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Design Parameters of Membrane Structures and Their Influence on Costs
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Discussion of design parameters in the design phase and evaluation by means of geometry studies

A Master's Thesis submitted for the degree of
"Master of Engineering"

supervised by
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Vienna, 15 October 2012

Affidavit

I, **MARIO GIRALDO**, hereby declare

1. that I am the sole author of the present Master’s Thesis, "DESIGN PARAMETERS OF MEMBRANE STRUCTURES AND THEIR INFLUENCE ON COSTS - DISCUSSION OF DESIGN PARAMETERS IN THE DESIGN PHASE AND EVALUATION BY MEANS OF GEOMETRY STUDIES", 66 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master’s Thesis as an examination paper in any form in Austria or abroad.

Vienna, 15 October 2012

Signature

To my lovely wife Vicky

for all her support and patience.

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Abstract

Architectural design is mainly driven by the available budget. Therefore it is beneficial for designers to know, how to control the costs with the help of their design. Those basic decisions at the very beginning of a project build the foundations for its (commercial and technical) success.

In this thesis only the design phase is taken into account. At this stage the controllable parameters are merely geometric; the location of the fixation points, the curvature of membrane and edges and the layout of the fixation points.

On basis of a simple four-point sail three independent design studies have been performed. Different design parameters were altered to analyze their effect on the costs. Therefore every sail was run a full predesign, considering the textile material, the primary and secondary steel structure as well as the foundations. The found dimensions were the basis for cost estimations.

The studies showed the costs are directly proportional to the reaction forces which rise exponentially the smaller (e.g.) the curvature gets. Charts of the cost shares of the individual building components illustrated that primary steel, guy cables and foundations respectively anchoring have the biggest potential for cost optimization.

This thesis should point the direction and be the basis for further investigations on this subject. The final target could be a design guide that discusses the structural behavior of different geometries including their correlation with the costs. Only, for a book like this more research work is required. Especially the potential of design parameters in later project phases or other geometries but hyper sails would be of big value.

1 Introduction

1.1 Motivation

Engineering and design are two disciplines which complete one another to equal parts. In engineering, design is one part of the engineering process. Engineering on the other hand assists design, with emphasis on function and the application of mathematics and science.

However, this opinion is not widely spread in many fields of engineering, but in the context of membrane architecture it is a necessity that design teams of people with different expertise collaborate in an integrated design process. Knowledge in disciplines, such as geometric design, engineering, installation, and costing as well as understanding of their correlation is fundamental for the success of membrane projects.

Especially cost estimation is often neglected in the early design stage. Only once the design is developed far enough and first cost estimations are done, decision makers can reason over realizing a project. As a consequence economic aspects are the main reason for cancelation of membrane projects. Alternatively the architectural design is amended until it meets the available budget.

For this reason it is beneficial for designers to have knowledge about the parameters to optimize the costs. Rigid structures may excuse unfavorable design through local strengthening measures. The sensibility of non-rigid, flexible, form-active structures[1] in contrast bears high risk but as well big potential and therefore is the most cost driving factor. Small adjustments and modifications on the design may significantly influence the total costs of a project.[2]

[1] Compare Engeld 2006.
[2] Compare Giraldo und Wehdorn-Roithmayr 2012.

1.2 Aim

The aim of this thesis is to define design parameters of mechanically prestressed membrane structures and to understand their influence on the costs. This work only focuses on the *design phase*. There, basic design decisions build the foundations for the success of the whole project. At the beginning of a new project the planner can control the design only by geometric parameters. Assignment of materials and detail solutions are part of later project phases.

It is to be discussed which parameters the designer can control in this phase. The importance of these factors and the effects of amendments should be analyzed with the help of design studies. Basis should be a most simple sail geometry and realistic preconditions. All building components should be pre-dimensioned. The cost impact of alterations of the previously defined design parameters is to be evaluated by means of cost estimations.

This master’s thesis should lay out the *basis* for a practical design guide to people being involved in designing membrane projects. Membrane structures are highly complex constructions in many aspects. Discussing this subject in detail certainly would exceed the scope of a master’s thesis. This additional research work would need to be part of further scientific papers and theses to gain enough information to be published in a comprehensive practical design guide. Anyhow, the present work intends to point the direction for further investigations.

1.3 Research questions

For a structured approach to the topic of this thesis, the author formulated precise research questions (RQ). This work is going to answer questions of three different types:[3]

[3]Compare Karmasin und Ribing 2011.

Description *(What is the case? How does reality look like?)*

- Which types of evaluating the cost effectiveness of membrane lightweight structures do already exist?

Explanation *(Why is this the case?)*

- What makes the evaluation of form-active structures more complicated/time consuming then the one of rigid structures?
- Which parameters have a direct impact on the costs of membrane structures?

Forecast *(What is the expected development? Which modifications will occur?)*

- Which is the advantage of an evaluation according to the parameters at hand in comparison to existing valuation modes?
- Which possibilities can follow from this?

1.4 Structure of this thesis

A discussion of already existing types of evaluating the cost effectiveness of membrane lightweight structures will open this thesis. General background information on the load bearing behavior of form-active structures will make the consequences of basic design decisions understandable (RQ of the section *description* and *explanation*). Furthermore different design parameters will be defined. Three independent design studies are the basis for discussing the effects of altering previously chosen factors. All investigated sails ran through a full predesign process including dimensioning of the main building components. The results are shown and interpreted with the help of charts and diagrams. The thesis will close with conclusions and an outlook on the potential behind the received results, further plans, and possible developments for the future (RQ of the section *forecast*).

2 General (background information)

Frei Otto says in one of his publications[4]:

> *"An object weighing little is 'light'. Or an object possessing little mass is 'lightweight', meaning 'poor in mass'. […] On the other hand objects consisting of a large mass such as stars are heavy. Objects which, in comparison, are lightweighter [sic!] than others are relatively light. […] Objects capable of transmitting forces with little mass are, generally speaking, 'built more lightly', i.e. they are 'lightweight constructions'."*

Membrane structures are lightweight structures. But what does "lightweight" actually mean respectively refer to?

Often lightweight is referred to as a useful characteristic, whereas heavy is seen as disadvantageous. This however, is not always true. A lightweight car, for example, is more maneuverable and more economical than a heavy one, but is more sensitive to crosswinds and other factors.

When trying to define the term "lightness" there is more than one explanation. Often we refer to an object as being lightweight in comparison to another one suitable for the same purpose. Objects designed or used for the same function only need to be weighed. The lighter one is "lightweight". A running shoe is lightweight in comparison to hiking boot but as well made for a different application. To be able to evaluate the (relative) weight of a hiking boot it needs to be compared with a shoe designed for the same purpose.

Another definition of "lightness" is to see objects in relation to their size. A cardboard box may be felt light in relation to its size. A small block of lead is likely to be called heavy although in absolute measures the cardboard box may be even heavier than the little chunk of lead.

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[4] Compare Otto und Klenk 1998.

In structural engineering masses play an important role. Masses are involved in every construction. They either rest or move. Masses activate forces and consequently load objects or they are transported along distances. In general there is no such thing as structures without mass. Masses are involved wherever forces are produced or transmitted.

The group around Frei Otto at the Institute for Lightweight Structures at the University of Stuttgart created measures to evaluate the effectiveness of structures.

As a construction transports loads from the point of occurrence to its supports, the product of force multiplied by length is an expression of “performance”. This measure is given a different name – Tra.

$$Tra = F \cdot s \tag{1}$$

F is the force to be transmitted. The transmission distance s is the length of the straight connection between the point of application and the point of discharge, like a construction support. Therefore it is measured in [Nm]. The direction of the force vector however, is not considered in these calculations.

Buckminster Fuller, the American architect and engineer, said once:

> *“If you want to know what a construction is really worth, you will have to weigh it.”*

He implied that structures are most economic if a form is found in which the used material is stressed in a way to meet its maximum load bearing capacity. Certainly this form would be different for materials with different strength and stress-strain behavior.

Following Fuller’s statement one could conclude “lightweight constructions” are constructed “meaningfully”. Here the term “lightweight” refers to the relation of the mass of an object and its capability to transmit forces. The capability to transmit forces is measured by means of *Tra*. The relation of the mass of an object to *Tra* is called *Bic*.

$$Bic = \frac{m}{Tra} \qquad (2)$$

If the mass *m* is used in [g], *Bic* is obtained in [g/Nm]. To be able to compare structures by these measures, *Tra* has to be calculated considering its ultimate limit state.[5]

The Institute of Lightweight Structures ran extensive research on the application of *Tra* and *Bic* for over 20 years in order to determine the validity of these two values. Besides their ability to define the effectiveness of structural systems, nevertheless *Tra* and *Bic* remained merely academic measures and did not find practical application.

In reality commonly used are measures like [kg/function] and [m^3/function] which indicate the amount of material respectively the volume used for a certain application. For example shopping centers are often compared by the useable area [m^2] in relation to the building volume [m^3].

These approaches may be suitable for conventional buildings but are not useful for comparison of membrane structures.

The main difference between rigid and form-active structures is the approach to find the geometry required for a certain purpose. In general one can say: rigid structures are shaped; form-active structures are derived.

Conventional (rigid) structures are given a specific shape or geometry. Spans, dimensions, and materials are chosen to be checked mathematically in relation to given load cases. If the proves fail, either the geometry, sections, or materials have to

[5] Compare Otto und Klenk 1998.

be changed. This iterative process continues until an acceptable result in ULS[6] and SLS[7] is achieved.

The form-finding of tensile surface structures on the other hand starts with the definition of the layout of an area to be covered as well as the arrangement of fixation points and boundary conditions (such as stiff or elastic edges, or stress ratios between warp and weft). Within these the membrane is supposed to find equilibrium. One layout of boundaries allows only for one mathematical solution, meaning one particular membrane shape. Every alteration of the arrangement results in a new variation of geometry.[8]

Kai-Uwe Bletzinger defines form-finding of membrane structures as *"… to find the optimal deflected and finally visual shape due to a given stress distribution acting on the deformed structure."*[9]

Rigid structures carry loads by shear forces and bending stresses. Tensile (surface) structures on the other hand transfer loads by means of axial stresses, such as tension and pressure. The majority of construction elements used in flexible constructions like this have a very low bending stiffness. For this reason external loads can cause higher deformations without the structure losing stability. To enhance stiffness of form-active structures, the curvature of membrane and edge cables is a crucial design element.

The author discuss in a published paper[10] the consequences of certain design decisions from the point of view of a structural engineer respectively an architect in relation to their influence on the project costs.

Anticlastic surfaces with a homogeneous and well-proportionate curvature[11] give higher mechanical stiffness to the membrane and further to the whole structure. As a

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[6] ULS = Ultimate Limit State.
[7] SLS = Serviceability Limit State.
[8] Compare Forster und Molleart 2004.
[9] Compare Bletzinger 2008.
[10] Compare Giraldo und Wehdorn-Roithmayr 2012.

consequence the weave needs less pretension and the deformations due to external loading are less. This results in smaller internal stresses and the material fatigues slower. Furthermore due to lower stresses and therefore smaller reaction forces in the fixation points, optimization of the adjacent structural elements and wider spans of the membrane are possible.

In general higher strain and therefore higher stresses in the membrane may require stronger material. More tensile strength is always directly related to more weight per surface area and bigger fabric thickness. Both factors have an impact on fabrication as well as on installation.

The settings of the welding machines for example strongly depend on the thickness of the material. The thicker the fabric the more power is needed respectively the longer it takes to achieve full load bearing capacity of the seam. The increasing of the internal stresses result as well in wider seams which certainly influence the welding process in the same way.

The classification of membrane materials in different types according to their tensile strength also allows for a differentiation by the surface weight. A Type 5 material is about twice as heavy as a Type 1. From this follows that stronger fabrics may be more bulky at handling. Furthermore different fabrics require different care in general. PVC/polyester is by far more flexible and less sensitive to folding than e.g. PTFE/glass fabrics."

Membrane elements of the same size are either more bulky or heavier. As result more man may be needed to handle the assembly pieces and as a consequence the sail may need to be split into smaller parts. The more elements have to be jointed on site the more time and manpower is needed for installation. Sometimes installation costs have a share of up to 40 percent of the overall project costs. Considering the risk involved, planning and preparing installation in every possible detail is time well spent.

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[11] Gaussian curvature $K = k_1 \cdot k_2 = \frac{1}{r_1} \cdot \frac{1}{r_2}$.

As discussed above, big curvature is very advantageous for the structural behavior of a membrane structure up to a certain extent. On the other hand more curvature requires as well more time and effort in fabrication. To avoid wrinkles and to achieve uniform surfaces with less polygonal appearance, strongly curved geometries need to be assembled of membrane stripes with smaller width. The same applies to edge cables with small radii. Welding of strongly curved cable pockets requires special care in fabrication.

A homogeneous stress-strain distribution in the fabric is the basis to have smooth surfaces without wrinkles. This means, big variations of the warp and weft directions of two adjacent weave elements are to be avoided. Therefore strongly curved cable pockets need to be assembled of narrow membrane elements to guarantee a most aligned orientation.

Radial stresses in fabrics may reach critical limits if edge cable forces become large. In this case offsetting the cable from the membrane's edge and linking it at intervals by a sequence of straps and clamp plates could be a viable solution. This option is mainly used for PTFE/glass fabric but also for PVC/polyester where edge spans are larger than 20m.[12]

The local soil conditions usually bear high vagueness and often are not known until short before detail design. Especially on extensive projects various foundation concepts may be required, as the actual soil configuration may differ at individual anchor points. For this reason the designer's main aim always has to be to minimize the reaction forces. Whether a tensile roof is anchored in an already existing structure or in the ground, no matter the foundation concept, high forces result in additional costs at all times.

This statement shows the importance of the arrangement of struts and the corresponding guy cables. The smaller the angle between the compression and tension elements is, the higher the internal forces in the construction components

[12] Compare Forster und Molleart 2004.

become. In case the available space is limited, every designer will strive for maximizing the area covered by the structure. Due to this focus, struts and guy cables are likely to be arranged in an acute angle. To avoid complications caused by high anchor forces, restraint columns could be a considerable alternative if used wisely. Either way, in case of high anchor forces, the lightweight characteristics of a membrane structure will end at soil level. Moment bearing as well as heavyweight foundations object the claim on light-weightiness by all means.

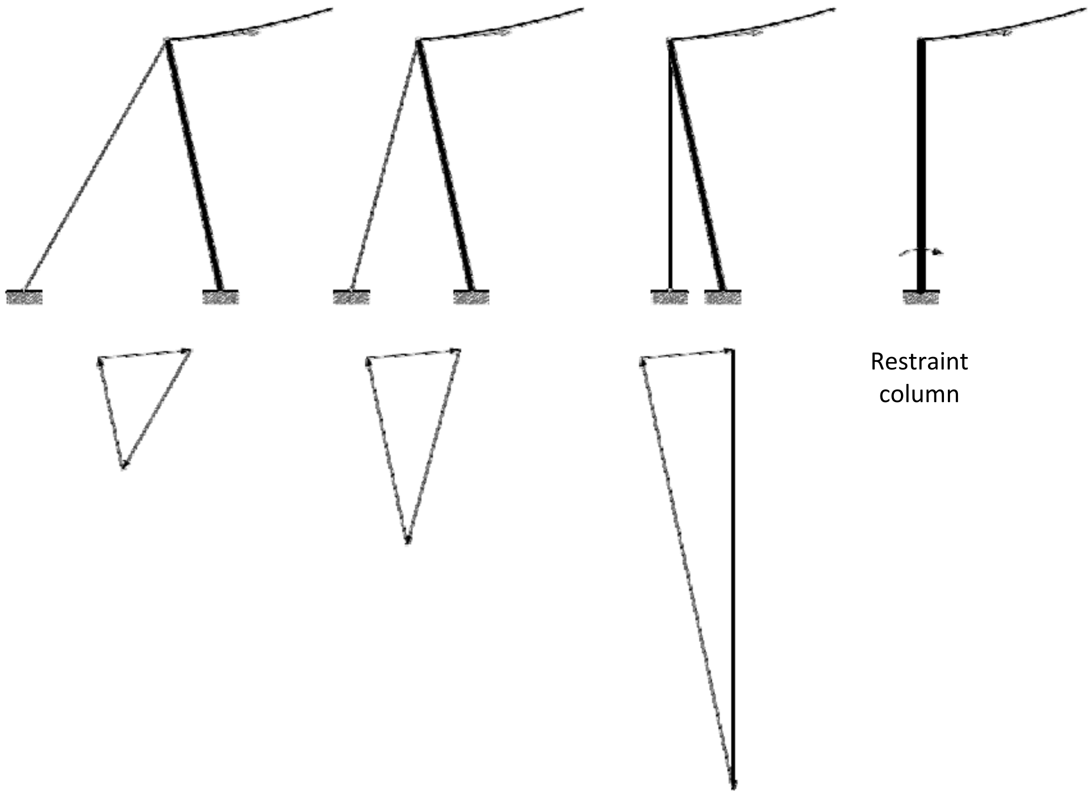

Figure 1. Guyed struts and the corresponding triangles of forces

To reduce anchor forces it may worth a thought to consider adding an additional anchor point and amend the design while keeping the overall appearance similar and knowing more foundations are needed.

