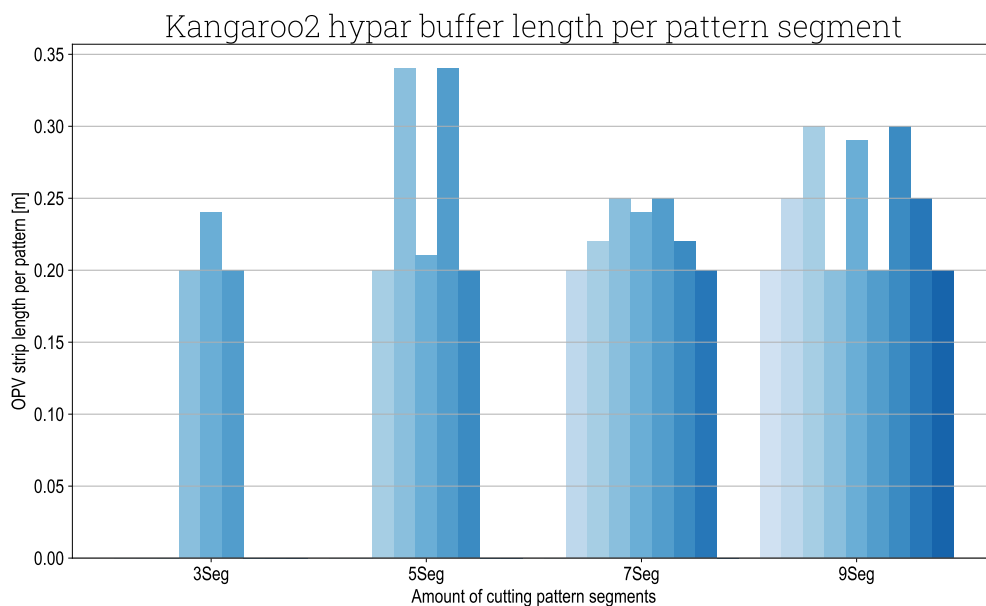


Figure 6.6: Overview of the hypar OPV strip length for increasing pattern segment counts.

The barrel vault shows a more constant distribution of OPV length, as shown in table 6.3, and therefore has a higher variation in buffer length, especially for the 3-segment layout. Figure 6.7 below shows this variation. When comparing these buffers to the hypar buffers in figure 6.6, the shapes with more pattern segments show more equal buffers, but the lower the segment count, the higher the disparity, especially for the 3-segment barrel vault shape.

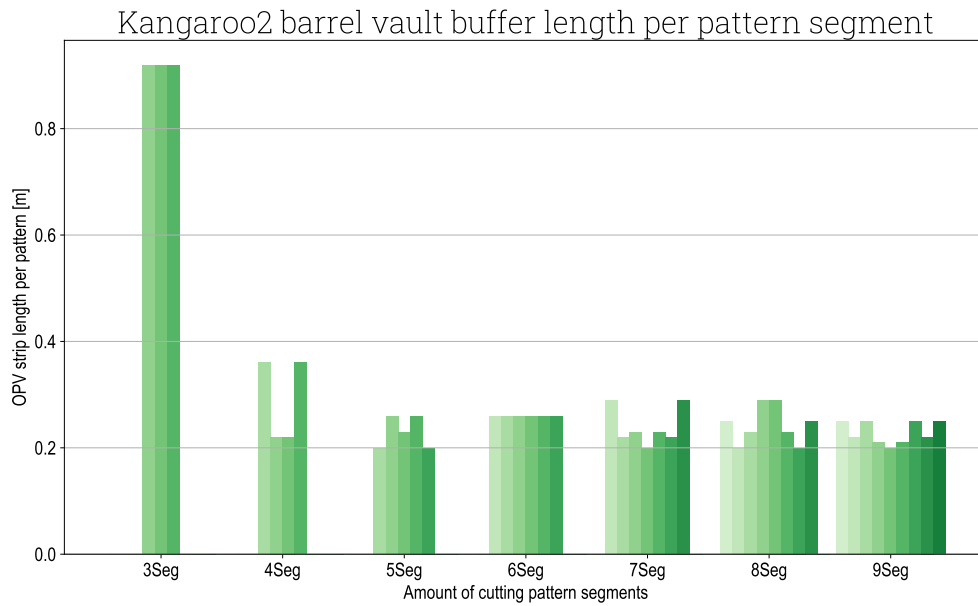


Figure 6.7: Overview of the barrel vault OPV strip length for increasing pattern segment counts.

Upon closer inspection of the 3-segment barrel vault, an explanation can be found for the relatively short length of the OPV strips. As is shown in table 6.5, longer OPV strips lead to a lower overall coverage, as the higher curvature at the far ends of the pattern segments does not allow the placement of long strips. Based on the curvature constraint, 102 strips are discarded in the case with the longer strips on the right hand side of the table, as opposed to only 8 in the case on the left. This results in a reduction of the coverage by almost 3%, or $0,9\text{m}^2$, even though more of the critical width of the segments is occupied by OPV strips. This reduction could further increase when dynamic loads are taken into account. As explained in chapter 3, dynamic loads are excluded from the scope of this thesis. However, the occurrence of dynamic loads during structural analysis could influence the coverage of the shapes. This is due to the fact that despite the shapes being inherently stable due to their curvature, as described in section 2.2, additional deformation due to wind loads is expected when the textile is placed outdoors. This can reduce the coverage in places where the sleeves are already curved close to their design limit.

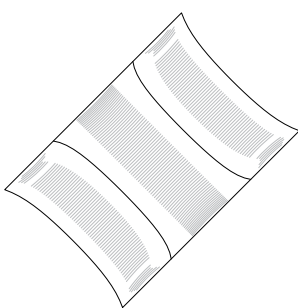
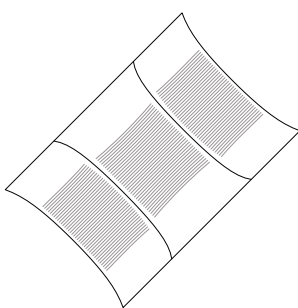
		
Shortest strip [m]	1,1	1,8
Longest strip [m]	1,2	1,9
Average buffer [m]	0,9	0,2
Discarded sleeves [-]	8	102
OPV coverage [%]	19,5	16,6
OPV total area [m^2]	5,8	4,9

Table 6.5: Differences between 3-segment best case scenario (left) and least-buffer scenario (right).

6.2. Computational modelling

Apart from the various design parameters, the models themselves have also influenced the outcomes of this research. The two modelling steps were introduced in chapter 4, including their strengths and limitations. Based on the results from chapter 5 and the observations from section 6.1, the aforementioned limitations can be looked into further to determine their influence on the results.

Firstly, the Easy workflow is given a closer look. Accurate input data for the analysis can be obtained through the form finding, structural analysis and cutting pattern generation within the program. The data accuracy is further improved by the fact that the cutting pattern can be brought back into space to form the shape, which provides a detailed overview of the behaviour of the textile under tension. Therefore, the assumption is made that the weft-oriented lines show behaviour that can be likened to reality. The major predicted drawback was the lack to automation. Based on the workflow as described in section 4.3, a limited amount of automation is possible, to the extent where manual overrides such as the adjustment of boundary sizes are not needed. Therefore, the shape, as well as the parameters to be varied, must be well-defined beforehand. This limits any form of parameter study that can be performed on the shape, so in order to accommodate such studies, additional work is required, or the shape database needs to be clearly defined before the start of the analysis. Within this thesis, the results of the Easy form finding were therefore only used as a template for shape generation in Grasshopper, as well as the validation of the analysis models, as was explained in section 4.5.

It is the validation of the Grasshopper results, using the Easy output, that is the slowest tool that was built. The translation of the line cloud into surfaces, as well as the translation of the weft lines into continuous curves, required various steps using large amounts of data. The surface translation is depicted below in figure 6.8. It shows that extra steps are needed to construct patch surfaces, cut them into the correct shapes and remove the trimmings. These steps, as well as the processing of redundant data, increase the computation time significantly, but are essential for the analysis of the shape. This is due to the fact that the tools in Grasshopper allow for the accurate determination of projection vectors and planes on these smooth surfaces, otherwise known as boundary representations. This use of boundary representations increases the accuracy of the results themselves.

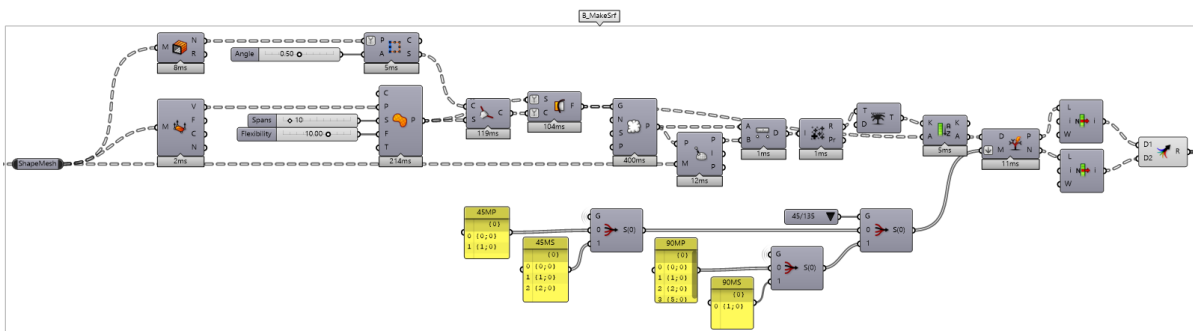


Figure 6.8: Workflow for the translation of the line cloud into a boundary representation, to be used for further analysis steps.

Another characteristic of the Grasshopper workflow that influenced the outcomes was its linear workflow. The nature of the Grasshopper program is to define a set of input parameters up front, and process them using a linear set of steps. These steps then produce different sets of output data. This process is shown below in figure 6.9.

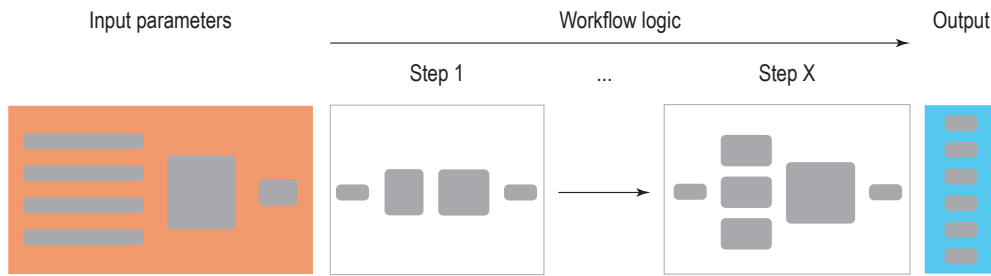


Figure 6.9: The linear nature of the Grasshopper program, where input parameters are processed in different steps in order to produce sets of output data.

In order to accomplish any type of iteration in this setup, additional tools were needed. Grasshopper plugins such as Galapagos link specific input parameters to specific output data and allow optimisation to take place. Within the scope of this thesis, this meant the maximisation of the coverage of a shape with OPV strips, given the design parameters as described in section 6.1. However, the evolutionary algorithm used by Galapagos is a relatively slow method of solving optimisation questions. Calculation times are further increased when the amount of parameters used in the optimisation is increased. Therefore, the decision was made not to change the buffer space as a parameter, and to not include OPV strip lengths of less than 20cm, or twice the buffer zone size. Another factor to contain the analysis time was the construction of two separate files for the two separate shapes. Ideally, one tool would serve any shape that is used as input, but within the scope of this thesis, too many manual overrides were required to control the different shapes. In figure 6.8, one specific example is shown with regards to the orientation of the warp and weft on the shape. Due to the added complexity and the increased calculation time, the option to vary this parameter had to be excluded from the analysis.

