DESIGN STRATEGIES FOR MEMBRANE STRUCTURES IN TROPICAL CLIMATES

Master-thesis by Jan-Frederik Flor

IMS e.V.

Design strategies for membrane structures in tropical climates

Master-Thesis

A thesis submitted in partial fulfillment
of the requirements for the degree of

Master Membrane Structures

submitted to

Anhalt University of Applied Sciences

Faculty of Architecture,
Facility Management and Geo Information

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Submission date: 11. 03. 2016

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Statement

I hereby declare that the work presented in this Master thesis, entitled

„Design strategies for membrane structures in tropical climates"

is entirely my own and that I did not use any sources or auxiliary means other than those referenced.

To my beloved tropics

Abstract

The aim of this thesis is to identify design strategies for semi-open membrane structures which have the potential to improve thermal comfort conditions in tropical climates. The first part of the study analyses the characteristic tropical climate conditions and relates them to the concept of thermal comfort and its defining parameters. An overview of the development and use of membrane structures in the tropical regions is outlined. In the second part the climatic elements which are relevant to thermal comfort are addressed with specific design strategies. The strategies are presented by means of theoretic descriptions of the underlying physical principles and further exemplified by schematic diagrams and drawings, outlining different analysis tools and design solutions for geometries and details of typical building practice. The effectiveness and relevance of each strategy regarding the impact on the improvement of thermal comfort is put in evidence by means of bibliographic research and the presentation of different case studies. The research concludes that passive design strategies applied on membrane structures are an important tool in order to enhance thermal comfort conditions in the tropics and argues for an adaptive approach towards a climate responsive design .

Keywords: membrane-structures, tropical climate
thermal comfort, design

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1. Introduction

Tensioned Membrane structures have undergone a rapid and successful development around the world over the last 50 years. In basically all parts of the world, as well as in the tropics, membrane structures have been built since the initiative of Frei Otto and his surrounding architect/engineer community in the fifties of the last century. The diffusion of the knowledge on how to design these structures combined with the large scale industrialization of membrane materials have lead to a global spreading of lightweight, and especially membrane construction. Some cultural regions where already intensely linked through their building history to membrane structures. Other cultures which had given up their nomadic live where about to reintroduce this building technology for large scale sports or cultural events. But only since the mid of the last century fabric structures have gained in popularity as the building system evolved and allowed to fulfill established building standards and to comply with the requirements for permanent and secure buildings.
Traditionally, and this can also be owed to Otto's approach, architects and engineers who deal with tensile structure are most of the time concerned with finding the correct form and calculating its structural behavior. The Visual impact and spacial impressions of membrane structures have also always played a strong role. They are naturally at-

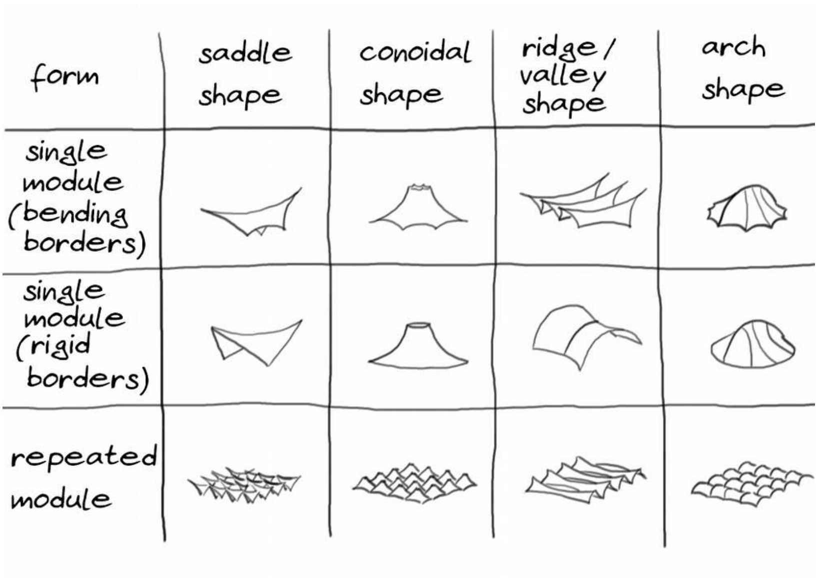


Fig. 1. Typology of basic membrane structure geometries

tractive as they remind with their organic forms and light presence on nature itself. (fig. 1)

Anyhow, the climatic behavior and the comfort which these structures can potentially provide has been notoriously neglected during the development of the modern membrane structures, even though historically its primer function was to protect its users/inhabitants from the wind, rain, sun and cold. The problem of the environmental behavior of membrane structures has been assumed to be solved either by the development of high-tech materials, provided by the producing industry, or by the application of mechanical conditioning systems which

allow for a high degree of freedom in design, but on the turn side require a lot of energy.
In the tropics the protection against rain and sun has traditionally been solved by means of nature. Natural materials like trees, branches and leafs have been converted to roofs and shelters by the indigenous inhabitants. The umbrella is one of the modern must-haves-everyday-gadgets when living in the tropics; protection from sun and rain is essential. Therefore it is only logical to build with fabrics in the tropics. A light skin, allowing for natural ventilation, providing shade and protecting from heavy rain, is what's required in the tropics. But, as it has happened with other technologies which were been developed in western countries of the northern hemisphere, they can not only be taken from

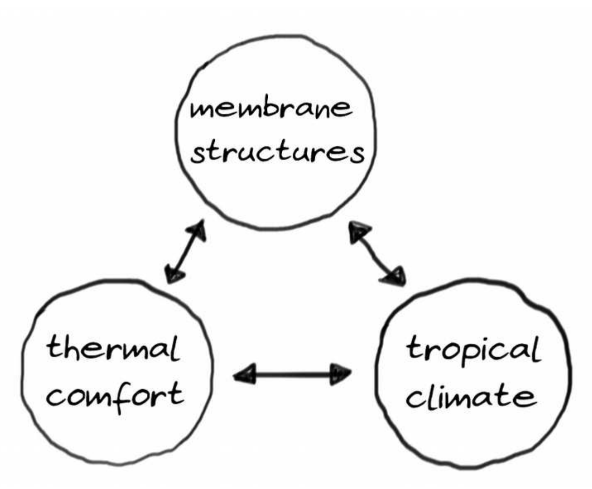


Fig. 2 Concept diagram

one point of the world and put into another. A process of modification is indispensable in order to adapt the technology to the cultural, financial, natural and also to climatic realities of the place where it is thought to be used. This proposal for a master thesis aims to be one step-stone in the process of this adaptation process of technology; in specific the climatic adaptation of membrane structures to the tropical regions. (fig. 2)

1. 1 Research Problem

How can membrane structures be designed in a way that they not only adapt, but further use the climatic elements as a resource to enhance positive comfort conditions in tropical climates ?

1. 2 Justification

A large percentage of the human population lives in tropical environments and has always been dealing with the special climate conditions of the tropics. Sun, wind and rain are the climatic elements which have the most influence on tropical climate, which is in general thermally very constant, but can sometimes provoke extreme whether conditions. Intense solar radiation, high humidity levels and heavy rain in the monsoon season combined with thunderstorms and strong winds have a huge impact on human activities and need to be addressed in the design of the built environment. In the advent of climate change these phenomena get even more intense and a mind-change regarding the relation

between human being and the natural environment has already happened over the last years. But still more action has to be taken and solutions for a sustainable future need to be addressed, not only by grass-root movements, politics and the industry, but also and especially by architects, engineers and designers who hold many of key positions when it comes to making decisions regarding how our built world will look like and how it will work in relation to nature.
in that sense the proposal of this master-thesis aims at providing basic guidelines which will help to take decisions for the design of membrane structures in the tropical climate in order to provide comfortable thermal conditions for the human activities without creating negative environmental impacts and dependencies on energy supplies.

1. 3 Hypothesis

The hypothesis resulting from the previous argument is that the relevant climatic parameters of the tropical climates, which are mainly responsible for the human comfort, can be addressed design vice with membrane structures.. By studying the conditions of tropical climates and exploring the thermal behavior of tensile membrane structures it will become possible to derivate design principles which can help to create comfortable thermal conditions.. The investigation seeks to determine in a qualitative approach if climate itself can be understood as a potential resource for the informed design process of membrane structures and in addition, which are the relating design principles necessary to convert them into true climate modifiers.

1. 4 Objective

The aim of the proposed research is to investigate tensioned membrane structures in regard to their climatic performance in tropical regions in order to propose design strategies, based on passive and bioclimatic principles that have the potential to enhance a positive thermal comfort condition, and can be used by architects and engineers in the early design stage of membrane projects.

1. 5 Specific Objects

- Investigate the phenomena of the tropical climates and identify elements and processes which affect the human comfort.

- Identify design strategies that have the potential to transform membrane structures into climate modifiers which have the ability to create positive higro-thermal conditions.

- Draft a series of design principles which enable architects and engineers to take decisions about climatic adaptation in the early design stage for membrane structures in the tropics.

1. 6 Literature Review /state of the art

The current state of the art regarding the use of passive strategies or bioclimatics in the design of membrane structures is not easy to be clearly identified, because very little about this topic has been published. The information regarding specific projects is held by private companies and is therefore mostly not available to the public. Although the project descriptions in many books and magazines which include membrane structures make almost always reference to „natural„ or „environmental„ construction, almost no documentation can be found regarding the techniques or design decisions which have been taken to achieve a better thermal comfort or energy performance. A few bigger projects like the Millennium Dome, or the new Bangkok airport include documentation of the simulations and performance assumption from the design stages, but realistic data from on-site measurements and long-term studies in order to compare the design intentions with the actual outcome are almost not available.

Harvie and Devuldner have both delivered comprehensive work on the thermal behavior of membrane structures in maritime climates of northern Europe. Thermal models were proposed and validated with on site measurements of some structures. Effects like thermal stratification, condensation and solar radiation in relation to the geometry have been covered. This approach is based on a scientific methodology, limited to the analysis of the physical processes which define the thermal behavior of spaces enclosed by membrane structures.

The ILEK in Stuttgart has also published various studies on the thermal behavior of membrane structures, especially on the development of multi-layered membrane systems and their insulating properties and behavior. Their approach is more design orientated. Several studies deal with the development of new building skin systems of multi-layered facade or roof elements. The design, simulation and further validation through tests on prototypes is essential to their research method.

Another author who has been dealing in her research particularly with the morphology of membrane structures as a design resource for modifying climatic conditions, is ElNokaly. She published several studies on the possibilities of climatic conditioning by passive means. While her studies focused on the climatic conditions of hot-arid climates, the methodological approach can possibly be translated to similar studies on the tropical climate.

However, besides a few more articles and publications about shading roofs in hot climatic regions and general climatic effects on membrane structures, from authors like Goldsmith, Pöppinghaus and Mollaert, almost no specific documentation on the climatic behavior of membrane structures is available in the common information repositories of the membrane world.

In other branches of architecture and engineering this seems to be a different story. As scarce as the available information on climatic behavior of

membrane structures is, as vast is the amount of books and articles on bioclimatic-, environmental, ecological- or as well sustainable architecture. Since the 70's of the last century various design guides for architectural design have been published all over the world for different climatic regions. Olgay, Koenigsberger, van Lengen, Neila, Serra, Yeang and Gut, to name only a few, have published design guides with a strong orientation towards climate, as a source of information for architectural design. With a few exceptions they all based their concepts on the tradition of vernacular architecture. Concepts of traditional architecture of ancient cultures were studied and then translated to modern building systems and requirements. The general design strategies presented are pretty basic, but combined with state of the art analysis tools, they can lead to design solutions with enormous efficiency and sophistication. Examples of this vernacular design concept approach in combination with digital simulation tools can be found in many publications of the vanguard architectural schools of the world.
Also governmental initiatives have let to the publication of a number of design guides and recommendations for climate adapted architectural design. The Australian government, as well as some Latin American countries within the tropical region have created general design guides which are available to the public.
Even though almost no direct information regarding the specific topic of this master-thesis is available,

it can be resumed that a lot of associated information was found which can be analyzed, filtered and the information adapted and further developed in order to respond to the research questions of this master-thesis.

1. 7 Research Methodology

The proposed investigation is based on a bibliographic research methodology. Resources and findings of the investigation are presented in text, conceptual drawings, diagrams and tables. The theoretical approach is based upon the bio-climatic or environmental design theory, introduced originally by Victor Olgay and other authors. This establishes a strong relation and correspondence between climate, thermal comfort and architectural design.

Physical principles of meteorological phenomena in the tropics, that affect the human comfort, are identified and addressed by passive strategies of climate control that already are proven technology in traditional building systems. The corresponding architectural design solutions for membrane structures with the resulting building skin morphologies and details are discussed, compared and presented through a series of examples and case studies. (fig. 3)

The study is limited to mechanically tensioned membrane structures which enclose semi-open spaces. The study is further constrained to woven and coated membrane materials which are of principal and most common use in the tropical regions..

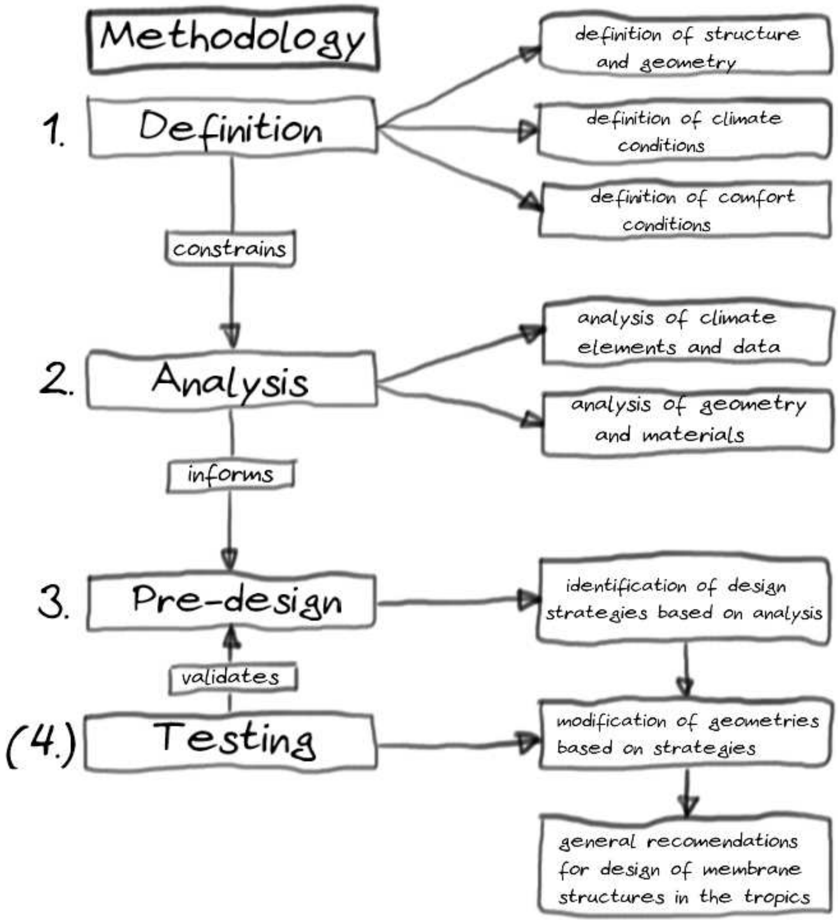


Fig. 3 *Flow diagram of methodology*

The proposed design strategies only include those based on passive principles and which are relevant to the response on tropical climate. The selected design strategies will be exemplified making use of three geometric base models (hyperbolic paraboloid-, conoid- and arc-geometry) which allow to demonstrate the principles and techniques and can serve as archetypes for further development of more complex structures. (fig. 4)

The testing of the proposed design strategies can be addressed by this study only to a limited extend and is exemplified by different case studies where passive design strategies have been employed. Methodical testing, with a quantitative approach and numerical outcome which will allow a comparison and evaluation of the effectiveness of different design strategies on a set of geometries, is not included in the scope of this investigation and will have to be carried out in further studies.
But the investigation will deliver certainly a overview of different design strategies which will serve for future research as a starting point and basis for the decision on relevant testing and validation.

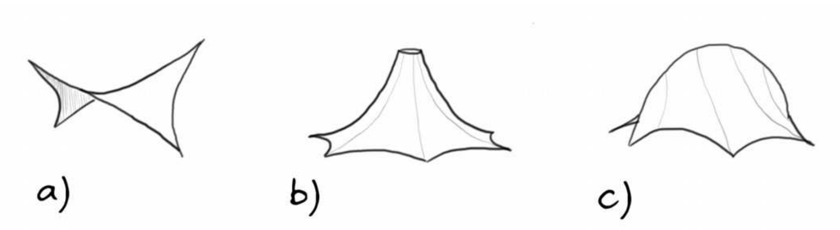


Fig. 4 Basic geometry models for investigation

2. Tropical climate

What comes immediately to ones mind when thinking about the tropics are images of lonesome islands within the celestial crystal clear ocean with beaches of white sand, lined with coconut palm trees under eternal sunshine and touched by a gentle warm breeze.
Even though such paradise-like places exist, the reality of the tropics is far more complex and diverse as the reduced stereotypes created by the tourism industry makes us belief. (fig.5)

Fig. 5 Tropical beach.

But what are the tropics then? How can they be characterized in climatic terms? What are the causes for such mild climate and exuberant lush vegetation that has attracted human beings since their existence?
This chapter will undergo the quest to answer these questions and set the fundamental framework for understanding how the human being is affected by the tropical climate, and further, how we can use membrane structures as „climate modifiers" to create higher levels of thermal comfort.

2. 1 Definition

The word tropic itself has no specific definition and only makes reference to the tropic of Capricorn and the tropic of Cancer which are the geographic turning points of the farthest possible latitude where the sun radiates at the solstice of summer from the zenith (overhead position) onto the earth (McGregor, 1998). Due to the tilt of the earth's rotation axis, these turning point positions span as parallels to the equator around the earth globe. At a latitude of 23,5° the tropic of cancer marks the limit of the tropical regions In the northern hemisphere and the tropic of Capricorn at 23,5° the limit on the southern hemisphere. These limits are in a way only a geographical convention, because the climatic conditions of the tropics are not strictly limited to this zone, and are a more or less a amorphous belt around the globe. Instead, on various attempts to define the tropical region by meteorological data were made throughout the history. Some scholars used precipitation as a parameter, others set the monthly mean temperature above 18°C as a criteria to establish boundaries for the tropical climate. One of the most commonly cited classification systems in literature is the Köppen-Geiger climate classification system.. The classification system evaluates the native vegetation as a reference for the expression of climate and combines annual and monthly values of average temperatures, and precipitation volumes as parameters for the definition of climate types, and the establishment of climate zone boundaries on a global scale.

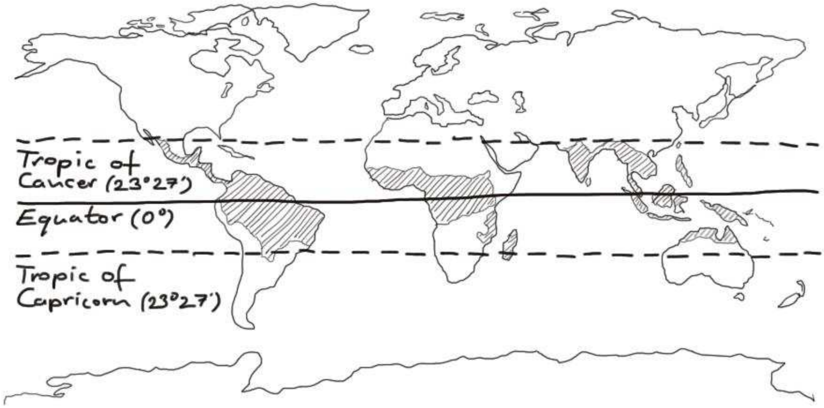


Fig. 6 Tropical climate zone

It must be said, that this is a rather simple model and climate zones are not that simple rigid as seen on the map. But it gives a rough general idea of the distribution and characteristics of climate zones around the earth and is therefore relevant to this study. (fig. 6)

2. 2 Macro dynamics of tropical climate

In order to further answer the questions, on what the tropics are, and what the origins of their climate conditions are, it is necessary to discuss the relation between the earth and the sun and the characteristic translation and rotation movements which planet earth performs, and the resulting meteorological dynamics which create the climate to what we refer to as tropical.

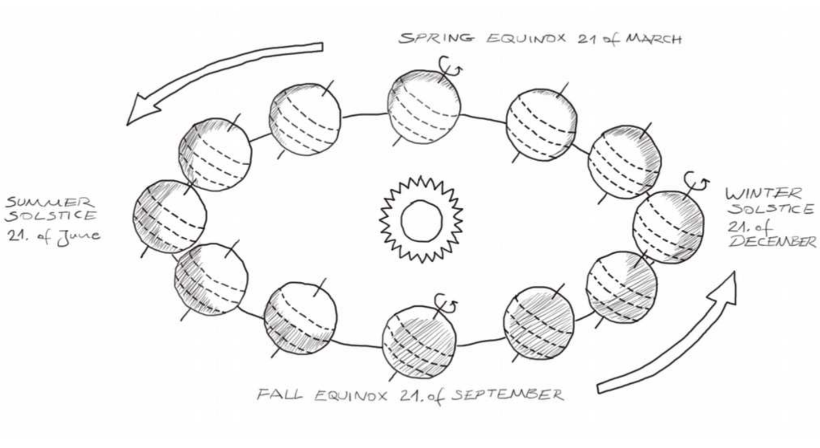


Fig. 7 Characteristic movements of the earth

The sun, a radiating star, is the gravitational center of our solar system and the energy source which makes live on earth possible. The earth rotates on an elliptical orbit at an average distance of 150 million kilometers around the sun, with the duration of one year per cycle. (fig. 7)
The earth itself rotates around its own tilted axis with the duration of one day per cycle, whilst the sun constantly radiates electromagnetic waves in the range of 100nm to 1mm wavelength towards the earth. The power of radiation that finally arrives at the earth´s surface after having been filtered by the atmosphere is round about 1,000 W/m^2 at a clear sky (wikipedia, 2015).