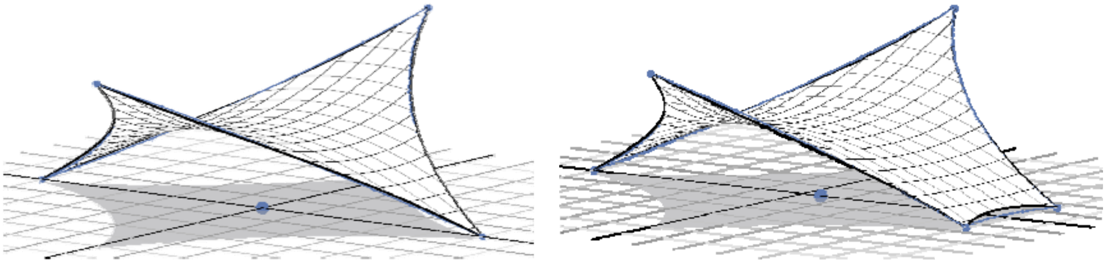

Figure 2. Implementation of an additional anchor point to reduce the anchor forces

3 Methodology

3.1 Research methods

Detailed cost estimation requires knowledge of a domain specialist capable of handling all design parameters and their influence on the project costs. To gain an overview about the complexity of this task design parameters are listed and categorized according to different schemes;

- by structural component,
- by geometric parameters, and
- by project phase.

To be able to evaluate these parameters it is crucial to understand what a cost planner focuses on and which aspects he neglects. With the help of questionnaires various interviews were lead with architects, engineers, project managers, and fabricators, each one with extensive experience in membrane industry. An additional aim of these interviews was to learn about project costs and cost shares of individual components, such as membrane, cables, primary steelwork, or foundations. Therefore the interviewees were asked if it was possible to provide data of already realized projects regarding size, total costs, and cost shares amongst others.

The knowledge gained in these interviews is very valuable and in many cases highly confidential data was shared. Nevertheless the information learned in this phase was not consistent and detailed enough to be used for the purpose of this thesis.

In comparison to (for example) the automotive industry whose products are manufactured in serial production facilities under controlled conditions meeting to the same quality standards thousand- or even million-fold. In construction industry (almost) every structure is a prototype which is built only once under the conditions at hand. This statement is valid for conventional rigid structures and even more so for tensile structures. For instance, due to the complexity and sensibility of membrane structures, the project costs translated into unit costs as well as the corresponding cost shares are highly individual project data. The variation of all cost-related data between different projects was too high to be able to be compared. Possible conclusions and tendencies would have missed any scientific standard.

In addition some interviewees refused (understandably) to provide the information asked for, due to company secrets and for not to lose their competitive position. Especially membrane industry highly relies on gained experience as hardly any standards and mandatory guidelines exist for materials, structural calculations, and standard procedures in fabrication.

Furthermore this information was considered to be the basis for evaluating the importance of individual design parameters. Therefore it was necessary to reconsider the approach to the topic of this thesis.

The effects of variation of curvature and of introducing (very) acute angles between struts and guy cables are part of every introductory lecture about membrane structures. To quantify the consequences either extensive experience or profound knowledge of structural engineering is required but to draw a conclusion on the cost development exceeds the capabilities of most.

Therefore the author decided to perform geometry studies and to run a full predesign on every sail variation. The dimensions of all main components were listed in a bill of quantities. Multiplying these items with unit costs derived from a market research and interviews with professional cost planners amounts to the total costs. The design parameters were evaluated in a generic cost analysis

Literature studies gave additional insight on the relation between design decisions and their cost impact.

3.2 Evaluation method

The results of the structural calculations (forces and stresses) and the cost estimations (costs) are visualized in charts and diagrams for qualitative comparison. Diagrams of cost shares of individual components show those items with the biggest potential for cost optimization.

3.3 Limitations of methodology

Mechanically prestressed membrane roofs are categorized in four base geometries:

- four-point sail
- high-point sail
- beam supported sail
- ridge-valley sail

Due to the differences in the load bearing characteristics of the individual primary structures the amount of material and the sections required differ widely. Certainly corresponding studies of all four roof types and the attempt of comparing would be of great interest and value but would clearly go beyond the scope of this thesis. Therefore only the four-point sail is addressed in this research paper.

However, the author is motivated to continue and deepen this study within the scope of a doctoral thesis.

4 Design parameters

4.1 General

Design parameters are constraints or specifications against which an object or system is to be designed. The *Business Dictionary* offers a more general definition but it meets the same point.

Design parameters are *"qualitative and quantitative aspects of physical and functional characteristics of a component, device, product, or system that are input to its design process. Design parameters determine cost, design, and risk tradeoffs in the item's development."* [13]

The definition of design parameters for a certain project should be one of the first tasks within the design phase. A list of characteristic gives structure to the process and minimizes wasted time and energy.

In general the process of designing consists of two steps: *quantification* (more ideas) and *qualification* (reduction of ideas)[14]. Following this approach it is necessary to decide over the final design up to a certain depth before realistic cost estimations can be performed. Precise cost estimation is a highly time-consuming and complex task. For conventional rigid constructions a detailed structural analysis under consideration of various aspects such as aesthetics, shape, materials, legal restrictions and requirements, etc. is needed. For non-rigid structures this complexity maximizes, since additional factors induced by the flexible nature of the membrane and its components occur; factors like additional requirements on individual components or material and the resulting consequences from using this type of material, more complex aerodynamic characteristics, or influences resulting from the planned period of usage (temporary or permanent use).[15]

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[13] Compare http://www.businessdictionary.com/definition/design-parameters.html; (accessed on 07 October 2012).
[14] Compare Höller 1999.
[15] Compare Giraldo und Wehdorn-Roithmayr 2012.

The more accuracy is required from cost estimations the higher its level of complexity gets. The number of parameters to be considered increases potentially. Every single factor's potential cost impact has to be evaluated.

In a previous publication the author defined two types of parameters; "*… parameters able to be determined and such which only can be valued either by chance or by experience.*"[16]

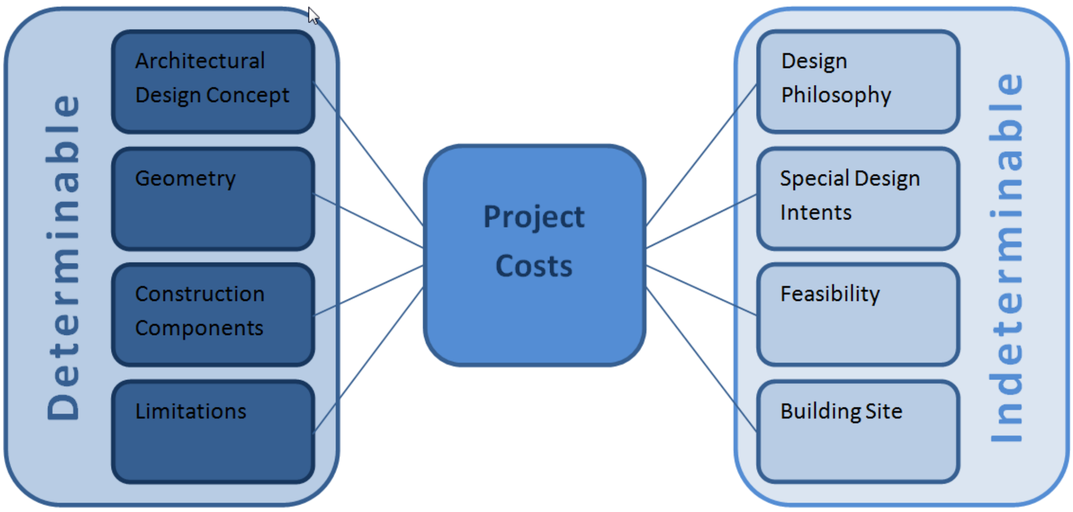

Figure 3. Determinable and indeterminable parameters for cost optimization

Examples for "*Determinable Factors*":

- *Architectural design concept and design intention* are facts which can be described e.g. by sketch, by reference projects or verbally.
- *Geometry* makes an intended layout describable by means of physical models or CAD tools (such as roof type, shape, curvature) and gives readability to a structure (e.g. flow of forces).
- *Construction components and details* include e.g. an "element catalogue", alternative solutions for certain components, membrane material, or edge cables.

[16] Compare Giraldo und Wehdorn-Roithmayr 2012.

- *Commercial, legal, and geographic limitations* are limitations such as available budget, building laws; external loading like wind load, snow load, and dynamic excitability; general climate conditions like weather, temperature, and local climate characteristics; period of usage.

Examples for "*Indeterminable Factors*":

- *Indeterminable architectural perception and requirements* that are not part of the design concept such as an individual “design philosophy” of the architect.
- *Special design intents* like the use of new materials or techniques; first of a kind-project.
- *Feasibility* of the structural concept.
- *Building site* defines the construction site, accessibility of site, infrastructure, or soil conditions.

Indeterminable parameters, however, are not directly in the sphere of influence of the designer but still can be controlled up to a certain extent at the very beginning, right after the project idea.

4.2 Categorizations

Referring to the title, the aim of this thesis is to discuss design parameters of membrane structures and their influence on the costs. There are different approaches to organize design parameters. Possible categories are for example:

- Construction component
- Geometric element
- Project phase

4.2.1 Categorization by construction component

The following figure shows the main components and the most important sub-groups. (Further sub-divisions are possible.)

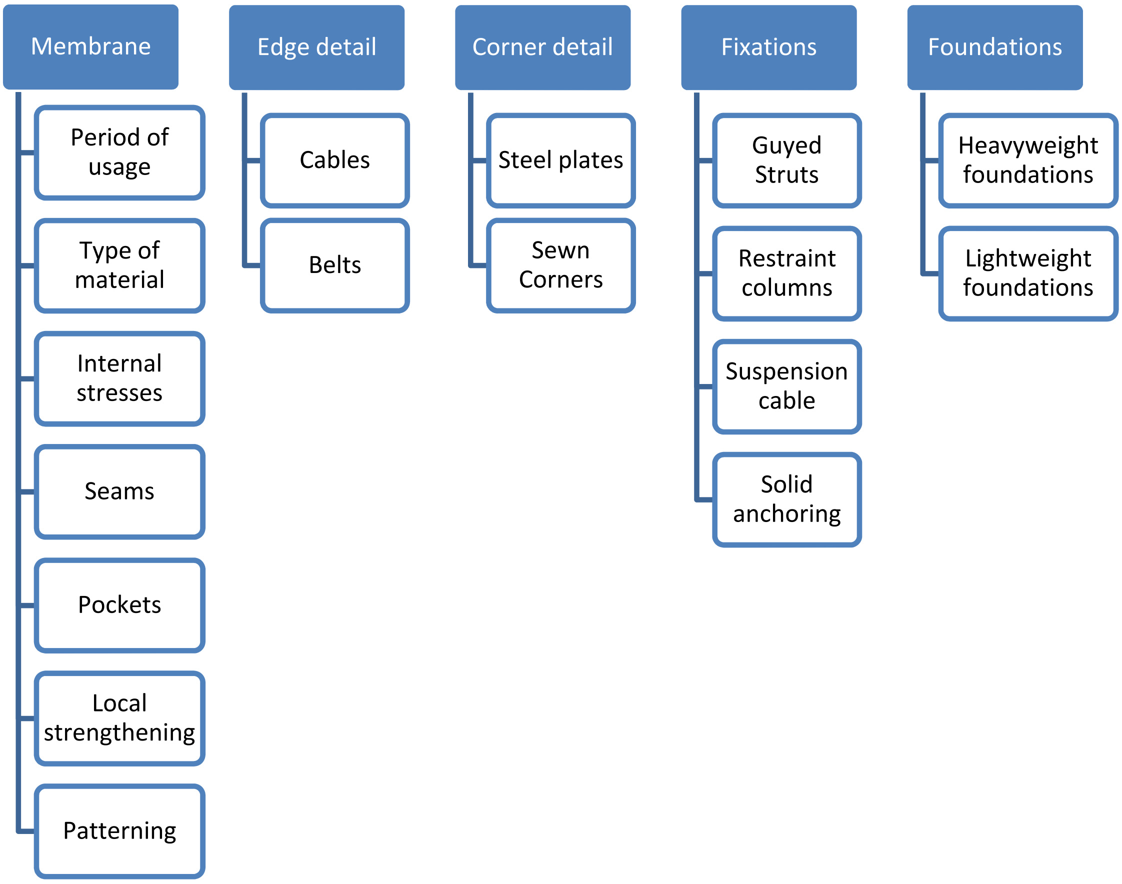

Figure 4. Design parameters by construction component

4.2.2 Categorization by geometric parameters

The shape of a membrane roof is found by the internal stress equilibrium of the membrane material. It is derived by solving a mathematical problem under consideration of certain constraints. Hence a categorization by geometric parameters seems evident.

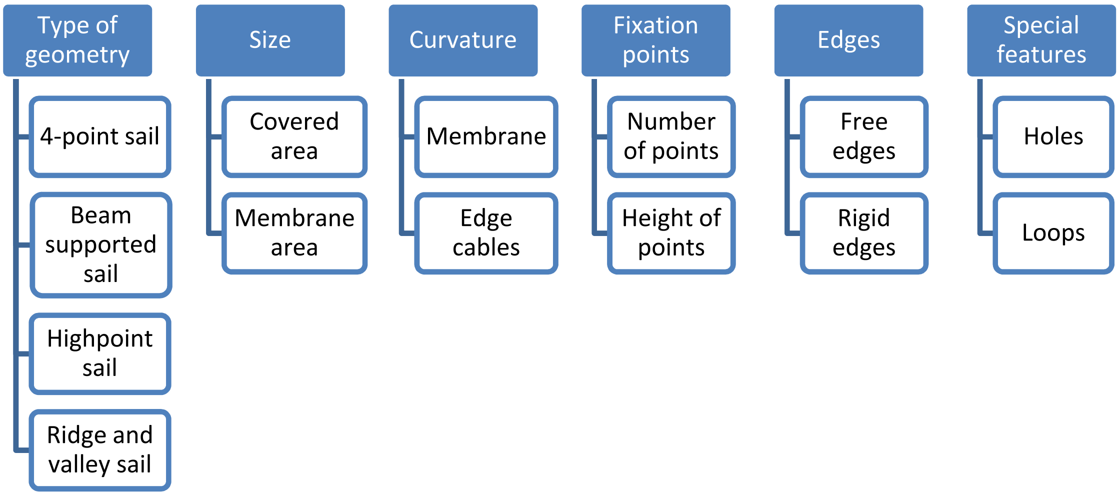

Figure 5. Design parameters by geometric parameters

4.2.3 Categorization by project phase

For the purpose of this thesis (being the basis for a general design guide) the approach to categorize by project phase seems the most reasonable. To allow for a continuous development of the design-guide-idea the research on the potential for optimization was started at the beginning of the project phase – the design stage.

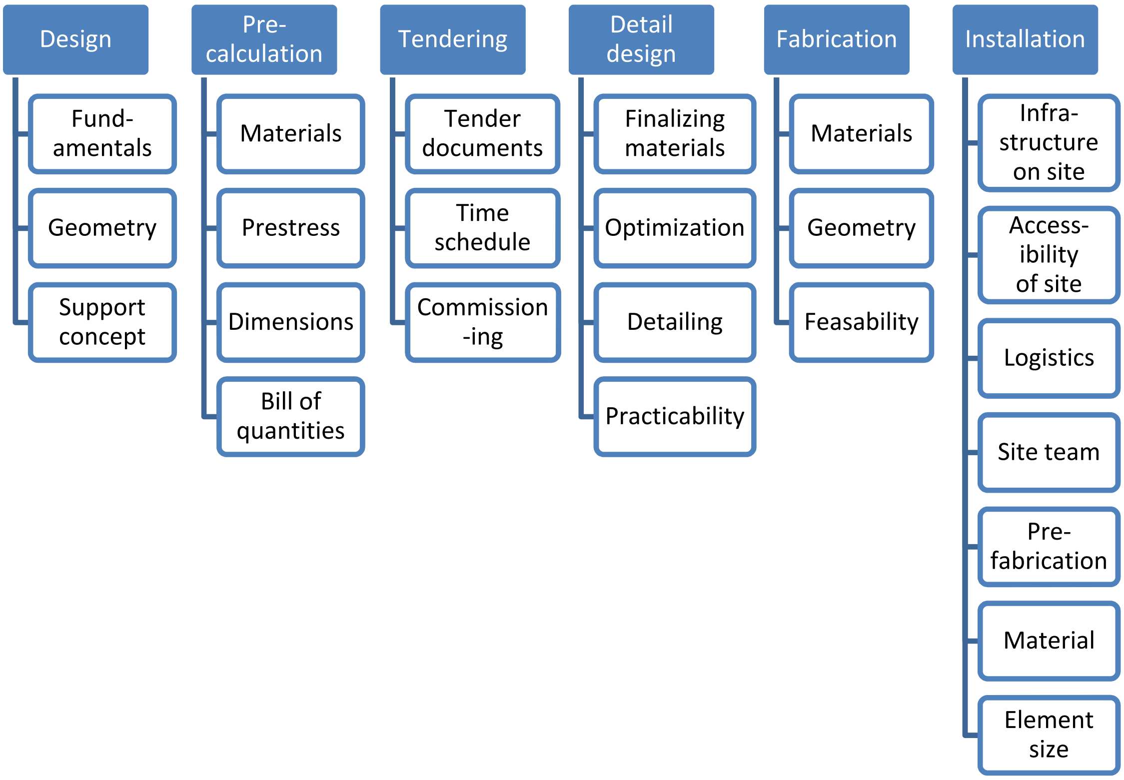

Figure 6. Design parameters by project phase

4.3 Limitations of study

As mentioned in the introductory chapter, this thesis is meant to become the basis of a practical design guide. It should make designers aware of the potential they have in hand to control the (commercial) success of a membrane project. Right after the project idea the first steps are the most important and have a major influence on the following design process. To start the research on the cost effects of design decisions, the focus is laid on the beginning of a new project. For this reason this thesis will only focus on the design phase.