In contrast, some standardised workflows that were applied to both shapes induced limitations spontaneously. One example of this includes the construction of the seam lines on the shapes. The hyper in particular is affected by this, as is shown in figure 6.10. In order to vary the amount of pattern segments, the four edges of the shape are divided into sections. The control points are numbered, and corresponding numbers are then connected diagonally in order to follow the principal axes of curvature. Due to the nature of the edges, a middle pattern will always be present, which limits the amount of segments to uneven numbers.

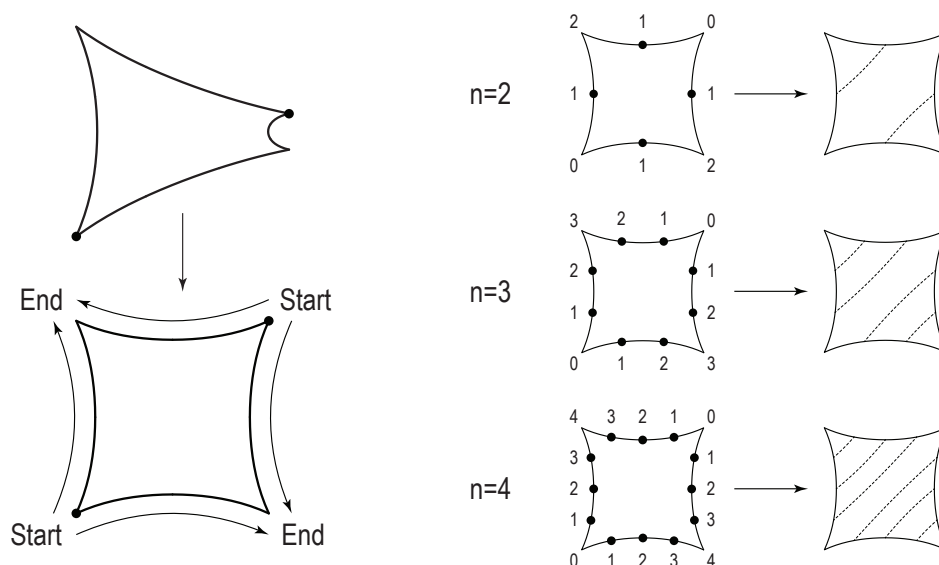


Figure 6.10: Steps to construct seam lines on the hyper shape. The n-number represents the number of cuts in each edge.

As explained in chapter 4, Easy makes use of the force density method, whereas Kangaroo2 uses the dynamic relaxation method. This difference in method, as well as the different types of inputs required for both, resulted in differences between the results for the same shape. This difference is shown below in figure 6.11, with the results from Easy in red and the Kangaroo2 shapes in blue. The difference in cutting pattern location can be attributed to the different types of workflow logic for each software. The Kangaroo2 shapes are divided based on equidistant curve start and end points on the edges, as explained in figure 6.10. The Easy workflow divides the surface based on a target segment width, resulting in slight changes in the locations of the seams.

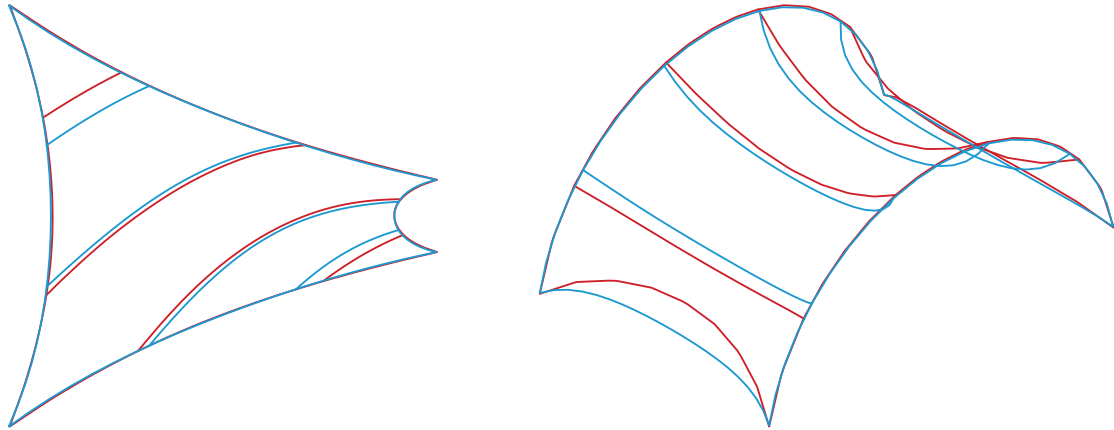


Figure 6.11: Shape overlay of both the hyperboloid and barrel vault, showing the distinctions between the Easy workflow (in red) and the Kangaroo2 workflow (in blue).

Another distinction from figure 6.11 is the difference in curvature, both in the membranes and the edges in the barrel vault shape. The hyperboloid constraints are easier to manipulate, as the surface is fixed in only four points. The barrel vault, in contrast, requires fixation along two arches. It is here that the workflows start to show different results, as the curvature of the barrel vault in the Kangaroo2 model flattens out towards the middle. The Easy shape seems to maintain a more consistent curvature throughout the entire shape.

Juxtaposing this curvature behaviour with the method to place the sleeves on the Grasshopper shapes provides further insights into the behaviour of the sleeves. As was explained in section 4.4, the weft sleeves were constructed by defining the weft direction based on the segment middle line and the curvature of the surface itself. These sleeves were then pulled onto the surface. It is this pulling component that introduces ambiguities into the workflow, as the pulling direction is not known. The direction of pulling can change the curvature of the sleeves locally and therefore influence their compliance with the minimum curvature radius requirement.

This discrepancy in compliance between the two workflows is shown below in table 6.6. In the image, the smallest and largest radii of curvature are shown in red and blue respectively, on the best cases of each shape. The aforementioned curvature differences of curvature between the Easy shapes and the Kangaroo2 shapes becomes clear when taking a closer look at the sleeves with the extreme curvatures.

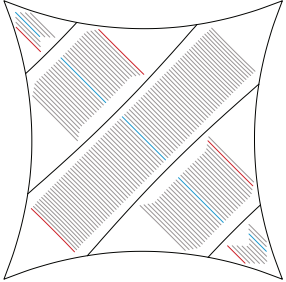
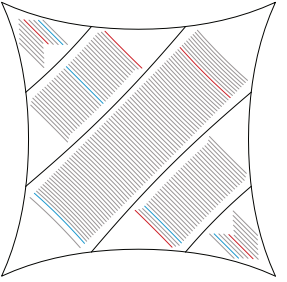
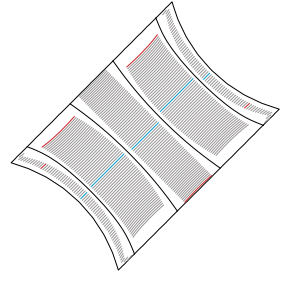
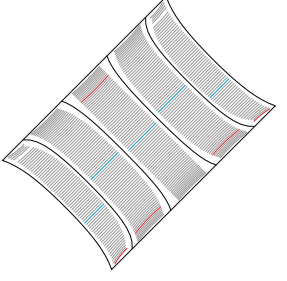
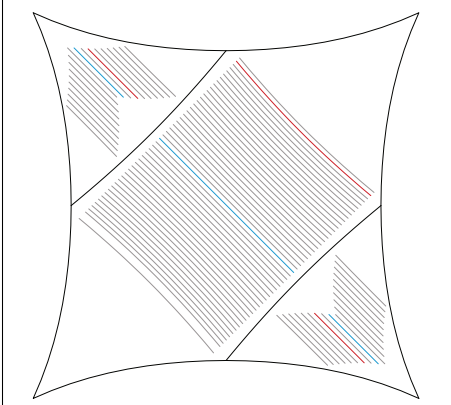
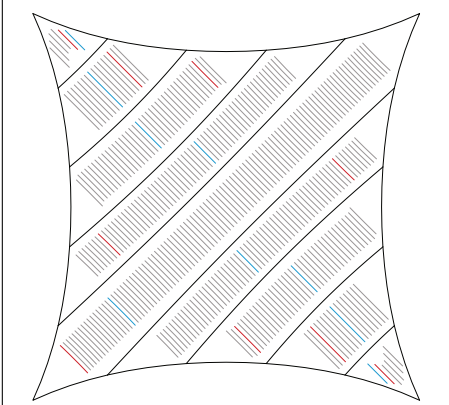
						
	R_{min} [m]	$R_{occ,min}$ [m]	$R_{occ,max}$ [m]	R_{min} [m]	$R_{occ,min}$ [m]	$R_{occ,max}$ [m]
Segment 1	12,3	395,3	4940,2	9,0	85,7	43351,1
Segment 2	42,3	68,3	10691,8	25,0	259,6	5608,2
Segment 3	30,3	39,2	1989,9	49,3	104,1	1253400,0
Segment 4	36,0	68,5	22027,9	25,0	260,0	6023,8
Segment 5	6,3	97,4	3777,0	9	85,8	31204,7
Discarded sleeves [-]	0			1		
OPV coverage [%]	22,8			21,5		
OPV strip area [m ²]	4,5			4,2		
						
	R_{min} [m]	$R_{occ,min}$ [m]	$R_{occ,max}$ [m]	R_{min} [m]	$R_{occ,min}$ [m]	$R_{occ,max}$ [m]
Segment 1	2,3	47,1	21279,5	20,3	31,5	13733,2
Segment 2	49,0	50,2	28455,4	30,3	118,9	104139,8
Segment 3	25,0	32,2	122601,7	25	53,6	7942,3
Segment 4	49,0	49,1	15048,4	30,3	119,0	103225,1
Segment 5	2,3	47,1	23452,9	20,3	31,5	13733,7
Discarded sleeves [-]	22			22		
OPV coverage [%]	26,0			29,6		
OPV strip area [m ²]	7,1			8,8		

Table 6.6: Overview of the best cases for the hypar (top row) and the barrel vault (bottom row), displaying the compliance of the sleeves with the geodesic requirement, as well as the resulting coverage and surface area of OPV.

Table 6.6 shows the difference in extreme curvature between the shapes. The Easy shapes on the left show a consistent pattern for the location of the sleeves with the least curvature (in blue). They are all placed in the middle of the pattern segments. The Kangaroo2 shapes on the right show more variation. As established previously in figure 6.11, the barrel vault shows little curvature in the middle of the segments, which explains the location of the sleeves with least curvature. The Kangaroo2 hypar, although showing near-identical curvature to the Easy hypar, shows much less consistency in the locations for the sleeves with least curvature. This is reflected by the numerical difference of the highest occurring radius of curvature, which differs by around 50% between the Easy and Grasshopper shapes. The barrel vault shows more consistency in this regard. With respect to the sleeves that display the most curvature, both Kangaroo2 shapes show more erratic behaviour. Firstly, none of the sleeves with most curvature is placed at the far end of a segment. The Easy shapes in contrast, show consistent behaviour. Secondly, in some instances on the hypar, the sleeves with most curvature are closer to the middle than the sleeves with least curvature. This behaviour becomes more erratic as the size of the segments decreases, as is shown below in table 6.7.

		
Discarded sleeves [-]	1	0
Smallest strip length [m]	1,0	0,4
Largest strip length [m]	2,5	0,7

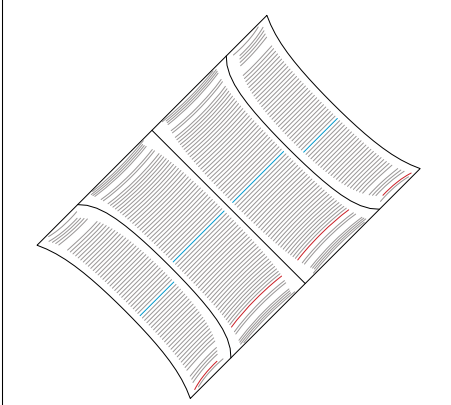
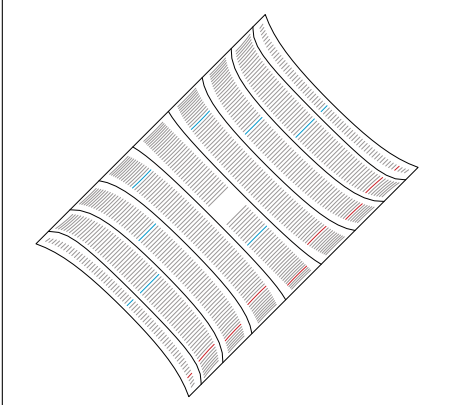
		
Discarded sleeves [-]	22	0
Smallest strip length [m]	1,1	0,2
Largest strip length [m]	1,4	0,6

Table 6.7: Overview of the locations of sleeves with least (in blue) and most (in red) curvature, for the cases with the longest strips on the left and the shortest strips on the right.