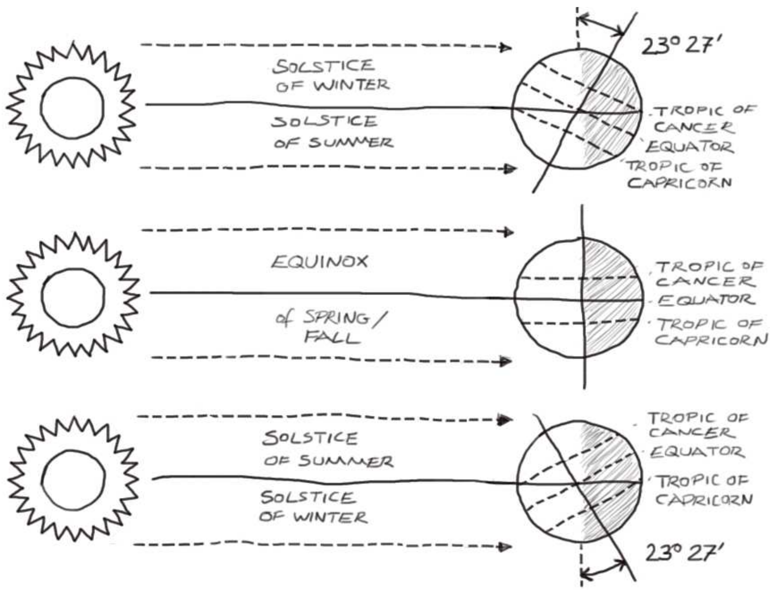


Fig. 8 Solar geometry

Through the tilt of the earth´s rotation axis of approximately 23°27' the tropical zone receives more radiation throughout the year, because this part of the earths surface is more or less perpendicular orientated towards the solar rays. The solar rays travel a shorter distance through the atmosphere and are therefore less filtered by clouds, particles and gasses which compose the atmosphere. This higher annual solar gain in the tropical region is the energy that powers mainly the meteorological dynamics of the tropics, and the climate on a global scale. (fig. 8)

2. 3 Intertropical convergence zone

The thermal dynamics on a global scale were discovered by George Hadley. He describes an atmospheric circulation system which was named after him: the Hadley cells. (fig. 9)

The Hadley cells consist of a low-pressure system which is created close to the equators within the boundaries of the tropical latitudes. The direct meteorological effects originated by this low pressure system are the main features of the tropical climate and all major world wind systems, like the trade winds or the jet streams. The dynamics of the Hadley cells are induced by the intense solar radiation which is almost perpendicular, close to the equator. The warmed up earth surface heats up the air which expands, and raises, due to the loss of density. A low pressure zone is created which is called as well the inter-tropical convergence zone

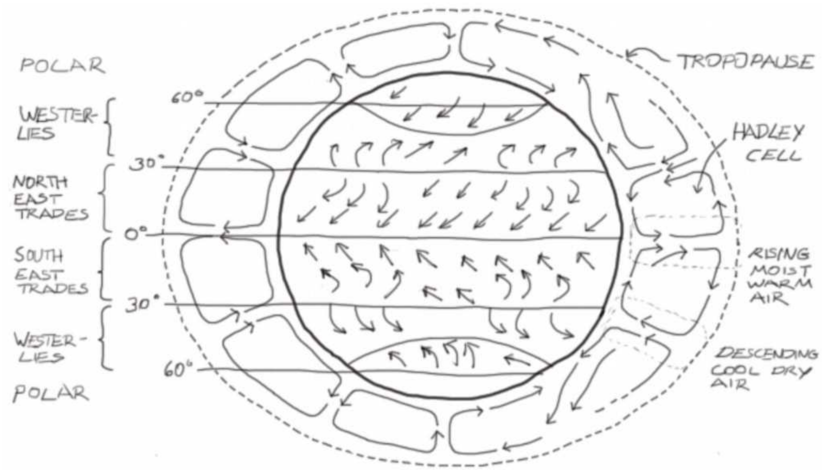


Fig. 9 Hadley cell

(ITCZ), characterized by the coincidence of maximum surface temperatures, cloudiness, heavy rainfall and convergence of trade winds (McGregor, 1998). While the warm air rises up, it also transports a lot of moisture taken up by evaporation and convection from the warm seas. While the warm and humid air rises up to stratopause heights, its humidity condensates and clouds built up. Following the thermodynamic laws the warm air moves further pole-wards , at both the southern and northern hemisphere, and when cooled down it falls back to the earth surface at subtropical latitudes creating a circulating flow belt. When the cool air is flowing back from high-pressure to the low-pressure-zone at the equator on lower altitudes, the well known northern and southern trades wind systems are created. These wind systems are deviated in their flow direction on the northern hemisphere to south-east direction and in the southern hemisphere to north-eats direction. This deviation is the direct effect of the Coriolis force which originates from the rotation of the earth around its own axis and which also is responsible for the rotation of large cyclones (wikipedia, 2015).

2. 4 Climatic elements and characteristic conditions of tropical climate

The concept of tropical climate is very ample and one should be aware that such a „one" tropical climate does not exist. In fact there are many types of tropical climates with very different climatic conditions. Furthermore within one climate zone there might be even more sub-zones, and at a smaller scale also kinds of micro-climates with very special climatic conditions and phenomena which are influenced by parameters like geographic latitude, altitude, topography and distance to main bodies of water. Given this complexity, it might be misleading to establish a general description of the tropical climate. But in order to outline a comprehensible picture of climatic situations which must be faced and addressed by the designer of tensile structures in a wider context, the attempt will be me made not without adverting that the individual consideration of the local climate conditions remains indispensable: The general conditions of the tropical climate on a perceptive level can thus be re-

Fig. 10 Tropical rain forest

sumed to a combination of high humidity levels and heat, induced by intense solar radiation, cloudiness and heavy rainfalls. These conditions create the basis for a high degree of biological diversity and extraordinary growth of vegetation which in turn creates meso- and micro-climates of special conditions. (fig. 10)

In meteorological terms the elements of climate which characterize the tropical climate are: temperature, humidity, wind, precipitation and atmospheric pressure. These terms are used in this study to classify different climate conditions.
The topical climates relevant to this study are the humid tropics in general, and in specific the regions which show a climate regime which corresponds to the tropical wet and dry climate zone, as defined by the Köppen classification system. This limitation is for practical reasons only and does not mean that design strategies do not apply to other tropical climates as well, but it must be kept in mind that the strategies must be adapted to the local conditions. The characteristics of the tropical wet and dry climate zone are further outlined by the presentation and comparison of three locations within this region.

2. 5 Tropical climate zones around the world:

The tropical region can be geographically divided into sub-regions as Mc Gregor (1998) suggest.

America, Africa, Asia and the oceanic Islands are the main tropical regions. These regions all have their own climatic characteristics and are under the influence of different seasonal macro scale climate dynamics, like the monsoon in Asia and the trade winds in America (McGregor, 1998). Therefore, each region is illustrated by one example, that serves to emphasize these differences between each region. For America, San José in Costa Rica at at latitude of 10°N has been chosen, for Africa Lagos in Nigeria at latitude 7°N, and for Asia Mumbai in India at latitude 19°N has been selected. (fig. 11)

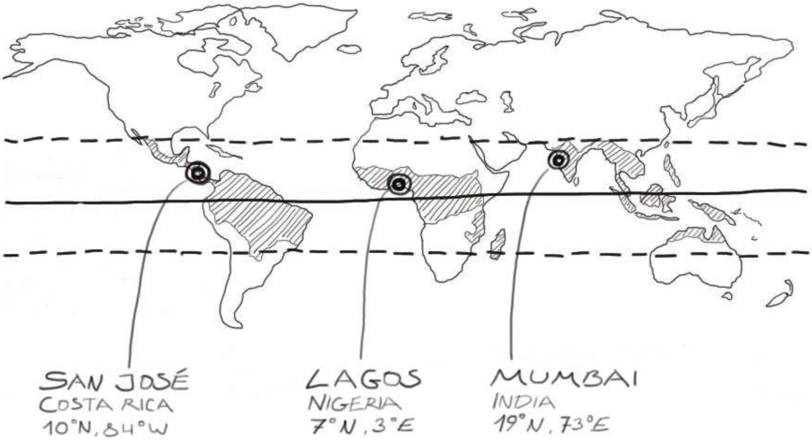


Fig. 11 Cities in the tropical climate zone

All three cities correspond to the tropical wet and dry climate zone by Köppen and maintain in

common a general tendency of climatic behavior. Regions within this climate zone present throughout the year a quite constant temperature with mean monthly temperatures between 22,0℃ in San José, 27,2℃ in Mumbai and 26,7℃ in Lagos. Although the monthly mean temperatures never fall below 18℃. All three cities receive moderate up to heavy rainfalls with annual averages of 1971 mm in San José, 2146 mm in Mumbai and 1538 mm in Lagos. A wet season of several month with escalating rain-fall volume is followed by a pronounced dry season for several months of the year. (fig. 12)
The Solar charts of each Location are shown in the following figures. (fig. 13, fig. 14, fig. 15).
In this study these examples will serve as a reference for different specific conditions of regional tropical climate types.

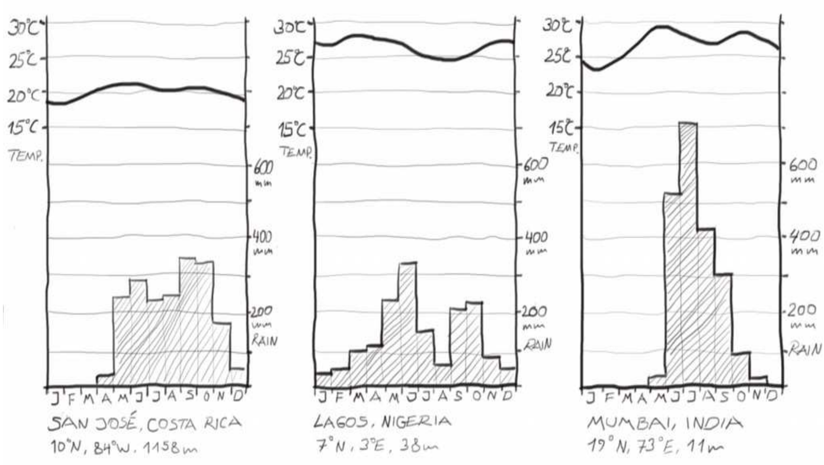


Fig. 12 Climate charts

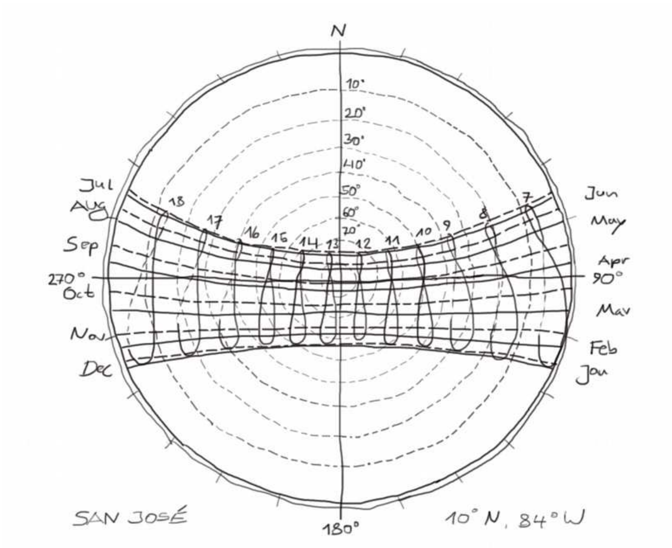


Fig. 13 Solar chart San Jose, Costa Rica.

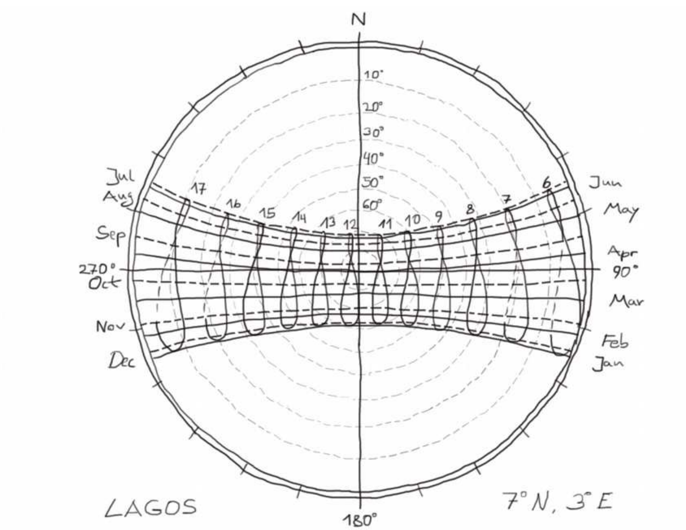


Fig. 14 Solar chart Lagos, Nigeria

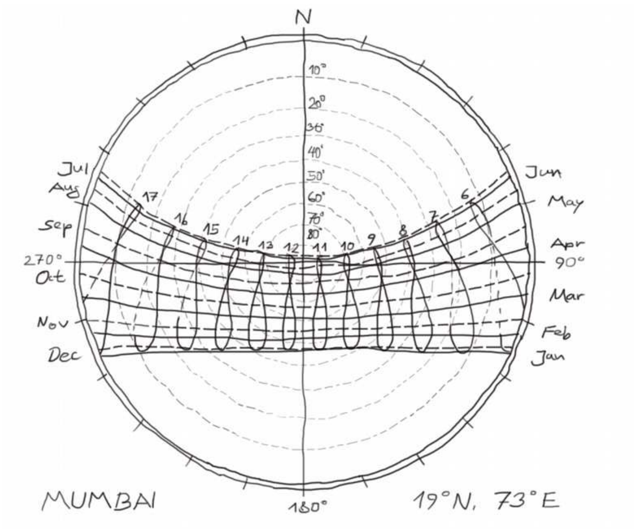


Fig. 15 Solar chart Mumbai, India

[Note: All indications of latitudes refer to the geographic coordinates of the meteorologic station closest to the selected cities and may defer from the official coordinates of the cities itself]

2. 7 Summary

The climate on earth is one of the most complex dynamic systems known to human beings. Comprehension of the basic mechanisms and characteristics of climate is one of the key requirements for designers who have the intention to design energy efficient structures which are adapted to the environment where they are placed in.
This chapter provides an outline of the very specific climate conditions of the tropics. An attempt

of a definition for tropical climate is given and the underlying dynamics and physical principles which create and affect these climate conditions have been resumed. Furthermore, meteorological data for three cities which are located on the tropical belt around the world are presented as examples for the characteristics of the tropical wet and dry climate zone which will be referred to in this study.

3. Comfort

Generally speaking, comfort is a state of satisfaction of the human body and mind. The world health organization (WHO) defines this concept in general terms, as a state of complete well being in a social, mental and physical way. This also includes the thermal well being, an equilibrium state of the human body with no necessity of thermal regulation. So, when talking about thermal comfort, we may refer to a state or condition where the majority of a group feels neither cold nor warm. The external factors of climate and micro climates play a important role on the thermal comfort, but the feeling of well being of the individual is also influenced by a series of physical conditions, psychological perceptions and cultural factors which should not be underestimated.

In tropical environments, thermal comfort is not always easy to achieve. As in the tropics the average temperatures never falls below 18°C and the relative humidity levels are very high as well. The constant sensation of heat is symptomatic. As a consequence, strategies to cool our bodies passively and actively is an important issue in the tropics. Examples like the use of light and airy cloth, the tradition of building open houses with large shading roofs and the use of mechanical fans and air condition devices are all common in the tropical regions, and demonstrate the need for thermal comfort.

3. 1 Physiological Mechanisms

Our body needs by design a steady working temperature of round about 37° in order to function well, and to keep all organs and metabolic processes at their optimum temperature. All our life-sustaining functions like breathing, heart-beat and blood circulation are designed to maintain a constant body core temperature. A slight variation of our body temperature has immediately impact on our well being and can even become life threatening. Thus, the thermal control of our body and the control of the climatic conditions of the environment in which we are living is very important.

While our core body temperature needs to stay at a steady temperature, our skin is more robust and has the ability to mitigate changes of temperature of the environment by employing different mechanisms such as by insulating against cold or transpiring at heat.

3. 2 Influencing factors

There are different body internal and external climate factors which affect our thermal comfort. Several of those are defined by the international ASHRAE standard 55:

-The Metabolic rate is a concept which defines the human power-, and in consequence, heat- production during activity. While at low activities, like sleeping or sitting on a chair, less power is required and the body internal heat production is also very low. The unit for measuring the metabolic rate is given in MET, where 1 met equals 58 W/m². The scale of the metabolic rate unit ranges from about 1 met for relaxed sitting up to 8 met or higher for fast running. The resulting radiating body heat can be calculated multiplying the MET value in W/m2 with the overall skin surface area of the human body in m². The metabolic rate value can give important hints for the selection of passive design strategies when the expected activity of the space occupants is already known. (fig. 16)

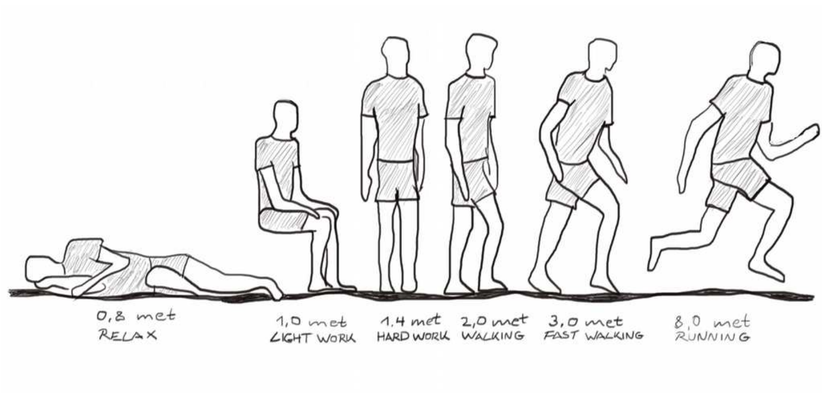


Fig. 16 Metabolic rate MET

-The Clothing insulation factor or CLO is also an important aspect which has great influence on our thermal comfort. Our clothing insulates us against cold and wind, and protects us as well from solar radiation and rain. In the tropical climates these characteristics may lead to a kind of contradiction which has been solved mostly in traditional vestures, and more recently by the outdoor industry, with airy and light clothes which permit breezes to pass on our skin and lower our skin surface temperature by convection. Furthermore they allow for effective transpiration while at the same time protecting from solar radiation. The clothing insulation factor basically defines the insulation capacity of our clothing and is measured in the unit clo where 1 clo equals 0.155 $K*m^2*W^{-1}$. The scale for CLO values ranges from 0 when naked to about 1 when wearing a formal western style businesses suite. When knowing beforehand what kind of clothes space occupants are likely to use most of the time, it becomes easier to define comfort conditions and address passive design strategies properly. (fig. 17)

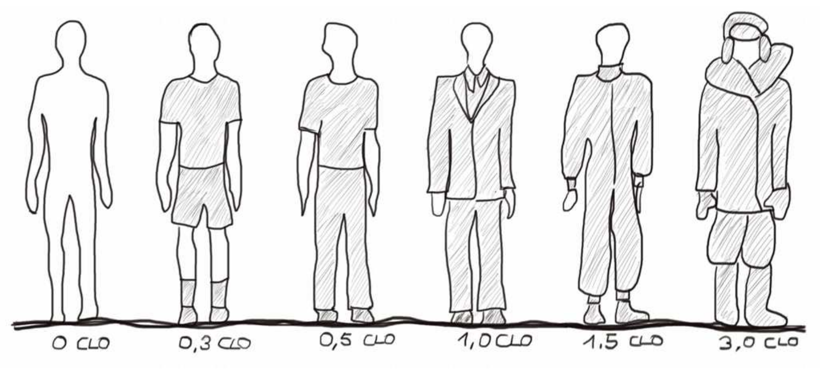


Fig. 17 Insulation effect of clothing, CLO

-The air temperature T is one of the external factors that has a very strong impact on our thermal comfort. The temperature of the circulating air is an average temperature at a specific moment in space and is measured in degree Celsius or Fahrenheit using a dry-bulb thermometer.

-The mean radiant temperature MRT is the average radiation of all heat emitting surfaces or objects around us, and is measured in degree Celsius or Fahrenheit. The MRT can be measured by sensors or theoretically calculated by knowing the surface temperatures of the radiating objects and its relative orientation angle towards the subject. The MRT is also a very import factor which affects our thermal comfort when considering for example being exposed to solar radiation during mid day.

-The Air speed can very effectively help to improve thermal comfort in the tropics. Increased air speed, by natural breeze or mechanical ventilation can provide chill effects by convection, and enhance effective evaporative cooling on our sweating skin. The air speed is measured by an anemometer and is given as an average value in units like meter per second (m/s), kilometers per hour (km/h) or Knots (kt). The power of wind is expressed generally in Beaufort defining on a scale from 0 – 12 the kind of wind or storm, and the effects which go along with it.

-The Relative humidity is one of the external factors which is most difficult to control. In combination with the air temperature it is one of the key factors which affect our thermal comfort sensation. The relative humidity is measured by a hygrometer and is given in percentage on a scale from 0-100%. The relative humidity always refers to the quantity ratio of water vapor contained in a volume of air at a specific temperature. The higher the air temperature the more water vapor can be held up in the air. This means that the absolute humidity in a warm environment can be much higher, than in colder climate at the same relative humidity levels. This fact becomes becomes particularly important when we consider that one of our main body cooling mechanisms is evaporative cooling by sweating. But when the surrounding hot air is already saturated with water vapor, then evaporation becomes very difficult and ineffective as a cooling mechanism.

3. 3 Thermal exchange processes

Considering ourselfs as small heat generators immersed in an environment, built or natural, where all objects are constantly radiating at each other, it becomes important to analyze the processes by which this heat exchange takes place. Following the first law of thermodynamics, all objects in space are constantly interchanging thermal energy in order to establish an equilibrium state while the energy flow is always oriented from the hotter to the cooler object, as defined by the second law of thermodynamics. The mechanisms by which the heat exchange takes place are conduction, convection and radiation. These mechanisms constantly affect our thermal comfort. Controlling them in our built environment means having a very effective tool to improve comfort conditions. The physical principals of heat exchange mechanisms are resumed below:

-Conduction is the heat transfer through a physical medium of specific material matter. The thermal heat conductivity and thickness of the material plays an important role when considering heat transfer through conduction in the built environment.

-Convection is the heat transfer through a fluid in motion which takes place when the fluid adds or removes heat from a solid object while getting in contact with it. Important factors for the effectiveness of the heat exchange are the characteristics of the flowing fluid, like speed, volume and the relative temperature difference. Furthermore, the characteristics of the object surface itself, like the surface ruggedness or the total area exposed to the convection fluid are of importance.