In the beginning the architect has to deal with a lot of uncertainties. At first the knowledge and the degree of detailing are very little and the risk for the project not to get realized is very high. The more time passes the more knowledge is gained and the risk of failure reduces.

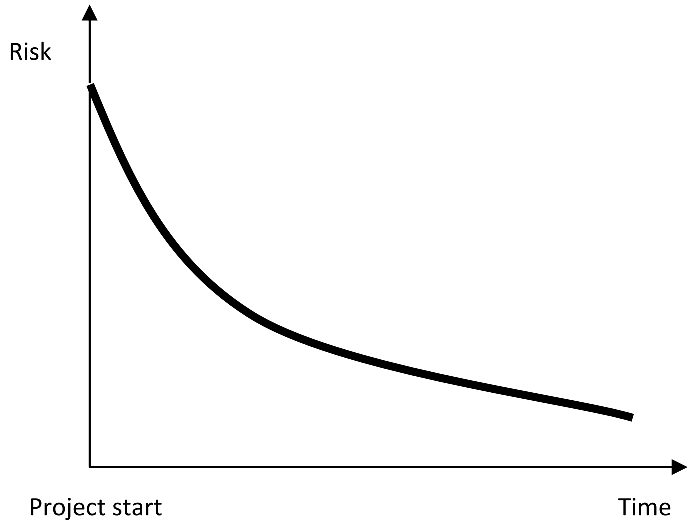

Figure 7. Risk of failure/time relation throughout the design progress

Due to the importance of the first decisions in a project, the topic was approached from a designer's point of view. For this reason it was necessary to understand how a project is started. Following questions arose:

- Which parameters describe a design idea?
- Which are the costs the designer is able to control by these parameters?

4.4 Authoritative design parameters

Form-finding of mechanically prestressed membrane structures requires profound understanding of the correlation between geometry, load bearing behavior and technical realization.

Three design parameters define a layout:

- Location of fixation points
- Curvature of edge cables
- Direction and arrangement of guy cables

In general a fixation point is a point of support which is used to transfer tension forces directly or indirectly via struts, guy cables, or cantilevers into the ground. Usually the geometric location is a result from architectural constraints. Their differences in elevation have to be set to allow for enough curvature in the membrane. Otherwise additional elements like high points, beams, or ridge and valley cables should be considered.

As membrane stresses mainly act orthogonal to a membrane edge, flexible edges form an almost circular arch. Therefore the cable force can be calculated according to the stresses in a thin-walled pressure vessel with

$$F = r \cdot \sigma \quad (3)$$

This equation illustrates the cable force F only depends on the radius r and the membrane stress σ. Mathematically the span is irrelevant. Although in reality the span does have influence on the cable forces. An increasing distance between two fixation points requires a bigger cable radius due to practical aspects and hence has an impact on the internal stresses.

The direction and arrangement of guy cables are of essential importance. They give stability to the whole structure. In addition these two parameters determine the size of reaction forces to be anchored. A well proportionate layout of, for example, a strut and two guy cables can either cause high anchor forces or reduce them to a reasonable size.[17]

4.5 Cost impact

The main question is, *"How could the estimated costs of any given design be reduced (in design stage)?"*

[17] Compare Knippers, et al. 2010.

For reducing the required budget two approaches are possible; making the structure cheaper or more economic.

To make a design cheaper, the designer could simply change the size of the covered area. Besides the fact this solution may reduce the intended applicability of the structure, it is important to note, the size of a membrane is not directly proportionate with the project costs. Certainly the costs become smaller but half the covered are does not mean half the total costs. The reaction forces would also decrease but the effect on the supporting elements is not big enough to split the total costs in half.

Considering a found geometry should remain as is, a possible reduction of the required budget could be achieved by using lower priced materials and products. The application of conventional steel instead of stainless steel or the use of cables with threaded fittings instead of fork fittings are cost-effective solutions. Additional potential for optimization lies in the time of usage. A temporary structure allows for reduced external loads which have an impact on the stresses and forces in all elements. Lower forces mean smaller sections and consequently lower costs.

To improve the cost effectiveness while keeping the same materials and types of construction components, an optimization of stresses and forces is obvious. Amending the curvature is the most effective way to do so. The result could be decreased internal forces, or improvements at the flexibility respectively stiffness of the structure. A minor effect but still worth to be mentioned would be amending the membrane shape could also reduce the external loading (e.g. reduced snow loads due to steeper surfaces). Depending on the purpose of use the designer has to decide the most suitable approach.

In most cases the list of design objectives is not likely to be amended essentially, regarding changing the time of usage. In reality aiming for a combination of both, (making a design cheaper as well as more cost-effective) should be the target. Either way, it is the designer's obligation to challenge his creativity for finding the optimum costs[18].

For the purpose of this study finding solutions with lower priced materials is neglected. When a designer sketches up his first ideas, materials are not an issue in this very moment. Primarily he focuses on finding the best design solution for the intended use under consideration of the space available. Hence, the following study only allows for optimization through improved geometry.

The cost estimations as part of the conducted geometry studies are based on structural pre-calculations. Therefore the only parameters known for certain are the dimensions of the building components. All others, such as soil conditions and external loading, are presumptions equal in all models for the purpose of comparison.

At this stage of a project only what the designer has sketched on paper can be quantified. For this reason only *manufacturing costs* will be considered in this study. Manufacturing costs are those costs which accrue when products are manufactured or services are provided. They are the sum of material costs and production costs.

$$\text{Manufacturing Costs} = \text{Material Costs} + \text{Fabrication Costs} \qquad (4)$$

Despite the economical difference between terms costs and price of a product[19], in this study they are used with equal meaning. Reason is the constantly changing the point of view: Assuming a membrane fabricator subcontracts the primary steel the price his subcontractor would ask for are his costs. When selling it to a client, he again would add a certain percentage for risk and profit. This new value will amount to the prize of the structure.

All unit prizes used in the following cost estimations are the result of a market research and interviews led with professional cost planners. They are derived from

[18] The word „optimum costs" instead of "lowest costs" is used on purpose. The decision for a membrane roof already implies the willingness of a client to except higher costs than absolutely necessary. The cheapest solution often is a conventional rigid canopy or shelter.
[19] Price = costs + risk + profit.

post-cost calculations with risk and profit included. According to the interviewees, the profits considered reflect a healthy market price while still being competitive.

Overhead and installation costs are as well allowed for in these unit prices. Overhead costs are highly individual costs of each company and therefore were not specified in detail. Installation is considered to be without any major difficulties, such as short transportation distances, easy site accessibility, or no heavy machinery required. Design costs are not specifically considered in this study.

The unit prizes used for different building components are listed in the appendix.

5 Analysis

5.1 General

The previously described values to evaluate the effectiveness of a structure, *Bic* and *Tra*, are merely scientific measures and are of no substantial practical use. In addition these measuring units merely quantify the structural efficiency in regards of forces, stresses, and the construction's mass. Tensile structures are most complex structural systems. In this industry the design has a major impact on the projects costs. Neglecting this effect is like not considering a client's list of objectives before first design ideas are put on paper. To understand and being able to estimate the effects of the design on the costs is mainly a matter of experience.

The effects of altering the curvature of membranes and cables are basic (engineering) knowledge and are taught in almost every introductory lecture on membrane structures. For this reason it is common knowledge in this industry, more curvature means higher mechanical stiffness of the structure and less required pretension. Consequently lower reaction forces occur in the fixations. Only experienced designers are able to quantify or evaluate this reduction of stresses and forces in relation to curvature but even less can estimate the effects on the project costs. This study will visualize these effects and show the corresponding cost cuts.

To visualize the relation between optimization of geometry and the resulting costs, design studies have been performed on a four-point sail. Every single variation of the base geometry ran through a complete predesign of all main construction components, such as membrane, edge cables, struts, guying cables, foundations, and anchors. In a next step the individual project costs were estimated and the gained values were visualized in figures for further analyses.

The three independent studies included the following:

1. Variation of the membrane curvature
2. Variation of the edge cables curvature
3. Variation of the inclination of the guying cables

5.2 Basics

5.2.1 Geometry

The list of objectives for the membrane geometry listed the following items amongst others:

- Most simple and symmetric geometry
- Uniform and realistic external loading
- Covered area of about $40m^2$
- PVC membrane
- Struts of CHS-profiles, standard steel quality
- Stainless steel edge and guy cables
- Corners with clamped plates
- Concrete block foundations for struts
- Earth anchors for guy cables
- Simple dimensioning by hand calculations

For easier understanding of the effects of altering the geometry the most simple roof type was used – a four-point sail.

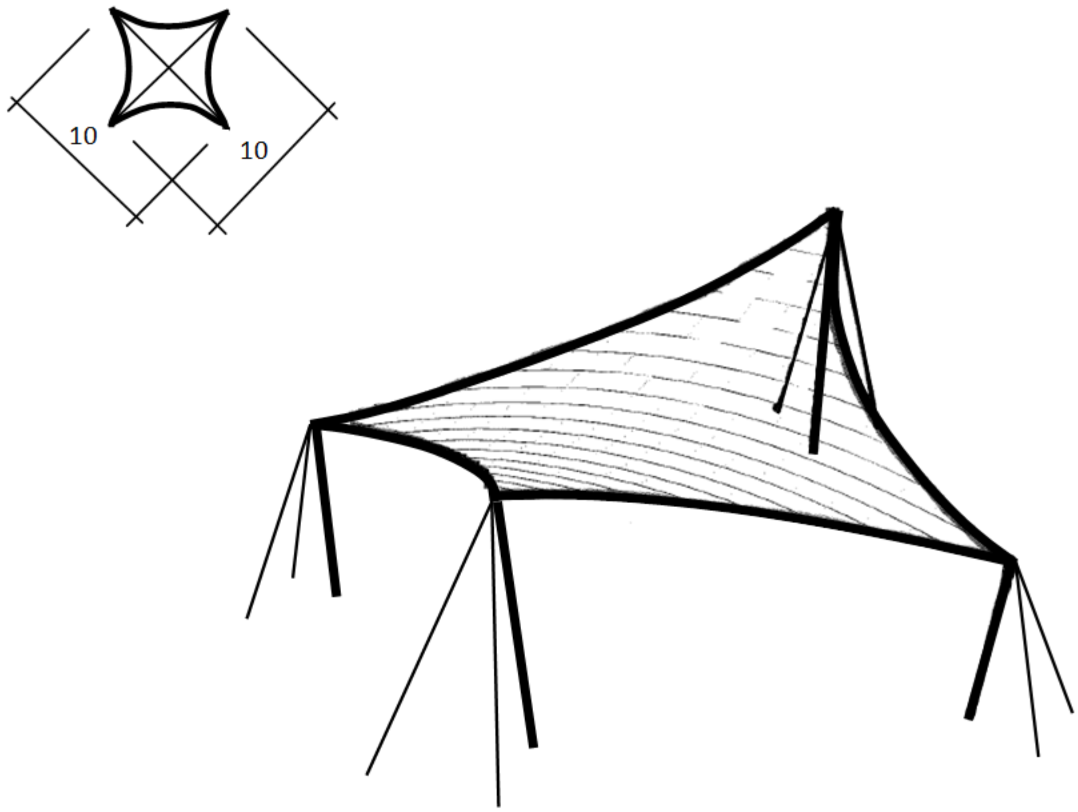

Figure 8. Layout of standard sail

In plan view the diagonals of the roof are orthogonal to each other and have a length *d* of 10m. Connecting the ends, the so found square has a side length *l* of 7.07m[20] and an area of 50m^2. The sag of the membrane as well as of the edge cables is 10%. The high points are set at 4m and the low points at 2m above ground level. All corners are supported by one strut with two guy cables.

[20] $l = \frac{d}{\sqrt{2}}$.

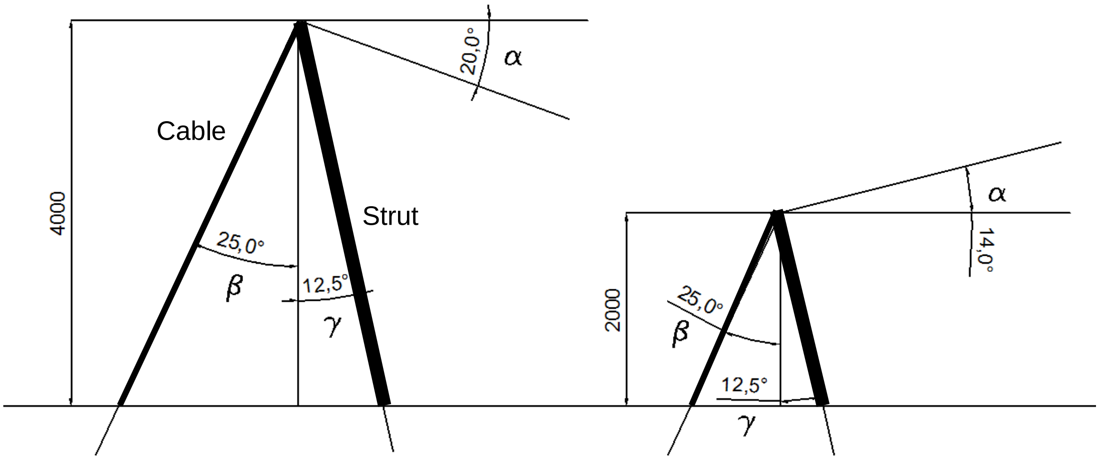

Figure 9. Layout of strut and guy cables

Their arrangement is defined by four angles:

- α angle between membrane and horizontal
  - High point α < 0
  - Low point: α > 0
- β angle between (projected) guy cables and vertical
- γ angle between strut and vertical
- δ angle between the guy cables

5.2.2 Components

- Membrane: PVC/polyester material;
  E_{warp} = 1200 kN/m; E_{warp} = 800 kN/m
- Struts: CHS profiles; steel quality S235
- Cables: CarlStahl, spiral strand, stainless steel
  - Edge cables: swaged fitting with thread on both ends
  - Guy cables: swaged fork fitting on one end + fork fitting with turnbuckle on other end
- Corners: clamped steel plates with tubes on both sides to take edge cables; swaged thread fitting fixed with nut bolts; steel quality S235

- Soil: sandy gravel; stiff to very stiff silts and clays; σ_{perm} = 200 kN/m^2
- Foundations: block foundations of reinforced concrete; thickness t = 80cm; minimum reinforcement considered;
- Anchoring: Manta Ray earth anchors

5.3 Design studies

5.3.1 General presumptions

To be able to compare all altered geometries, the membranes needed to be optimized up to the same limiting state.

Considering a constant load case *wind*, only membrane stresses or deflections could be compared. Both approaches could cause problems at extreme geometries. Roofs with big curvature would cause very little deformations even at very low pretension, whereas very flat membranes would show big displacements despite strong pretensioning. To keep either of those parameters constant throughout the study, geometries would lead to designs far outside reality. In addition wind loads strongly depend on the geometry. A constant load over all geometries would again be very theoretical.

For this reason an external load case *snow* of 1.0 kN/m^2 was considered. According to Eurocodes, only once the inclination of the sail exceeds 30° the applied snow load needs to be decreased. This fact just would have to be considered at models with big membrane curvature. Hence, for simplification this effect was neglected in this study.

While changing the curvature either of the membrane or the edge cables, the *pretension* was altered in steps of 0.1 kN/m until that point where ponding was just to be avoided.