Taking the aforementioned reflections on the computational workflow into account, the results are re-evaluated. The differences between the shapes in Easy and Kangaroo are displayed below in figure 6.12 for the hyper. The total amount of OPV area is slightly lower in the Easy result than in the Kangaroo2 result, at a difference of 0,4m². This is supported by the (marginal) proportional difference, which is displayed in figure 6.12 at 1%.

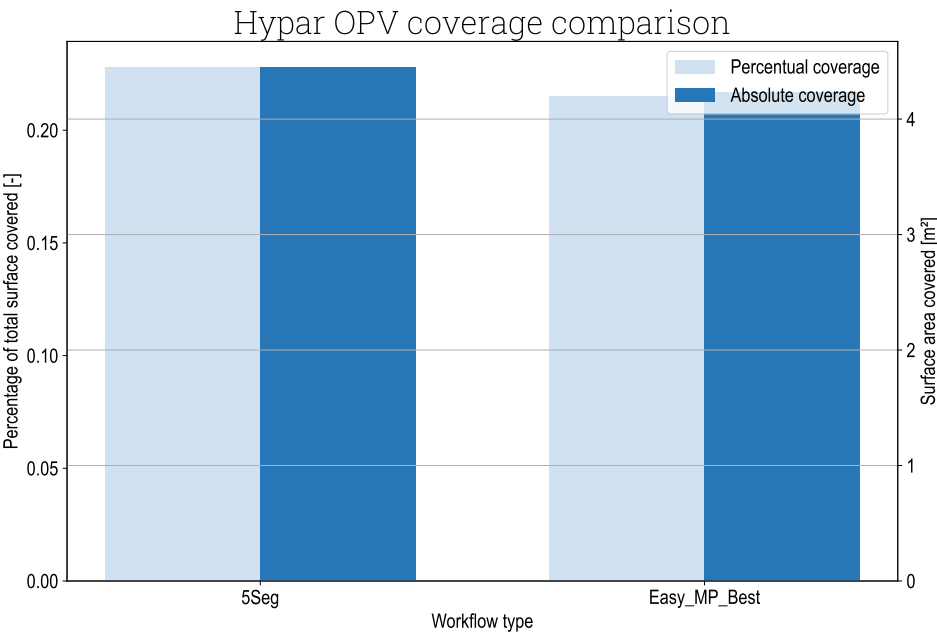


Figure 6.12: Comparison of coverage in the Easy and Kangaroo2 setups with equal setting of the design parameters

Below in figure 6.13, the graphs highlighting the difference of coverage between Easy and Kangaroo2 are displayed for the barrel vault. As discussed before, the increased complexity of the computational workflow has led to a greater difference in shape when comparing the Easy and Kangaroo2 shapes. This was also shown in figure 6.11. The result of this is a difference of absolute coverage between the shapes of 1,7m². The resulting difference in proportional coverage is 3,6%.

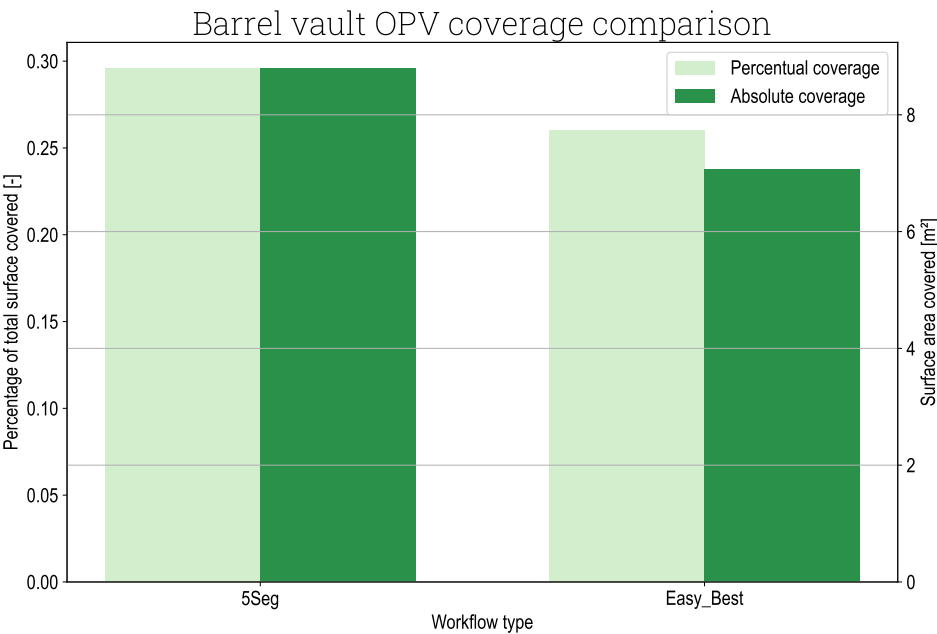


Figure 6.13: Comparison of coverage in the Easy and Kangaroo2 setups of the barrel vault

The aforementioned complexities and resulting anomalies require a re-evaluation of the design parameters and constraints. For instance, the distance between the OPV strips was fixed, and a single construction buffer size on the ends of the OPV strips was given. The compliance with conventional textile design practices posed another constraint with respect to the orientation of the OPV strips on the shapes. However, the results of this thesis show that a parametric study can provide added value when used to study the feasibility of the coverage of a curved shape with strips, especially when done at the beginning of the research. Without the constraints of OPV strip orientation or distance, a shape can be freely covered to find the maximum possible surface area of OPV on any shape. This can then inform decisions with respect to fabric materials and composition. Iterating through these steps can then provide the researcher with boundary conditions regarding material properties and sleeve layout. In contrast, from a production standpoint, the current order of research has merit, as current knowledge has informed the fabric itself, which then informed the applicability of the textile on curved shapes according to industry standards.

6.3. Design workflow integration

The results of this research, as well as the review of the design parameters and methodology, allow for the evaluation of the integration of this research into industry standard design workflows as introduced in section 2.1. This evaluation begins with a review of the coverage determination process, which is highly iterative. The iterative nature aligns with the combination of form finding and structural analysis. However, the cutting pattern generation and subsequent repositioning of that pattern in space also have to be taken into account. These steps are not as iterative and require multiple manual steps in order to be completed. This complicates the process, as on the one hand, a primary, quick analysis is useful in order to estimate the extent to which a shape is suitable. On the other hand, a detailed analysis is necessary in order to find a realistic estimate of the OPV strip coverage.

The workflow lends itself to quick analyses of the cutting pattern segment distribution through the cloning of the Easy output in Grasshopper. Therefore, one preliminary model could serve as a starting point, which can be altered according to design needs in parallel to the analyses being conducted in Grasshopper. The results from these preliminary analyses can then be used in order to make final decisions on the design. Afterwards, the final analyses steps are performed using the final shape design. This workflow proposal will require refinement of the analysis of the Easy shapes, as these models can be very heavy. This slows the design process, especially if an initial model is to be used for quick upfront assessments.

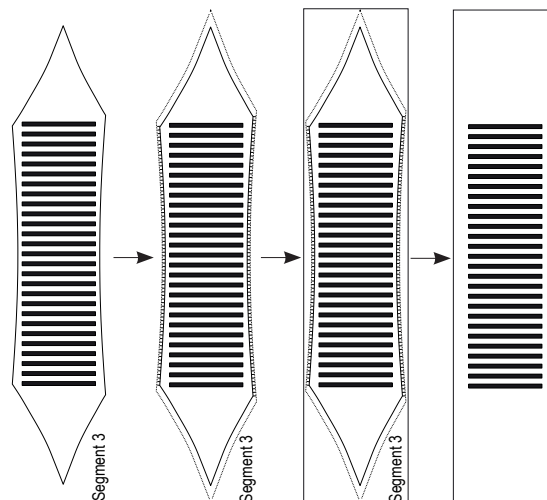
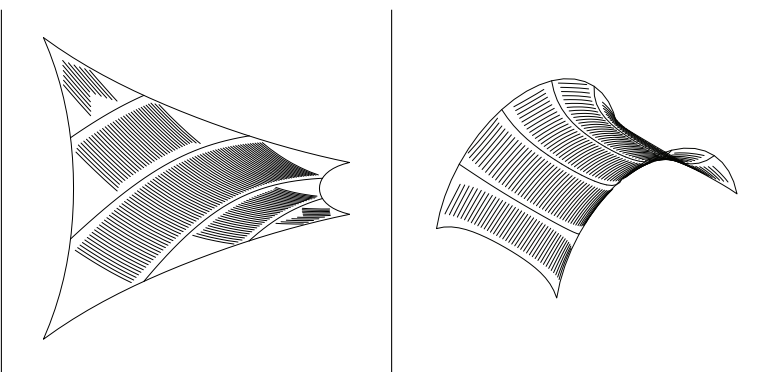


Figure 6.14: Overview of steps to get from model results to producible textile

When deliberating the integration of the SUNTEX research into industry production standards, the sizing of the pattern segments requires extra attention. The sizes of the segments within the shapes can be altered parametrically in the workflow itself. However, in order to produce the fabric, its production measurements have to be taken into account. In order to scale up the production of SUNTEX, unitizations have to be put in place. This means that the pattern segments are ideally as close in shape and size as possible, and ideally only one length of OPV strip is used. However, going from a factory sheet of fabric to a pattern segment requires the cutoff of parts of the sheet. In order to account for this, OPV strips cannot be placed throughout the entire sheet. The extent to which they can be placed will depend on the size and shape of the pattern segment. This reduces the proportional coverage of a sheet of SUNTEX even further from the 50% as set as a design goal by Bakr [4].

This is shown in figure 6.14, where the middle segment of the hypar is isolated to illustrate how to get from a digital cutting pattern segment to a produced panel of SUNTEX. Firstly, extra buffer space is added along the edges of the segment in order to account for seam overlap and cable sleeves on the edges of the shape. Then, this larger shape is outlined by a rectangle that represents the pane of fabric as it will be produced in a weaving loom. On the right-hand side of the image, the outlines of the pattern segment and additions are taken away to reveal the pane of SUNTEX the way it would look after production. From this image, it is observed that more buffer space is needed on either side of the PV cells, compared to the 10cm that is assumed in the model. Below in table 6.8, the measurements for the best cases in the hypar and barrel vault are displayed. All other measurements can be found in appendix B. The OPV coverage losses emphasize the need for efficient solar panels once again. As discussed previously, the OPV strips in this research have an active area of only 52,8% of the total strip area. When taking the longest day of the year, June 21st, as a reference, 16,5 hours of sunlight were expected by the KNMI [21]. In combination with the power output of 6,8 W/m², as given in section 4.1, the total power output for both shapes can be calculated using the active area, see table 6.8. The hypar result is 0,3 kWh. According to the Environmental Protection Agency, one full smartphone charge requires 0,022 kWh [16]. Therefore, the hypar output enables 12,2 full smartphones charges. The barrel vault has a total power output of 0,5 kWh, which equates to 23,5 full smartphones charges. Simple calculations such as this can inform the current use cases, and provide further research with a starting point for the development of the OPV itself, as well as the methods to cover curved shapes.