-Radiation is the heat exchange through electromagnetic waves. Every object in space emits radiation. The intensity of the radiation which is emitted by an object is related to the emisivity characteristics of its surface, surface area and the object temperature. The resulting radiation with specific wavelengths gets reflected, absorbed or transmitted by other objects. (fig. 18)

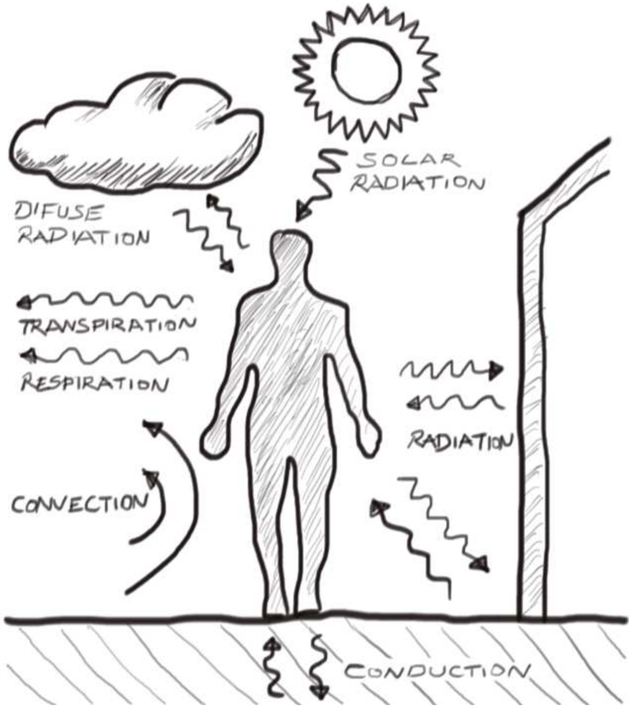


Fig. 18 Thermal exchange mechanisms,

3. 4 Thermal comfort models

Knowing now the factors which mostly affect our thermal comfort and the underlying physical process which allow for thermal exchange between us as human beings and our surrounding environment, it is necessary to establish criteria for thermal comfort in the tropical climates. As already mentioned in chapter 1, this is not an easy task, because of the great variety and complexity of the tropical climate itself. Having said this, the task becomes even more complex, because of the subjective perception of thermal comfort which is experienced by every single individual. In order to establish more or less precise conditions of comfort and to find out about the factors which are most influential, various research projects were launched in the 70's by military and academic institutions. One of the most prominent investigations, led by Ole Fanger, collected data in laboratory experiments where thermal comfort was measured in isolated controllable environments (Wikipedia 2015). The results of these studies showed that most of the people felt comfortable at higro-thermal conditions of around 21°C at 50% relative humidity (McGregor, 1998). The statistical data derived from the experiment was then used to establish theoretical models which permitted to calculate and predict thermal comfort based on meteorological data and personal factors, like CLO and MET. While these models evolved, it even became possible to generate recommendations based on the data to increase and improve thermal comfort conditions by modifications of the built and natural environment.

The most relevant models for human comfort which are linked to bioclimatic design and green building, were developed in the last century. A selection of three basic, most common models which are still used today as planning and design tools in architecture and the building industry are presented below. A more complete overview and comparative study of the different thermal comfort models can be found in the doctoral thesis of Visitsak [2007].

-The Bioclimatic chart which was developed by Victor Olgay is based on the bioclimatic design theory which intends to use natural elements to create comfortable living conditions in architectural spaces with the minimum use of external energy sources. (fig. 19)

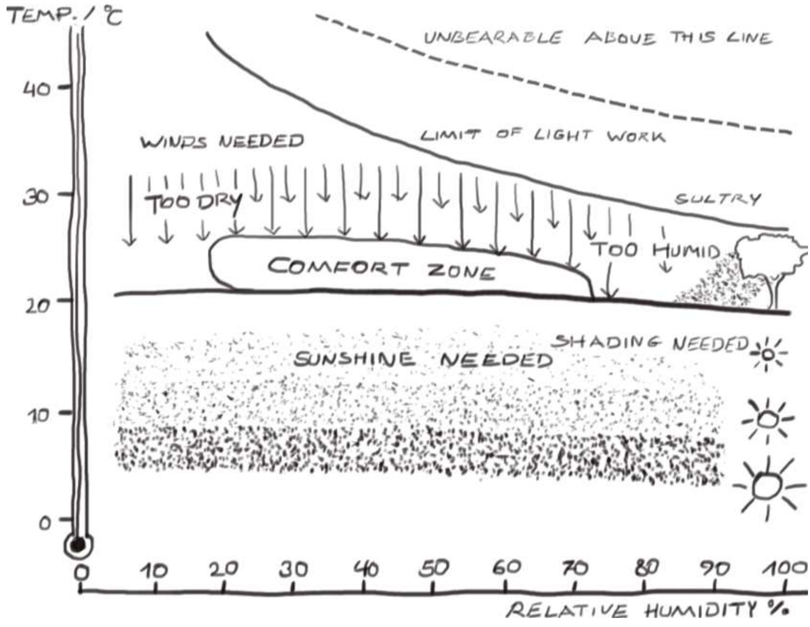


Fig. 19 Bioclimatic chart

Hygro-thermal comfort is the underlying principal of the chart, combining temperature and relative humidity as the main factors for thermal comfort Monthly meteorological data can be plotted onto the chart and general recommendations for extending the comfort zone can be derived from the it. For hot and humid climates for example the need to ventilate or to shade in certain months of the year is recommended. The bio-climatic chart is a very basic design tool and will work fine for the early design stages.

-The Mahoney tables were developed by Carl Mahoney, J.ohn Martin Evans and Otto Königsberger and were published by the United Nations as an analysis tool for climate. The outcome of the tables provide some basic recommendations to improve comfort conditions and can be used as a design-tool for early stage decision taking in energy efficient building practices. The Mahoney tables are basically a spreadsheet where basic meteorological data, like monthly temperatures and relative humidity (min. , max. and mean), rainfall and wind speed, must be filled in. The data is then compared to the target comfort condition. Seasons with critical climate conditions, were measures for achieving comfort are required, get highlighted. As a analysis result schematic design recommendations are given, for example for a hot and humid climate as follows: „Orientation north and south (long axis east-west to reduce sun exposure), open spacing for breeze penetration, permanent provision for air movement, large openings 40%-80% in north south walls at body height on windward side, exclude direct sunlight, provide protection from rain, light walls with low thermal capacity, light well insulated roofs, adequate rainwater drainage".

-The climographs developed by Baruch Givoni and Milne emphasize the concept of hygro-thermal comfort. Based on a psychrometric chart, which graphically correlates temperature and relative humidity, a comfort zone is traced on the chart, derived from the monthly weather data. (fig. 20)

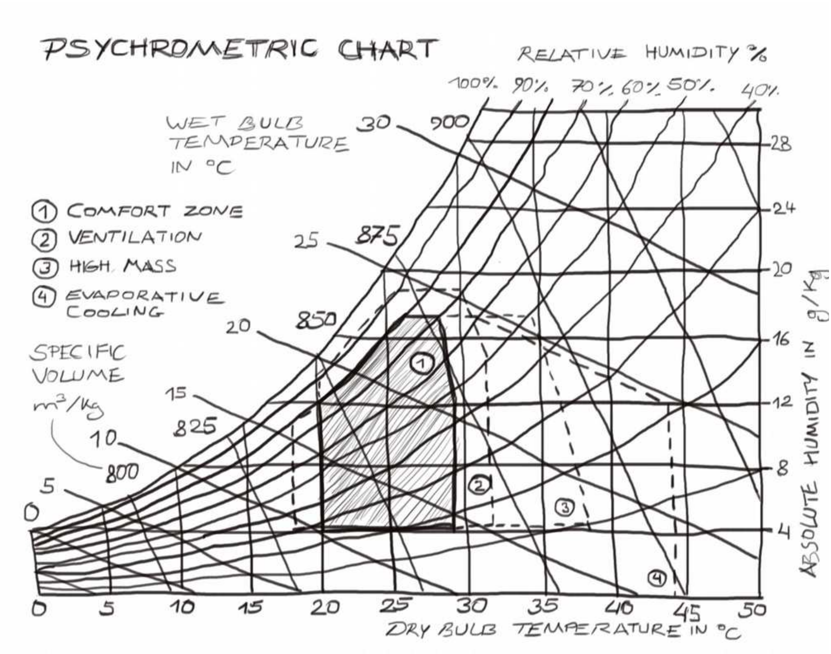


Fig. 20 Psychrometric chart

The comfort zone is a range of temperature and relative humidity values wherein statistical the majority of individuals will feel comfortable. This zone can be augmented by applying passive strategies, meaning that tougher climate conditions can be supported. The interpretation of passive strategies into practical design decisions can then be performed. The general recommendations are given in a range from cross ventilation, thermal inertia, selective ventilation, evaporative cooling and humidification to passive solar systems. The sophistication of the chart lies in the values which are specified for the effectiveness of each passive strategy. The effectiveness largely depends upon the specific climate conditions. It is thus absolutely necessary to provide accurate meteorological data.

3. 5 Summary

Designing energy efficient structures which require a minimum of energy input while providing a maximum comfort for its occupants has become a necessity in times of climate change and the general scarcity of resources. Hygro-thermal comfort models are powerful tools to understand the relation between climate and human well being. Furthermore, they provide essential information for planning and designing and how to use natural forces in favor of well acclimatized architectural spaces.

At present there are a wide range of models, varying in complexity, with multiple software tools available for calculation. Some of them are web based and available as freeware such as the „Climate Consultant" developed by the University of California or the „Comfort Calculator" by Marsh and Raines, which meets the ISO7730-1993 standard. It must be kept in mind that the results are only as good as the input data. Meteorological data is a must-have requirement for correct analysis when using these kinds of tools. It should also be considered that not all occupants can be satisfied, neither can all climatic conditions be addressed by passive strategies. While applying passive strategies, the focus should always be put on average conditions. Peak situations or extreme weather phenomena are to be addressed by either conventional mechanical conditioning or ultimately left to the adaptive capacity of the human being itself. The importance is to meet general comfort requirements most of the time, and not always at any cost. This approach by Koch-Nielsen [2007] is an alternative to the conventional modern understanding of complete independence from nature which should be carefully considered in the advent of climate change.

4. Membrane structures in the tropics

The use of tensioned membrane structures, as a building technology, in the tropical regions is a relatively recent development which can look back on an increasing use in architectural designs over the last 25 years. Tensile membrane structures have several advantages, compared to other building techniques which make them very suitable to address the special conditions of tropical climate. Intense solar radiation and precipitation combined with high levels of humidity can be addressed by semi-open lightweight roofs which provide many opportunities for the enhancement of shading, cover from rainfall and natural ventilation just by means of an informed design of the structure. On the material side the resistance to microorganism growth, biodeterioration, UV rays and aging as well as not being susceptible to corrosion, make membranes an ideal building material which should be evaluated for the use in extreme atmospheric conditions like those of the tropics.

However, the opportunities go along with difficulties. The relatively young building industry, with little building experience, a lack of education on a technical level, and the availability of suitable materials as well as the compromising economic situation in the developing tropical countries have to be overcome. This would allow for a broader use of membrane structures and make it possible to develop, by experimentation and technological exchange, feasible approaches and models for a culture of adapted and efficient design regarding tropical climate.

4. 1 History

Although, the history of tensioned membrane structures in the tropics is very recent, the use of light materials and textile building elements has a long tradition in tropical regions. The availability of resources in nature, the need for mobility demanded by nomadic life, and the conditions of climate, which require protection from heavy rain and intense solar radiation have let to a development of textile architecture. This development has started over a few thousand years ago with the use of proto-textiles of vegetable fibers for the shelters of indigenous cultures.
A very outstanding example of an indigenous building type which makes use of lightweight building techniques and materials is the conical house of the indigenous tribes of Costa Rica. The Bribri culture, located in the Talamanca region in southern Costa Rica developed a cosmological building approach, in which the universe is represented by the shelter itself. The conical house is build by a series of wooden bars and posts which are arrayed around a center mast which is removed after construction. The posts are tied together with flexible lianas and then covered by overlapping leafs of a special

palm leaf. This proto-textile roof is extremely watertight, whilst being sufficiently permeable for natural ventilation. The tall building height and the resulting large air volume in the interior is also beneficial for thermal stratification effects, where the hot air rises while the livable space keeps cooler temperatures. The efficiency and lightness of this conical structure and its response to tropical climate is remarkable. (fig. 21)
Hernandez (2006) points out that in the history of fabric architecture nomadic cultures in different parts of the world have made use of natural fibers or animal skins to built mobile shelters and incorporated passive environmental control systems..

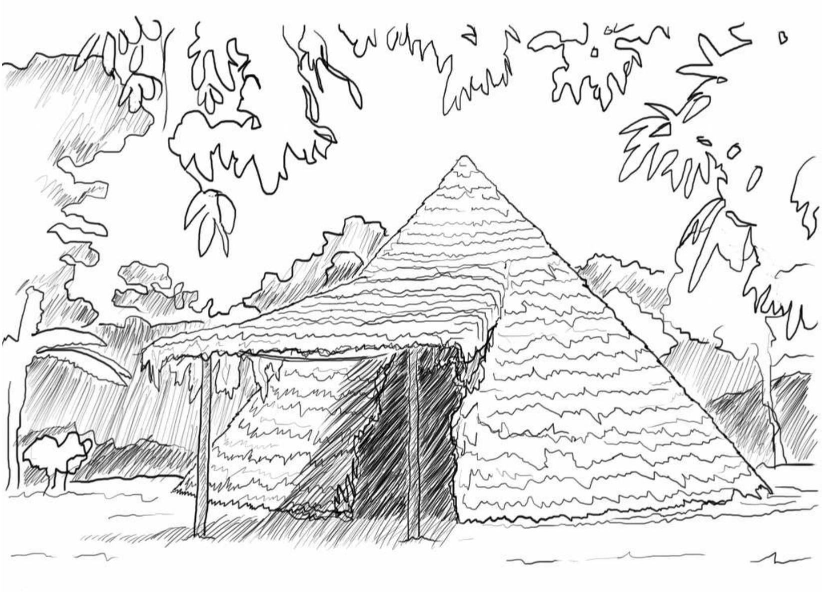


Fig. 21 Conical house, Talamanca, Costa Rica

Andean and meso-american cultures, for example, developed fabrics which were woven and braided using natural fibers of different species of plants.. Modular mats were produced which were then used to cover the walls, roofs and floors of the houses. The mats and other woven textiles were also commonly used in public spaces to cover market plazas and provide shading. In many countries around the world, a lot of them within the tropical belt, similar developments of proto-fabrics and their application in architecture can be observed. In ancient cultures in the tropical regions of Africa and Asia and in many other countries these traditional woven mats and textiles are still in use today. (fig. 22)

Fig. 22 Woven mats from natural fibers

Today, these proto-textiles can be found mostly in the traditional or so called vernacular architecture where natural lightweight structures built with materials such as bamboo and wood, are covered with these modular textile elements. These building techniques have widely been used in the tropical regions with a history of several hundred if not thousand years of development and constant adaptation to the conditions of the natural environment.
The traditional wooden houses of Cambodia are a good example for this kind of use of natural lightweight structures and proto-textiles in tropical architecture. (fig. 23)

Fig. 23 Traditional cambodian wood house

Colonization also had an impact on the further development of lightweight buildings and adaptation to climate. Rapidly the invading forces noticed that their way of building was of no use in the tropical regions and adapted their building types, even though formally still of european style, to the local climate conditions. The large military campaigns which were part of the conquering strategies also used in their missions tarps and tent like structures of textile materials, which had been proven already through many wars to be very effective, light and mobile structures. The same tents and tarps were used by several scientific expeditions, such as the dutch Papua New Guinea Expedition in 1903 led by Arthur Wichmann. They explored the geographic landscape, availability of resources, possible trading routes and established relations with authorities of the native population. While traveling mostly on horseback or on small boats the use of canvas tents made it possible for the expedition groups to travel light with a minimum of package volume. At the same time it allowed them to be very flexible about setting up camp. This provided a kind of self-sufficiency and independence from natural resource while traveling through hostile environments. (fig. 24)

Around the mid of last century, after having learned many lessons in terms of building and living in the tropics, mainly through experiences in the colonial times and the world wars, another architectural approach arose, addressing with the theo-

Fig. 24 Canvas tarps and tents of the dutch Papua New Guinea Expedition

ry of bioclimatic architecture issues beyond the classical building design concerns of economy, utility, durability, and comfort. Now concerns about the efficiency of the use of resources throughout the building life-cycle became an important issue, as well as the occupants' health and the reduction of waste and material during the building processes. Mahoney, Koenigsberger, Evans and Olgay were some of the most renown initiators of this building theory that has since been put worldwide into practice by many architects, engineers and planners. An early modern response to building in the tropics was in this sense the Bungalow which fur-

ther developed and evolved according to regional conditions. Being pushed by the energy crisis of the last century and during the 21. century, through the awakening consciousness of climate change and ecological responsibility and escalating prices for materials and energy, due to scarcity of resources, the concept of bioclimatic architecture has proven to be an important tool to address conflicts between human necessity for housing and the natural environment.
Membrane structures have proven to be in many cases part of the solution in projects with a bioclimatic approach as they offer many possibilities in terms of material reduction and climatic adaptability. These overlap in many cases with the goals of bioclimatic architecture as Nicolas Goldsmith (2008) states:
"In lightweight structures many of the same principles that apply to conventional buildings also apply to this building technology."

Contemporary examples of this kind of membrane structures which are not bioclimatical in a strict sense, but offer several features of adaptation to the tropical climate, are presented in the following three case studies.

4. 2 Case studies

-Holcim headquarters, Alajuela, Costa Rica:
The Holcim headquaters office building is located in San Rafael de Alajuela very close to San José

the capital of Costa Rica, at a latitude of aproximately 10.1° in the northern hemisphere. The building was designed by the Costarican architect Bruno Stagno in 2003. The project showcases different features of bioclimatic design and incorporates several membrane structures on the roof and the facade. A PVC coated Polyester membrane covers a total area of 995 m2. It was engineered and manufactured by FTL and Eurotoldos S.A. In 2004. The main roof of the building complex is covered by a conic membrane structure with several high and low edge points, while two separate buildings are equipped with longitudinal membrane strips of paraboloid geometries which span between an array of masts in front of the facade and serve mainly as shading devices.

Fig. 25 Holcim headquarters, Alajuela, Costa Rica

According to the architect, the textile lightweight elements were incorporated to regulate the solar radiation and to lower in consequence the heat gain in order to operate the building without the use of mechanical air conditioning. (fig. 25)

-Velodrome, Abuja, Nigeria:
In 2003 a large sports complex was built in Abuja, Nigeria (latitude 9.3° northern hemisphere, within the same climate zone as Lagos) for the African Games. Part of the development was a Velodrome which was covered by a large membrane dome of approximately 10650 m2. The main purpose was to shelter the velodrome and the circumferential stands from sun and rain. The structure, designed and built by a team of several companies (form TL ingenieure für tragwerk und leichtbau gmbh, Pfeifer Seil und Hebetechnik GmbH, Canobbio S.p.A, Montageservice SL GmbH), consists of a cable reinforced pre-tensioned PTFE coated glass-fiber membrane, which is anchored with 16 columns at the low edges and with a upper cable net system, which is tied back over 8 mast of 50 meter height at the high points, resulting in a semi open space without internal supports. The internal stratification and heat built up is resolved by air outlets at every high-point of the pentagonal and hexagonal conoidal modules, allowing the rising warm air to escape. The open plan and the absence of lateral enclosures allows for cross ventilation which further enhances better comfort conditions, while the roof provides shade and reflects a large part of

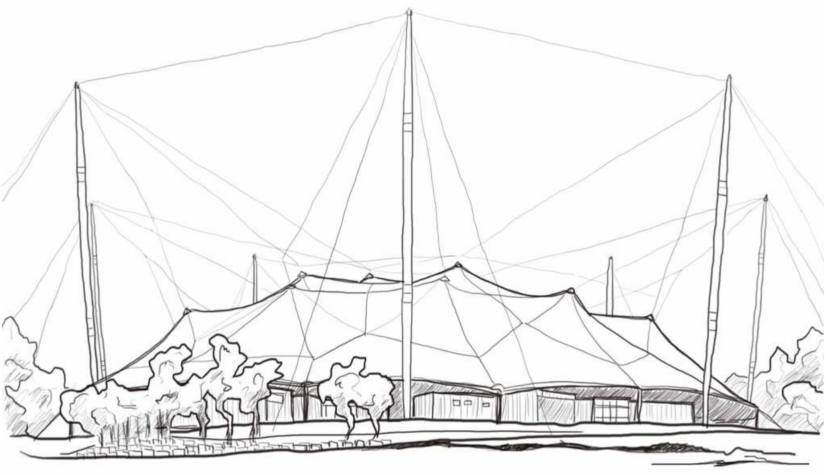


Fig. 26 Velodrome, Abuja, Nigeria

the solar radiation due to the highly reflective PTFE coating. This results in lower solar heat gains. (fig. 26)

-DY Patil International Cricket Stadium, Mumbai, India: With a capacity of 55000 seats one of the largest cricket stadiums in the world, was inaugurated in 2008 in India. The stadium is located in Mumbai at latitude 18.6° in the northern hemisphere. The circular stadium is covered by a large cantilevered membrane roof of 9300 m2. The membrane spans between arrayed cantilevered steel arches which give form to paraboloidal membrane geometries. The semi-open roof structure was designed by Hafeez Contractor and manufactured by Eco Designs Pvt with the main purpose of providing sun protection for the spectators. This has been

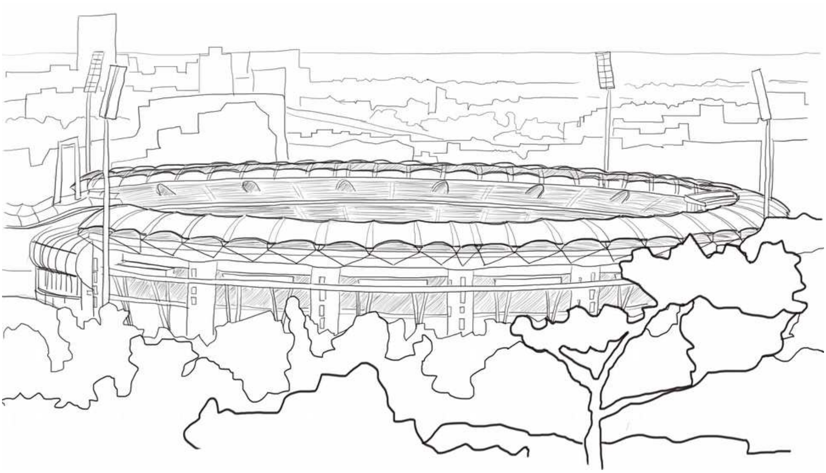


Fig. 27 DY Patil International Cricket Stadium, Mumbai, India

achieved by spanning the PVC coated Polyester membrane all around the grandstand. By design optimization of the geometry it avoids any unnatural shadows on the playground. The design of the roof took also into account the dynamic wind flow behavior in order to allow for natural ventilation whilst avoiding an up lift situation.. (fig. 27)

4. 3 Technology and climate

When approaching the topic of adaptation of technology to climate from a general perspective, conceiving at the same time the need for action regarding climate change and the limitation of natural resources, it becomes obvious that the adaptation of buildings to climate is the principal objective in order to create architectural spaces which achieve the highest levels of thermal comfort for the users with a minimum input of resources (Flor, 2011).