For the cost estimation only the authoritative fixation point (= high point) was structurally analyzed. The arrangement of the struts and the associated guy cables was considered to be identical in all four points. Only the incidence angle of the membrane differs between high points and low points. This would lead to variations of the axial forces in struts and guy cables. For reasons of simplicity no optimization concerning the difference of high points and low points was performed. Therefore all struts and guy cables were assigned to the same cross sections respectively cable diameters. Following the same presumption, the foundations and anchors have identical dimensions in all four locations.

All struts were checked for buckling according to DIN 18800. While using standard CHS profiles a maximum utilization smaller or equal 1.0 was aimed for. Where required the next bigger diameter with thinner wall thickness was used. The main focus was on optimization of the steel weight. Architectural aspects, like rather using small tubes with thick walls, were not considered in this study.

To introduce the cables' tension loads into the ground, earth anchors were planned. Due to the assumed soil conditions (more or less appropriate for the area of Vienna, Austria) in extreme cases two anchors per cable need to be allowed for. In these cases the anchors need to be organized in a V-like arrangement.

5.3.2 Study 01 – Variation of membrane curvature

The membrane surface of the base roof is designed with an arch rise of 10%. In this study the curvature of the membrane was altered from 3-20%. As an additional precondition the minimum clearance of the sail at the highest point was set 3m. As a result the height of the corners changes from model to model.

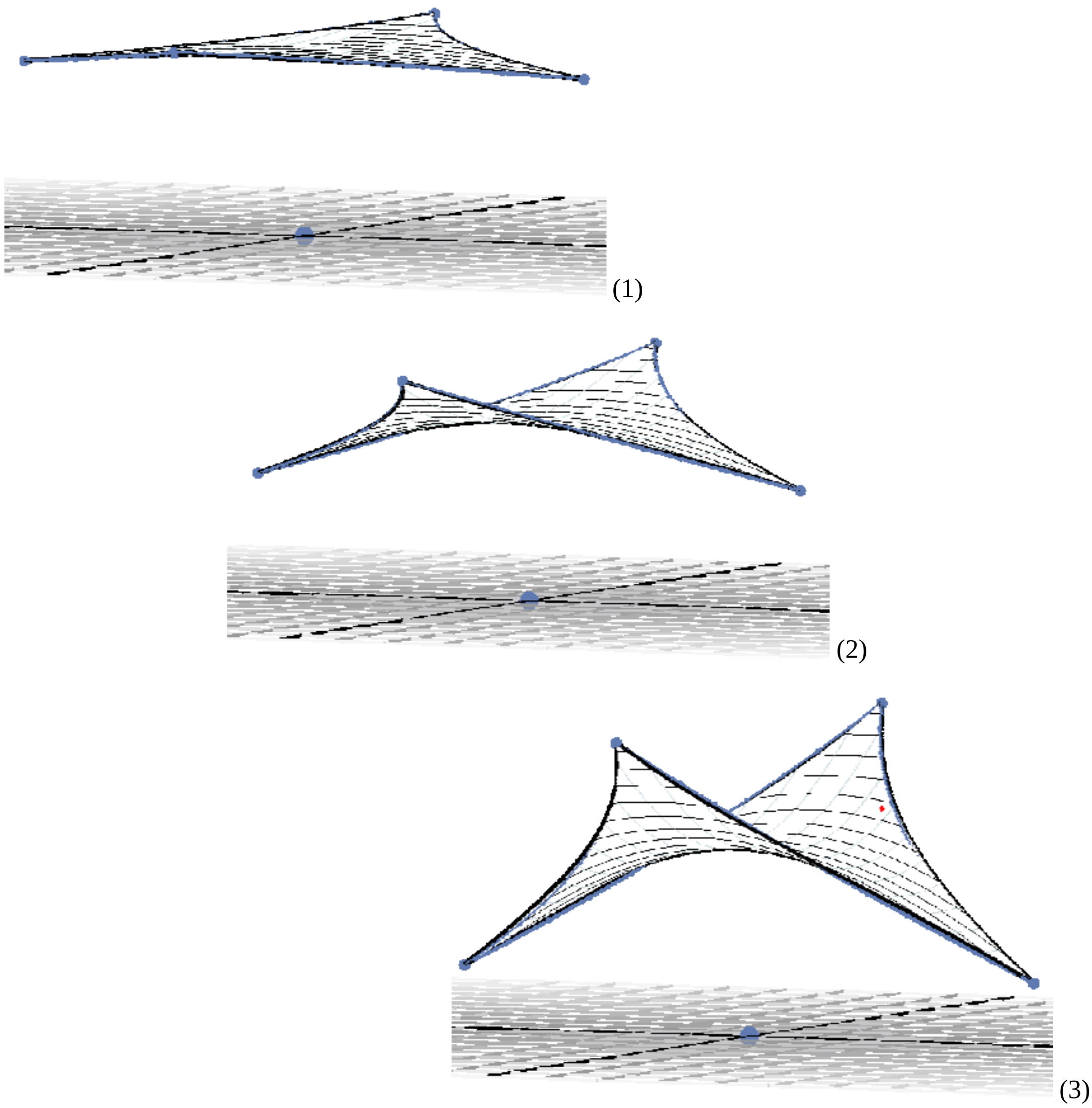

Figure 10. Study 01 – Variation of membrane curvature
(1) 3%; (2) 10%; (3) 20%

5.3.3 Study 02 – Variation of edge cable curvature

In this study the effects of different curvatures of the edge cables were analyzed. Starting with the base roof, the considered range of the arch rise is 3-20% of the fixation point distance. The clearance and the lengths of the struts remain the same in all models.

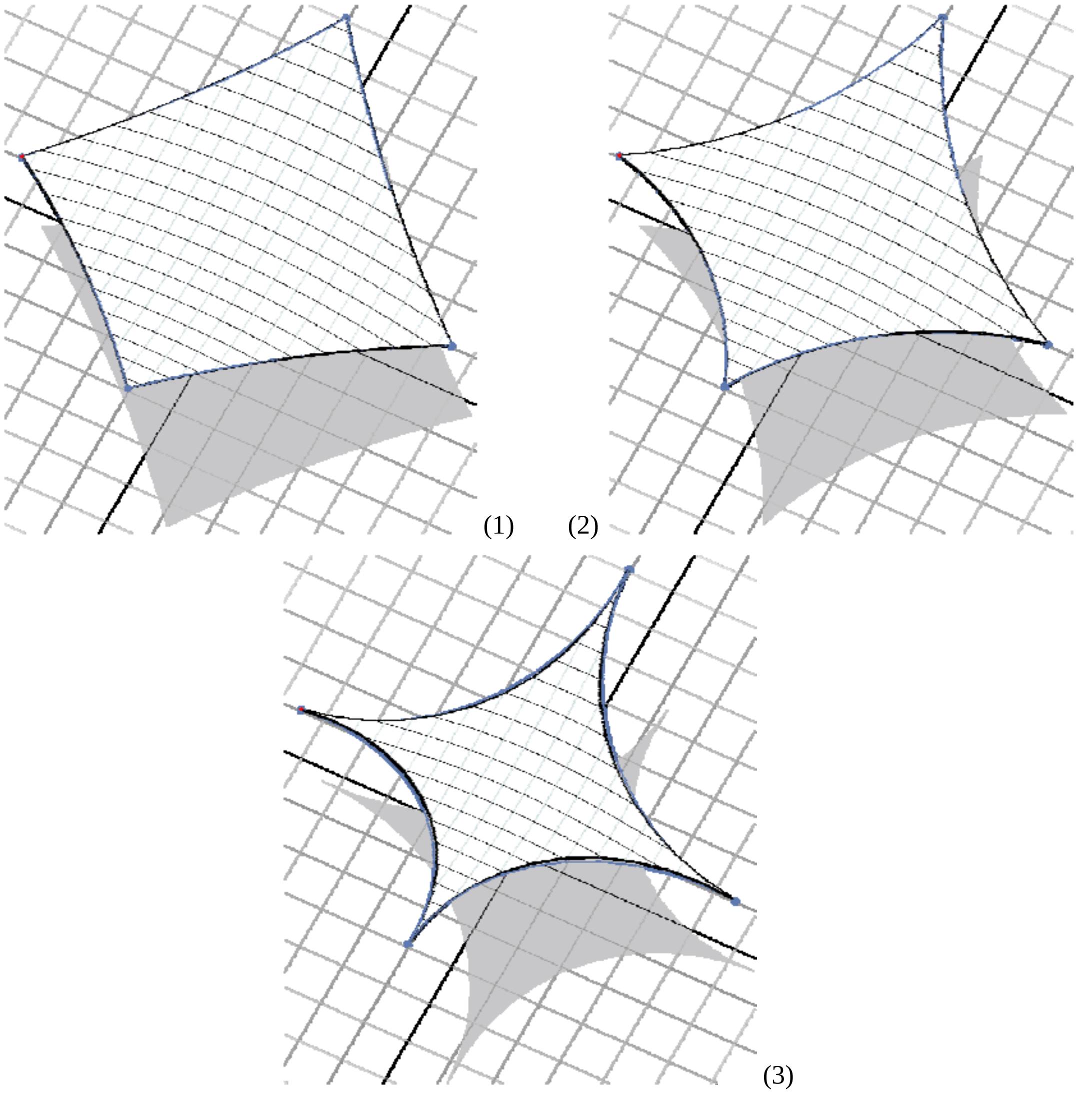

Figure 11. Study 02 – Variation of edge cable curvature
(1) 3%; (2) 10%; (3) 20%

5.3.4 Study 03 – Variation of inclination of guy cables

On basis of the reactions of the standard roof, the angles of the guy cables against the vertical were altered. The study was performed on a high point with following layout:

- Membrane angle $\alpha = -20°$
- Guy cable angle $\beta = -5°$ to $45°$
- Strut inclination $\gamma = 12.5°$
- Internal angle of guying cables $\delta = 40°$

Therefore the angle between the strut and the guy cables varies from 7.5 – 57.5°. For a visualization of the strut layout please refer to Figure 9 in chapter 5.2.2.

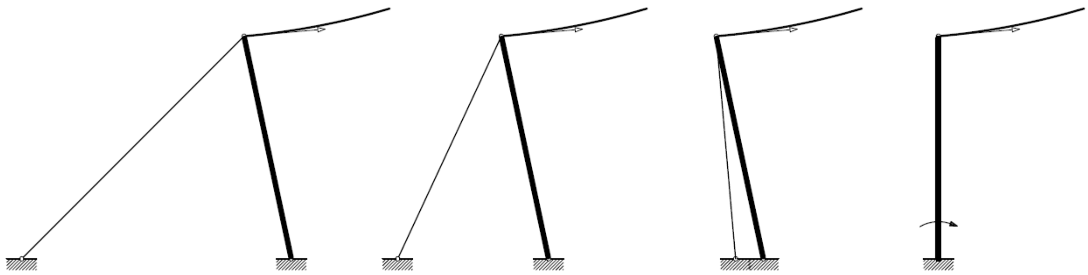

Figure 12. Study 03 – Variation of inclination of guy cables
(1) 45°; (2) 25°; (3) -5°; (4) restraint column

5.3.5 Procedure

Various software packages helped with automated structural calculations. The membrane analysis was conducted with *Formfinder (Formfinder)* and the *EASY* software package *(Technet)*. The steel sections were dimensioned by hand respectively the *RSTAB* software package *(Dlubal)*. Corresponding product catalogues gave dimensions of cables and anchors. The concrete foundations resulted again from hand calculations. The results were listed in spread sheets and assigned with unit prizes.

6 Results

6.1 General

This chapter contains charts and diagrams to visualize the results gained in the conducted studies. The structural analyses were performed with the help of the *EASY* software package which is based on the force density method. This analysis has, as do all other computer aided calculations, a finite accuracy. Due to preset boundary limits within the software, the iterations have been stopped at values considered to be close enough to reality. The graphs in faded colors show the actual calculation results. Some of the graphs seem locally distorted and have dents where a continuous and even progression would be expected and in reality actually is. Reason for this imprecision is the finite accuracy of the computer aided calculations.

For this reason the polygonal graphs in *pale colors* connecting the computed values are superposed with trendlines in corresponding *bold colors*. These are based on polynomial functions[21].

6.2 Study 01

6.2.1 Data analysis

To visualize the effects of altering the membrane curvature the following figure gives an overview of the development of the bearing loads (*red* and *green graphs*) and the forces in the edge cables (*purple graph*). To meet the precondition of avoiding ponding, the prestress (*blue graph*) increases with the diminishing curvature.

[21] To process the data and to calculate the trendlines the spreadsheet software *Microsoft Excel* was used.