Textile width at widest point [m]	1,7	1,7
OPV strip length [m]	1,3	1,1
Cutting buffer [m]	0,2	0,2
OPV active area [m ²]	2,4	4,6

Table 6.8: Production measurements for the best cases of the hypar and barrel vault

Conclusions & Recommendations

This chapter outlines the findings and conclusions of the research, as presented in this report. Also, the research questions from chapter 3 will be answered. Apart from that, recommendations will be made, both for future research and for industry on how to move forwards with the methods and findings from this thesis. First, the conclusions will be drawn in section 7.1, after which the recommendations will be described in section 7.2.

7.1. Conclusions

In this section, the findings of the research are given, as well as answers to the research questions. The findings are structured per sub-question. Since the sub-questions were needed to answer the main research questions, these are answered first. Lastly, the main research question is answered.

1. Which design parameters are important to consider when covering textile with OPV strips?

Based on the research as presented in this thesis in chapter 4, as well as the results and their interpretations in chapters 5 and 6 respectively, the following design parameters are deemed significant to obtain reliable results regarding the coverage of textile with OPV strips:

- The distance between the OPV strip sleeves. Within the scope of this research it was set at 3cm. However, the variation of this parameter will directly influence the amount of OPV strips that can be placed on the textile, and therefore its coverage.
- The construction buffer left on either end of the OPV strips. This buffer was set at 10cm at the narrowest point of the pattern segments. Varying this minimal buffer space directly translates to varying coverage levels.
- The OPV strip length. Within the bounds of the cutting pattern segments, the OPV strip length can be maximised to an extent in correlation with the cutting buffer. If within a pattern segment a different cutting buffer size is required, this directly influences the length of the OPV strips.
- The cutting pattern segment count. Having a lower number of pattern segments in a shape means a smaller total amount of cutting buffer is needed, giving room for larger uninterrupted lengths of OPV strips. However, a lower pattern segment count does not always result in larger overall coverage due to the correlation between OPV strips length and geodesic curvature. Therefore, an optimisation study has to be performed in order to find the highest coverage based on this parameter.

2. How can the coverage of a textile with OPV strips be modelled computationally?

The interaction between OPV strips and textile can be modelled by applying a combination of software packages. Within the scope of this thesis, the form finding software by the name of Easy was used to do the initial form finding, the structural analysis and the cutting pattern generation. The next step involved the re-erection of this pattern into space. This three dimensional result is then imported in Grasshopper, where the OPV sleeves are placed on the textile in accordance with the behaviour of

the weft lines in the model. These sleeve lines are then evaluated for their rate of geodesic curvature and subsequently subjected to a unity check with a predetermined maximum curvature requirement. The compliant sleeves are then displayed, and numerical data is gathered on the design parameters as listed above.

3. *Where does functional integration fit in the general design workflow for textile?*

From the state of the art, the conventional design steps for textile architecture have been derived. They comprise the form finding, structural analysis, cutting pattern generation and construction engineering. In order to apply a hybrid textile to a membrane shape however, additional steps are required to check the additional curvature boundaries. The process for this was described in this thesis. It is an iterative process which consists of form finding and cutting pattern generation steps which happen in parallel to the conventional design. Therefore, the additional requirements should be tested twice after the cutting pattern generation. Once after an initial design draft in order to establish the maximum possible coverage, and once after the final design and cutting pattern have been generated in order to determine the exact measurements of the textile components that will make up the hybrid textile.

To what extent can an uncoated woven hybrid textile, using non-adhesively integrated solar cells, be applied in doubly curved tensile structures?

Taking into account the aforementioned, it is possible to determine the coverage of doubly curved membranes with OPV strips. This requires extra steps that should be taken in accordance with the conventional design work flow. Taking into account the length of the OPV strips, the distance between strips and the cutting buffer on the ends of the strips, a proportional coverage of 23% is possible on a standard hyperbolic parabola with a total surface area of 4,5m² or an active area of 2,4m². With regards to the barrel vault, 30% proportional coverage can be reached, with a total surface area of 8,8m², or an active area of 4,6m². Compared to the target proportional coverage of 50%, which stems from the OPV layout on a flat piece of fabric, around half of the full potential of the textile can be reached for solar energy harvesting.

7.2. Recommendations

This section includes the recommendations that are made with regards to future research steps, as well as recommendations for the use of the analysis tool and the results by industry. The recommendations will be structured accordingly.

7.2.1. Recommendations for future research

With regards to future research based on the work as presented in this thesis, the following concrete recommendations are made:

1. *Increase the shape variety*

Within the scope of this thesis, a shape database of very limited proportions was used. As explained earlier, any anticlastic shape can be brought back to a combination or variation of four basic anticlastic shapes. Only two of those were investigated, with only one variant per shape type. Therefore, in order to increase the validity of the results of this thesis, the analyses should be performed on a larger, more diverse dataset of curved shapes.

2. *Increase the parameter variation*

In this thesis, various parameters were kept constant during the analysis, while they might provide insights into the coverage potential of OPV strips on curved surfaces. The two most important ones are the amount of cutting buffer, as well as the shape curvature. Since the curvature is the main criterion which is tested in the analysis tool, it is important to find out where the design boundary lies with regards to this parameter. On top of that, the cutting buffer is the same on all cutting pattern segments, but its influence might change when its size changes. Therefore, investigating these two parameters can provide important insight into the design scope of SUNTEX.

3. *Provide physical validation*

When applying digital fabrication tools in order to come up with designs, it is important to know how these tools act in reality. For this thesis, the results of the Easy software were taken at face value due to its proven efficacy in industry. However, the Grasshopper implementations are case specific, and therefore will greatly benefit from physical modelling in order to validate the results. Apart from that, a more detailed look into the digital re-erection of cutting patterns into space in relation to the physical result can provide more insight into how accurate the digital models are, especially in cases where functional integration is applied, as in this thesis.

4. *Improve the current analysis tool*

The current analysis tool is effective in obtaining coverage results. However, it relies on Easy models for curvature accuracy, but those models are heavy and require longer running times. The manual overrides for placing curves on the Kangaroo2 surfaces provided temporary answers, but they are ambiguous and a more robust solution still needs to be found. If the size of the Easy models can be reduced as well, this will drastically improve analysis runtime and is therefore an interesting and even necessary area to research further. Additionally, connecting design parameters during the analysis, specifically the cutting pattern segment size and the OPV strip length, could provide an increase in efficiency, as they remove independent variables from the optimisation tool. Lastly, an accurate Kangaroo2 representation of the Easy shapes will need to be developed in order to accurately explore the cutting pattern segment distribution. Alternative parametric tools to better facilitate the iterative analysis should be considered.

7.2.2. Recommendations for industry

With the conclusions in place as discussed in section 7.1, and the questions regarding future research still open as described in subsection 7.2.1, the following recommendations are listed for industry in order to use the methods and tools as set out in this research:

- *Regarding the analysis tool:*

As discussed earlier in section 7.1, it is advised to apply the analysis twice. Once as a preliminary study to determine the feasibility of applying SUNTEX on a shape, and once after the design is finalised to determine how much solar energy can be harvested, as well as how to position the OPV strips precisely. This will provide valuable input for the production process in the later stage.

- *Regarding the production process:*

It is difficult to standardise cutting patterns, as they depend on the shape of the design. Therefore, in order to determine the size of the produced panes of textile, it is advised to use the tool to extract the widest part of the cutting pattern segments, add the seam and cable buffers and use that width as the width of SUNTEX to be produced. The OPV strip length can be determined by finding the narrowest part of the segment and subtracting the cuffing buffer from it. The strips can be unitized per segment, which eases the production process. Apart from this, unitization of cutting pattern segment shapes can provide further improvements on the efficiency of the production process.

- *Regarding more complex shapes:*

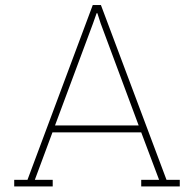
When it comes to designs which are bigger or curved in a more complex manner, this current analysis tool and its results will need to be used and interpreted slightly differently. Due to the current computation times, it is advised that critically curved areas are identified, and consequently isolated and modelled independently. These can then be analysed and evaluated in order to check the coverage of OPV on the curved shape. If the critical zones can be covered with SUNTEX to a satisfactory degree, then the cutting patterns can be produced and the final layout of SUNTEX on the shape can be determined.

References

- [1] Iea - International Energy Agency. *Renewables 2022*. Tech. rep. 2022. URL: www.iea.org.
- [2] Matthew Adams et al. *Disclaimers Suggested citation Production Penrose CDB*. 2021. ISBN: 978-92-807-3984-8. URL: www.globalabc.org.
- [3] Sean Ahlquist et al. "Physical and numerical prototyping for integrated bending and form-active textile hybrid structures". In: *Rethinking Prototyping: Proceeding of the Design Modelling Symposium, Berlin*. 2013, pp. 1–14.
- [4] Ahmed Bakrasedik Mohamed Ahmed. "Structural Solar Textile: Design & Analysis of Woven Solar Cell-Integrated Textile For Textile Architecture Application". PhD thesis. Delft University of Technology, 2022.
- [5] Asim Tahir. *Dragonscale: a beautiful approach to solar*. Oct. 2021. URL: <https://blog.google/outreach-initiatives/sustainability/dragonscale-solar/>.
- [6] Paolo Beccarelli. *Biaxial Testing for Fabrics and Foils - Optimizing Devices and Procedures*. Tech. rep. 2015, pp. 25–28. URL: <http://www.polimi.it>.
- [7] Stephane Berny et al. "Solar Trees: First Large-Scale Demonstration of Fully Solution Coated, Semitransparent, Flexible Organic Photovoltaic Modules". In: *Advanced Science* 3.5 (May 2016), p. 1500342. ISSN: 2198-3844. DOI: 10.1002/ADVS.201500342. URL: <https://onlinelibrary.wiley.com/doi/full/10.1002/advs.201500342> <https://onlinelibrary.wiley.com/doi/abs/10.1002/advs.201500342> <https://onlinelibrary.wiley.com/doi/10.1002/advs.201500342>.
- [8] H. Bögner-Balz, R. Blum, and J. Köhnlein. "Structural behaviour of fabrics and coatings for architectural fabric structures". In: *Fabric Structures in Architecture* (Jan. 2015), pp. 123–157. DOI: 10.1016/B978-1-78242-233-4.00004-8.
- [9] B. Bridgens and M. Birchall. "Form and function: The significance of material properties in the design of tensile fabric structures". In: *Engineering Structures* 44 (Nov. 2012), pp. 1–12. ISSN: 0141-0296. DOI: 10.1016/J.ENGSTRUCT.2012.05.044.
- [10] *BUSSTATION LEIDSCHER RIJN - Tentech*. URL: <https://tentech.nl/textiele-architectuur/busstation-leidsche-rijn/>.
- [11] *COP28 Agreement Signals "Beginning of the End" of the Fossil Fuel Era | UNFCCC*. URL: <https://unfccc.int/news/cop28-agreement-signals-beginning-of-the-end-of-the-fossil-fuel-era>.
- [12] Pauline van Dongen et al. "Suntex: weaving solar energy into building skin". In: *Journal of Facade Design and Engineering* 10.2 (Dec. 2022), pp. 141–160. ISSN: 2213-3038. DOI: 10.47982/JFDE.2022.POWERSKIN.9. URL: <https://jfade.eu/index.php/jfade/article/view/244>.
- [13] Amy C. Edmondson. *A Fuller Explanation: The Synergetic Geometry of R. Buckminster Fuller*. URL: https://books.google.nl/books?hl=en&lr=&id=03fSBwAAQBAJ&oi=fnd&pg=PP12&dq=buckminster+fuller&ots=WZVEJ5e-it&sig=FaMJ_2cI5Qj8DLqrawme1ZVvONE&redir_esc=y#v=onepage&q=buckminster%20fuller&f=false.
- [14] Eneco. *Electricity from largest Dutch solar park to power local Google data centre*. July 2017. URL: <https://news.eneco.com/electricity-from-largest-dutch-solar-park-to-power-local-google-data-centre/>.
- [15] Energypedia. *Building Integrated Photovoltaics (BIPV)*. URL: https://energypedia.info/wiki/Building_Integrated_Photovoltaics_%28BIPV%29.
- [16] Environmental Protection Agency. *Greenhouse Gases Equivalencies Calculator - Calculations and References | US EPA*. URL: <https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references>.