„Features like topography, local climate, sun and site orientation and wind should all have a significant role in the form finding of a tensile structure" (Elseragy, 2003)

Furthermore ElNokaly proposes the idea that:

„Fabric structures can be merely used as a filter for creating an intermediate climate or meso-climate, which acts between the external climate and the environmentally controlled interior of the building to moderate and regulate them, rather than shutting it out completely". (ElNokaly, 2003)

and that,

„the fabric's form and topology can play an effective role in the ventilation and natural cooling of spaces in their immediate vicinity". (ElNokaly, 2003)

This potentially beneficial performance of membrane structures with regard to their climatic response is also a result of their physical properties. Besides the high capacity for reflection of radiation and the low emission of some of the most advanced materials the rather low thermal mass can become a benefit in tropical climates. As a consequence of their low mass, they react very fast on changes in the environment around them, heating rapidly during periods of bright direct sunshine, but cooling down very quickly, as soon as it becomes cloudy. This effect can even become a cooling strategy for hot tropical nights when the membrane can actually become cooler as the ambient air temperature when radiating against the cool night sky.

In this sense, tensioned membrane structures become the ideal response to tropical climates creating large open spaces, which are self-ventilating, reflecting most of the solar radiation, providing effective shade and protecting from heavy rainfall with wide overhangs like a large umbrella (fig. 28).

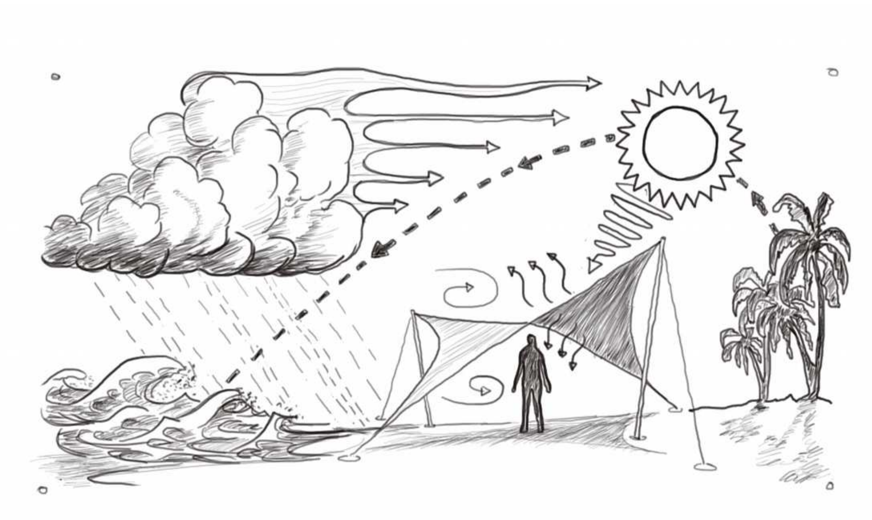


Fig. 28 Membrane structures in tropical climate

On the other hand the most obvious difficulty with climate adaptive design of membrane structures is that their geometry is to a certain extent stable, and is not modifiable. It's topology doesn't normally change much, except to loads from wind and precipitation, or when they are especially designed for geometric transformation like retractable and foldable structures. This creates a certain design problem, because the climate conditions are dynamic and this means that for the structure an ideal solution with as little trade-offs has to be found in order to respond with the best performance on a average level to the cyclic climate conditions. In this sense analysis of weather data and local site conditions become the most effective and important tool for a successful climatic adaptation of the the design itself.

Wang (2015) together with other authors states that tensioned membrane structures have been applied with success in the tropics even though they still present some defects specific to the tropical regions. He points out that the most common defects, according to a study in Malaysia, like deterioration of roof coatings, fungal decay, mold growth and dirt accumulation, as well as corrosion on fixings and anchor cables are closely related to the tropical weather conditions where UV radiation and precipitation are highlighted as the climatic elements which have the greatest influence on the deterioration of membrane structures in the tropics. What is true in the tropical regions of Asia can be said also about tropical America where, like Hernandez (in „Fabric Structures in Architecture" , 2015) states, the development of membrane structures is still suffering from mistakes in design and manufacturing, as well as of rapid deterioration of membrane covers due to a lack of availability of appropriate materials or an inappropriate material selection, which has let to a reputation of an unreliable technology in the public opinion. Consequently this led to a more conservative approach in the building industry when it comes to the choice of building system for new constructions.

It has to be remarked that these disadvantages, or difficulties, of the use of membrane structures in the tropics are related mostly to the fact that this technology is still considered as a developing technology in these regions, where industry keeps on struggling with establishing standardized building practices. A high quality standard for membrane structures is often compromised by the lack of technical knowledge, the availability of tools and materials which meet the state of the art technology, and in general the tight economic situation of these developing countries. This situation not always allows to apply the best available solution.. It must also be said that the most encountered difficulties are related to material behavior, manufacturing quality and structural engineering, and not so much in regards to the potential climatic performance of membrane structure. But this could also be due to the fact that climatic performance is mostly not taken into account in the design and/or not documented. It is desirable in this sense to aim future investigations at conducting, real time measurements of climatic indicators on membrane structures in on site, in order to obtain reliable date on the climatic performance of membrane structures in the tropics..

4. 4 Outlook

It can be said that right now the development of membrane structures in the tropical regions is flourishing. During the last 25 years membrane structures have undergone a development in the tropics as never before, a lot of structures have been built since 1990 to the present day with an increasing level of quality and originality. Many young companies have been established with a high degree of professionalism and an interdisciplinary approach among engineers and architects. The worldwide tendency of globalization has given access to the markets of the industrialized world, and increased the availability of high quality materials. Furthermore, on a professional level the internationalization has let to the foundation of organizations which are starting of to establish their own, networks. International conferences are now more frequently organized and facilitate the exchange of information between professionals. Universities have started to incorporate workshops and courses on membrane structures which create the knowledge basis in students and young professionals for a further popularization of membrane structures which can be observed to evolve slowly in the built industry. The market for membrane structures is in this respect developing positively and has still great opportunities of growth.

However, there is still much work to be done and the success of further development of membrane structures in the tropics will not only depend on the establishment of standards of reliability, safety and durability. Neither will only their beautiful forms and lightweight appearance or better and cheaper materials lead to a more popular use, but the capacity of efficiently addressing unsolved design problems and, ultimately, improving the conditions for their users while preserving natural resources.
Therefore education at universities, training of technical personnel, standardization of building techniques, promotional activities, exchange of knowledge between professionals within and outside the tropical regions is needed. On the technical side there is also much room for innovation, as the technology has not yet been fully explored in terms of optimization and adaptation to the tropical environment. More durable materials with better characteristics concerning environmental behavior (fungus, translucency, reflection, heat transmission) must be developed. Ultimately, membrane structures should overcome the status/reputation of an exclusive, expensive building solution which relies on high-tech materials, and instead become an every day solution for semi-open spaces in tropical regions.

5. Design Strategies - SUN

Solar radiation is one of the climatic elements that have the greatest influence on the thermal comfort of human beings. Many studies, as those of Bouyaret (2007, cited in Goshayeshi, 2013), have shown that diminishing the amount of direct sun light in humid climate can impressively improve the the comfort level of individuals in semi outdoor spaces. Researchers like Ghaddar and Hoyano (2011, 2010 respectively, cited in Goshayeshi, 2013) have found out in site measurements that the air temperature under membrane structures could be 2-4°C lower than ambient temperature on a sunny day with low wind ventilation situation.. These Investigations justify the high potential of effective shade design in order to increase thermal comfort. Therefore in this chapter various strategies will be presented to reduce the solar radiation in semi open spaces covered by membrane structures. As a first step towards a solar design concept the orientation of membrane structure geometries in relation to the daily and annual sun path will be analyzed and compared, as well as shading techniques in relation to the geometry of the membrane. Furthermore the mechanisms of heat and light transmittance will be addressed and set in relation to the choice of materials to meet tropical climate requirements. Advantages and disadvantages of shapes and anti-clastic topology will be introduced, as well as thermodynamic effects that are related to the behavior of classical anti-clastic shapes. Finally several design tools for an effective solar shading design of membrane structures will be presented.

5. 1 Orientation

The correct orientation of a building, or in this case a membrane structure, towards the sun is a first step towards a design that responds efficiently to the solar radiation in order to control lightning and heat gains. Creating with a structure a maximum of shaded area during an extended period of the day and throughout the year is essential to achieve comfortable spaces in the the tropics.. The orientation and proportion of a shading structure are the most effective, and most easily adjustable parameters in an early design stage. The solar sun-path is a key concept to successfully control these parameters.

Seen from the earth surface the sun performs a daily movement on an imaginary arc on the sky, rising in the morning hours in the east and, reaching a vertical position, called zenith, on mid day and falls in the evening hours behind the western horizon. The inclination of the trajectory towards north and south depends on the latitude and changes throughout the year according to relative inclination of the earth's axis towards the sun.. The position of the sun at the sky can be described by a horizontal angle, called azimuth, and an angle in vertical plane, called altitude or solar height. (fig. 29)

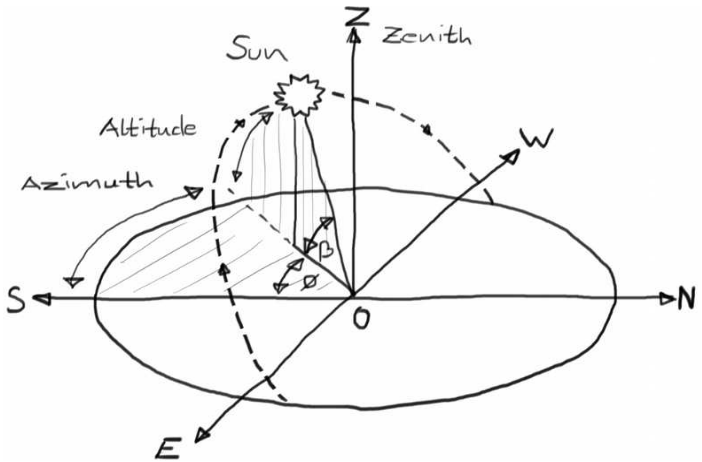


Fig. 29 Solar sun-path

The proportion of the membrane structure should be in accordance with the solar sun path. The surface of the structure should ideally be oriented perpendicular to the sun position. As the sun moves, an geometry has to be found which offers most of the time maximum protection from sun rays, whilst providing a maximum shading area and offering a favorable ratio of surface to volume. This design principle is recommended by Paul Gut (1993) who explains in his book „Climate Responsive Building - Appropriate Building Construction in Tropical and Subtropical Regions" that *„the heat exchange between the building and the environment depends greatly on the exposed surfaces"*.
Having this in mind it becomes obvious to prefer designs of shading structures which have an elongated geometry on an east-west axis where the surface

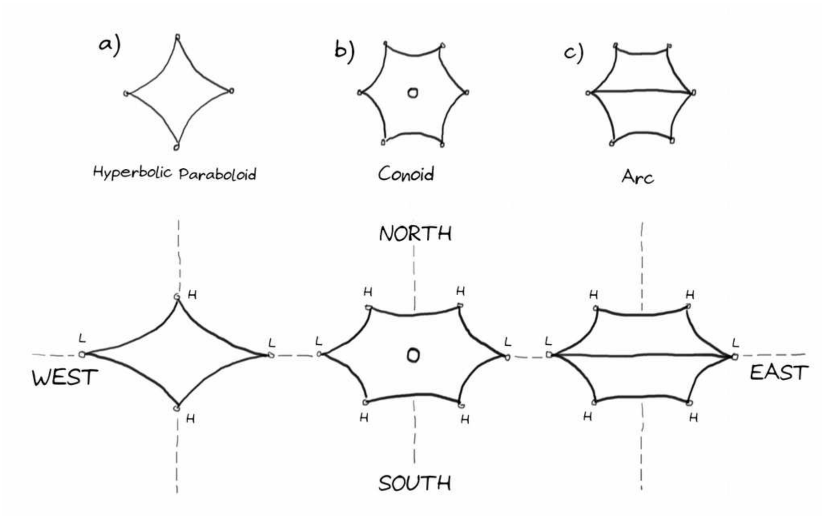


Fig. 30 Proportion and orientation

towards the low points blocks the almost horizontal sun rays of sun rise and dawn whilst providing a acceptable ratio of volume per exposed area to solar heat gain. (Fig. 30)

5. 2 Effective shading

The effectiveness of a shading structure depends largely on the correct orientation and the geometry. The emplacement of the structure within its surrounding environment is as important as correctly interpreting the solar geometry of the latitude and the design of extensions and overhangs of the structure, in regards to the desired shading area and time. A key factor is to understand the annual sun-path and the characteristic sun angles on the

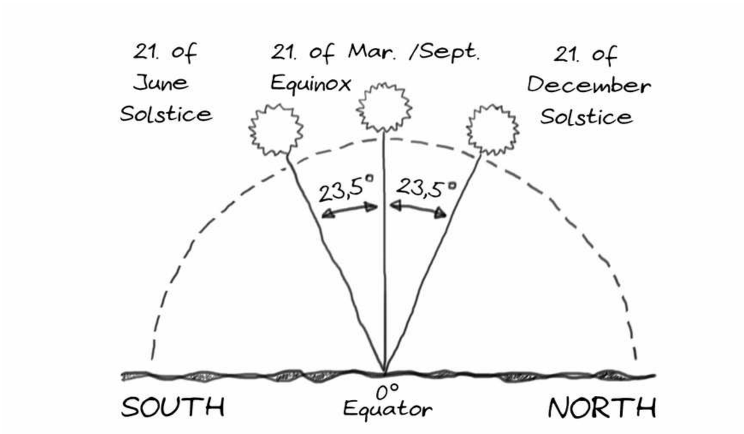


Fig. 31 Annual sun-path

solstice and equinox which are the most important dates to analyze when it comes to shade design. (Fig. 31)
The incidence angles vary according to the latitude where the structure is located. The summer or winter solstice (depended on whether the northern or southern hemisphere) on the 21th of June marks the most southward oriented position of the sun during the year, and the 21th of December the most northward oriented position. The correspondingly angles for the solar heights are correspondingly the lowest and therefore the most critical ones. The equinox at the 21th March and September represents the mid point path between north- and southward orientation of the sun, reaching at the equator a zenith position at midday while having equal hours of day and night. In figure 32 it can be observed how daily and annual solar sun-

paths can be schematically visualized according to a proposed design of a membrane structure with a typical anti-clastic geometry. However, the analysis has only been performed in a simplified scheme of plan, elevation and section, but it also should be conducted in three dimensions in order fully visualize the shade which the membrane surface projects on the ground and on itself. A good tool is a stereo-graphic solar model that enables the designer to project the shades at a selected latitude at a specific date and hour. Sun angles can be read out in numerical values, and shade projections can be overlapped to create shade masks for specific time frames.. The analysis can then be plotted out in two dimensional solar charts for the critical dates.. (Fig. 33 and 34)

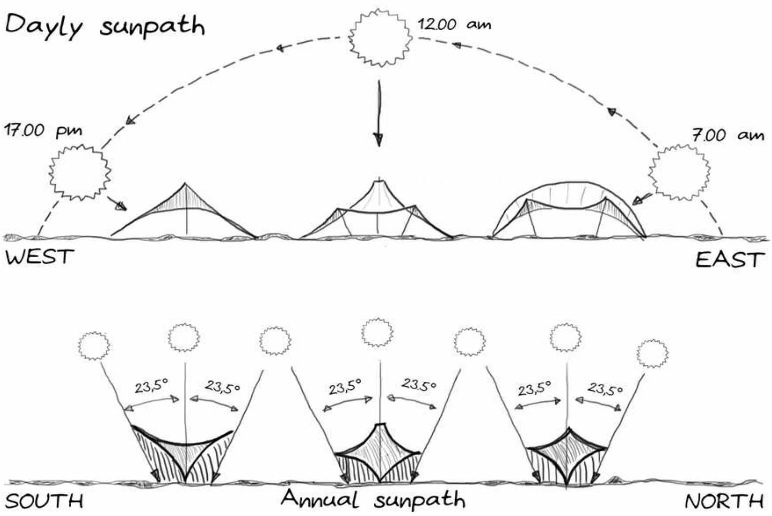


Fig. 32 Daily and annual sun-path shade effects

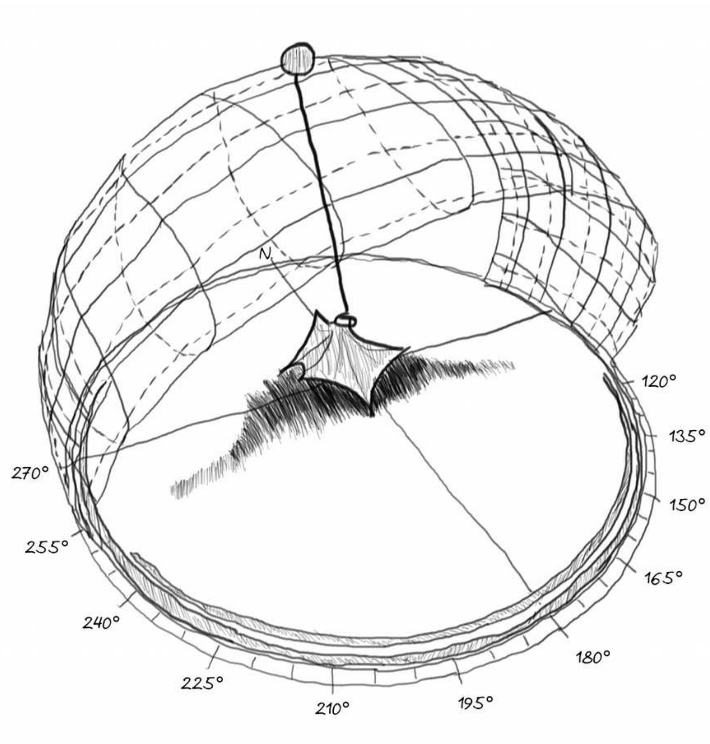


Fig. 33 Stereoscopic shade projection in three dimensions

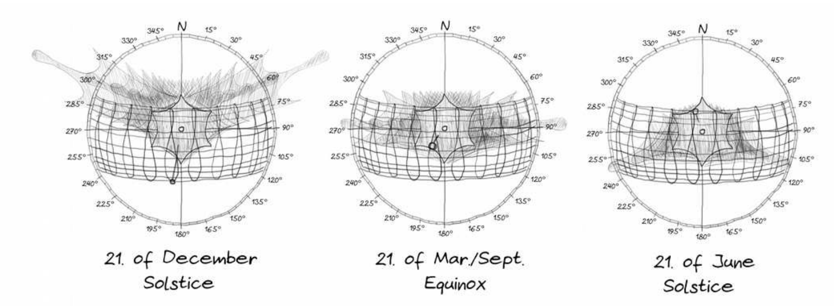


Fig. 34 Solar charts with overlapping shade projection

As important as considering the shade projected by the structure and the shade projecting on itself is the shade which might be created by elements in the surrounding environment. Understanding the external shading can in some cases help when shading is difficult to achieve by the design of the structure. Careful analysis of the site can lead to discovering that a building or a large tree is already providing the shade which is required by the design brief. In order to carry out such an analysis a site survey is needed. All relevant elements of the built environment in the immediate vicinity of the building site should be schematically modeled in 3D, and can then be projected and plotted on to a stereo-graphic solar chart for further analysis.. (Fig. 35 and 36)

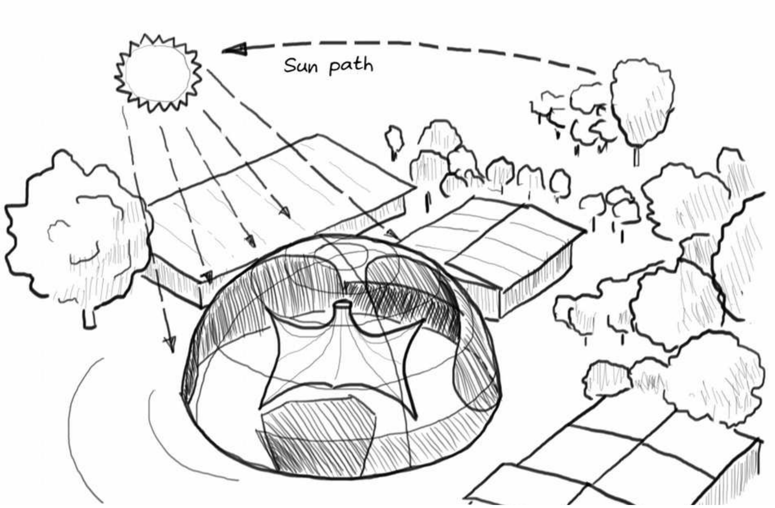


Fig. 35 Shadow projection of surrounding elements

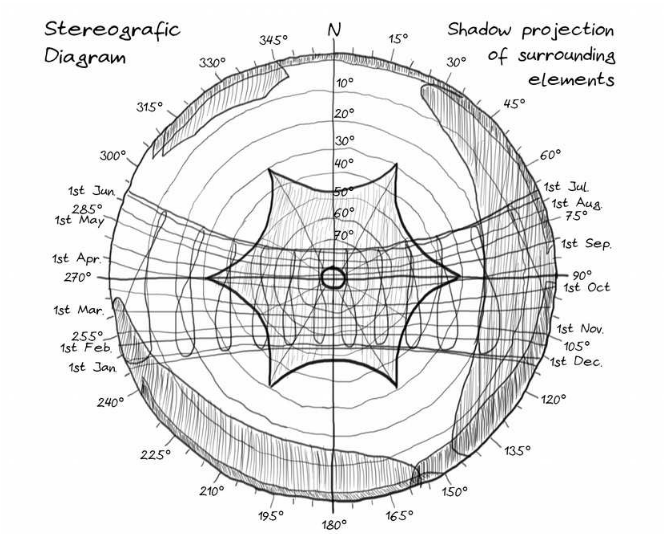


Fig. 36 Stereo-graphic solar chart with projection of surrounding shade elements

Through careful analysis of the solar geometry and the projection of shade it can be found that the plan of the structure does not coincide with the projected shade. The shaded area on the ground, which can be called a comfort area, is always shifted according to the sun position. This fact cannot be neglected and should be addressed by optimizing the design itself. Figure 37 shows a series of schematic diagrams for the relation of proportions between the overhang width of the membrane roof and the height of the edge borders.. It becomes evident that lower and deeper overhangs provide a larger shading area in regions close to the equator. (Fig. 37)