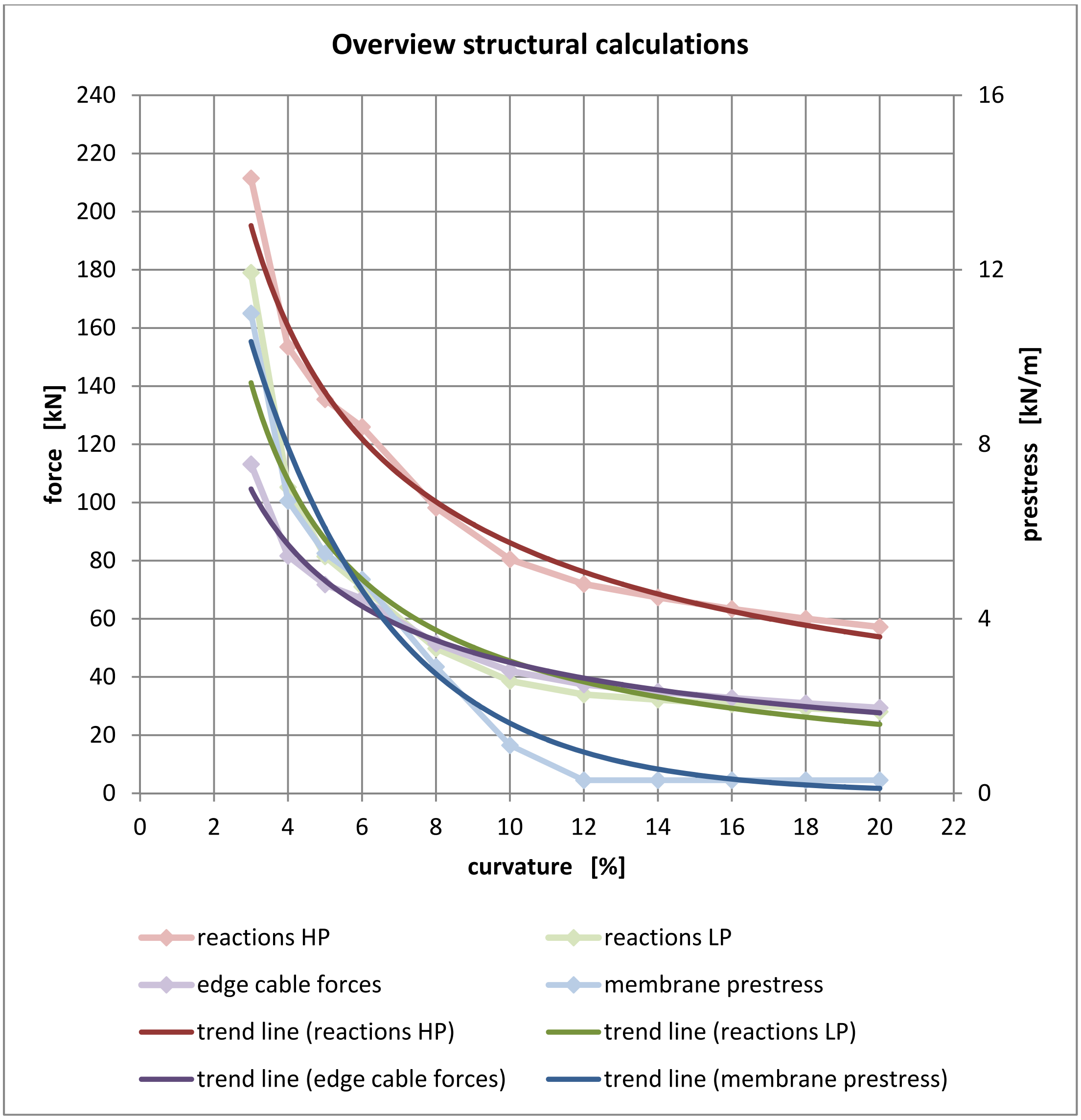

Figure 13. Study 01 – Overview structural calculations

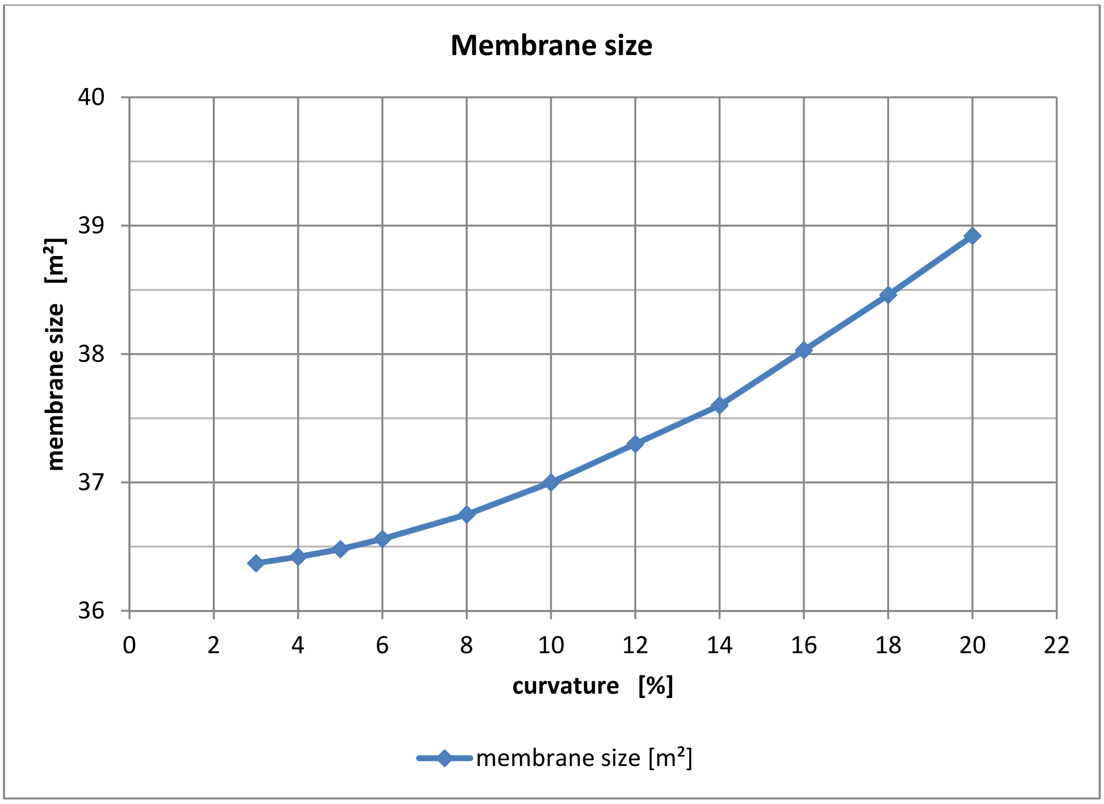

Figure 14. Study 01 – Membrane size

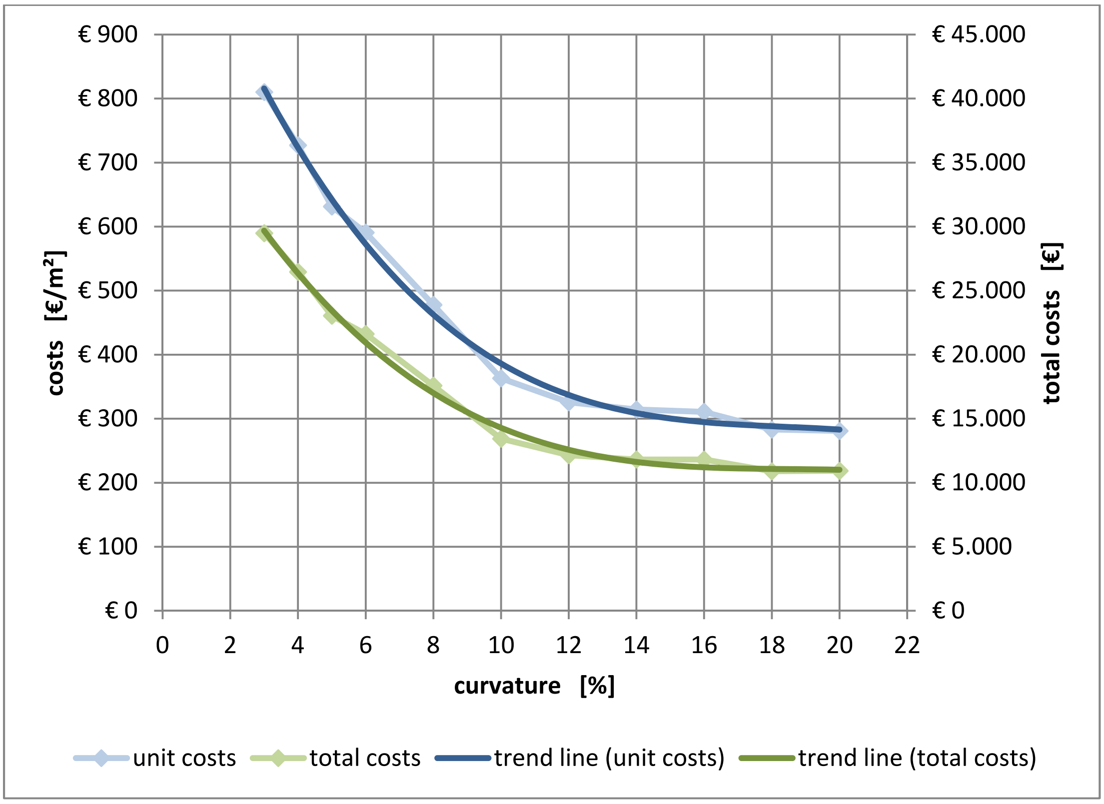

Figure 15. Study 01 – Cost calculation

Analysis of cost shares

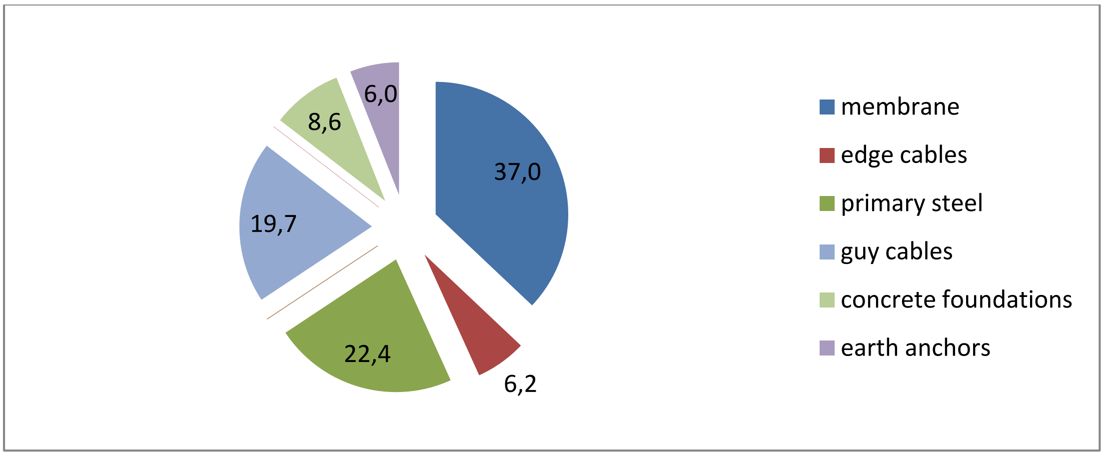

Figure 16. Study 01 – Cost shares; membrane curvature 20%

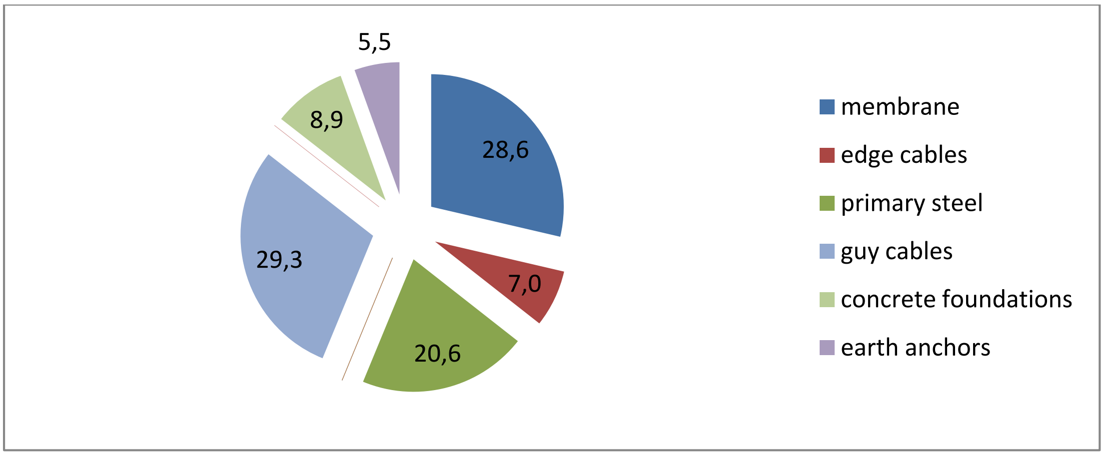

Figure 17. Study 01 – Cost shares; membrane curvature 10% (base geometry)

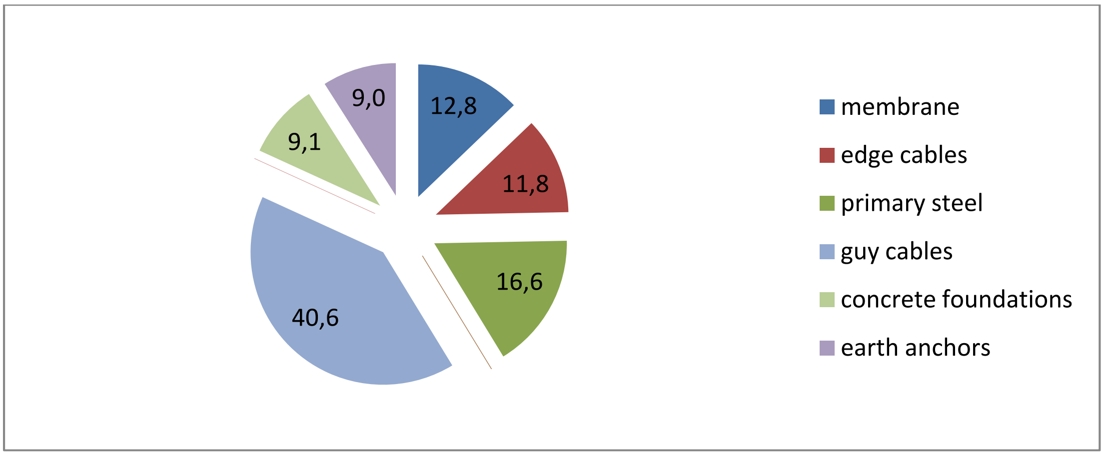

Figure 18. Study 01 – Cost shares; membrane curvature 3%

6.2.2 Interpretation

As generally known, a reduction of membrane curvature causes bigger internal stresses and reaction forces (Figure 13). Taking the standard sail as a point of reference, the results show, when the curvature increases from 10 to 20 percent ($\Delta = 10\%$), the reaction forces decrease only by 25 percent. Almost the same variation occurs when the curvature is reduced from 10 to 8 percent ($\Delta = 2\%$). At the extreme end of the investigated range (curvature = 3%), the reaction forces are 175 percent higher than at the base geometry.

As expected, the less the membrane is curved the higher the total costs grow (Figure 15). The unit costs change almost in parallel to the project costs. Looking at the cost shares of the base sail (Figure 17), the main cuts take membrane, primary steel and guy cables, to almost equal parts. Comparing the three diagrams, the plus on reaction forces with diminishing membrane curvature reflects in increasing cuts of the cables. Although the guy cables gain more importance, even the edge cables take bigger shares. The membrane on the other hand looses significance. While the portion of the concrete foundations remains more or less the same, the percentage of the earth anchors goes with the growth of the anchoring forces. The significantly higher costs for anchors at geometries with low membrane curvature originate from the anchoring system used. On the two most planar roofs, guy cables have to be grounded with two earth anchors each. For this reason these two sails require twice the amount of anchors than all the others. Certainly this has an impact on the total costs.

The total share of the (edge and guy) cables ranges from 26 up to almost 53 percent. Although excluded in the presumptions of this study, the choice of material bears considerate potential for cost optimization. Using cables made of galvanized steel instead of stainless steel could reduce the cable costs by a factor of 2 to 4[22] and hence significantly reduce the total costs especially in structures with high cable forces.

[22] Information provided by *Pfeifer Seil- und Hebentechnik*; depending on cable length, diameters and type of fittings used.

6.3 Study 02

6.3.1 Data analysis

In Study 02 the altered design parameter is the edge cable curvature. Figure 19 summarizes the development of the bearing loads (*red* and *green graphs*) and the edge cable forces (*purple graph*). In contrary to Study 01, here the prestress (*blue graph*) rises with the increasing curvature.