- [17] *FTL Design Engineering Studio | Tensile Architecture, Lightweight Structures*. URL: <https://ftlstudio.com/#>.
- [18] FutureArc. *Google Bay View: A new step in reaching the mega-company's carbon goals*. May 2022. URL: <https://www.futurarc.com/project/google-bay-view-a-new-step-in-reaching-the-mega-companys-carbon-goals/>.
- [19] *Home - Pauline van Dongen*. URL: <https://www.paulinevandongen.nl/>.
- [20] Harm Jeeninga. *Solar panel yield rises*. Nov. 2023. URL: <https://www.tno.nl/en/sustainable/renewable-electricity/solar-modules-mass-customization/solar-panel-yield-rises/>.
- [21] KNMI. "Tijden van zonopkomst en -ondergang 2024". In: ().
- [22] Qingxiang Li and Alessandra Zanelli. "A review on fabrication and applications of textile envelope integrated flexible photovoltaic systems". In: *Renewable and Sustainable Energy Reviews* 139 (2021), p. 110678.
- [23] J. Cleland McVeigh. "Alternative energy sources". In: *Mechanical Engineer's Reference Book* (Jan. 1994), pp. 12–1. DOI: 10.1016/B978-0-7506-1195-4.50016-6. URL: <https://linkinghub.elsevier.com/retrieve/pii/B9780750611954500166>.
- [24] Forrest Meggers et al. "Co-optimization of Solar Tracking for Shading and Photovoltaic Energy Conversion". In: Aug. 2017. DOI: 10.26868/25222708.2017.605.
- [25] Marijke Mollaert and Brian Forster. *European Design Guide for Tensile Surface Structures*. English. TensiNet, 2004. ISBN: 90-808687-1-X.
- [26] J Monjo-Carrió and J Tejera. "12 - The use of textile materials for architectural membranes". In: *Fibrous and Composite Materials for Civil Engineering Applications*. Ed. by R Figueiro. Woodhead Publishing Series in Textiles. Woodhead Publishing, 2011, pp. 325–387. ISBN: 978-1-84569-558-3. DOI: <https://doi.org/10.1533/9780857095583.3.325>. URL: <https://www.sciencedirect.com/science/article/pii/B9781845695583500120>.
- [27] Konrad Polthier and Markus Schmies. "Straightest Geodesics on Polyhedral Surfaces". In: *Mathematical Visualization: Algorithms, Applications and Numerics*. Ed. by Hans-Christian Hege and Konrad Polthier. Berlin, Heidelberg: Springer Berlin Heidelberg, 1998, pp. 135–150. ISBN: 978-3-662-03567-2. DOI: 10.1007/978-3-662-03567-2_{_}11. URL: https://doi.org/10.1007/978-3-662-03567-2_11.
- [28] Helmut Pottmann et al. "Geodesic patterns". In: (July 2010), pp. 1–10. DOI: 10.1145/1833349.1778780.
- [29] Stephanie Ramos. "Shear characterisation of a novel woven solar cell integrated textile for tensile structures application". PhD thesis. Delft University of Technology, 2023.
- [30] Amit Rawal, Abhijit Majumdar, and Vijay Kumar. "Textile architecture for composite materials: back to basics". In: *Oxford Open Materials Science* 3.1 (Jan. 2023). ISSN: 26336979. DOI: 10.1093/oxfmat/ITAD017. URL: <https://dx.doi.org/10.1093/oxfmat/itad017>.
- [31] Elizabeta Šamec, Petra Gidak, and Krešimir Fresl. "Iterated Ritz and conjugate gradient methods as solvers in constrained form-finding: A comparison". In: *Heliyon* 7.5 (May 2021). ISSN: 24058440. DOI: 10.1016/J.HELIYON.2021.E07011.
- [32] H. J. Schek. "The force density method for form finding and computation of general networks". In: *Computer Methods in Applied Mechanics and Engineering* 3.1 (Jan. 1974), pp. 115–134. ISSN: 0045-7825. DOI: 10.1016/0045-7825(74)90045-0.
- [33] Cornelia Sennewald, Gerald Hoffmann, and Roland Kleicke. "Woven Semi-finished Products and Weaving Techniques". In: *Textile Materials for Lightweight Constructions: Technologies-Methods-Materials-Properties*. Springer, 2016, pp. 159–211.
- [34] N. Stranghöner et al. "Prospect for European Guidance for the Structural design of Tensile Membrane Structures Support to the implementation, harmonisation and further development of the Eurocodes". In: 2023. ISBN: 9789268000533. DOI: 10.2760/335999. URL: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0102>.

- [35] technet GmbH. *Easy 2022 Program Description*. English.
- [36] Unfccc. *ADOPTION OF THE PARIS AGREEMENT - Paris Agreement text English*. Tech. rep. 2015.
- [37] Vitro Architectural Glass. *Vitro Architectural Glass launches Solarvolt™ building-integrated photovoltaic (BIPV) glass modules*. URL: <https://www.vitroglazings.com/about/news/vitro-architectural-glass-launches-solarvolt-building-integrated-photovoltaic-bipv-glass-modules/>.
- [38] Johannes Wallner et al. "Tiling freeform shapes with straight panels: Algorithmic methods." In: *Advances in architectural geometry 2010*. Springer, 2010, pp. 73–86.
- [39] Qingxuan Wei and Dianyun Zhang. *A Textile Architecture-Based Discrete Modeling Approach for Fabric Draping Simulations*. Tech. rep.
- [40] Dacheng Xu et al. "Flexible photovoltaic power systems: integration opportunities, challenges and advances". In: *Flexible and Printed Electronics* 2.1 (Mar. 2017), p. 013001. ISSN: 2058-8585. DOI: 10.1088/2058-8585/AA5750. URL: <https://iopscience.iop.org/article/10.1088/2058-8585/aa5750%20https://iopscience.iop.org/article/10.1088/2058-8585/aa5750/meta>.
- [41] Sun Zexin and Hongyuan Mei. "Robotic Form-Finding and Construction Based on the Architectural Projection Logic". In: *IOP Conference Series: Materials Science and Engineering* 216.1 (July 2017). ISSN: 1757899X. DOI: 10.1088/1757-899X/216/1/012058.



Physical shaping trials

A.1. Physical modelling

The experimental program within this thesis consists of the physical modelling of textile to gain a better understanding of how it behaves. As explained in chapter 2, there are various different ways to achieve a scaled physical model, like soap films, hanging models or built models. The aim for all of these is similar, being the better understanding of how the geometry should be formed, and how the used material contributes to achieving a certain form. Physical modelling is therefore very suitable for examining specific cases [3]. This is also its biggest downfall, being that there is no universal physical model to describe any case.

With this in mind, the goal of the experimental program regarding SUNTEX is two fold:

1. Gain a better understanding of textile behaviour in geometries
2. Investigate the behaviour of developable surfaces when placed on prestressed textile

This section will explain the process to achieve these goals, and draw conclusions that will inform the computational program later on. Firstly, the test setup will be elaborated on. Then, the physical trials will be discussed.

A.1.1. Test setup

The test frame is a timber frame with a design space of 1m^3 . Two squares are formed out of beams and connected with four more beams. Lateral stability is ensured by spanning a rope cross in between the squares. This cross is also part of the tensioning system in the frame. The fabric samples are connected to the frame using clasps, which are connected to the frame using rings and rope. The main benefit of this modular system is the demountability, making it relatively easy to transport the frame. The drawbacks include the fragile stability of the structure, as well as the lack of uniform tension distribution.

A.1.2. Iterations

Three trials were performed. The first trial was an initial study into the design steps that need to be taken in order to produce a sample that could be tensioned. An initial design of a conic anticlastic shape was made using Easy (see image). This shape was translated into cutting patterns of varying size, dividing the total shape into 4 or 8 pieces for trials 1.1 and 1.2 respectively.

Trial 1 made use of a calibration fabric that was readily available. The properties of this fabric do not align with those of SUNTEX at all, and therefore this trial was mainly performed to get a better understanding of the design steps from geometry to physical sample.

The second trial used cotton fabric, which behaves more like SUNTEX. It is uncoated, and the squares on the fabric provided clear visual cues during the tensioning phase. The first part of this trial was a reference to trial one, to determine how the fabrics differ when used in the same geometry. The second part of the trial comprised the same shape, but different cutting patterns. This was done to understand their influence on the curving behaviour of the fabric. It also provided nice insights into the formation of 'redundant' areas in the patterns, where SUNTEX would not fit.

A.1.3. Preliminary conclusions

From the trials, a number of conclusions was drawn ahead of the computational phase:

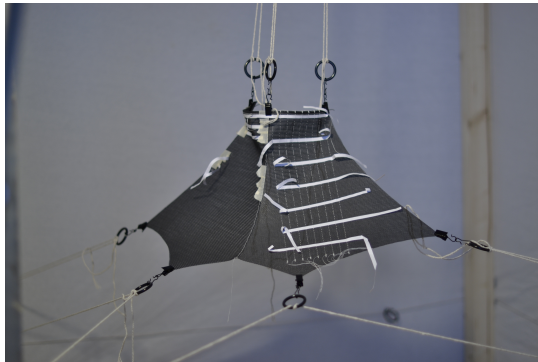
1. The tensioning system does not suffice for keeping homogeneous tension in the fabric
2. Cable forces in the edges of the fabric need to be investigated
3. Body cable forces need to be adjustable, the clasps need to be used differently in order to prevent flattening of the fabric
4. The behaviour of developable surfaces when placed on prestressed textile needs to be investigated

A.2. Physical testing results

Below, the results of the physical experimentation trials are displayed. They are split between the trials as described in section A.1, and will be discussed accordingly. These results are qualitative in nature, and will be discussed and evaluated in further detail in chapter 6.

A.2.1. Trial 1

The results of trial 1 comprise the shapes executed in the PVC coated nylon. Trial 1.1 resulted in a semicircular shape with 2 cutting pattern segments, whereas in trial 1.2, a fully circular shape was constructed. Overviews of the shapes can be seen in figure A.1.



(a) Trial 1.1 shape



(b) Trial 1.2 shape

Figure A.1: Trial 1 shape results

A further detailed view of the trial 1 can be seen in figure A.2, which it shows the behaviour of the textile within the tensioning system up close.



(a) Trial 1.1 shape detail

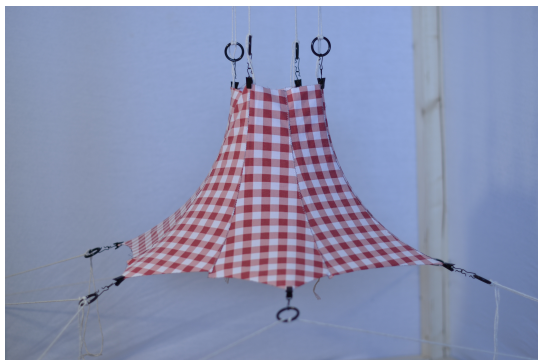


(b) Trial 1.2 shape detail

Figure A.2: Trial 1 shape results

A.2.2. Trial 2

In trial 2, the fabric type was changed to a non-coated cotton fabric, in order to vary the cutting pattern segment size more. Trial 2.1 was constructed as a tool for comparison with trial 1.2, and trial 2.2 was constructed in order to investigate the segment size further. Their results are displayed in figure A.3.



(a) Trial 2.1 shape



(b) Trial 2.2 shape

Figure A.3: Trial 2 shape results

The shapes in this trial also show distinct behaviours when looked at in detail. These closeups are given in figure A.4.