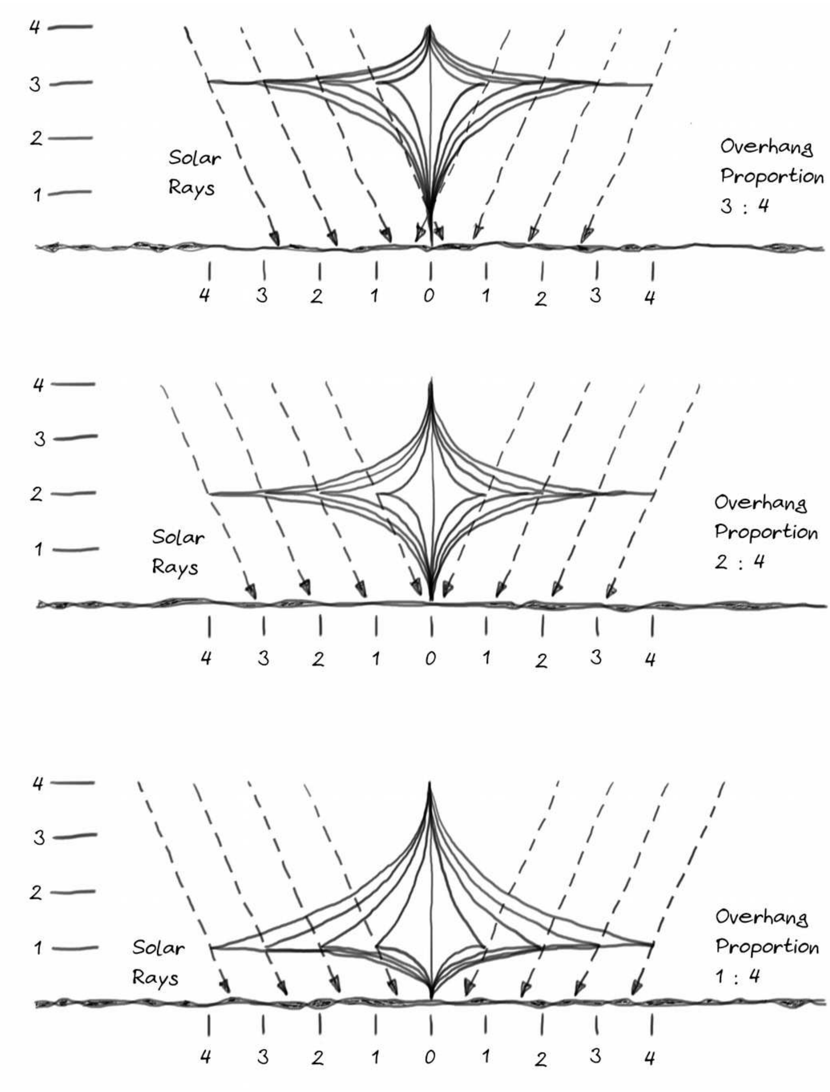


Fig. 37 Relation between roof proportions and shade projection

When being confronted with design tasks like coverings for large areas or facades, the repetition of modules with a rather simple geometry are in some cases a solution which can provide an architecturally interesting, but cost-effective solution whilst solving the issues of shading. The following three examples show that by repetition and superposition of single modules a three-dimensional screen can be created in which the concept of self-shading is inherent. As each module projects shades onto the next, and vice-versa, the overall shaded area is incremented and therefore the solar heat gain is reduced. This has direct impact on the thermal comfort of persons behind or below the superstructure. Similar solutions can be found in the traditional Mediterranean an Arabic architecture. (Fig. 38, 39, 40)

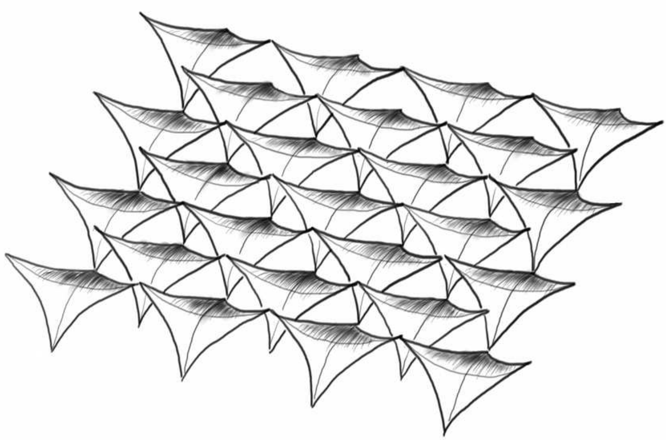


Fig. 38 Repeated hyperbolic, self-shading, geometry

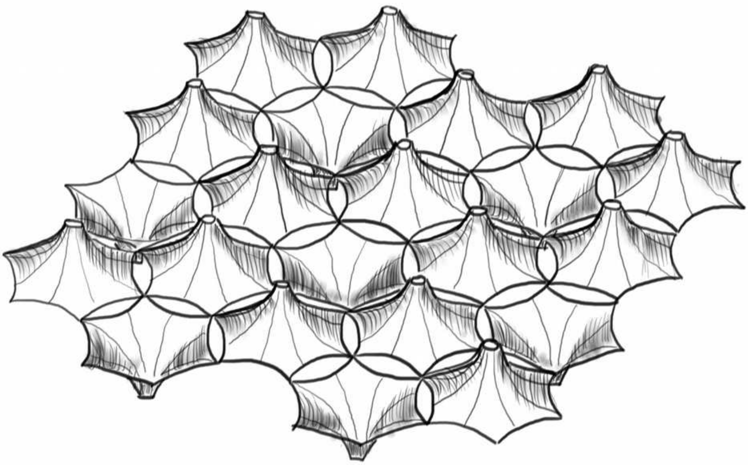


Fig. 39 Repeated conoidal, self-shading, geometry

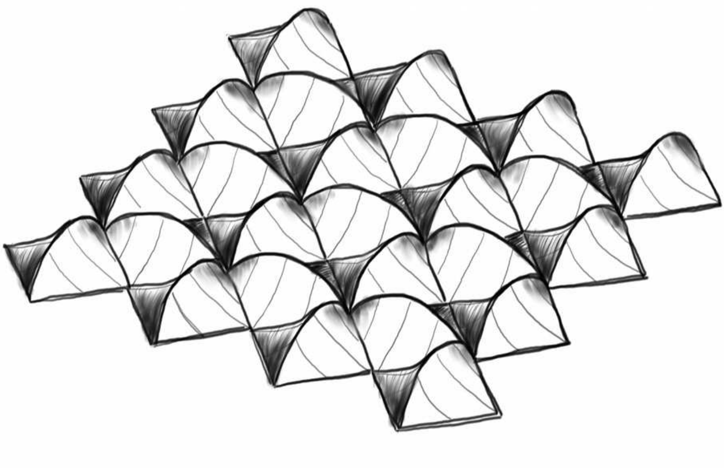


Fig. 40 Repeated arc, self-shading, geometry

5. 3 Heat and light transmittance

The building envelope is classically understood as a modifier or filter of the outside climate conditions. Insulation of the inside space from outside heat or cold are some of its primer functions, such as providing good lighting and ventilation conditions. Modern membrane materials open up a lot of opportunities to address these issues, but their behavior differs drastically from traditional building materials. Due to the very low mass of fabric membranes their thermal resistance is very low. The thermal behavior of membrane materials derives almost completely from convective heat transfer mechanisms on their surface and their optical absorbency. This is, according to ElNokaly, the reason why solar transmission, solar reflectance/ absorbency, emissivity and the surface wind velocity all play important roles in the heat transfer and its calculation.. (ElNokaly, 2003, cited from Harvie and Wu), (fig. 41)

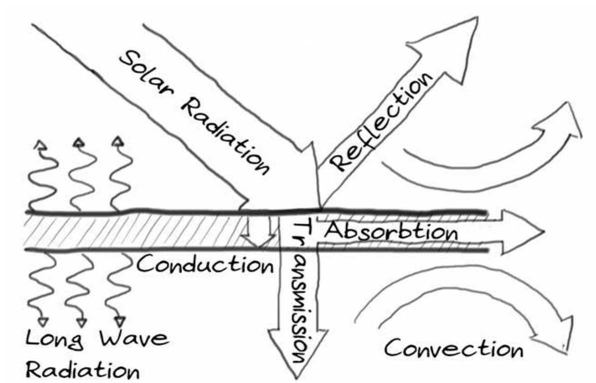


fig. 41 Heat transmission mechanisms on membrane materials

Most of the membrane materials used in tensioned membrane structures are to a certain degree translucent and provide good lighting conditions on the inside. A typical graph of the spectrical reflectance, absorbtance and transmission behaviour of a PVC coated Polyester fabric can be observed in fig. 42. It becomes clear that most of the radiation in the visible range gets reflected while only a small percentage gets absorbed and transmitted. This is different to the shortwave range of the spectrum, where a greater percentage gets absorbed and consequently re-radiated as long wave radiation to the sky, and also to the usable space below. For the use of membranes in the tropics white materials with highly reflective coatings on the outside and low emissivity coatings on the inside should be preferred, as well as the use of totally opaque materials..

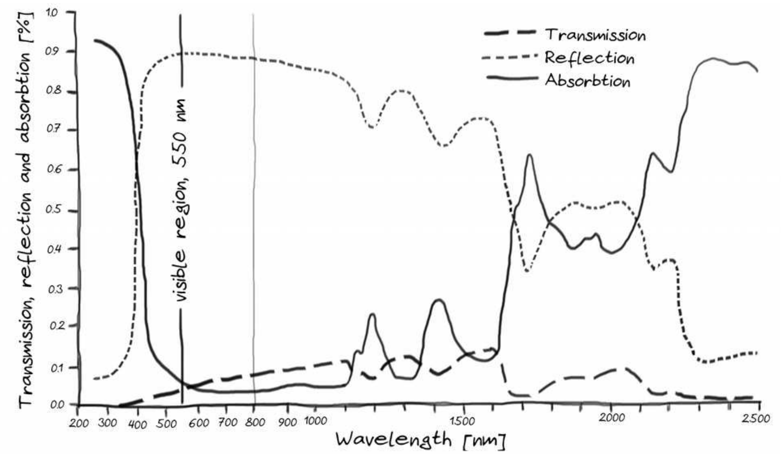


Fig. 42 Spectral reflectance, transmittance and absorbency

The overall thermal performance of a membrane is difficult to describe and even more difficult to predict. Several attempts have been made to create reliable simulation models (Harvie, Devuldner). Most of these models relate to spaces enclosed by membrane structures but in fact in the tropics it can be assumed that most of the time spaces covered by membrane structures are semi-open spaces, where these models apply only partially. In semi open spaces the actual outside climate plays an important role, as these conditions can be considered initially the same as the inside conditions. In this context Effects of natural ventilation, convection and indirect radiation and glare play an important role on the heat exchange behavior of the membrane structures in tropical climates. (fig. 43)

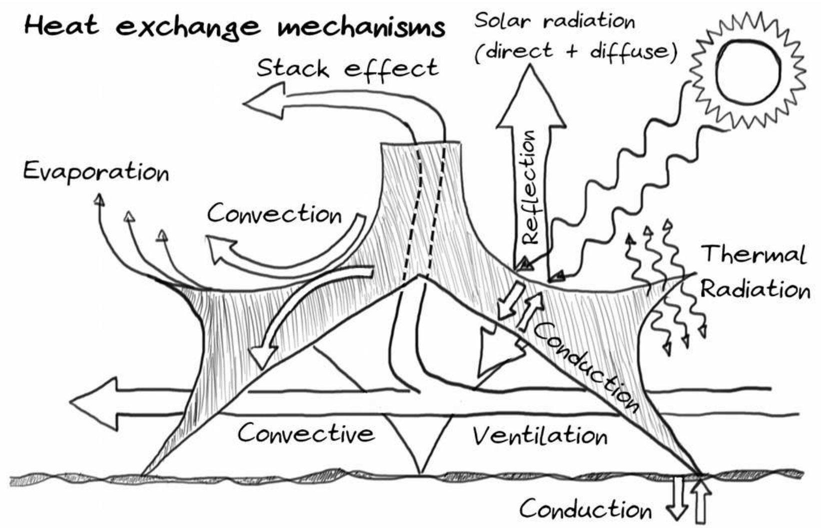


Fig. 43 Heat exchange mechanisms on semi-open membrane

Figure 44 shows a typical example of the behavior of semi open membrane structures in the tropics. It can be clearly seen that the inside temperature of the covered space closely follows the outside temperature, being a little bit higher at night time due to the absence of solar radiation.. During daytime when the solar radiation peaks, the thermal effects of radiation are mitigated by the membrane cover and inside temperatures are between two and three degrees Celsius lower than outside. This behavior clearly shows an increase of internal thermal comfort, which can be attributed to the climatic filtering/modifying effect of the membrane cover, that reflects a certain amount of the solar radiation and provides shade on the inside, which in turn lowers the long-wave heat radiation from below the surfaces.

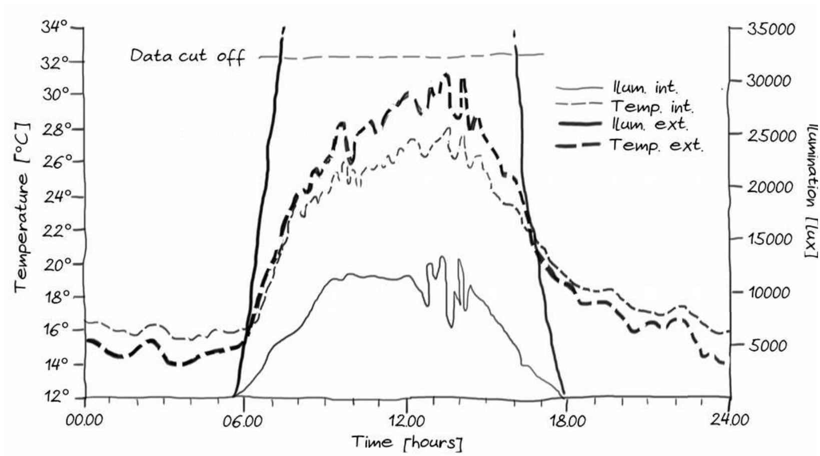


Fig. 44 Temperature and illumination in-and outside membrane

5. 4 Thermo-dynamic effects

Semi open Membrane structures in the tropics cover big volumes of air/space with a thin layer of material.. Their large surface area is under the effect of intense solar radiation while the space below is open enough to be affected also by general climatic conditions like the air temperature, wind and humidity. This situation leads to complex thermo-dynamic effects on the in- and outside of the membrane structure and has influence on the thermal comfort conditions of the occupants. One of the principal dynamic phenomena is the thermal stratification, which basically describes the rise of warm air up to the high points of membrane structures or the layering of warmer and cooler air relative to the height of the covered space. The direct heat transfer to or from the fabric roof contributes to the warming up of the air in the immediate vicinity of the fabric membrane and the internal heat sources, as ElNokaly states (2003). This permits to have masses of air with a lower temperature at the height of the used spaces at floor level, providing more thermal comfort. This phenomena has been measured and described extensively by Harvie and Devuldner and can also be observed in membrane structures in the tropics. (Fig. 45)

But the thermal dynamic effects here get additionally affected by convective turbulence and natural ventilation due to their semi-open condition. Ventilation vents on the high points can help to dis-

charge the warm air and create an additional effect, that is denominated „stack-effect". This effect is created by the difference of temperature between the in- and outdoor air which in turn creates a vertical pressure gradient resulting in an air flow from positive to negative pressure areas.. The warm air becomes buoyant, rises and escapes to the outside, creating a depression on the inside that draws again air to the inside space below the membrane. This causes a constant temperature driven airflow (Forster, Mollaert, 2004).
The generated air flow can help to improve comfort conditions. Although the air flow at body height has the same mean temperature as the air temperature, the increase of air velocity crates a positive effect on evaporative cooling, due to transpiration on the human skin..

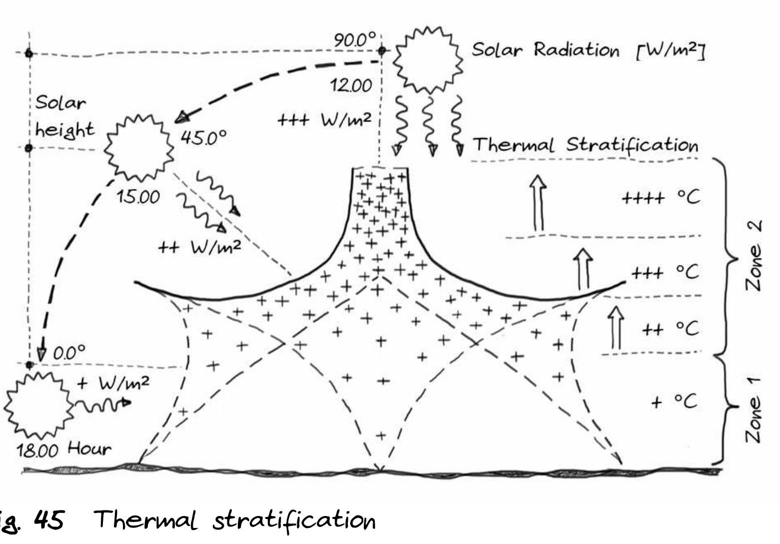


Fig. 45 Thermal stratification

Other thermodynamic effects between radiation and convection occur on the in- and outside of the membrane surface. A special case is the use of double layer membranes which can be employed to improve the thermal resistance of the covering. An additional layer is added and the solar heat gains can be effectively reduced. Because of the high relative humidity across most of the tropical climates the use of insulating material is not recommended, as it would trap much humidity and create favorable conditions for mold and fungus growth. Instead the resulting air gap between the inner and outer membrane layer can be ventilated and warm air effectively removed through high point outlets.. (Fig. 46)
The spacing between the two layers should however be carefully engineered in order to achieve an positive effect on the thermal comfort.

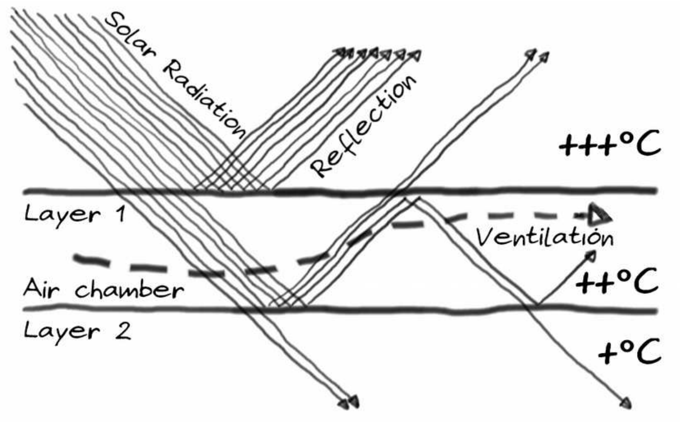


Fig. 46 Ventilated double layer membrane

5. 5 Design and analysis tools

For an effective solar design with membrane structure it is essential to conduct a proper analysis of the site and the climatic conditions. Meteorological data should be accessible and information on solar hours, mean radiant, and air temperatures should be reviewed. Also a solar chart of the correct latitude should be available, in order to analyze the solar path and the shading conditions of the site. Furthermore a visit to the site with a survey on shading elements and the micro-climatic conditions should be part of the analysis before approaching the design task.. For the analysis of the data several digital tools are available on the market, like Ecotect or other plug-in shading tools for 3D modeling packages.. Some freeware online tools are also available on various internet platforms: http://www.builditsolar.com/References/SunChartRS.htm
However one of the best analogue analysis tools for solar shading remains the Heliodon. (Fig. 47)

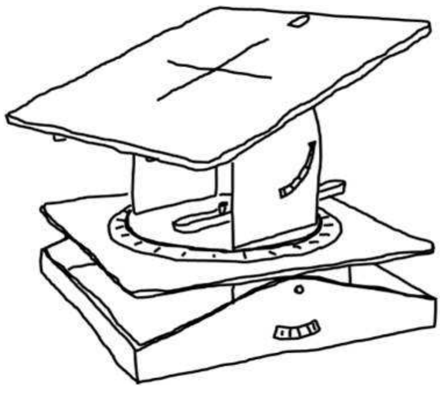


Fig. 47 Heliodon

6. Design Strategies - WIND

Wind is one of the most powerful climatic elements and has been exploited by humanity throughout history of civilization for mobilization and transport over the seas. It has also been a source of power for machinery using the windmills as the archetype structure which converts wind into mechanical force. In this sense the understanding of wind-patterns has been essential for human development and survival, and has regained importance in recent years in relation to the search for renewable energy sources in advent of climate change.
Wind phenomena are closely connected to cultural activities all over the planet and strongly affect the well being of people, especially in the tropics. The annual monsoon cycle is just one example, as well as the trade winds, which define climate conditions in the tropics and are an important factor on the success of agricultural activity. But wind can also become a threat, and natural disasters provoked by tropical storms are becoming more and more frequent and intense due to climate change. Another effect of wind, which is of importance for this study, is its positive influence on thermal comfort in hot and humid climates. Natural ventilation is one of the most ancient cooling strategies used in architecture, while at the same time being considered one of the simplest passive strategies that can be used in order to provide thermally comfortable conditions. (Elnokaly, 2003 and Albadra 2014)

In this sense, understanding the wind and its fluid dynamics can become an effective design tool when planning habitable spaces in the tropics. Especially membrane structures offer, due to their light and flexible nature, a lot of opportunities to improve natural ventilation by pure means of geometry optimization and become a kind of climate modifier. Understanding the airflow rate and pattern around the membrane structures is therefore of vital importance in order to asses appropriate comfort levels during the design process. (Elnokaly, 2014)
In this chapter the main effects of wind on a global and local scale will be introduced and a series of design strategies will be presented which use wind as a natural resource for natural ventilation in order to improve thermal comfort conditions.
Furthermore, a series of analysis tools will be presented which can help to inform and asses the design process of membrane structure with regards to wind and air-flow dynamics.