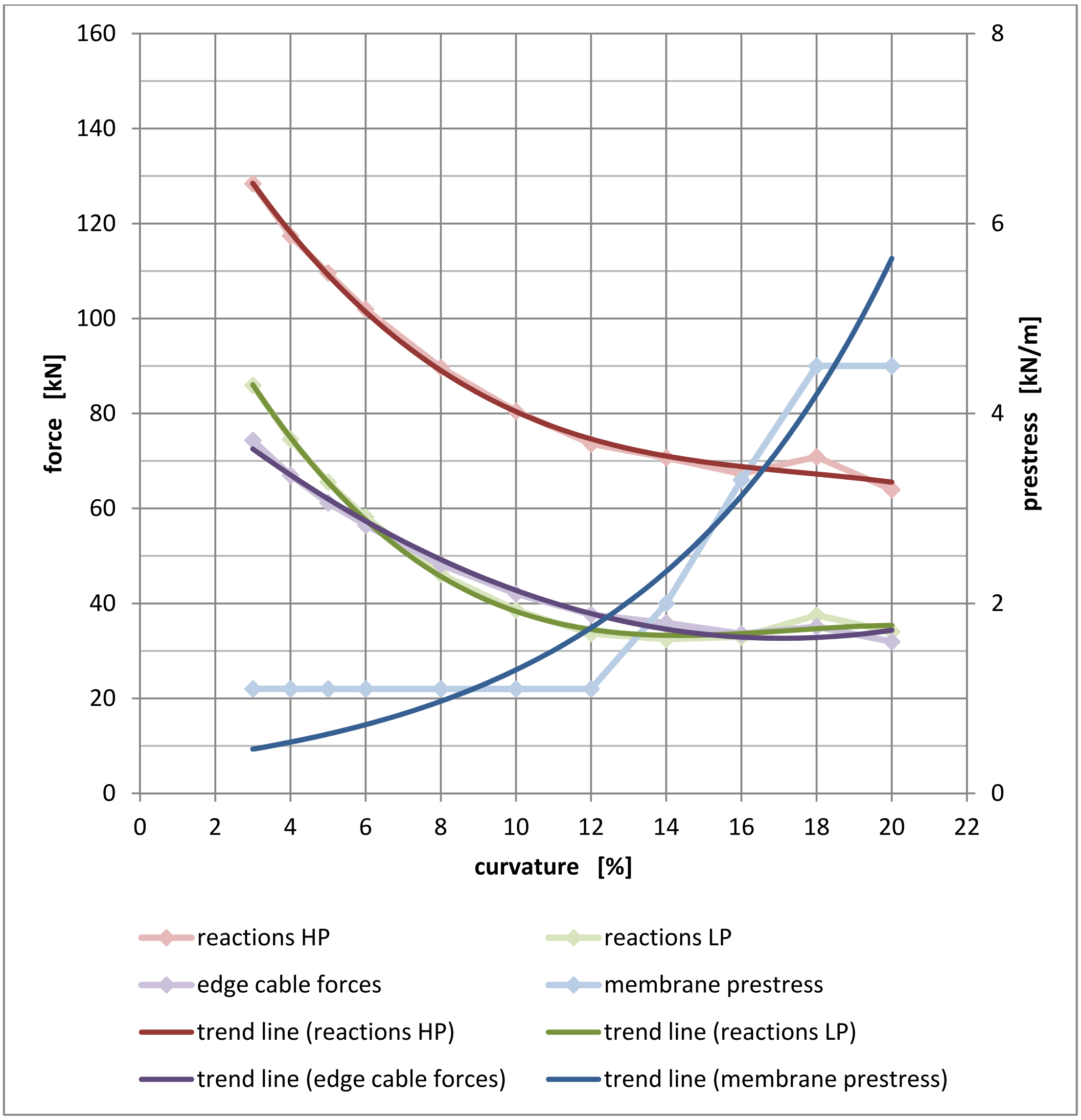

Figure 19. Study 02 – Overview structural calculations

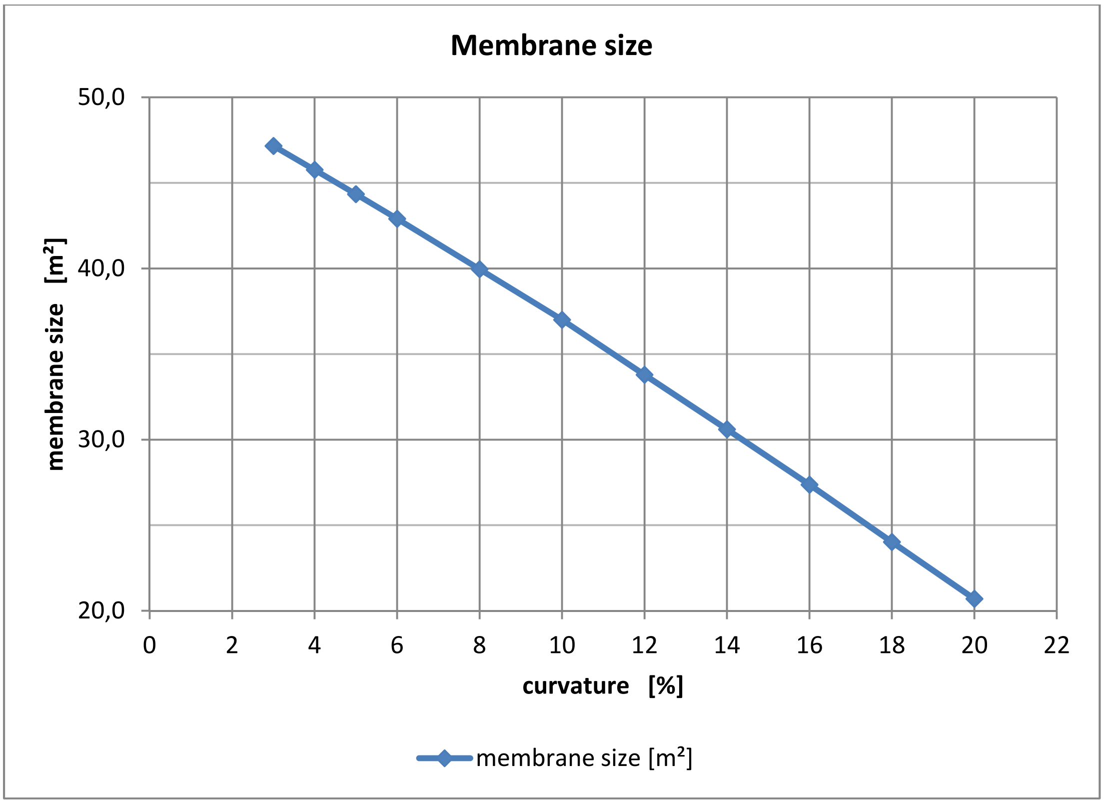

Figure 20. Study 02 – Membrane size

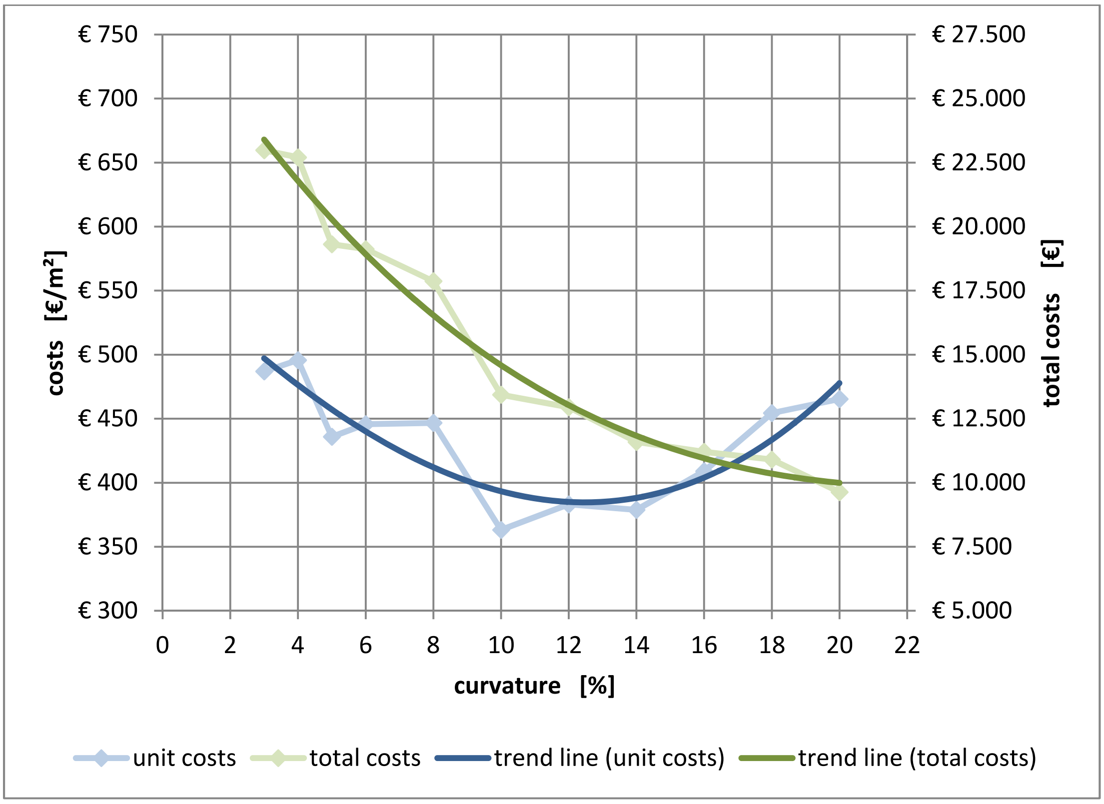

Figure 21. Study 02 – Cost calculation

Analysis of cost shares

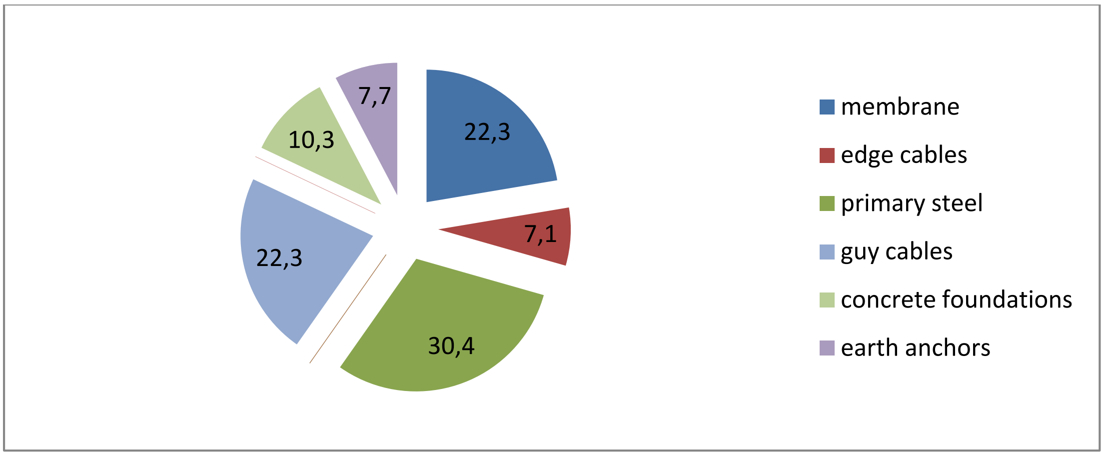

Figure 22. Study 02 – Cost shares; cable curvature 20%

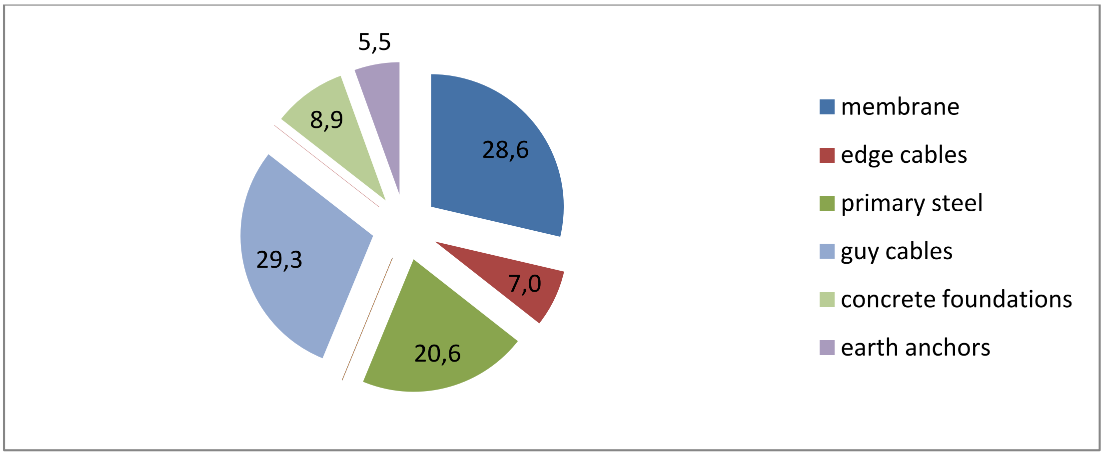

Figure 23. Study 02 – Cost shares; membrane curvature 10% (base geometry)

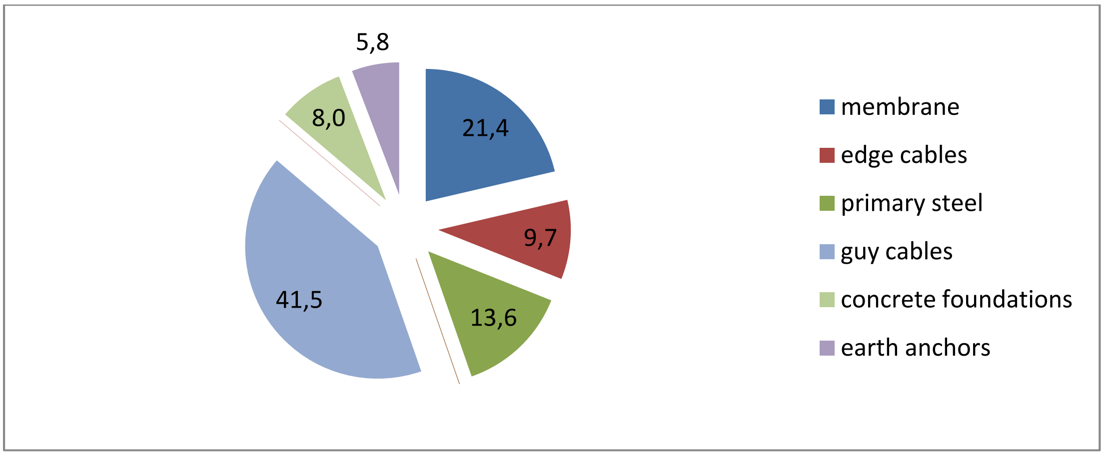

Figure 24. Study 02 – Cost shares; cable curvature 3%

6.3.2 Interpretation

Throughout Study 02 the location of the fixation points remains identical to the base geometry. The most obvious effect of reducing the edge cable curvature is a bigger membrane surface. Furthermore the edge cables become stressed more and consequently the reaction forces increase. Having the same membrane curvature in all models, bigger arch rises at the borders reduce the membrane stresses. As a result the sail requires higher pretensioning the more the edges are curved.

The variation of the edge cable geometry has a major impact on the development of the covered and the membrane surface area (Figure 20). While the progression is almost linear over the whole range, the membrane surface of the biggest sail measures 2.3 times the smallest.

Looking at the data of the structural calculations (Figure 19) the progression of the forces eases at a curvature of about 12 percent and does not vary much until 20 percent. Although the total costs grow from high going to lower edge curvature (caused by higher reactions forces), the development of the unit costs is misleading. Dividing the costs (having a polynomial progression) by the surface area (almost linear development) results in a U-shaped graph. First the unit costs follow the total costs but at 12 percent curvature the chart comes to a turning point. From this point on the unit costs grow again. The reason is the membrane surface decreasing faster than the costs.

In reality this situation is more of a theoretical kind. The roof geometries of the last models (with strong curved edges) do not seem reasonable from an architectural, practical, and economical point of view. In reality strong curved edge cables will be used for architectural reasons or if local stress reduction is required.

While the cost shares of concrete foundations, earth anchors, edge cables, and membrane remain rather constant and even their sum hardly deviates, primary steel and guy cables swap their significance. At strongly curved geometries the steel elements are more authoritative. Once the flexible edge is close to be straight the guy cables exceed the struts.

6.4 Study 03

6.4.1 Data analysis

The following diagram indicates the progression of the strut forces (*blue graph*) respectively the forces in the guy cables (*red graph*) and as a result the required size of concrete foundations (*green graph*).