(a) Trial 2.1 shape detail



(b) Trial 2.2 shape detail

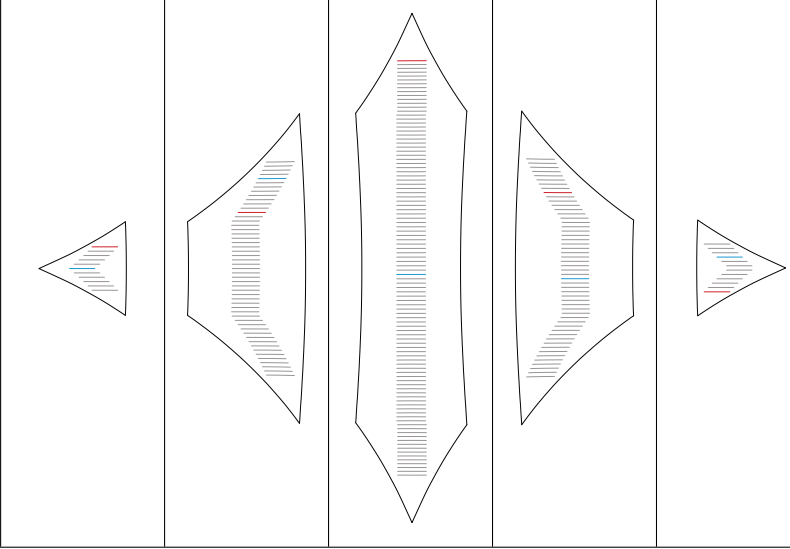
Figure A.4: Trial 2 shape results

B

Additional results

B.1. Hypar data

The first section of this appendix contains all data from the hypar shape. First, the Easy data is shown per shape. Afterwards all the Grasshopper data is shown per shape.



Total OPV coverage [%]	12				
Total surface area [m ²]	19,61				
OPV strip area [m ²]	2,28				
OPV active area [m ²]	1,20				
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5
OPV coverage [%]	13	11	12	11	14
Segment area [m ²]	0,83	4,61	8,64	4,68	0,86
OPV strip area [m ²]	0,11	0,51	1,02	0,52	0,12
OPV active area [m ²]	0,06	0,27	0,54	0,27	0,06
OPV strip length [m]	0,4	0,4	0,4	0,4	0,4
R _{min} [m]	4,00	4,00	4,00	4,00	4,00
R _{crv,min} [m]	48,28	76,65	13,57	75,16	54,75
R _{crv,max} [m]	4202,20	19937,18	2252,19	22809,4	3944,30
Smallest width [m]	0	1,72	1,37	1,72	0
Largest width [m]	1,38	1,72	1,55	1,72	1,40

Table B.1: Overview of the Easy hypar with one uniform length of OPV strip for the entire shape, showing the shortest possible OPV strip length.

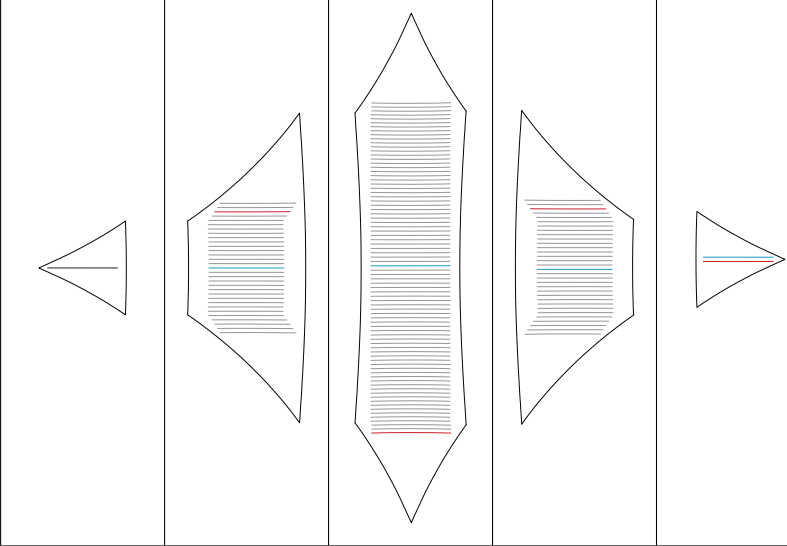
					
Total OPV coverage [%]	21				
Total surface area [m ²]	19,61				
OPV strip area [m ²]	4,02				
OPV active area [m ²]	2,12				
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5
OPV coverage [%]	3	18	25	19	6
Segment area [m ²]	0,83	4,61	8,64	4,68	0,86
OPV strip area [m ²]	0,03	0,85	2,20	0,88	0,06
OPV active area [m ²]	0,02	0,45	1,16	0,46	0,03
OPV strip length [m]	1,1	1,1	1,1	1,1	1,1
$R_{\min}$ [m]	30,25	30,25	30,25	30,25	30,25
$R_{\text{crv},\min}$ [m]	4467,35	70,51	39,21	69,91	806,5
$R_{\text{crv},\max}$ [m]	4467,35	10926,12	1989,86	22399,37	2221,97
Smallest width [m]	0	1,72	1,37	1,72	0
Largest width [m]	1,38	1,72	1,55	1,72	1,40

Table B.2: Overview of the Easy hypar with one uniform length of OPV strip for the entire shape, showing the best possible OPV strip length.

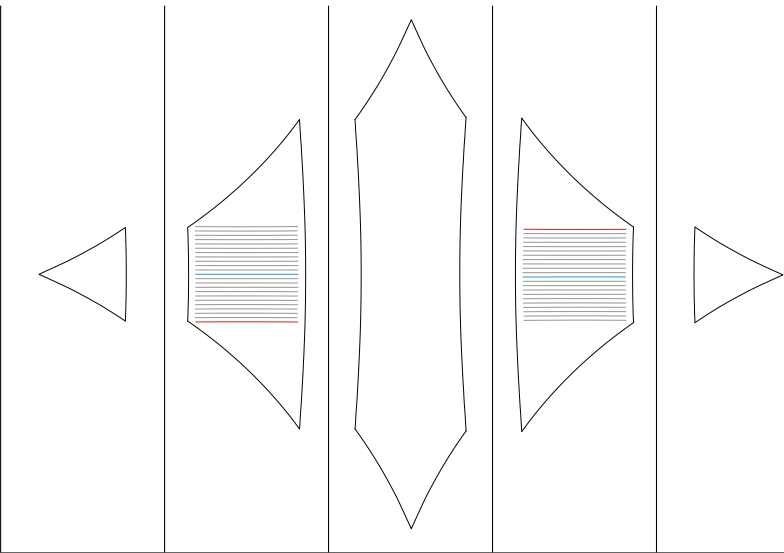
					
Total OPV coverage [%]	9				
Total surface area [m ²]	19,61				
OPV strip area [m ²]	1,69				
OPV active area [m ²]	0,89				
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5
OPV coverage [%]	0	19	0	19	0
Segment area [m ²]	0,83	4,61	8,64	4,68	0,86
OPV strip area [m ²]	0	0,86	0	0,83	0
OPV active area [m ²]	0	0,45	0	0,44	0
OPV strip length [m]	-	1,5	-	1,5	-
$R_{\min}$ [m]	-	56,25	-	56,25	-
$R_{\text{crv},\min}$ [m]	-	93,43	-	94,65	-
$R_{\text{crv},\max}$ [m]	-	10427,73	-	21163,47	-
Smallest width [m]	0	1,72	1,37	1,72	0
Largest width [m]	1,38	1,72	1,55	1,72	1,40

Table B.3: Overview of the Easy hypar with one uniform length of OPV strip for the entire shape, showing the longest possible OPV strip length.

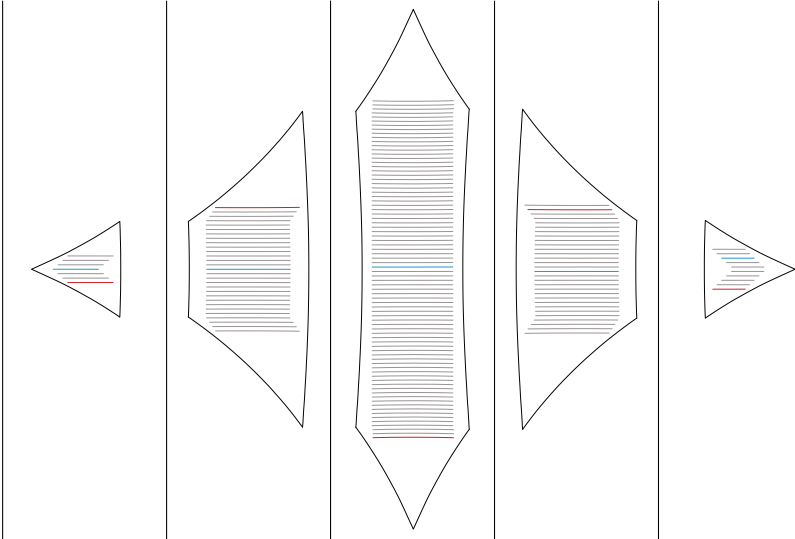
					
Total OPV coverage [%]	22				
Total surface area [m ²]	19,61				
OPV strip area [m ²]	4,20				
OPV active area [m ²]	2,22				
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5
OPV coverage [%]	15	19	25	19	15
Segment area [m ²]	0,83	4,61	8,64	4,68	0,86
OPV strip area [m ²]	0,12	0,88	2,20	0,90	0,13
OPV active area [m ²]	0,06	0,46	1,16	0,48	0,07
OPV strip length [m]	0,7	1,3	1,1	1,2	0,5
$R_{\min}$ [m]	12,25	42,25	30,25	36,00	6,25
$R_{\text{crv},\min}$ [m]	395,30	68,34	39,21	68,47	97,42
$R_{\text{crv},\max}$ [m]	4940,15	10691,79	1989,86	22027,94	3776,98
Smallest width [m]	0	1,72	1,37	1,72	0
Largest width [m]	1,38	1,72	1,55	1,72	1,40

Table B.4: Overview of the Easy hypar, showing the best case for a separate OPV strip length per pattern segment.

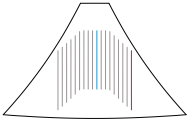
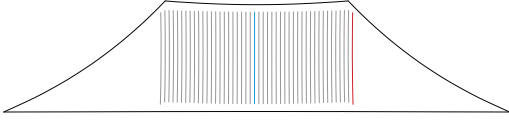
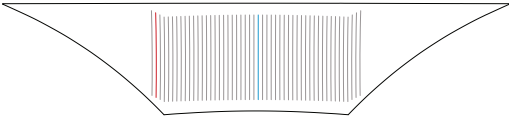
						
Total OPV coverage [%]	19					
Total surface area [m ²]	19,60					
OPV strip area [m ²]	3,81					
OPV active area [m ²]	2,01					
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	Segment 6
OPV coverage [%]	0	17	21	21	17	0
Segment area [m ²]	0,10	2,45	7,31	7,21	2,43	0,10
OPV strip area [m ²]	0	0,88	2,20	0,90	0,13	0
OPV active area [m ²]	0	0,46	1,16	0,48	0,069	0
OPV strip length [m]	-	0,9	1,2	1,3	0,9	-
R _{min} [m]	-	20,25	36,00	42,25	20,25	-
R _{crv,min} [m]	-	86,62	60,64	65,85	87,89	-
R _{crv,max} [m]	-	2577,13	3617,02	5543,27	2550,35	-
Smallest width [m]	0	1,77	1,53	1,52	1,77	0
Largest width [m]	0,50	1,77	1,58	1,57	1,77	0,49

Table B.5: Overview of the Easy hypar, showing a layout with a central seam as opposed to a central pattern segment.