6. 1 Wind effects

Wind can be defined as the movement of atmospheric gases which is caused by the differences in atmospheric pressure, originated by the varying exposure of the earth globe to solar radiation. The dynamics of wind on a global scale are as well strongly influenced by the rotation of the earth and the friction with the earth's surface. The wind speed is determined by the gradient of differ-

ences of air pressure. The steeper the gradient between high and low pressure zones, the faster the air flows from one to another. On the other hand the wind direction is subject to the relative position of the pressure areas., but it is also influenced by the Coriolis force and topography. (Krautheim, Pasel and others, Berlin, 2014)
The tropical regions are dominated by the circulation of the Hadley cells. These are characterized by ascending air masses around the equator and descending branches on their pole-ward sides of the earth globe. This circulation creates a constant airflow on the northern and southern hemispheres towards the equator, denominated the trade winds. The intensity of these movements is largely controlled by the seasonal solar cycle and creates the special atmospheric conditions of the so called intertropical convergence zone (ITCZ). (McGregor , 1998)
The tropical low pressure condition combined with elevated water temperature of the oceans and and intense solar radiation is likely to produce tropical low pressure storm systems, which are generically called cyclones, hurricanes, in the american tropics; and typhoons in the asian regions. Cyclones are a typical seasonal wind phenomena which can develop destructive forces. They are defined as warm-core, non-frontal, low pressure systems which develop under their rotation high wind speeds up to 250 km/h, which is an important factor to take into account when designing membrane structures in the tropics. (fig. 48)

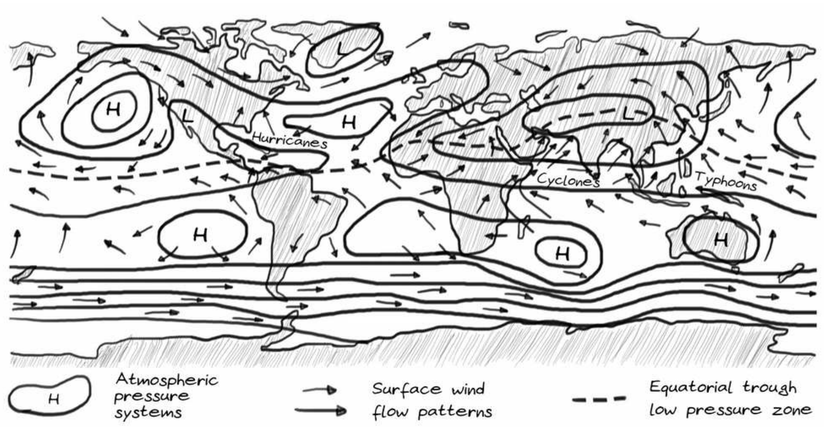


Fig. 48 Mean pressure systems and representative wind vectors at the earth surface

The access and review of meteorological data is therefore of special importance in order to understand the wind behavior of the specific construction site. A wind rose is a helpful tool to graphically map the direction and speed of wind at a particular location.. It allows the designer to trace specific wind conditions and provides data on the frequency and speed of wind, which is required to anticipate exceptional wind situations or prevailing wind flows, and take this information into account for the design of the structure. (Krautheim, Pasel and others, 2014), (fig. 49)

On a meso-scale other wind effects also come to play an important role and should be taken into account when visiting the site in the pre-design phase of a project. The land-ocean breeze is likely to

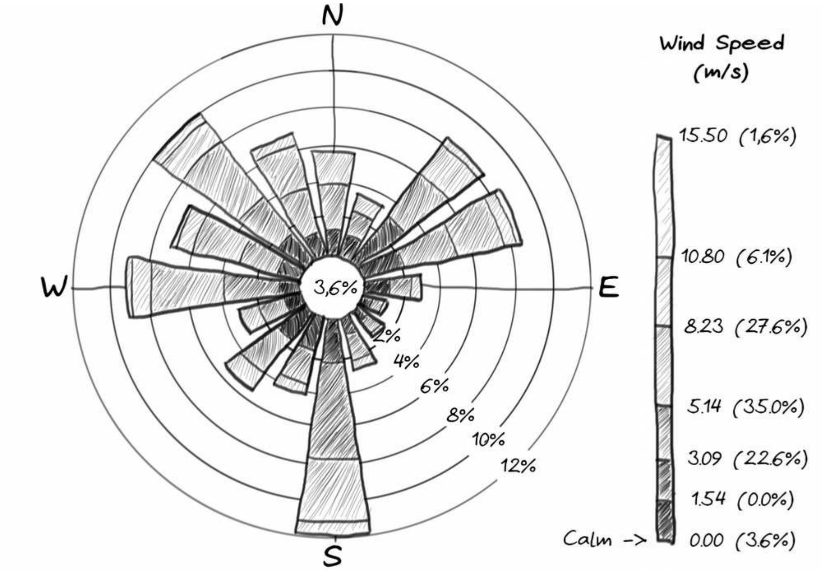


Fig. 49 Wind rose

occur in all coastal areas of the tropics and is originated by the thermal dynamics occurring between ocean and land. During the day the land masses on the coastal shore heat up, the air pressure drops and the warm air rises. The pressure above the cooler water mass is relatively higher and an airflow from seaside to the land is created, which provides a cool breeze. During night time the opposite occurs. After sun set the air temperature on the land-side drops and air pressure increases while at the same time the relatively warmer ocean creates a low pressure area which provokes a breeze with the inverse flow direction, from land-side to the sea-side. (fig. 50)

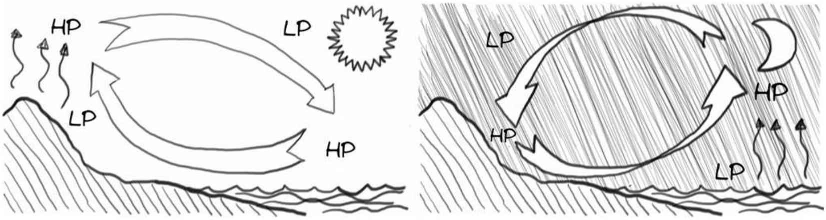


Fig. 50 Land - ocean breeze

Another similar phenomena which provokes local wind effects is the mountain-valley breeze which is originated by the thermal dynamics occurring between mountain and valleys, like its name suggests. After sunrise the exposed mountain surfaces heat up quickly creating a low pressure zone, while the colder air masses are in the lower valleys at high pressure zones. This creates an uprising air flow from the valleys to the mountain peaks. During the day the air masses in the valleys also heat up while at night the mountains, and the surrounding air masses, rapidly cool down creating high pressure zones. The air flow is now inverted, flowing at night from the mountain peaks to the valleys. (fig. 51)

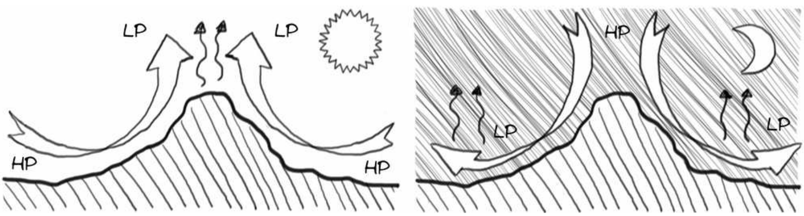


Fig. 51 Mountain - valley breeze

On a micro scale, local wind effects have to be considered as well, because they are often overlapping or in counter-position to the general wind conditions registered by meteorological weather stations. Site visits in different seasons and time of the day can provide a good overview on the intensity and direction of wind flows on the building site. As wind is a dynamic force, different scenarios must be considered. Many aspects of the site can have an influence on the wind flow like the topography, roughness of the terrain, vegetation or the existence of a lake or river. These elements can provoke an intensification, like the slopes of a valley which create a funnel effect, or a total absence of wind and breeze, like for example a dense area of jungle next to the building site which blocks the wind, creating a wind shadow.. Increase of urbanization around the world is an issue, so the urban wind effects should also be taken into account when designing membrane structures in the tropics. Existing houses and buildings in the urban landscape can block wind flows, provoke turbulences and create wind shadows, or accelerate air speed in narrow streets, which act like channels creating the funnel effect which can convert breezes into heavy gusts. Knowing the site conditions prevents from having a lack, or an excess of natural ventilation. The site can also provide valuable information about where to position the membrane structure, and give hints to the correct orientation and shape of the geometry. (fig. 52, 53)

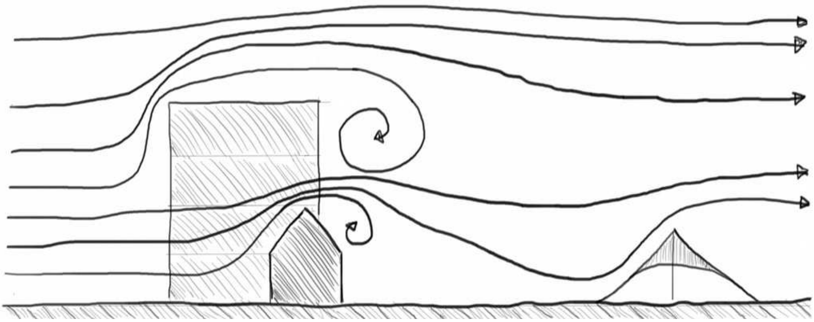


Fig. 52 Urban wind shadow

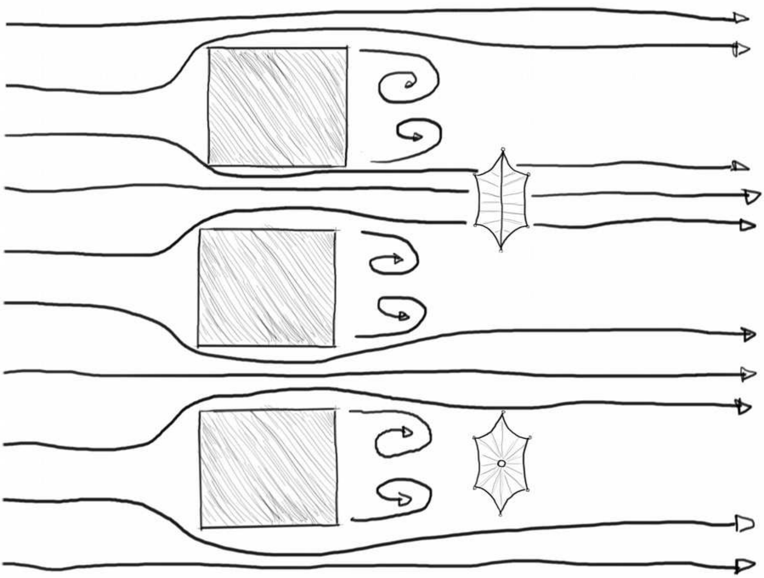


Fig. 53 Funnel effect

6. 2 Effective Ventilation

In the hot and humid tropical cimates ventilation is one of the most effective strategies to improve the sensation of thermal comfort (Goshayeshi, 2013). Several studies have shown that particularly semi-open spaces, like membrane structures, have the potential to modify the micro-climate in and around their boundaries, by enhancing the wind speed and thus improving the human comfort levels (Elnokaly, 2014). Increased air velocity allows to remove excessive humidity from the built space and create evaporative cooling effects on the skin of man and structure.

The effectiveness of ventilation relies on the control of the air velocity and availability when climate conditions are most suffocating. But the effectiveness of ventilation should also be measured in terms of costs and energy consumption in comparison to its benefits. In this sense, natural ventilation, without the use of any mechanical machinery, is probably the best choice in order to create healthy and comfortable environments with a sustainable approach. Passive design strategies therefore take into account the global and local wind conditions as a primary resource for ventilation, and envision the building or structure as a climate modifying apparatus which enhances satisfying comfort conditions. Regarding the semi-open membrane structures, one of the most influencing elements, concerning the effectiveness of natural ventilation, is the geometry of the structure itself. (fig. 54)

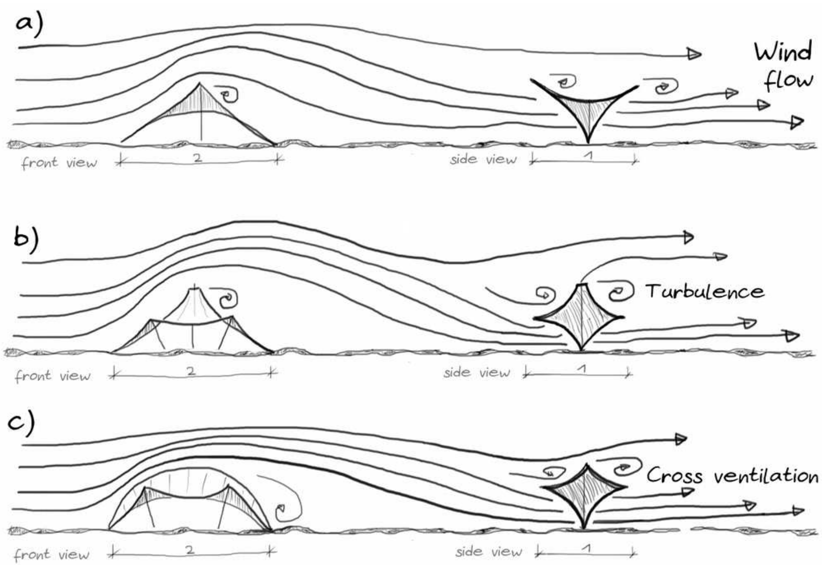


Fig. 54 Geometry and airflow

The structure as an object with a particular geometry modifies the airflow pattern in and around itself. Depending on the specific geometry and its orientation towards the predominant wind direction, the structure modifies the direction and speed of the air flow, which can have beneficial or counter-productive results.
The possibility of flexible-freeform-geometric-operations within the form-finding design process of membrane structures allows to modify the topology of the surface in such a way, that aerodynamic effects can be enhanced to increase the wind-speed in and around the structure, and to improve the effectiveness of natural ventilation. (fig. 55)

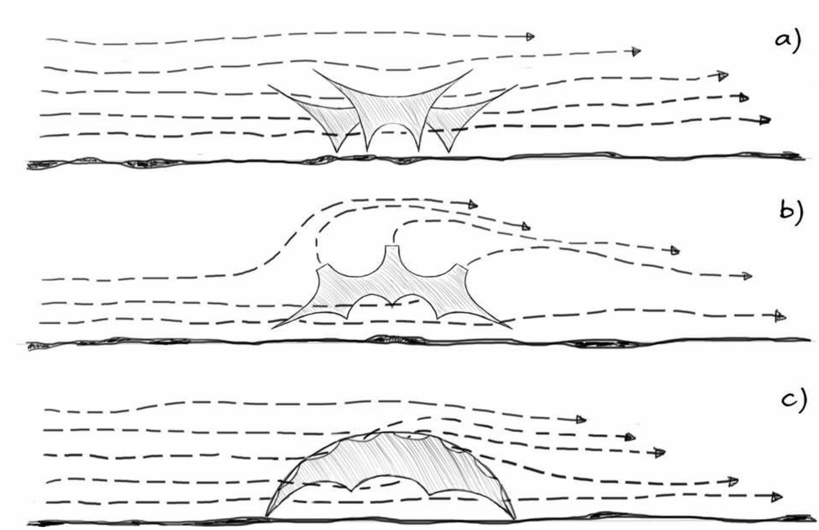


Fig. 55 Topology enhanced ventilation

The proportion and orientation of the structure should be considered in a first step, as they are commonly the first decisions to be made in a design process. The shallowest section of the structure should be orientated perpendicular to the wind direction, predominantly during the hottest season of the year, in order to allow an airflow under neath the structure. The geometry should be designed in a way that even the smallest breeze can be captured and directed towards the activity space areas. Open plan and no obstruction of the lateral facades should be achieved, as well as the implementation of high-point openings which should be designed to provide sufficient ventilation regardless of wind direction. (Forster and Mollaert, 2004)

The stack effect and the pressure induced ventilation are common methods in vernacular architecture for enhancing natural ventilation. These methods can also be applied to membrane structures. While pressure induced ventilation is dependent on wind, the stack effect is caused by rising warm air, creating a buoyancy action. By having openings located at high points in the structure, the warm air can escape, creating an air flow which will pull then more air back in from the outside on lower levels. This chimney effect by itself cannot create enough air flow to achieve a positive effect on thermal comfort. Especially under hot and humid climatic conditions, when the low temperature differences between indoor and outdoor temperature are not sufficient to create an efficient ventilation. Even though the performance of the stack effect in the tropics is far from effective, it should not be neglected and it is still of much benefit to let the hot air accumulation, beneath the membrane skin, escape through ventilation openings. (Haw, 2012), (fig. 56, 57)

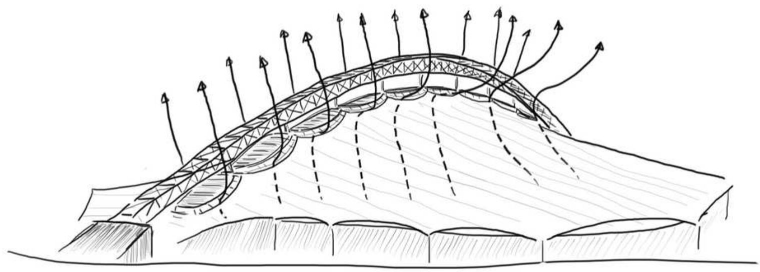


Fig. 56 Ventilation detail for arc structure

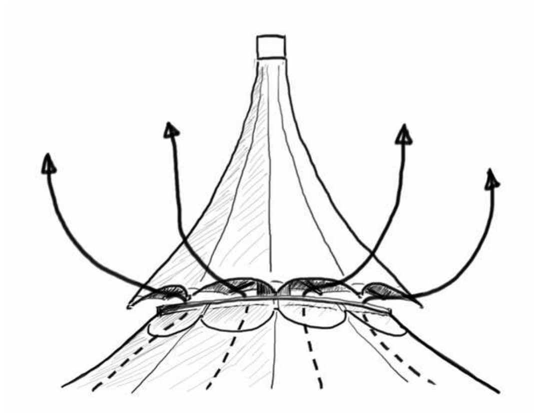


Fig. 57 Ventilation detail for a high point

The same strategy can be applied to double layer membrane structures. The air space between them can be ventilated and the hot air be removed from the gap through high-point vents, while taking in cooler air at openings at lower levels. Even though this strategy has no effect on the ventilation performance of the overall structure, this way the thermal performance of the membrane roof can be improved. (Forster and Mollaert, 2004).

The performance of the second ventilation method is independent of low temperature differences. Therefore, it has a higher potential to increase the thermal comfort conditions in hot and humid climate. Pressure or Wind-induced natural ventilation is based on pressure differences on and inside the building skin, created by the wind. The geometric shape of the membrane skin has an influence on

the airflow pattern around and through the structure. The part of the surface which is facing the windward direction is compressed, creating positive pressure. On the opposite, the surfaces on the leeward side of the wind direction face a lower pressure caused by higher air velocity. This pressure, difference between the two opposite sides of the membrane surface is the driving force of the wind-induced natural ventilation. (Haw, Selangor, 2012)
Additional to this general assumption that positive pressure develops on the windward side of the membrane surface and negative pressure on the leeward facing side, it must be also taken into account that pressure drop,s and turbulence can also occur on the leeward side of singularities in the membrane geometry, like for example parts of the supporting structures like mast or arches. (Forster and Mollaert, 2004), (fig. 58)

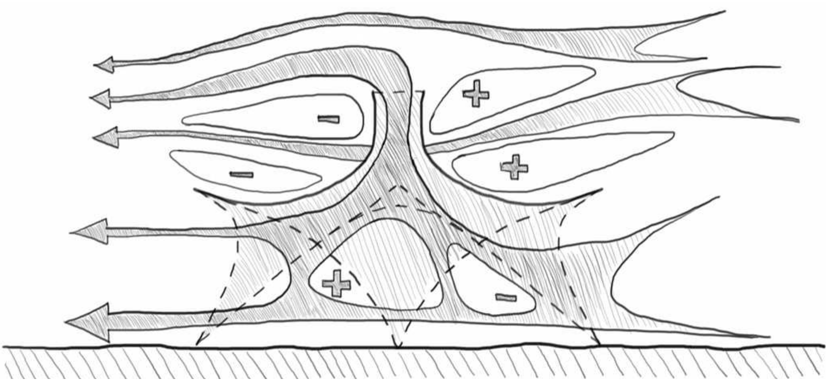


Fig. 58 Ventilation by difference of pressure

The wind driven airflow beneath and around the membrane structure is largely dependent on the direction and speed of the wind. The speed of the airflow increases proportional to the wind speed and to the difference of pressure between the openings. While the wind speed is out of the designer's control, it also offers great potential to improve the pressure coefficient between air inlets and outlets in opposing pressure zones, which makes it possible to effectively ventilate the space beneath the membrane structure, even with lower velocities of natural wind. Greater wind velocities are usually to be expected at high points, therefore these elements should be exploited to enhance suction and increase airflow through the openings. (Forster and Mollaert, 2004)
These effects can be studied during the design process using scale models for wind tunnel tests where the overall ventilation performance of the membrane geometry and detail performance ,such as ventilation openings, can be evaluated. (fig. 59)
A more time and cost effective analysis can be achieved by digital simulations with the use of computer fluid dynamics (CFD). A 3D model of the membrane surface geometry is placed into a virtual wind tunnel where the model can be tested under different wind conditions, speed and directions, as well as the influence of surrounding structures and elements. Specific information about pressure levels and air velocities can be plotted out at every section or plan, what is of advantage. (fig. 60)

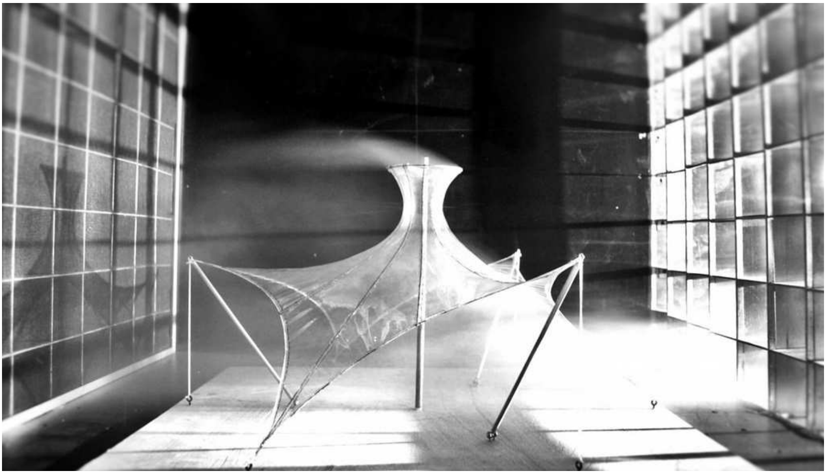


Fig. 59 Wind tunnel test

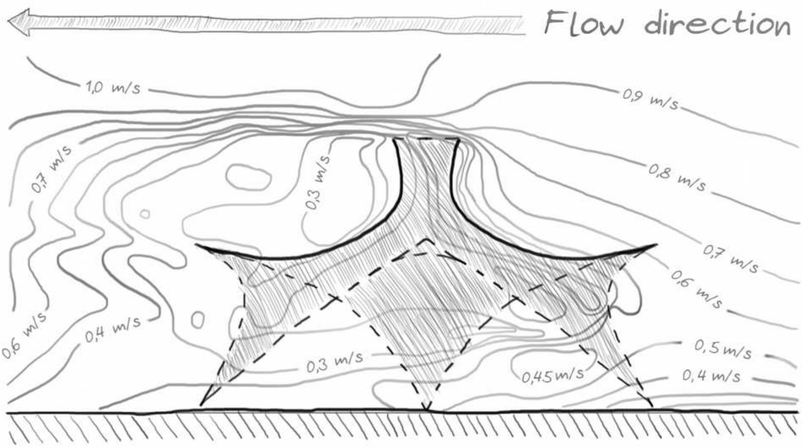


Fig. 60 CFD analysis – air flow rate

The limitations of natural ventilation are clear: the rate of ventilation may not be sufficient, due to low or no wind, or very little temperature difference between inside and outside, but even though natural ventilation is largely dependent on incontrolable climate conditions, it is still one of the most effective strategies to enhance positive thermal comfort conditions. A strategy for membrane structures which has not yet been fully exploited when it comes for example to the design of ventilated facades in urban environments. (fig. 61)
Therefore the following chapters will address some more common concepts of vernacular architecture and fluid dynamics in order to translate them into applicable passive design concepts for membrane structures.