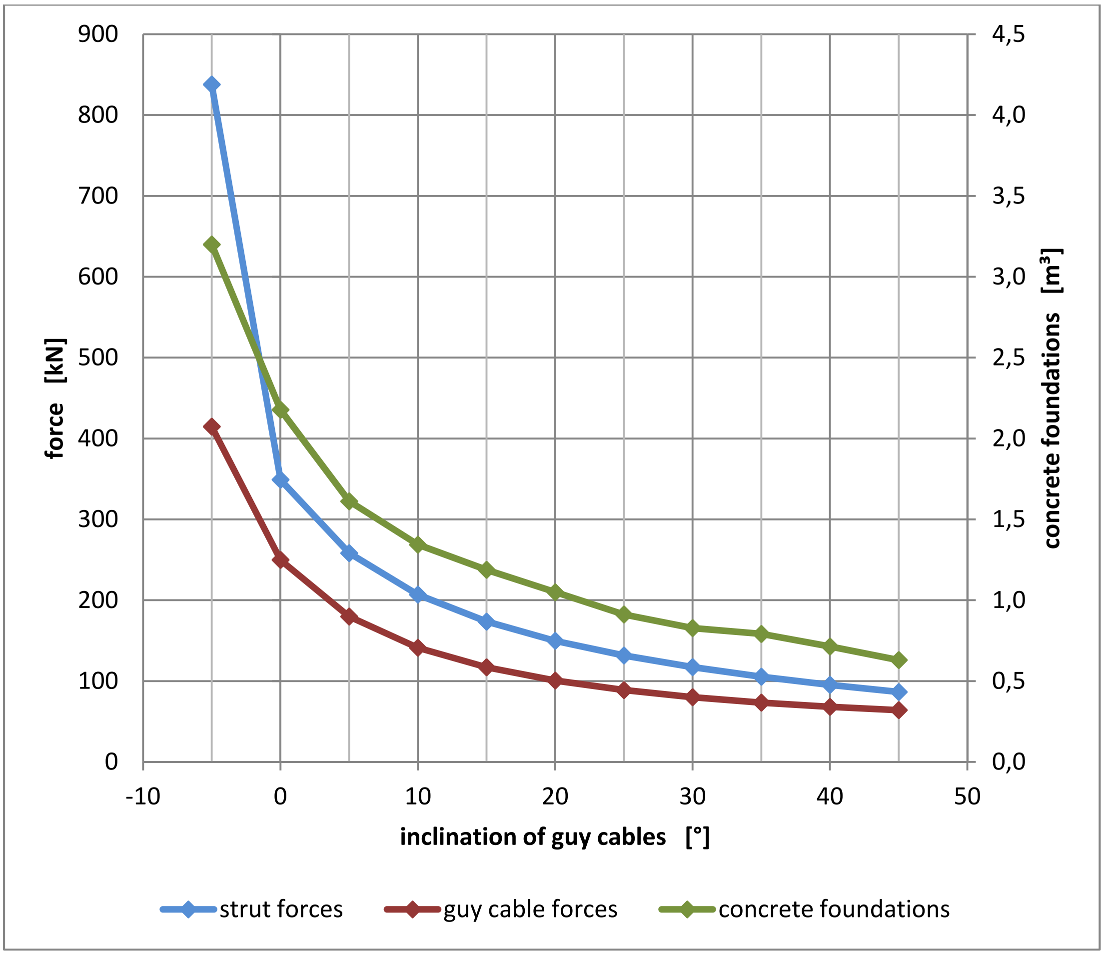

Figure 25. Study 03 – Overview structural calculations

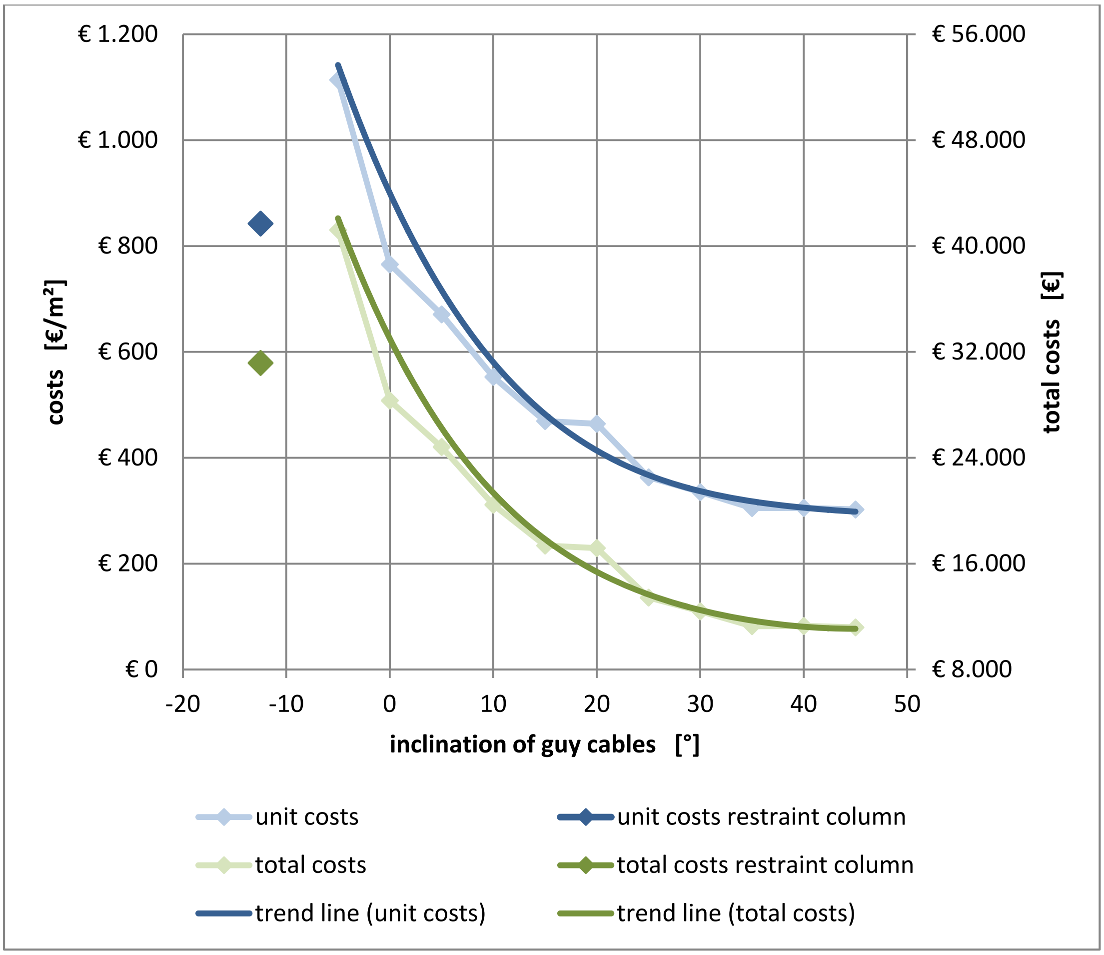

Figure 26. Study 03 – Cost calculation

Analysis of cost shares

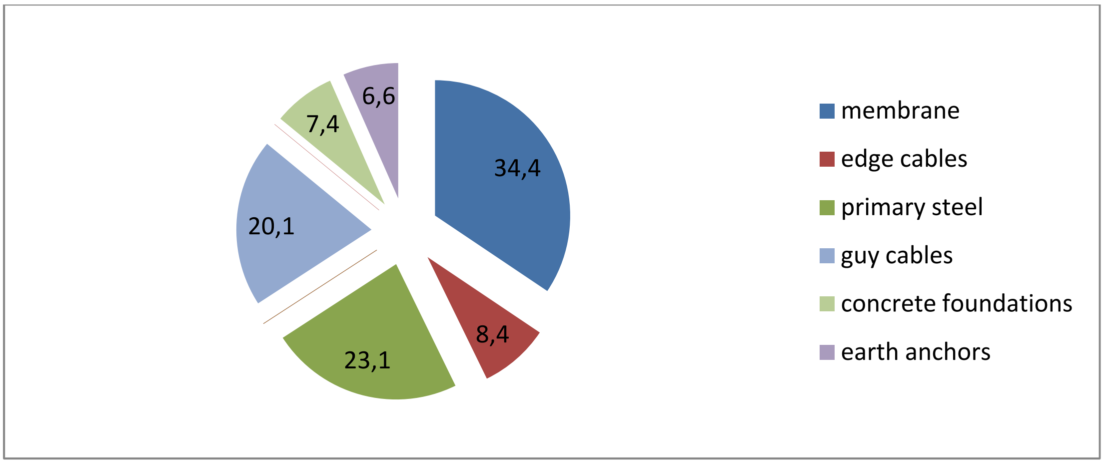

Figure 27. Study 03 – Cost shares; cable inclination β = 45°

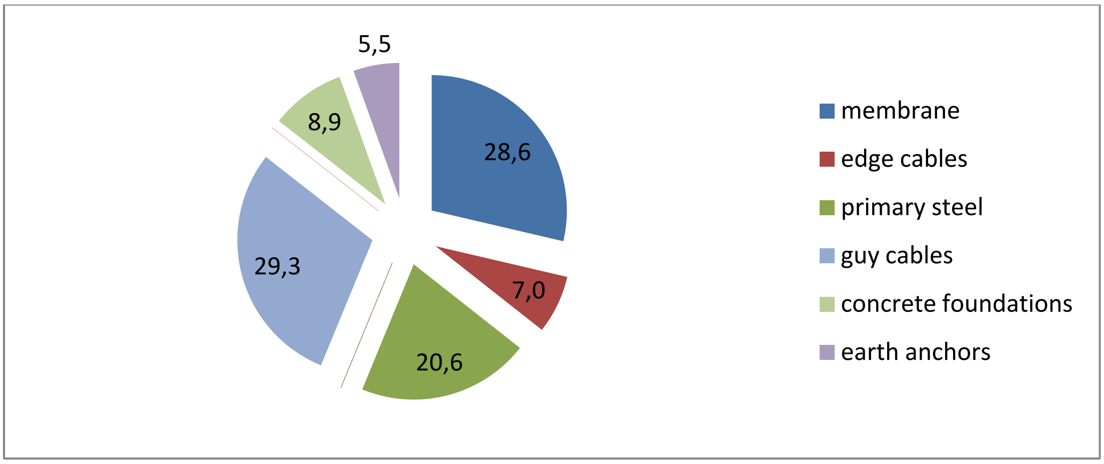

Figure 28. Study 03 – Cost shares; cable inclination β = 25° (base geometry)

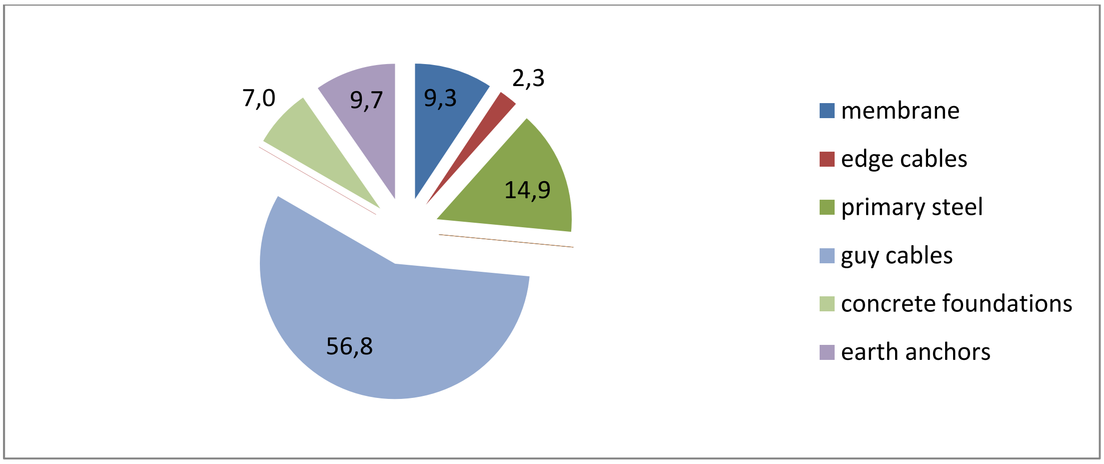

Figure 29. Study 03 – Cost shares; cable inclination β = -5°

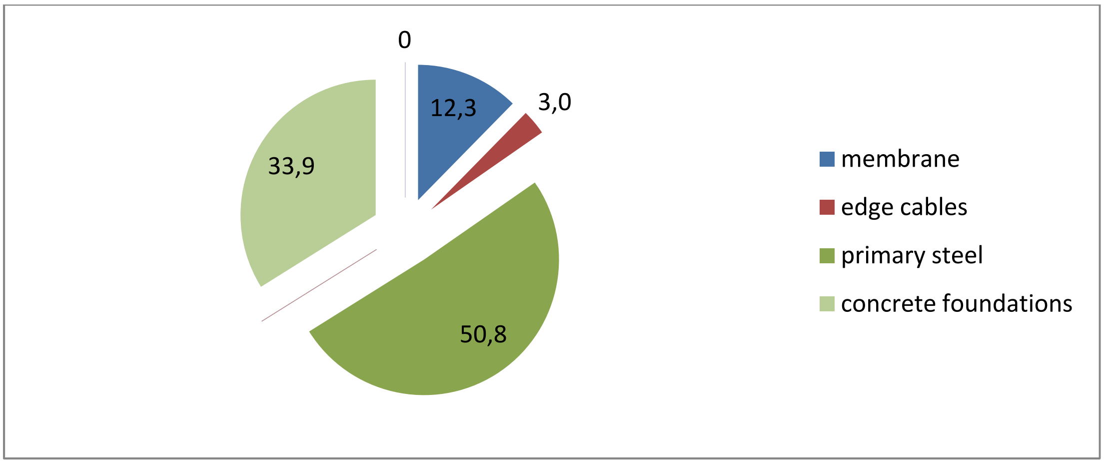

Figure 30. Study 03 – Cost shares; restraint columns; no guy cables

6.4.2 Interpretation

As only the strut and guy cables were considered in this study, Figure 25 only shows the progression of the reaction forces and the corresponding size of the block foundations. The strut is constantly inclined at 12.5°. Therefore the angle between the strut and the guy cables varies from 7.5° to 57.5°. As expected, the smaller the angle, the higher become the reaction forces of guys and struts. In the range from 57.5° to 37.5° the forces develop almost linear. While the investigated inclinations augment in steps of 5°, in this range the internal forces grow by about 10 percent from model to model. From 37.5° up to 7.5° the augmentation is more exponential. The size of the block foundations evolves accordingly.

The effect of a variation of the enclosed angle between guy cables and struts is best seen when related to the costs (Figure 26). The visualization shows a development according to the progression of the forces. The single points on the left give the derived values for a support solution with restraint columns. It is interesting that the costs of sails with very narrow strut-cable-arrangements top the ones of restraint column solution. In this case architectural reasons may still be controlling. At an enclosed angle of 7.5° the required steel profile is a CHS 168.3/6 (buckling stresses authoritative) while the restraint column has to be a CHS 406.4/12 (bending stresses authoritative). As explained in the presumptions the more disadvantageous high point (h = 4m) was dimensioned and taken for all fixation points. The conclusion is that restraint columns are only reasonable up to a certain column length.

The costs certainly mirror the progression of the forces. Looking at the cost shares of $\beta = 45°$ and $\beta = 20°$ the portions of all components are roughly identical. From this point on the guy cable cut scales up rapidly. Evidently the cost shares of the restraint sail solution are controlled by the concrete foundations.

7 Conclusion

7.1 Summary

In building industry every construction is a prototype and designed and built under individual circumstances. Even for comparison of conventional buildings a lot of additional information, besides the pure building data, is needed and has to be taken into account. The complexity and the sensitivity of membrane structures make a comparison of realized projects even more difficult. For this reason this study compared theoretical projects. All designed under the same preconditions including certain simplifications. In this way the consequences of amendments at the geometry appear unfiltered and clear without any external distortion.

The aim was to show the effects of basic design decisions, in terms of structural engineering and cost planning. This thesis only considered the *design phase*. Here the planner can alter just three (geometric) design parameters:

- Location of the fixation points
- Curvature of the membrane and the edges
- Layout of the supporting structure

Three independent design studies were conducted. In each of them one of the mentioned design parameters was varied. The created membrane roofs ran a full predesign. On basis of the found dimensions cost estimations were performed. Charts and diagrams visualized the results for further analysis.

For the purpose of this thesis it was important to make it sizeable how much low curvature would increase the costs of a sail. Further the progress of the cost development was discussed. The research results were visually prepared to help with interpretation. Line diagrams and pie charts illustrated the course of the costs and the cuts of different components on the total costs.

The outcome was that the design phase is the very right moment for important (cost-driving) decisions. Here the designer has a huge influence on the commercial success of a membrane project. These very first decisions on the general design, such as definition of the curvature and the layout of the supporting points, are crucial and have to be very well considered.

All three studies have shown, the total costs progress exponentially correspondent to the development of the reaction forces. One can say, reaction forces and costs are directly proportional. High anchor forces always mean additional costs. Although this correlation has already been commonly known, the progress in absolute values has not been broadly discussed before.

Comparing the costs of the three studies in absolute values (Appendix D) the biggest variations occur at Study 01 and Study 03. The influence of the edge cable curvature (Study 02) is not as significant as the one of the membrane curvature (Study 01) and the layout of the fixation points (Study 03). In both cases, the costs of the most unfavorable solution are about three times higher compared to the one least stressed. Although the lowest costs are nearly the same throughout all studies, the maximum values in Study 01 and 03 top Study 02 by about 40 percent. The conclusion is, to control the costs in design phase membrane curvature and the layout of the fixations are the best parameters to amend.

As well interesting is the shift in the cost shares of the individual building components across the whole research (and across the three studies). The growth on anchoring forces at extreme geometries always requires heavy-duty support elements. The charts of the cost cuts illustrate clearly where the biggest potential for optimization is hidden. Struts, guy cables, and foundations were the cost driving elements in all three studies.

7.2 Perspective / Outlook

When the group around Frei Otto developed *Tra* and *Bic* their main focus was put on the efficiency of the load bearing behavior of any structure, no matter the type of construction. Evidently this approach also allows for conclusions on the cost effectiveness although no such investigation is known of. Their applicability was tested and cross-checked in extensive research over more than two decades. Anyway it never reached the stage of suitability of daily use and remained merely a scientific measure.

The idea for the topic of this thesis is based on the fact that there are plenty of different cost estimation (software) tools for conventional rigid structures on the market. All of them needed a certain degree of detailing for more or less reasonable results. Yet, there is no such tool for form-active structures. Some design guides give advice regarding geometry and detailing based on research and on practical experience. Only the relation to the costs is not discussed in any of those.

Due to the strong influence of the design on the project costs, rough estimations with unit prizes (which should count for general application[23]) could be highly misleading. These structures are too material sensitive for neglecting the one or other component. Thinking (for example) of a hospital building, saving money on one end of the building by choosing cheaper material or amending the design, does not have any influence on the rest of the structure. The shifting of the cost shares will be relatively small, whereas the effect on membrane structures could be substantial.

Presenting first thoughts on this topic at various occasions on international conferences the responses received were always very positive. People of all possible backgrounds (engineers, architects as well as fabricators) expressed their interest and requested further investigations on design parameters and their effects on the project costs. Especially calculations by means of geometry studies were of high interest.

As mentioned in the introduction it is valuable to know about the efficiency of a structure (regarding the load transfer). However in reality the costs are the most authoritative *design parameter*. Very often architecture is driven by the available

[23] Clients usually ask about the costs of a membrane structure even before a first design is sketched. Interviews with professional cost planners have shown, to define generally valid unit costs is hardly possible. Too many parameters influence these values. Therefore everyone who has built a certain amount of membrane structures gathers his own database by post-cost calculations of those projects.

budget. Maximization of profits usually is the main aim. Concerning textile architecture aiming for a cheap solution may not be an issue. Deciding for a membrane roof already implies, an architectural solution is desired for the intended purpose. This means that tensile structures are usually not the cheapest one. Anyhow, regarding sustainable design a meaningful utilization of resources is to aspire at all times.

As mentioned in previous chapters, this thesis should lay the basis for a series of investigations and studies on design parameters and how the optimum costs can be achieved by considerate amendments. The intention is to extend this research to other types of geometries as well as to other stages of the project. This thesis even leaves space for further investigations on the four-point sail. Additional fixation points, rigid edges, use of other materials and products, or special design elements (like loops) are additional design parameters and their effects are interesting for everyone involved in membrane design.

The idea is to collect data and to publish the results in a *real* design guide. In schools design is often seen as a combination of appearance and function of a product. Reality shows that the commercial aspects, costs and return on investment, are at least as important. This design guide should focus on all of these aspects. *The wheel will not be invented anew* but established knowledge will be extended by and associated with new aspects in design.

Furthermore the data gained could be used in a software tool that gives designers an instant cost estimation of the current design. An interactive tool integrated into a design-software for form-active structures[24], would allow for a significant simplification of the calculation process. Reduced complexity increases the understanding of the cost-driving parameters. Furthermore this tool should visualize these cost factors and support designers to keep their own design by providing a set

[24] The author has specific plans to create such a tool in collaboration with *Formfinder*. A first version is already developed but not released yet.

of positive arguments to convince decision makers of the design intention and the design concept.[25]

I believe, comprehensive research on this topic can make a difference. If more and more people involved in membrane design understand the complex relation between design and costs, the number of realized projects will increase. Eventually this could encourage the whole industry and make membrane architecture more common.