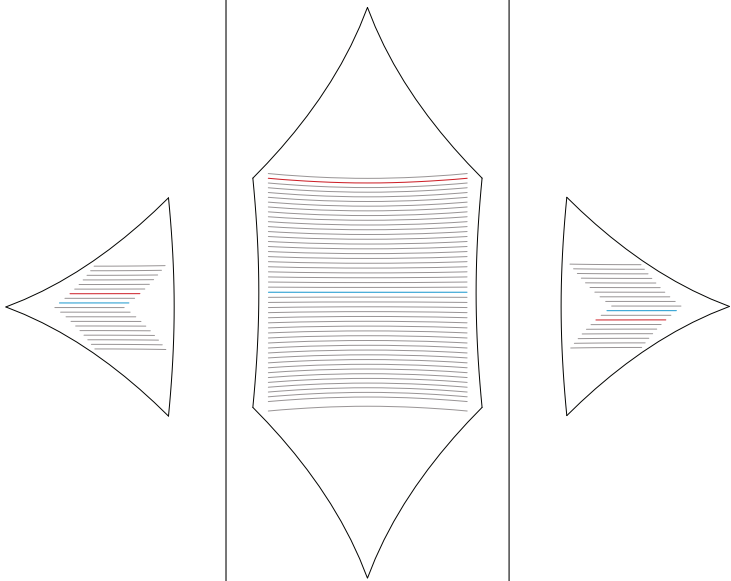
			
Total OPV coverage [%]	20		
Total surface area [m ²]	19,54		
OPV strip area [m ²]	3,95		
OPV active area [m ²]	2,09		
	Segment 1	Segment 2	Segment 3
OPV coverage [%]	16	22	16
Segment area [m ²]	2,94	13,66	2,94
OPV strip area [m ²]	0,48	3,00	0,48
OPV active area [m ²]	0,25	1,58	0,25
OPV strip length [m]	1,0	2,5	1,0
R _{min} [m]	25,00	156,25	25,00
R _{crv,min} [m]	158,55	189,37	158,58
R _{crv,max} [m]	2553,70	25028,91	2417,46
Smallest width [m]	0	2,74	0
Largest width [m]	2,42	2,89	2,42

Table B.6: Overview of the Kangaroo2 hypar, showing the best case for a 3-segment surface layout.

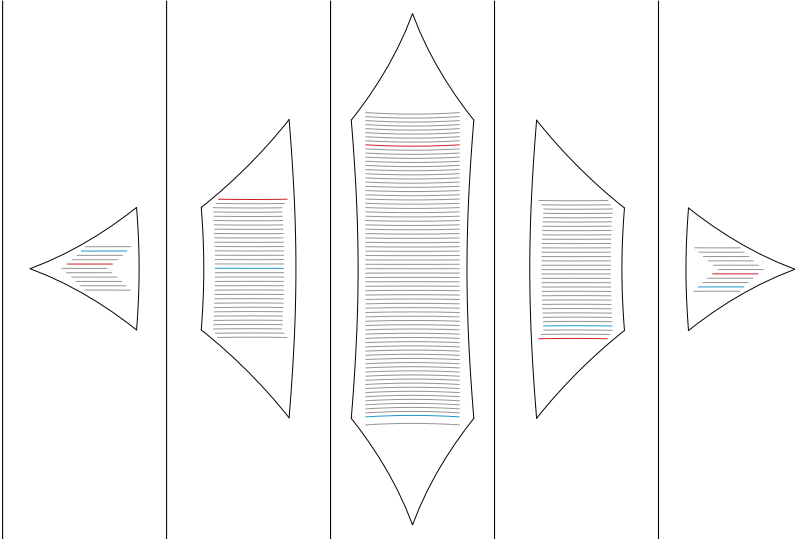
					
Total OPV coverage [%]	23				
Total surface area [m ²]	19,54				
OPV strip area [m ²]	4,45				
OPV active area [m ²]	2,35				
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5
OPV coverage [%]	15	21	26	21	15
Segment area [m ²]	1,27	3,89	9,22	3,89	1,27
OPV strip area [m ²]	0,20	0,83	2,41	0,83	0,20
OPV active area [m ²]	0,11	0,44	1,27	0,44	0,11
OPV strip length [m]	0,6	1,0	1,3	1,0	0,6
$R_{\min}$ [m]	9,00	25,00	42,25	25,00	9,00
$R_{\text{crv},\min}$ [m]	85,72	259,63	104,10	260,04	85,80
$R_{\text{crv},\max}$ [m]	43351,05	5608,15	1253400	6023,77	31204,70
Smallest width [m]	0	1,34	1,51	1,34	0
Largest width [m]	1,69	1,36	1,71	1,36	1,69

Table B.7: Overview of the Kangaroo2 hypar, showing the best case for a 5-segment surface layout.

Total surface area [m ²]	19,54						
Total OPV coverage [%]	23						
OPV strip area [m ²]	4,44						
OPV active area [m ²]	2,34						
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	Segment 6	Segment 7
OPV coverage [%]	14	20	23	26	23	20	14
Segment area [m ²]	0,70	2,24	3,40	6,87	3,40	2,24	0,70
OPV strip area [m ²]	0,10	0,45	0,78	1,78	0,78	0,45	0,10
OPV active area [m ²]	0,05	0,24	0,41	0,94	0,41	0,24	0,05
OPV strip length [m]	0,5	0,9	0,6	0,8	0,6	0,9	0,5
$R_{\min}$ [m]	6,25	20,25	9,00	16,00	9,00	20,25	6,25
$R_{\text{grv,min}}$ [m]	88,91	174,01	41,48	39,47	41,54	171,97	88,93
$R_{\text{grv,max}}$ [m]	324760,92	11180,39	16769,24	646896,1	16516,69	11150,79	334758,81
Smallest width [m]	0	1,12	0,85	1,04	0,85	1,12	0
Largest width [m]	1,29	1,12	0,90	1,12	1,29	1,12	0

Table B.8: Overview of the Kangaroo2 hypar, showing the best case for a 7-segment surface layout.

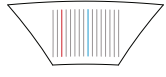
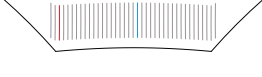
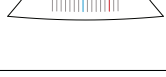
									
Total surface area [m ²]	19,54								
Total OPV coverage [%]	21								
OPV strip area [m ²]	4,14								
OPV active area [m ²]	2,19								
OPV coverage [%]	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	Segment 6	Segment 6	Segment 6	Segment 6
Segment area [m ²]	14	20	21	22	23	22	21	20	14
OPV strip area [m ²]	0,44	1,42	2,34	2,86	5,43	2,86	2,34	1,42	0,44
OPV active area [m ²]	0,06	0,28	0,49	0,63	1,23	0,63	0,49	0,28	0,06
OPV strip length [m]	0,03	0,15	0,26	0,33	0,65	0,33	0,26	0,15	0,03
OPV strip length [m]	0,4	0,7	0,5	0,4	0,5	0,4	0,5	0,7	0,4
R _{min} [m]	4,00	12,25	6,25	4,00	6,25	4,00	6,25	12,25	4,00
R _{conv,min} [m]	155,63	121,63	139,07	49,71	30,65	50,20	135,70	131,83	155,56
R _{conv,max} [m]	3877,02	1218,24	25649,76	1332700	16550,09	4492600	24651,71	1197,77	3865,57
Smallest width [m]	0	0,95	0,80	0,60	0,79	0,60	0,80	0,95	0
Largest width [m]	1,05	0,95	0,82	0,66	0,90	0,66	0,82	0,95	1,05

Table B.9: Overview of the Kangaroo2 hypar, showing the best case for a 9-segment surface layout.

B.2. Barrel vault data

The second section of this appendix contains all data from the barrel vault shape. First, the Easy data is shown per shape. Afterwards all the Grasshopper data is shown per shape.

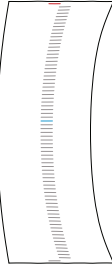
					
Total OPV coverage [%]	7				
Total surface area [m ²]	27,55				
OPV strip area [m ²]	1,79				
OPV active area [m ²]	0,95				
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5
OPV coverage [%]	10	5	6	5	10
Segment area [m ²]	3,40	7,38	5,98	7,38	3,40
OPV strip area [m ²]	0,35	0,37	0,37	0,37	0,35
OPV active area [m ²]	0,18	0,20	0,20	0,20	0,18
OPV strip length [m]	0,2	0,2	0,2	0,2	0,2
R _{min} [m]	1,00	1,00	1,00	1,00	1,00
R _{crv,min} [m]	47,25	25,08	32,24	25,29	47,26
R _{crv,max} [m]	21513,88	27449,43	124904,97	14380,24	23711,36
Smallest width [m]	0,54	1,62	1,26	1,62	0,54
Largest width [m]	1,47	1,95	1,62	1,95	1,47

Table B.10: Overview of the Easy barrel vault with one uniform length of OPV strip for the entire shape, showing the shortest possible OPV strip length.

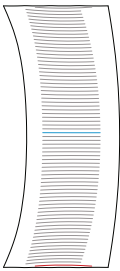
					
Total OPV coverage [%]	21				
Total surface area [m ²]	27,55				
OPV strip area [m ²]	5,88				
OPV active area [m ²]	3,10				
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5
OPV coverage [%]	6	25	31	25	6
Segment area [m ²]	3,40	7,38	5,98	7,38	3,40
OPV strip area [m ²]	0,20	1,83	1,83	1,83	0,20
OPV active area [m ²]	0,11	0,97	0,97	0,97	0,11
OPV strip length [m]	1,0	1,0	1,0	1,0	1,0
R_{min} [m]	25,00	25,00	25,00	25,00	25,00
$R_{crv,min}$ [m]	163,96	26,90	32,17	27,13	164,02
$R_{crv,max}$ [m]	1975,85	28104,69	122601,69	14756,34	1642,52
Smallest width [m]	0,54	1,62	1,26	1,62	0,54
Largest width [m]	1,47	1,95	1,62	1,95	1,47

Table B.11: Overview of the Easy barrel vault with one uniform length of OPV strip for the entire shape, showing the best possible OPV strip length.

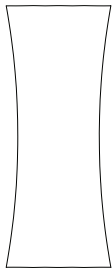
					
Total OPV coverage [%]	15				
Total surface area [m ²]	27,55				
OPV strip area [m ²]	4,20				
OPV active area [m ²]	2,22				
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5
OPV coverage [%]	0	28	0	28	0
Segment area [m ²]	3,40	7,38	5,98	7,38	3,40
OPV strip area [m ²]	0	2,10	0	2,10	0
OPV active area [m ²]	0	1,11	0	1,11	0
OPV strip length [m]	-	1,4	-	1,4	-
R_{min} [m]	-	49,00	-	49,00	-
$R_{crv,min}$ [m]	-	50,15	-	49,14	-
$R_{crv,max}$ [m]	-	28455,44	-	15048,42	-
Smallest width [m]	0,54	1,62	1,26	1,62	0,54
Largest width [m]	1,47	1,95	1,62	1,95	1,47

Table B.12: Overview of the Easy barrel vault with one uniform length of OPV strip for the entire shape, showing the longest possible OPV strip length.

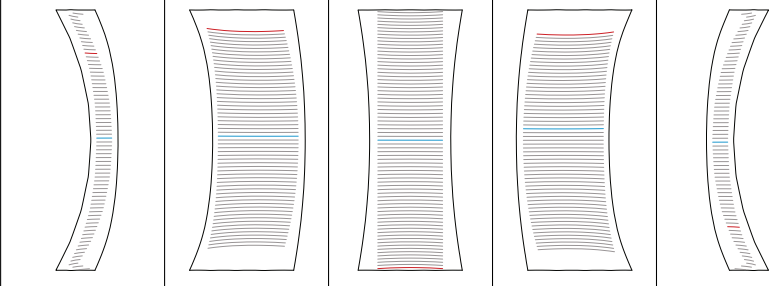
					
Total OPV coverage [%]	26				
Total surface area [m ²]	27,55				
OPV strip area [m ²]	7,06				
OPV active area [m ²]	3,73				
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5
OPV coverage [%]	15	28	31	28	15
Segment area [m ²]	3,40	7,38	5,98	7,38	3,40
OPV strip area [m ²]	0,52	2,10	1,83	2,10	0,52
OPV active area [m ²]	0,27	1,11	0,97	1,11	0,27
OPV strip length [m]	0,3	1,4	1,0	1,4	0,3
R_{min} [m]	2,25	49,00	25,00	49,00	2,25
$R_{crv,min}$ [m]	47,06	50,15	32,17	49,14	47,07
$R_{crv,max}$ [m]	21279,46	28455,44	122601,69	15048,42	23452,85
Smallest width [m]	0,54	1,62	1,26	1,62	0,54
Largest width [m]	1,47	1,95	1,62	1,95	1,47

Table B.13: Overview of the Easy barrel vault, showing the best case for a separate OPV strip length per pattern segment.