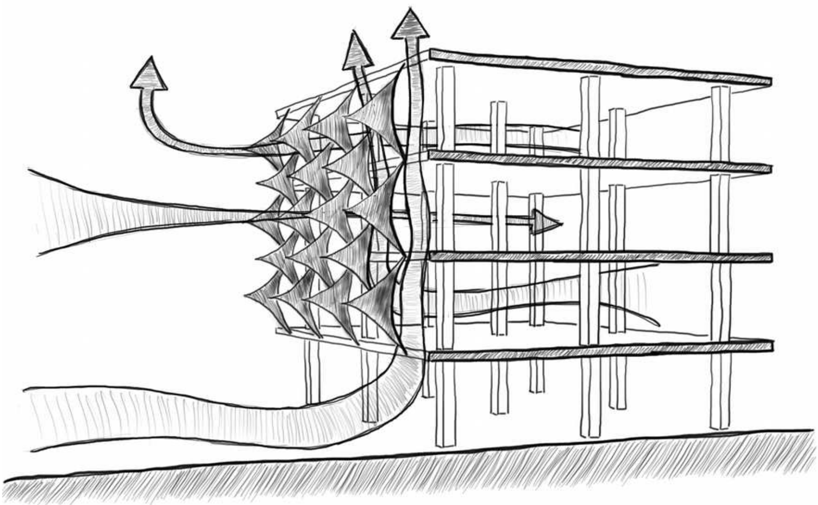


Fig. 61 Ventilation strategy for facades

6. 3 Cross ventilation

Cross ventilation is one of the most well known passive strategies for natural ventilation. This concept has been used widely in vernacular architecture and has proven its effectiveness through the history of architectural evolution. The high humidity levels and warm temperatures of the tropics require maximum ventilation. The lessons learned from traditional architecture are that very open buildings with permeable facades and floor plans best fulfill this requirement. Free passage of air for cross-ventilation through the interior is important (Gut, St. Gallen, 1993). Cross ventilation occurs when air passes through the structure from one end to the other. Therefore the long axis of the structure would be ideally oriented perpendicular to the summer wind patterns, when cooling is most needed. The windward side facade should be designed with more cover and smaller air-inlets than the leeward side exhaust out-lets, in order to take advantage of the Venturi effect. (fig. 62)

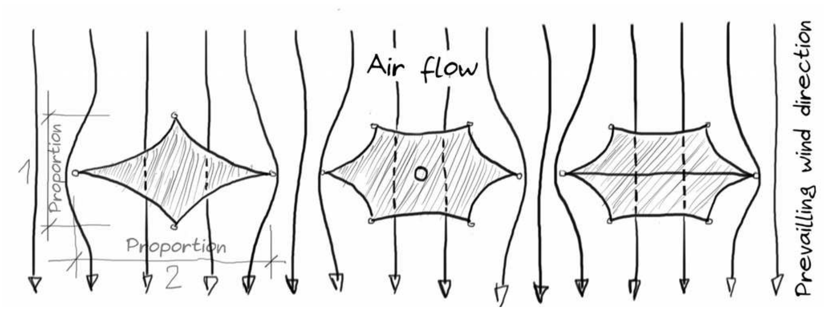


Fig. 62 Cross ventilation – orientation and proportion

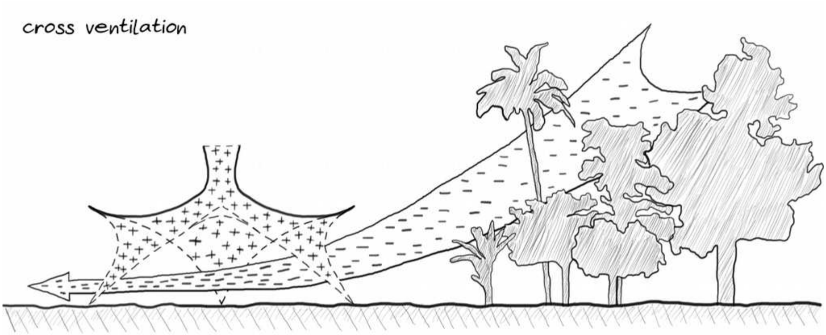


Fig. 63 Cross ventilation and vegetation

Even greater advantage can be taken of cross-ventilation as a cooling strategy to improve thermal comfort, when the breeze which is directed through the structure has previously passed through areas covered with vegetation. The mean temperature around trees and vegetation has proven to be always several degrees cooler than its surroundings. When such pre-cooled air is flowing through the membrane structure, the warmer air accumulated beneath there can be removed and chilled by the cooler air provided by cross ventilation. A careful site analysis can provide information about the feasibility of such a strategy. (fig. 63)

6. 4 Venturi effect

The Venturi effect is also a longtime known physical phenomenon from the studies of the flow of fluids, and can be used as a design principle for natural ventilation and passive cooling. Positive and negative air pressure zones can be created by

geometric design in such a way that the air flow, which passes through a membrane structure, can be increased in velocity, enhancing a cooling effect and have been studied extensively by Haw and Selangor (2012). The physical principle behind this concept is described in fluid dynamics as follows:
„a fluid's velocity must increase as it passes through a constriction in accord with the principle of continuity, while its static pressure must decrease in accord with the principle of conservation of mechanical energy." (Wikipedia, 2015) (fig. 64)

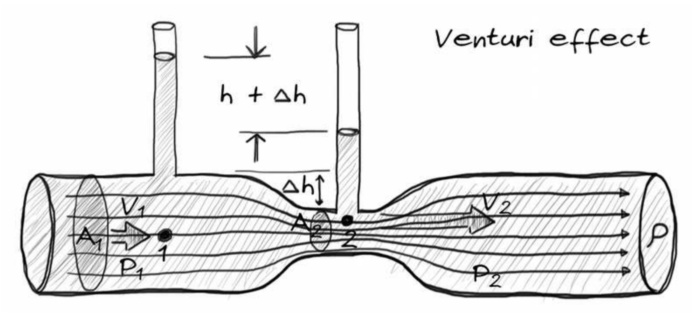


Fig. 64 Venturi effect – theoretic principle

Translating this theoretical concept to membrane structures, it can be noted that the parameters affecting the air flow velocity are related to the initial wind flow speed and pressure; and the section area of the inlet and outlet area. The most fitted anticlastic shape to exploit this ventilation strategy most effectively is a conoidal geometry where the proportions of high-point openings can be

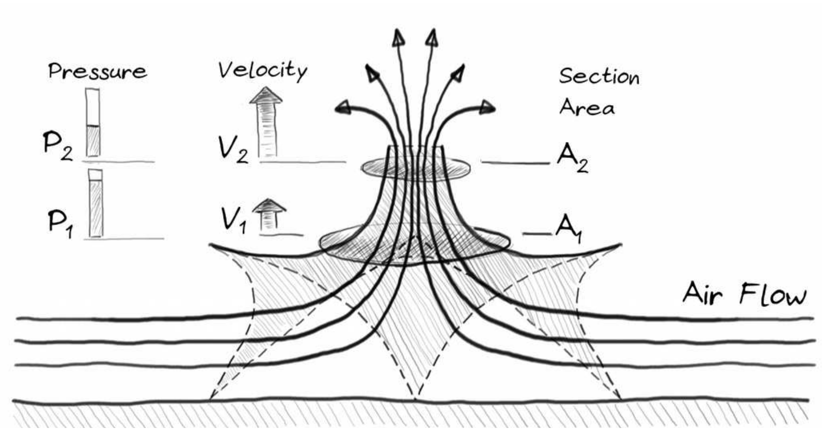


Fig. 65 Venturi effect on membrane structures

designed in such a way that the speed of the air flow within the structure increases. (fig. 65)
According to the laws of fluid dynamics the volumetric air flow rate within the cone can be calculated with the following formula. (fig. 66)

$$Q = A_1 \sqrt{\frac{2}{\rho} \cdot \frac{(p_1 - p_2)}{\left(\frac{A_1}{A_2}\right)^2 - 1}} = A_2 \sqrt{\frac{2}{\rho} \cdot \frac{(p_1 - p_2)}{1 - \left(\frac{A_2}{A_1}\right)^2}}$$

Fig. 66 Venturi effect – formula: volumetric air flow rate

Conoidal geometries are only one possible solution to create a Venturi effect within membrane structures. Other anticlastic geometries should be explored in further studies and their effectiveness for ventilation purposes should be tested.

6. 5 Design and analysis tools

In order to design a membrane structure which is properly ventilated and enhances positive thermal comfort conditions, a proper analysis of both, the wind flow patterns on a global and local scale, and the behavior of the membrane structure geometry in regards to the fluid dynamics, is required. The most effective tool to understand seasonal wind flow patterns is a reliable set of meteorological data for the site, as well as the analysis of local wind patterns which should be checked with a handhold anemometer on several site visits at different times of the year, and the day, in order to get a reference on the actual wind speed on site. Sometimes local people are also a good source of information to find out about typical, and special wind conditions of the micro-climate on site. (fig. 67)

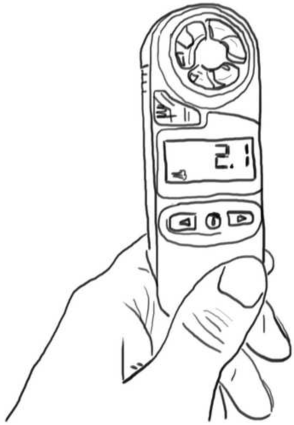


Fig. 67 Anemometer

For the analysis of the membranes's geometry aerodynamic behavior, it is of great advantage to conduct wind tunnel tests. A wind tunnel commonly is used in aerodynamic research to study the effects of air moving around solid objects. A wind tunnel generally consists of a tubular passage where the model to be tested is placed in the middle. Powerful fan systems provide a unidirectional air flow with controllable speed. The testing model can be equipped with sensors in order to measure aerodynamic forces, like pressure distribution, or the air flow speed at different points. Because wind-tunnel tests are very expensive they are only be recommended for large scale projects. (fig. 68)

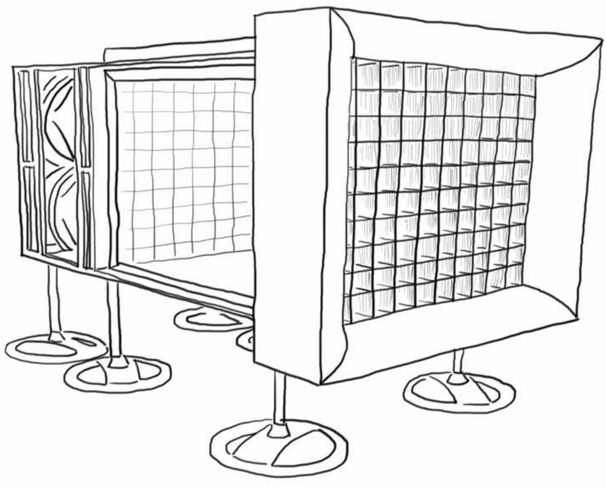


Fig. 68 Wind tunnel for architectural models

For smaller projects with lower budget a digital analysis is probably most suitable. Computational fluid dynamics (CFD) can provide this kind of analysis. This analysis method was developed in the field of fluid mechanics and uses numerical analysis and algorithms to solve and analyze problems that involve fluid flows, which include as well air.. These calculations are performed by powerfull computers, which are required to simulate the interaction of structure and environment within a defined virtual boundary condition.. The most sophisticated CFD software combines the thermodynamic with the aerodynamic effects and delivers results of specific accuracy which may give hints to patterns and tendencies of the aerodynamic behavior of the membrane structure. The output of the simulations allows to visualize the airflow and also to extract numerical results of different climate scenarios and ventilating strategies. Nevertheless, these results should never be trusted blindly, but should be critically evaluated and set into the specific context of the total environmental situation of the site. Some of the most commonly used software packages for Computational fluid dynamics analysis are the following:

-ANSYS Fluent software
-VirtualWind
-Ecotect+Winair
-IES
-DesignBuilder
-CFdesign

7. Design Strategies - RAIN

Rain and humidity are maybe the climatic elements that most appropriately characterize the tropical climates. Around two thirds of the annual global precipitation fall down in the tropical regions, and even more in the cloud forests, where humidity levels are almost always close to 100% (McGregor, 1998). In these regions water is cycling constantly in an accelerated flow, changing state from water to vapor, and precipitating in heavy discharges and elongated rainy seasons. The high volumes of rain in combination with intense solar radiation have allowed nature to develop the most complex and diverse ecological systems. Humankind has largely benefited from this biodiversity, but has also encountered struggles of survival with the vast amount of cycling water in the tropical atmosphere. Protection from the heavy, torrential rainfalls during the rainy seasons has always been an issue for mankind in the tropical latitudes, and adaptation of architectural typologies to climate is thus a necessity. Steep roofs, with wide overhangs, and means of ventilation to control the humidity, to achieve protection and comfort, have been employed throughout the tropics. In this chapter the effects of tropical rain patterns and the influence of humidity on thermal comfort will be addressed. Strategical and technical issues on the design of membrane structures in response to the tropical climate conditions of rain and humidity will be outlined.

7. 1 Rain and humidity effects

The characteristic condition of humidity in the tropical climates is the result of the intense solar radiation and the warm ocean waters, which fuel the evaporation process and allow an enormous amount of water vapor to be suspended in the atmosphere, which flows continuously through. the hydrologic cycle by the different means of physical processes (fig. 69). In the warm and humid zones of the tropical regions the relative humidity almost never drops below 50%. As a consequence, the frequency and intensity of precipitation is also very high, with a mean annual rainfall well above 1000 mm, while the global mean annual rainfall is usually around 800 mm (Mollison, 2012), (fig. 70). The continuous presence of a general cloudiness and the formation of large cloud systems, like cumulus nimbus, are the physical evidence of the condensing

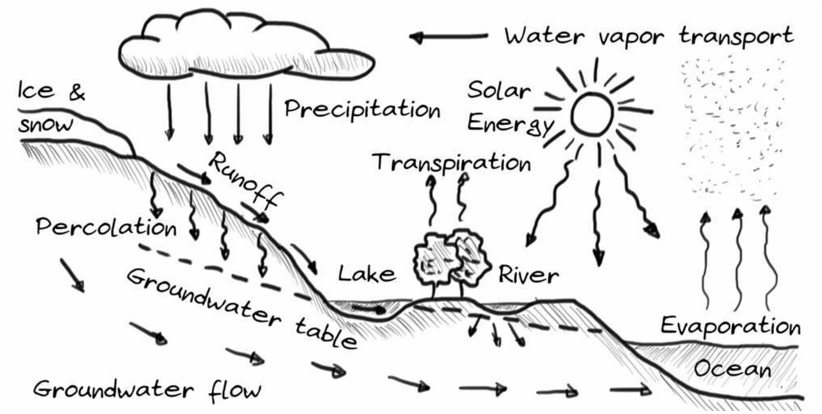


Fig. 69 Hydrologic cycle

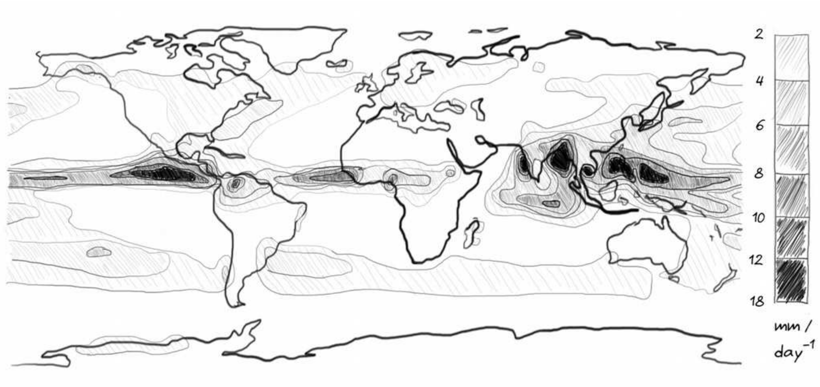


Fig. 70 Mean global, seasonal precipitation

humidity in the atmosphere, and often precede the typical heavy rainfalls (Koch-Nielsen, 2007)
Even though the rainfall and humidity levels are one of the most important quantitative indicators to characterize tropical climates, they are at the same time the most variable, not only regionally but also temporally. The mean annual rainfall volume can vary drastically within a few kilometers, and often shows important differences from one year to another, not only in volume, but also in intensity, frequency, duration and annual distribution.. These variations are subject to many parameters, including global warming, as well as oceanic and atmospheric anti-cyclic phenomena like EL NIÑO. Besides these special phenomena the most notable feature of tropical rainfall is its annual regime, characterized typically by one dry and one wet period, called rainy season or monsoon, with high intensities and frequencies of precipitation (McGregor, 1998).

7. 2 Effective rain protection and humidity control

Protection from precipitation is one of the essential functions of a roof structure, especially in the tropics. While membrane structures are often referred to as high-tech, avantgarde building solutions, the use of waterproof textile materials for rain protection is not new at all. Umbrellas and rain coats are of common use for rain protection. on an individual scale and deliver the perfect concept model for tensioned membrane structures. (fig. 71)
The effective protection from rain, also in combination with other climatic elements like wind, along with the controlled evacuation of the water, away

Fig. 71 Umbrella and raincoat

from the structure and its users, is one of the main goals to achieve within the functional design approach. A second, but not less important task is the mitigation of the high humidity, considering the fact that the relative humidity in combination with temperature is the most relevant factor responsible for our thermal well being The so called higro-thermal comfort condition is largely dependent on the levels of humidity suspended in the air, relative to its temperature. Therefore, it is a design objective to reduce the amount of humidity in and around the built environment in order to increase the thermal comfort. While the control of humidity can be addressed, in the case of semi-open membrane structures, only through the application of ventilation strategies, outlined in the previous chapter, the protection from rain and the drainage of water, which includes the analysis and design of the membrane geometry itself, is more a task in the field of structural and mechanical design..
The first task in the design process for rain protection and drainage is the analysis of the meteorologic data and the specific site conditions. It is important to know the mean quantities of rain, which are usually to be expected on a annual and monthly basis, but only as a general information. For the specific design and dimensioning it is more important to know the extreme events expected to occur, because the maximum amounts of water per square meter in a certain time will be the limiting factors for the dimensioning of drainage systems and slope inclinations (Mollison, 2012).

As a second step the proposed geometry should be analysed with the criteria of rain protection and drainage in mind. Questions of most feasible drainage paths on the surface and drainage points on the edge should be answered. Effective drainage is of much importance in climatic regions where a diurnal rainfall during the rainy season can reach up to 30 mm The consideration of the minimum slope inclination of the surface is also of important in order to identify areas of risk for ponding. The projection of iso-curves onto the membrane surface very quickly reveals the drainage paths which are driven by gravity and normally direct the water on the hydrophobic membrane material to the lowest points of the surface geometry. Areas where a risk of water ponding is to be expected, can be identified. (fig. 72)
Ponding describes the situation of water accumulating on the membrane surface, creating by its own weight a depression on the surface which will

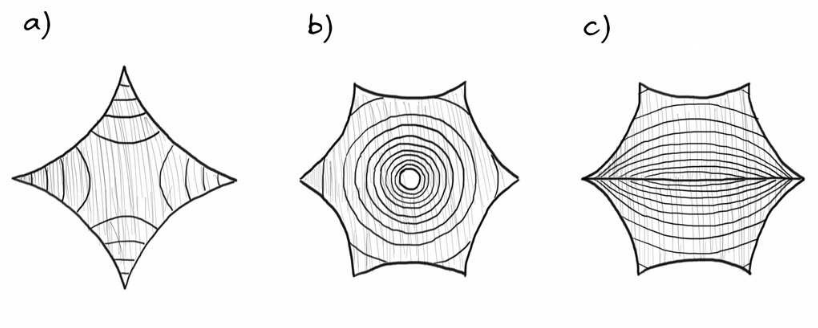


Fig. 72 Isocurves on different membrane geometries

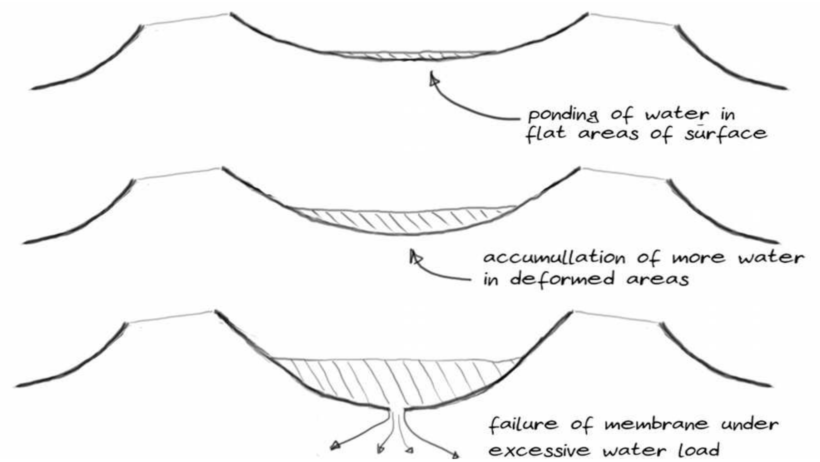


Fig. 73 Water ponding

lead to attract even more water. This can create a structural overload and provoke the failure of the membrane. (fig. 73)
Therefore, this situation needs special attention, even though ponding is more an issue for structural considerations, it can not be neglected in the design of an efficient rain protection. Analysis of the curvature of the surface slope is required in order to identify critical areas.. (fig.74)
Generally rain hardly occurs without the presence of wind. Hence considerations of the combined effect of rain and wind on the membrane design should be taken into account. The wind driven rain is a design issue, because it considerably reduces the protected area beneath the membrane structure. The raindrops are driven along by the gravitational

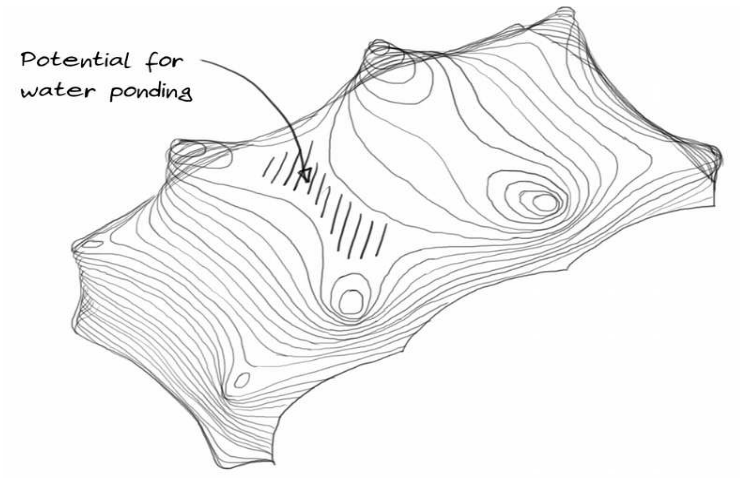


Fig. 74 Analysis of drainage and water ponding

force and the drag force of the wind. The inclination angle of the raindrop trajectory will increase in line with wind speed and it can be observed during storms, that raindrops move in an almost horizontal direction, and travel through the membrane structure, leaving the area underneath unprotected. (fig. 75)

Studies of different authors indicate that wind driven rain is influenced by many factors, but the most important dependencies on wind driven rain effects are within the membrane shape itself, and the aerodynamic effects created by it, so that the raindrop trajectories in consequence are strongly affected by the local flow around the structure (Choi, 1991). Geometries with high-points and overhangs, far projecting further than the perimeter