[25] Compare Giraldo und Wehdorn-Roithmayr 2011.

8 Bibliography

Bletzinger, Kai-Uwe. *membranes24.com.* Herausgeber: Johannes Linhard und André Lähr. 2008. www.membranes24.com (Zugriff am 1. October 2012).

Engeld, Heino. *Tragsysteme / Structure Systems.* 4. Auflage. Ostfildern, Germany: Hatje Cantz Verlag, 2006.

Forster, Brian, und Marijke Molleart. *European Design Guide for Tensile Surface Structures.* Tensinet, 2004.

Giraldo, Mario, und Robert Wehdorn-Roithmayr. „An Instant Cost-Estimation Tool - Assistance to Designers of Form-Active Structures.“ *Advanced Building Skins.* Graz, Austria, 2012.

—. „Step-by-Step Cost Estimation Tool For Formactive Structures.“ *Membranes 2011*. Barcelona, Spain, 2011.

Höller, Ralf. *FormFindung. Architektonische Grundlagen für den Entwurf von mechanisch vorgespannten Membranen und Seilnetzen.* Mähringen: Verlag Dr. Thomas Balistier, 1999.

Karmasin, Matthias, und Rainer Ribing. *Die Gestaltung wissenschaftlicher Arbeiten.* 6. Auflage. Vienna, Austria: Facultas Verlags- und Buchhandels AG, 2011.

Knippers, Jan, Jan Kremers, Markus Gabler, und Julian Lienhard. *Atlas Kunststoffe + Membranen.* München: Institut für International Architektur-Dokumentation, 2010.

Otto, Frei, und Frieder Klenk. *IL 24 - Lightweight Principle.* Übersetzung: Institute for Lighweight Structures University of Stuttgart. Stuttgart: Karl Krämer Verlag, 1998.

9 List of figures

10 List of appendices

Appendix A. **Study 01 – Calculation results**

model	membrane				edge cables					struts					weight	weight
	[m²]	σ_{pre} [kN/m]	σ_{max} [kN/m]	δ_{max} [m]	N_k [kN]	N_d [kN]	CarlStahl	tot [m]	arch r. [%]	N_k [kN]	N_d [kN]	type	HP [m]	LP [m]	[kg/m]	tot [kg]
m03-c10	36,4	11,0	21,8	0,23	113,2	169,7	d22	29,14	3,00	-331,8	-497,7	CHS 139,7/8	3,38	2,77	26,0	319,8
m04-c10	36,4	6,7	19,9	0,26	81,6	122,5	d18	29,22	4,00	-243,6	-365,4	CHS 139,7/6	3,48	2,66	19,8	243,1
m05-c10	36,5	5,5	19,5	0,24	71,8	107,6	d16	29,32	5,00	-216,5	-324,8	CHS 139,7/5	3,58	2,56	16,6	203,8
m06-c10	36,6	4,9	18,4	0,21	66,9	100,3	d16	29,45	6,00	-202,6	-303,9	CHS 139,7/5	3,69	2,46	16,6	204,2
m08-c10	36,8	2,9	16,7	0,17	51,5	77,3	d14	29,77	8,00	-159,6	-239,4	CHS 114,3/6	3,89	2,25	16,0	196,5
m10-c10	37,0	1,1	14,7	0,23	42,1	63,1	d14	30,17	10,00	-131,7	-197,6	CHS 114,3/5	4,10	2,05	13,5	166,1
m12-c10	37,3	0,3	13,3	0,22	37,4	56,2	d12	30,66	12,00	-118,1	-177,2	CHS 114,3/5	4,30	1,84	13,5	165,8
m14-c10	37,6	0,3	12,2	0,20	34,9	52,4	d12	31,23	14,00	-110,7	-166,1	CHS 114,3/4	4,51	1,64	10,9	134,1
m16-c10	38,0	0,3	9,0	0,19	32,8	49,2	d12	31,87	16,00	-103,9	-155,9	CHS 114,3/4	4,71	1,43	10,9	133,9
m18-c10	38,5	0,3	8,6	0,18	30,9	46,4	d12	32,58	18,00	-98,0	-147,0	CHS 114,3/4	4,92	1,23	10,9	134,1
m20-c10	38,9	0,3	8,3	0,19	29,4	44,1	d12	33,36	20,00	-92,8	-139,2	CHS 114,3/4	5,12	1,02	10,9	133,9

model	guy cables					foundations				anchors		
	N_k [kN]	N_d [kN]	CarlStahl	HP [m]	LP [m]	L [m]	W [m]	H [m]	V [m³]	N_d [kN]	type	pc.
m03-c10	173,4	260,1	d26	3,87	3,17	1,70	1,50	0,80	2,04	260,1	AS200	2
m04-c10	123,9	185,8	d26	3,99	3,05	1,50	1,30	0,80	1,56	185,8	AS200	2
m05-c10	107,9	161,9	d22	4,11	2,94	1,40	1,25	0,80	1,40	161,9	SR1	1
m06-c10	99,1	148,7	d22	4,23	2,82	1,40	1,20	0,80	1,34	148,7	AS200	1
m08-c10	74,9	112,4	d18	4,46	2,58	1,30	1,05	0,80	1,09	112,4	AS200	1
m10-c10	59,3	88,9	d16	4,70	2,21	1,20	0,95	0,80	0,91	88,9	MR1	1
m12-c10	51,1	76,7	d14	4,93	2,11	1,15	0,90	0,80	0,83	76,7	MR1	1
m14-c10	46,1	69,2	d14	5,17	1,88	1,10	0,90	0,80	0,79	69,2	MR1	1
m16-c10	41,6	62,4	d14	5,40	1,64	1,10	0,85	0,80	0,75	62,4	MR1	1
m18-c10	37,8	56,7	d12	5,64	1,41	1,05	0,85	0,80	0,71	56,7	MR2	1
m20-c10	34,4	51,6	d12	5,87	1,17	1,05	0,85	0,80	0,71	51,6	MR2	1

notation of models	
m10-c10	membrane 10% curvature
m10-**c10**	edge cable 10% curvature
m10-c10	standard sail

Appendix B. **Study 02 – Calculation results**

model	membrane				edge cables					struts					weight	weight
	[m^2]	σ_{pre} [kN/m]	σ_{max} [kN/m]	δ_{max} [m]	N_k [kN]	N_d [kN]	Pfeifer type	CStahl type	tot [m]	N_k [kN]	N_d [kN]	type	HP [m]	LP [m]	[kg/m]	tot [kg]
m10-c03	47,2	1,1	11,5	0,36	74,4	111,6	PE 20	d18	29,46	-210,7	-316,1	CHS 139,7/5	4,10	2,05	16,6	204,2
m10-c04	45,8	1,1	11,5	0,31	67,0	100,5	PE 20	d18	29,52	-192,6	-288,9	CHS 139,7/5	4,10	2,05	16,6	204,2
m10-c05	44,3	1,1	11,5	0,30	61,2	91,8	PE 20	d16	29,59	-179,7	-269,6	CHS 139,7/5	4,10	2,05	16,6	204,2
m10-c06	42,9	1,1	12,7	0,25	56,5	84,7	PE 15	d16	29,68	-167,1	-250,7	CHS 114,3/6,3	4,10	2,05	16,8	206,6
m10-c08	40,0	1,1	13,4	0,22	48,2	72,3	PE 15	d14	29,89	-146,9	-220,4	CHS 114,3/6,3	4,10	2,05	16,8	206,6
m10-c10	37,0	1,1	14,7	0,23	42,1	63,1	PE 15	d14	30,17	-131,7	-197,6	CHS 114,3/5	4,10	2,05	13,5	166,1
m10-c12	33,8	1,1	13,9	0,19	37,6	56,4	PE 10	d12	30,51	-120,4	-180,6	CHS 101,6/6,3	4,10	2,05	14,8	182,0
m10-c14	30,6	2,0	14,6	0,16	35,9	53,8	PE 10	d12	30,91	-115,4	-173,1	CHS 101,6/6,3	4,10	2,05	14,8	182,0
m10-c16	27,4	3,3	16,2	0,11	33,6	50,4	PE 10	d12	31,36	-109,6	-164,4	CHS 101,6/6,3	4,10	2,05	14,8	182,0
m10-c18	24,0	4,5	19,1	0,09	35,2	52,7	PE 10	d12	31,87	-115,3	-173,0	CHS 101,6/6,3	4,10	2,05	14,8	182,0
m10-c20	20,7	4,5	15,9	0,09	32,0	47,9	PE 10	d12	32,44	-103,9	-155,9	CHS 101,6/6,3	4,10	2,05	14,8	182,0

model	guy cables			high	low	foundations				anchors		
	N_k [kN]	N_d [kN]	CStahl type	tot [m]	tot [m]	L [m]	W [m]	H [m]	V [m^3]	N_d [kN]	type	pc.
m10-c03	92,1	138,1	d22	4,70	2,21	1,45	1,20	0,80	1,39	138,1	AS200	1
m10-c04	84,5	126,7	d22	4,70	2,21	1,40	1,15	0,80	1,29	126,7	AS200	1
m10-c05	79,3	119,0	d18	4,70	2,21	1,35	1,10	0,80	1,19	119,0	AS200	1
m10-c06	73,9	110,9	d18	4,70	2,21	1,30	1,10	0,80	1,14	110,9	AS200	1
m10-c08	65,6	98,4	d18	4,70	2,21	1,25	1,00	0,80	1,00	98,4	AS200	1
m10-c10	59,3	88,9	d16	4,70	2,21	1,20	0,95	0,80	0,91	88,9	MR1	1
m10-c12	54,3	81,4	d16	4,70	2,21	1,15	0,95	0,80	0,87	81,4	MR1	1
m10-c14	52,8	79,2	d14	4,70	2,21	1,15	0,90	0,80	0,83	79,2	MR1	1
m10-c16	51,0	76,5	d14	4,70	2,21	1,10	0,90	0,80	0,79	76,5	MR1	1
m10-c18	53,8	80,7	d14	4,70	2,21	1,15	0,90	0,80	0,83	80,7	MR1	1
m10-c20	48,9	73,3	d12	4,70	2,21	1,10	0,85	0,80	0,75	73,3	MR1	1

notation of models	
m10-c10	membrane 10% curvature
m10-**c10**	edge cable 10% curvature
m10-c10	standard sail

Appendix C. **Study 03 – Calculation results**

model	fixation layout				struts					weight	weight	guy cables				
	α [°]	β [°]	γ [°]	δ [°]	N_k [kN]	N_d [kN]	type	HP [m]	LP [m]	[kg/m]	tot [kg]	N_k [kN]	N_d [kN]	CarlStahl	HP [m]	LP [m]
m10-c10	-20,1	-5,0	12,5	20,0	558,5	837,8	CHS 193,7/8	4,10	2,05	36,6	450,2	276,5	414,7	2x d26	4,26	2,13
m10-c10	-20,1	0,0	12,5	20,0	232,7	349,1	CHS 168,3/6	4,10	2,05	24,0	295,2	166,6	249,9	2x d18	4,26	2,13
m10-c10	-20,1	5,0	12,5	20,0	172,2	258,3	CHS 139,7/8	4,10	2,05	19,8	243,5	119,9	179,9	d26	4,27	2,14
m10-c10	-20,1	10,0	12,5	20,0	138,0	207,0	CHS 139,7/5	4,10	2,05	16,6	204,2	94,2	141,3	d22	4,32	2,16
m10-c10	-20,1	15,0	12,5	20,0	115,7	173,6	CHS 139,7/4	4,10	2,05	13,4	164,8	78,1	117,1	d18	4,41	2,20
m10-c10	-20,1	20,0	12,5	20,0	99,9	149,8	CHS 139,7/4	4,10	2,05	13,4	164,8	67,1	100,7	d18	4,53	2,26
m10-c10	-20,1	25,0	12,5	20,0	87,8	131,7	CHS 114,3/5	4,10	2,05	13,5	166,1	59,3	88,9	d16	4,70	2,35
m10-c10	-20,1	30,0	12,5	20,0	78,2	117,3	CHS 114,3/5	4,10	2,05	13,5	166,1	53,4	80,1	d14	4,92	2,46
m10-c10	-20,1	35,0	12,5	20,0	70,3	105,5	CHS 114,3/4	4,10	2,05	10,9	134,1	48,9	73,4	d12	5,20	2,60
m10-c10	-20,1	40,0	12,5	20,0	63,6	95,4	CHS 101,6/5	4,10	2,05	11,9	146,4	45,5	68,2	d12	5,56	2,78
m10-c10	-20,1	45,0	12,5	20,0	57,7	86,6	CHS 101,6/5	4,10	2,05	11,9	146,4	42,7	64,1	d12	6,02	3,01
m10-c10	restraint				-43,5	-65,2	CHS 406,4/12	4,10	2,05	116,7	1435,4					

model	fixation layout				foundations				anchors		
	α [°]	β [°]	γ [°]	δ [°]	L [m]	W [m]	H [m]	V [m^3]	N_d [kN]	type	pc.
m10-c10	-20,1	-5,0	12,5	20,0	2,0	2,0	0,8	3,2	414,7	AS200	3,0
m10-c10	-20,1	0,0	12,5	20,0	1,7	1,7	0,8	2,2	249,9	AS200	2,0
m10-c10	-20,1	5,0	12,5	20,0	1,6	1,3	0,8	1,6	179,9	SR1	1,0
m10-c10	-20,1	10,0	12,5	20,0	1,4	1,2	0,8	1,3	141,3	AS200	1,0
m10-c10	-20,1	15,0	12,5	20,0	1,4	1,1	0,8	1,2	117,1	AS200	1,0
m10-c10	-20,1	20,0	12,5	20,0	1,3	1,1	0,8	1,1	100,7	AS200	1,0
m10-c10	-20,1	25,0	12,5	20,0	1,2	1,0	0,8	0,9	88,9	MR1	1,0
m10-c10	-20,1	30,0	12,5	20,0	1,2	0,9	0,8	0,8	80,1	MR1	1,0
m10-c10	-20,1	35,0	12,5	20,0	1,1	0,9	0,8	0,8	73,4	MR1	1,0
m10-c10	-20,1	40,0	12,5	20,0	1,1	0,9	0,8	0,7	68,2	MR1	1,0
m10-c10	-20,1	45,0	12,5	20,0	1,1	0,8	0,8	0,6	64,1	MR1	1,0
m10-c10	restraint				4,0	2,0	1,0	8,0			

notation of models	
m10-c10	membrane 10% curvature
m10-**c10**	edge cable 10% curvature
m10-c10	standard sail

Appendix D. **Cost estimations**

Although the costs used in this study are based on a market research (in Austria), the accuracy of the used costs for the individual construction components is secondary. All cost estimations are based on the same unit costs and eventually the derived cost variations are compared and analyzed in qualitative measures. Though the gained costs were checked for plausibility, the absolute values only count for the sail used under the assumed preconditions on the Austrian market.

Considered unit costs

- Membrane material (PVC/Poly.) + manufacturing — € 80,-/m^2
- Primary steel (CHS, S235) + manufacturing — € 8,-/kg
- Steel plates (S235) + manufacturing — € 5,-/kg
- Concrete block foundations (C25/30) + reinforcement + excavation + no formwork — € 300,-/m^3

Prizes of cables (CarlStahl) and anchors (Manta Ray dealership) are taken from standard prizing catalogues (no special discounts included).

Results

Study 01		
sail type	[€]	[€/m²]
m20-c10	€ 10.926	€ 281
m18-c10	€ 10.894	€ 283
m16-c10	€ 11.807	€ 311
m14-c10	€ 11.818	€ 314
m12-c10	€ 12.146	€ 326
m10-c10	€ 13.436	€ 363
m08-c10	€ 17.584	€ 478
m06-c10	€ 21.620	€ 591
m05-c10	€ 23.044	€ 631
m04-c10	€ 26.468	€ 727
m03-c10	€ 29.490	€ 810

Study 02		
sail type	[€]	[€/m²]
m10-c20	€ 9.633	€ 465
m10-c18	€ 10.904	€ 454
m10-c16	€ 11.205	€ 409
m10-c14	€ 11.591	€ 379
m10-c12	€ 12.949	€ 383
m10-c10	€ 13.436	€ 363
m10-c08	€ 17.871	€ 447
m10-c06	€ 19.122	€ 446
m10-c05	€ 19.310	€ 436
m10-c04	€ 22.705	€ 496
m10-c03	€ 22.983	€ 487

Study 03		
sail type	[€]	[€/m²]
β=45°	€ 11.186	€ 302
β=40°	€ 11.292	€ 305
β=35°	€ 11.279	€ 305
β=30°	€ 12.397	€ 335
β=25°	€ 13.436	€ 363
β=20°	€ 17.180	€ 464
β=15°	€ 17.365	€ 469
b=10°	€ 20.448	€ 553
β=5°	€ 24.821	€ 671
β=0°	€ 28.320	€ 765
β=-5°	€ 41.211	€ 1.114
restraint	€ 31.163	€ 842