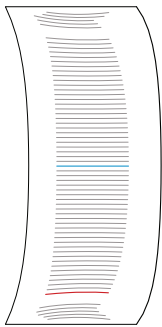
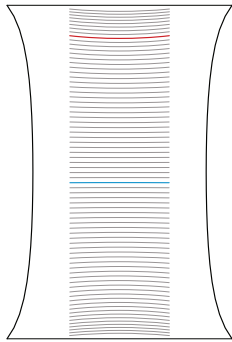
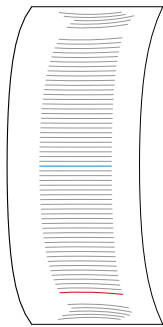
			
Total OPV coverage [%]	20		
Total surface area [m ²]	29,58		
OPV strip area [m ²]	5,77		
OPV active area [m ²]	3,05		
	Segment 1	Segment 2	Segment 3
OPV coverage [%]	19	21	19
Segment area [m ²]	9,52	10,54	9,52
OPV strip area [m ²]	1,79	2,19	1,79
OPV active area [m ²]	0,95	1,16	0,95
OPV strip length [m]	1,1	1,2	1,1
R _{min} [m]	30,25	36,00	30,25
R _{crv,min} [m]	47,35	41,43	47,34
R _{crv,max} [m]	11646,17	8065,24	11727,29
Smallest width [m]	2,02	2,12	2,02
Largest width [m]	2,80	2,80	2,80

Table B.14: Overview of the Kangaroo2 barrel vault, showing the best case for a 3-segment surface layout.

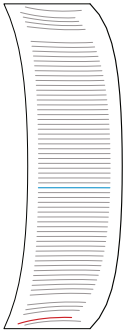
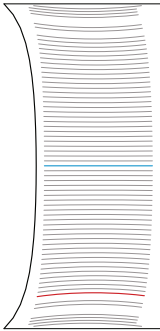
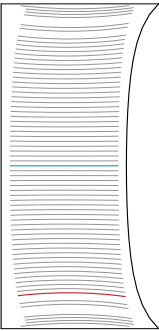
				
Total OPV coverage [%]	28			
Total surface area [m ²]	29,58			
OPV strip area [m ²]	8,16			
OPV active area [m ²]	4,31			
	Segment 1	Segment 2	Segment 3	Segment 4
OPV coverage [%]	25	29	29	25
Segment area [m ²]	6,83	7,96	7,96	6,83
OPV strip area [m ²]	1,73	2,35	2,35	1,73
OPV active area [m ²]	0,91	1,24	1,24	0,91
OPV strip length [m]	1,1	1,4	1,4	1,1
R _{min} [m]	30,25	49,00	49,00	30,25
R _{crv,min} [m]	32,27	51,82	51,81	32,31
R _{crv,max} [m]	2392,70	149148,77	157929,12	2392,71
Smallest width [m]	1,46	1,62	1,62	1,46
Largest width [m]	2,10	2,10	2,10	2,10

Table B.15: Overview of the Kangaroo2 barrel vault, showing the best case for a 4-segment surface layout.

					
Total OPV coverage [%]	30				
Total surface area [m ²]	29,58				
OPV strip area [m ²]	8,80				
OPV active area [m ²]	4,65				
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5
OPV coverage [%]	29	30	30	30	29
Segment area [m ²]	5,20	6,50	6,18	6,50	5,20
OPV strip area [m ²]	1,49	1,98	1,83	1,98	1,51
OPV active area [m ²]	0,79	1,05	0,97	1,05	0,80
OPV strip length [m]	0,9	1,1	1,0	1,1	0,9
$R_{\min}$ [m]	20,25	30,25	25,00	30,25	20,25
$R_{\text{crv},\min}$ [m]	31,52	118,94	53,59	118,95	31,54
$R_{\text{crv},\max}$ [m]	13733,16	104139,78	7942,25	103255,07	13733,71
Smallest width [m]	1,10	1,36	1,23	1,36	1,10
Largest width [m]	1,68	1,68	1,68	1,68	1,68

Table B.16: Overview of the Kangaroo2 barrel vault, showing the best case for a 5-segment surface layout.

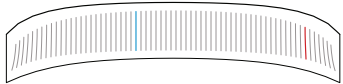
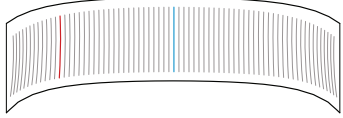
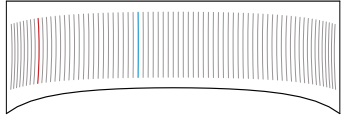
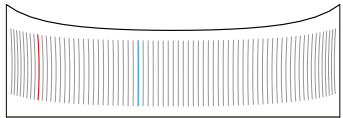
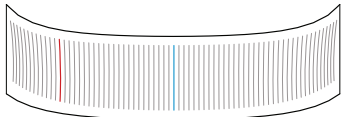
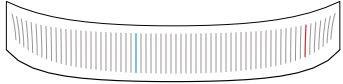
						
Total OPV coverage [%]	27					
Total surface area [m ²]	29,58					
OPV strip area [m ²]	8,01					
OPV active area [m ²]	4,23					
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	Segment 6
OPV coverage [%]	24	30	28	28	30	24
Segment area [m ²]	4,11	5,41	5,27	5,27	5,41	4,11
OPV strip area [m ²]	0,99	1,60	1,46	1,46	1,60	0,99
OPV active area [m ²]	0,52	0,84	0,77	0,77	0,84	0,52
OPV strip length [m]	0,6	0,9	0,8	0,8	0,9	0,6
R_{min} [m]	9,00	20,25	16,00	16,00	20,25	9,00
$R_{cgv,min}$ [m]	28,00	196,30	84,62	84,63	196,35	28,02
$R_{cgv,max}$ [m]	5013,4	13645,19	97802,84	93917,43	13631,93	5009,39
Smallest width [m]	0,86	1,16	1,06	1,06	1,16	0,86
Largest width [m]	1,4	1,4	1,4	1,4	1,4	1,4

Table B.17: Overview of the Kangaroo2 barrel vault, showing the best case for a 6-segment surface layout.

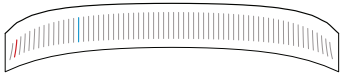
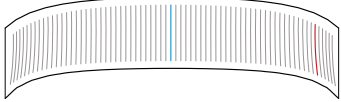
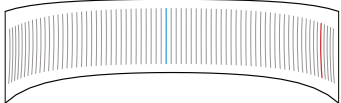
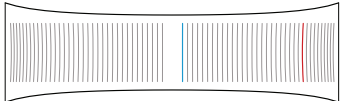
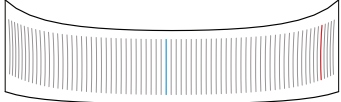
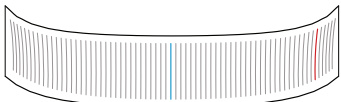
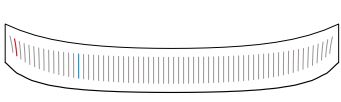
							
Total OPV coverage [%]	27						
Total surface area [m ²]	29,58						
OPV strip area [m ²]	7,90						
OPV active area [m ²]	4,17						
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	Segment 6	Segment 7
OPV coverage [%]	20	30	28	27	28	30	18
Segment area [m ²]	3,33	4,66	4,55	4,50	4,55	4,66	3,33
OPV strip area [m ²]	0,66	1,40	1,28	1,23	1,28	1,40	0,66
OPV active area [m ²]	0,35	0,74	0,68	0,65	0,68	0,74	0,35
OPV strip length [m]	0,4	0,8	0,7	0,7	0,7	0,8	0,4
R _{min} [m]	4,00	16,00	12,25	12,25	12,25	16,00	4,00
R _{grv,min} [m]	30,69	104,65	153,37	110,58	152,96	104,69	30,69
R _{grv,max} [m]	16969,27	25418,46	7609,83	7756,96	7604,55	43275,19	17075,64
Smallest width [m]	0,69	1,02	0,93	0,90	0,93	1,02	0,69
Largest width [m]	1,20	1,20	1,20	1,20	1,20	1,20	1,20

Table B.18: Overview of the Kangaroo2 barrel vault, showing the best case for a 7-segment surface layout.

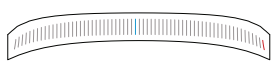
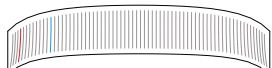
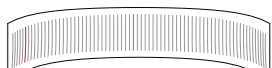
								
Total OPV coverage [%]	25							
Total surface area [m ²]	29,58							
OPV strip area [m ²]	7,41							
OPV active area [m ²]	3,91							
OPV coverage [%]	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	Segment 6	Segment 7	Segment 8
Segment area [m ²]	18	30	27	23	23	27	30	18
OPV strip area [m ²]	2,75	4,09	4,01	3,94	3,94	4,01	4,09	2,75
OPV active area [m ²]	0,49	1,23	1,08	0,91	0,91	1,08	1,23	0,49
OPV strip length [m]	0,26	0,65	0,57	0,48	0,48	0,57	0,65	0,26
OPV strip length [m]	0,3	0,7	0,6	0,5	0,5	0,6	0,7	0,3
R _{min} [m]	2,25	12,25	9,00	6,25	6,25	9,00	12,25	2,25
R _{crv,min} [m]	36,10	205,39	138,94	233,69	233,58	138,84	205,46	36,07
R _{crv,max} [m]	5091,90	7455,45	7106,33	16756,82	17395,01	7179,57	5687,38	5060,53
Smallest width [m]	0,55	0,90	0,83	0,79	0,79	0,83	0,90	0,55
Largest width [m]	1,05	1,05	1,05	1,05	1,05	1,05	1,05	1,05

Table B.19: Overview of the Kangaroo2 barrel vault, showing the best case for a 8-segment surface layout.

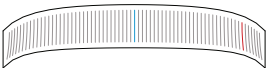
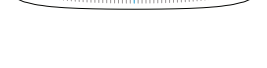
									
	24 29,58 7,17 3,79								
Total OPV coverage [%]	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	Segment 6	Segment 7	Segment 8	Segment 9
Total surface area [m ²]	14	28	25	26	24	26	25	28	14
OPV strip area [m ²]	2,29	3,64	3,59	3,52	3,50	3,52	3,59	3,64	2,29
OPV active area [m ²]	0,33	1,04	0,90	0,91	0,83	0,91	0,90	1,04	0,33
OPV strip length [m]	0,17	0,55	0,48	0,48	0,44	0,48	0,48	0,55	0,17
	0,2	0,6	0,5	0,5	0,5	0,5	0,5	0,6	0,2
R_{min} [m]	1,00	9,00	6,25	6,25	6,25	6,25	6,25	9,00	1,00
$R_{conv,min}$ [m]	74,79	99,56	331,00	215,29	200,82	215,25	331,10	99,46	74,92
$R_{conv,max}$ [m]	19404,10	6775,69	155257,54	793598,98	11415,16	441455,48	12519,30	6778,50	19125,30
Smallest width [m]	0,45	0,82	0,75	0,71	0,70	0,71	0,75	0,82	0,45
Largest width [m]	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,93

Table B.20: Overview of the Kangaroo2 barrel vault, showing the best case for a 9-segment surface layout.