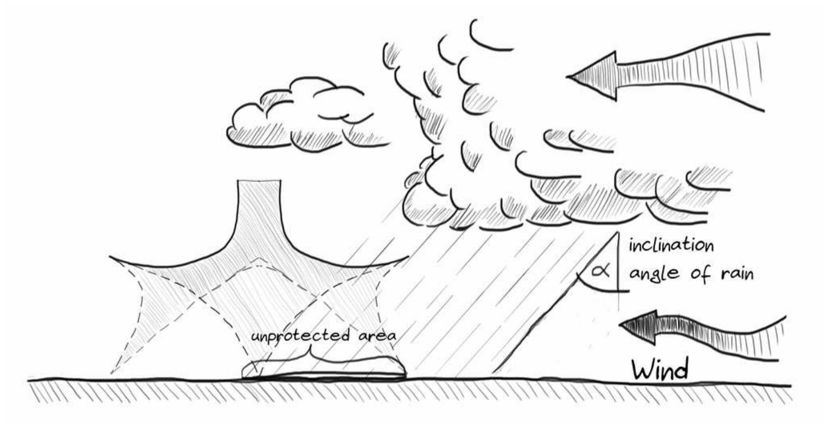


Fig. 75 Wind driven rain

of the habitable area, can redirect air-flows up and over the structure at a distance further away from the limits of the perimeter, and this way reduce the deposition of driving rain beneath the membrane cover (Straube, 2010).
The generally high levels of humidity can provoke different problems on membrane structures which are at a first glance not as evident as the protection from rain or drainage. Having said that, relative humidity has an important influence on thermal comfort. The design task is to avoid the accumulation of humidity. In a semi-enclosed structure this is almost impossible, but effective strategies of ventilation can significantly reduce the relative humidity beneath a membrane cover. A high relative humidity can also lead to problems of mold and fungus

growth which is an issue for the aesthetic appearance of membrane materials, because they produce colorful patches, from yellow to pink, green, blue and black on and inside the fabric. But the growth of fungus and mold can also turn into a health problem and should be considered seriously during the choice of materials. Various manufacturers include anti-fungicidal substances in the coatings of their products.
The other issue about humidity is the high potential for condensation. During rainy season the air in the tropics is so highly saturated with water that the slightest drop of temperature can provoke condensation resulting in rain or dew. (fig 76)
Condensation can be a problem in membrane structures in different ways: In open space membrane structures the surface can cool down below the

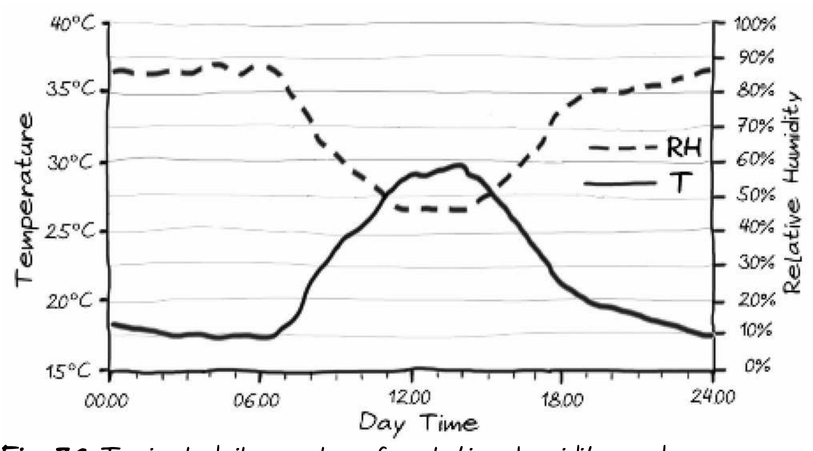


Fig. 76 Typical daily cycle of relative humidity and temperature in humid tropical climates

air temperature when the membrane radiates against a clear sky at night. The surrounding warmer air holds a certain amount of moisture which condensates when the air gets in contact the cooler membrane surface. The relative humidity of the air, which hits the cool membrane, rises as it cools down on the membrane surface, until it reaches its dew-point and condensation occurs. Droplets built up and run down on the inside of the membrane skin until they encounter a dripping edge, and fall down on the activity space below, which can lead to further problems, if the activities or installations below are sensitive to humidity. (fig. 77)
The susceptibility of membrane structures to condensation is linked to their very low thermal mass and the poor insulation behavior of the membrane material itself. Due to the thinness and resulting

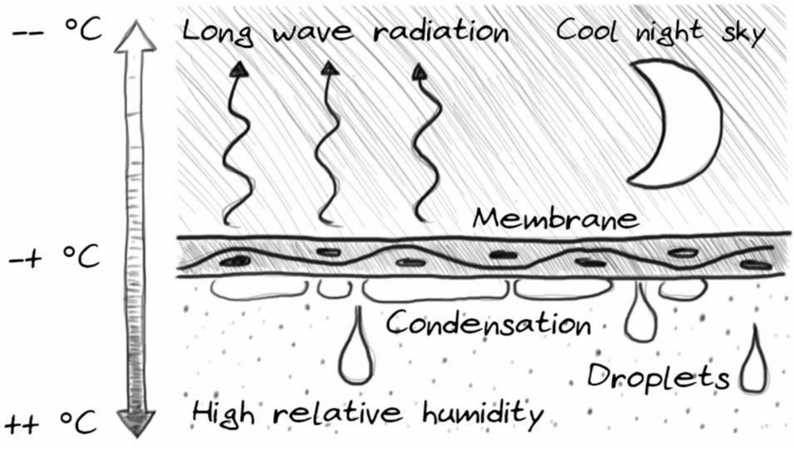


Fig. 77 Condensation on membranes

low mass, the membrane is unable to compensate temperature swings of the environment. Another issue is the hydrophobic nature of coated membrane materials. which does not absorb any excessive humidity (Forster, Mollaert, 2004).
While the climate conditions are largely responsible for the abundance of condensation, the use of the building has also a lot of influence on how much and when. condensation is occurring. A membrane roof covering for example a sports center, where large groups of people gather and increase by their activity the relative humidity underneath the cover, is more likely to develop condensation, than structures which host other activities or fewer people. When condensation is expected to occur, and cannot be mitigated by means of ventilation, the best strategy is to anticipate it during the design stage by foreseeing the possible pathways of draining condensation water, and the drainage points. In case that the drainage points are matching with sensitive areas beneath, dripping edges on the inside can be introduced into the membrane detail design in order to effectively control the condensation water. Although condensation is not very likely to occur in semi-enclosed spaces, humidity should be considered as a design issue and be taken into account during the analysis of environmental factors, in order to anticipate any condensation problem. In any case, sufficient means of ventilation should be part of the design strategies in order to dissipate any possible condensation effectively (Forster, Mollaert, 2004).

7. 3 Draining details

The drainage of water from roof structures is generally solved by the force of gravity. Tensioned membrane structures are not different from that. Their three-dimensional geometries of large curvatures are beneficial for effective drainage, but then also present difficulties in calculating of how much water per area will actually collect at different draining points. The drainage paths of the water on the membrane surface must be anticipated and draining barriers planned, to guide the water along the edges towards the draining points. These generally coincide with the vertices edges. If neglected, there is the risk of converting the entire perimeter edge of the membrane roof into a waterfall, where the water is draining in freefall, becoming unpassable for people during heavy rainfall.. of These water-barriers can be welded onto the outer membrane side with a defined offset from the edge. The dimensioning should be considered individual for every project's specific climate pattern. (fig. 78)
The design and dimensioning of the draining details

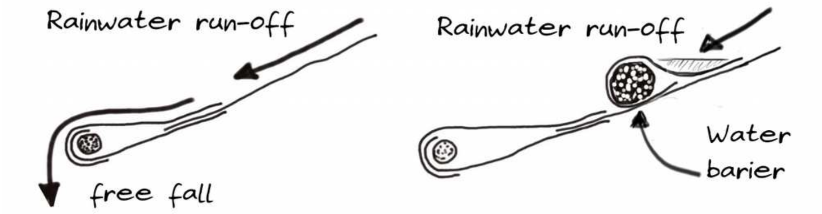


Fig. 78 Draining barrier for borders and edges

is the most critical part of the total drainage strategy. The excessive amount of water which can fall down in just a few minutes during a tropical thunderstorm, make it necessary to assume rather high water volumes to be on the safe side when calculating the dimensions of gutters and down-pipes. The more generous they are designed the more efficiently they will drain the water and less risk of ponding can be expected. Accumulation of dirt and biological material should also be considered. The obstruction of down-pipes can be avoided by means of checkpoints and removable meshes, which act like filters. (fig. 79, 80)

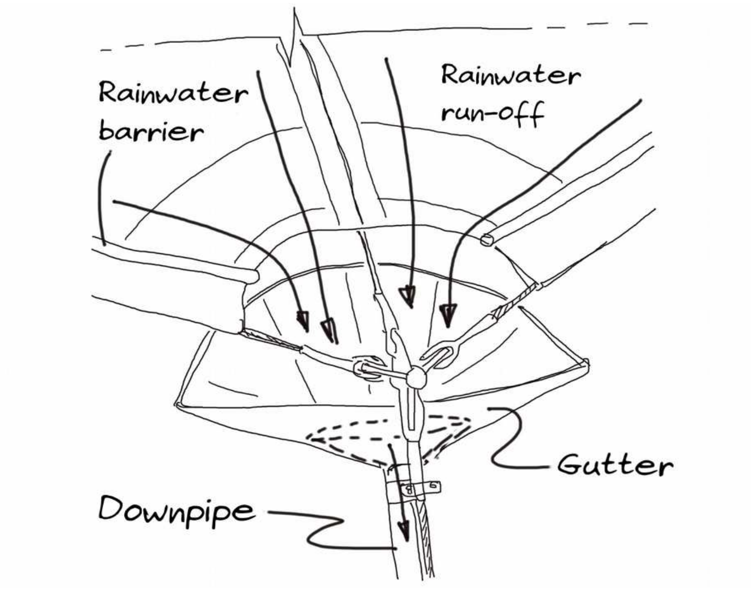


Fig. 79 Drainiage detail 1

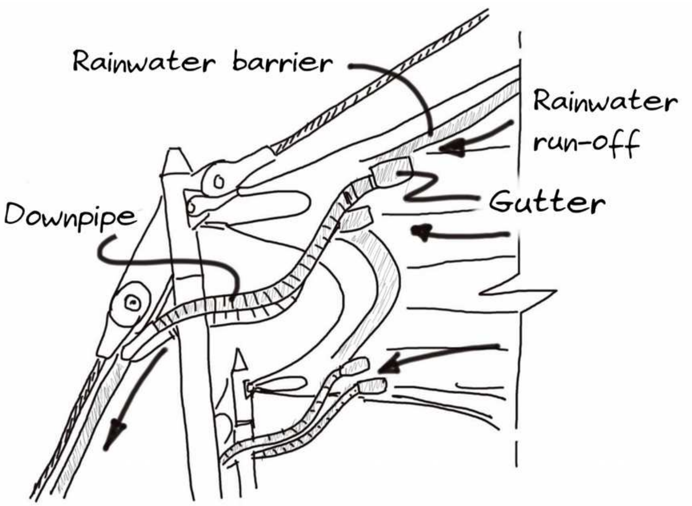


Fig. 80 Drainiage detail 2

7. 4 Design and analysis tools

When seeking for a membrane design which effectively addresses the rain protection and humidity control, it is necessary to conduct an analysis of the meteorologic data on precipitation, relative humidity and wind. The monthly and annual data of the closest weather station should be reviewed and the most severe situations identified in order to derive relevant data for the design. (fig. 81)
Furthermore, the specific site conditions should be taken into account. Various studies have shown the very significant influence of exposure and orientation of building in a specific climate. The combination of high exposure and choice of the membrane shape make the difference for the overall rain

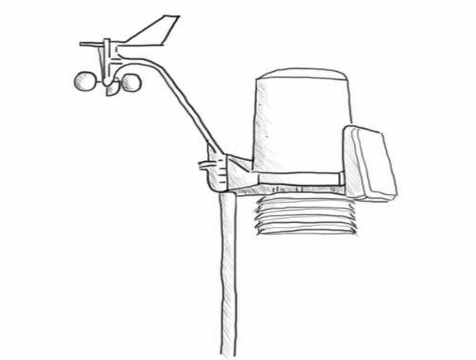


Fig. 81 Weather station

deposition (Straube, 2010). In response to the analysis, the design of the membrane geometry should be coherent with the parameters of climate and site conditions. At an early design stage the form-found geometry should be analyzed with reference to the slope inclination, drainage paths, and drainage points as well as the design of overhangs, facade protection and orientation. In order to address these issues the use of a 3Dmodel with projected contour lines or ISO-curves is indispensable. (fig. 82)

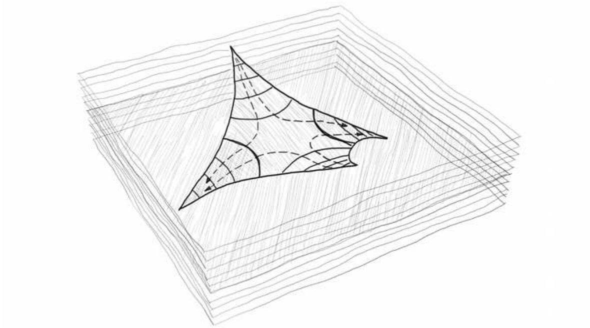


Fig. 82 Iso-curve projection for analysis of rainwater flow

8. Case studies

The following case studies are a collection of membrane structure projects which have been designed and built in Costa Rica from 2008 to 2011. As the country is located very close to the equator between the 8th and 10th degree of latitude on the northern hemisphere, its climate is largely defined by tropical meteorological patterns. The selected projects have largely been influenced in their design process by issues and thoughts regarding the responsiveness to the tropical climate. In some of the projects it was even explicitly requested by the clients to address climactic issues like shading, natural ventilation and the protection from heavy rain. Naturally, these aspects are always an obvious and intrinsic objective of any roof design. But, due to their complex geometries and lightness, the climatic behavior of membrane structures is not always easily predictable by a straight forward design approach, neither is the complexity of tropical climate to be underestimated. The documentation on the presented projects exemplifies an analytic design approach where the form-finding process is not only guided by structural and aesthetic considerations, but also supported by the analysis of climatic data, the site specific micro-climate and simulations of environmental phenomena. The intention of presenting the following case studies is to outline one possible design path towards an adaptation to tropical climate.

Membrane cover for a shopping-center

Location:	Guadalupe, San José, Costa Rica,
Year of completion::	2008
Architect:	Gerardo Lopez
Structural Consultor:	Ramon Sastre
Manufacturer:	Eurotoldos S.A.
Cover material:	PVC coated Polyester fabric
Covered area:	182 m2

This Tensile structure is located in San José, Costa Rica and was planned in order to provide formal hierarchy and a cover for the main entrance area of a shopping-center. The efficient shading and rain protection was one substantial requirement of the brief. The geometry is based on the outline of the existing building structure and has an irregular polygon shaped footprint in plan. Three inclined masts hold up two high points, with conic shapes of different sizes and heights, and one edge peak projection, which all together generate a volcanic cordillera-like topography. The upstanding, prow-like, peak opens up in height and marks the entrance to the shopping center's main avenue. The membrane structure creates a covered plaza that offers place for different activities in a semi-outdoor space. In order to determine, whether natural ventilation be efficiently enhanced by the openings of the conic shapes at the high points, a CFD analysis was carried out, which proofed that the geometry of the membrane increased the natural airflow by convection and pressure differences at their openings through the Stack-, and Venturi-effect.

Fig. 83 Picture: Front view

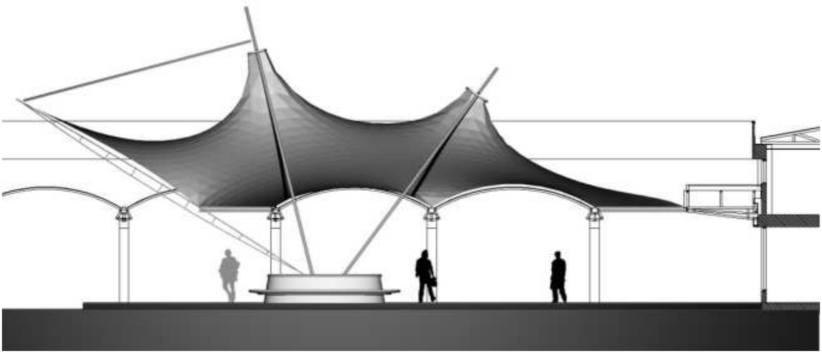


Fig. 84 Schematic section

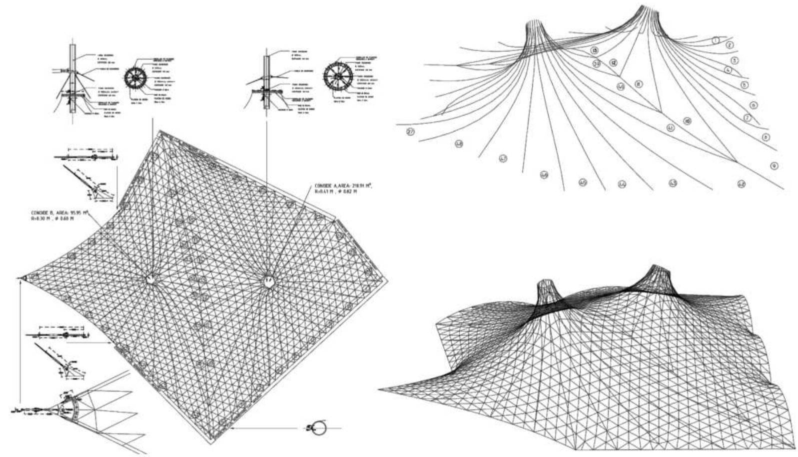


Fig. 85 Drawings: Plan, perspective, pattern layout, details

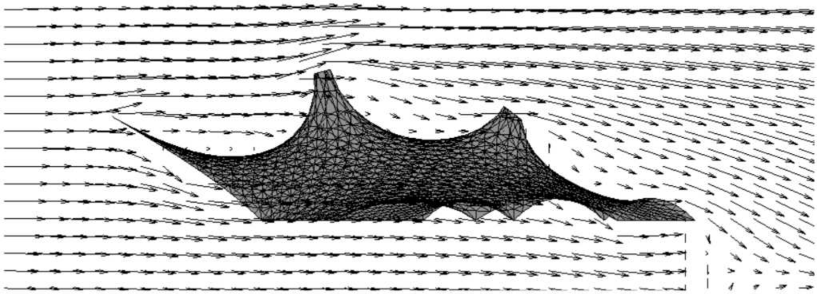


Fig. 86 Flow vector analysis (CFD)

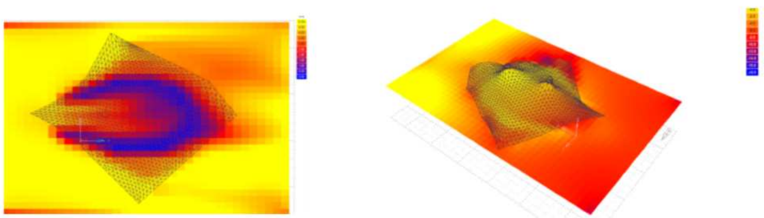


Fig. 87 Air flow analysis, speed and pressure (CFD)

Shading-sail for a movie theater

Location:	Escazú, San José, Costa Rica,
Year of completion::	2010
Architect:	Mario Trejos, 506 Studio
Structural engineer:	Manuel Ugarte
Manufacturer:	Eurotoldos S.A.
Cover material:	PVC coated Polyester fabric
Covered area:	60 m2

This shading-sail was designed as part of the facade of an existing building complex which hosts a large movie theater center. The design intention of the architects was to create with the organic membrane structure a special element at the entrance to the cinema which would add at a formal contrast to the facade. The anti-clastic, butterfly-like, free-form shape seems to glide out of the entrance while accomplishing at the same time the primary function of protecting the visitors at the main entrance from rain and sun. The form of the membrane was found by identifying symmetrical anchorage points and projecting them into space by cables and horizontal masts, so that there was no need for obstructing, vertical supports.. The chosen material was a polyester fabric, coated with PVC. During the design stage, various questions arose regarding the aerodynamic behavior of the membrane structure as an additional part of the facade, and the capacity of protection from rain in combination with wind. CFD analyses were carried out to determine if the proposed structure would work well together with the existing building..

Fig. 88 Picture: View from below

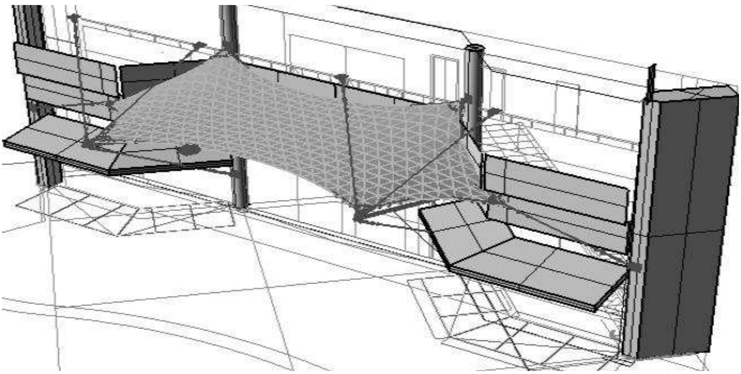


Fig. 89 Perspective view

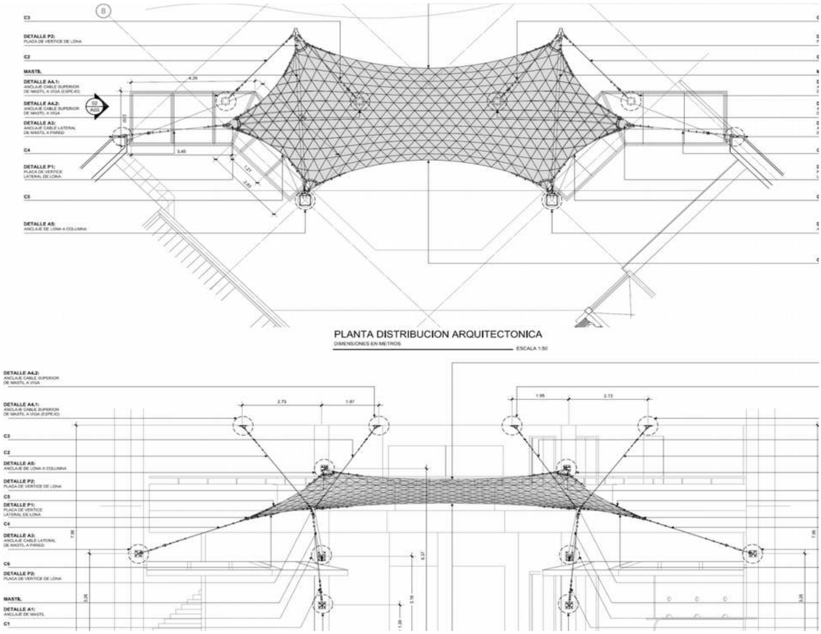


Fig. 90 Drawings: Plan and front view

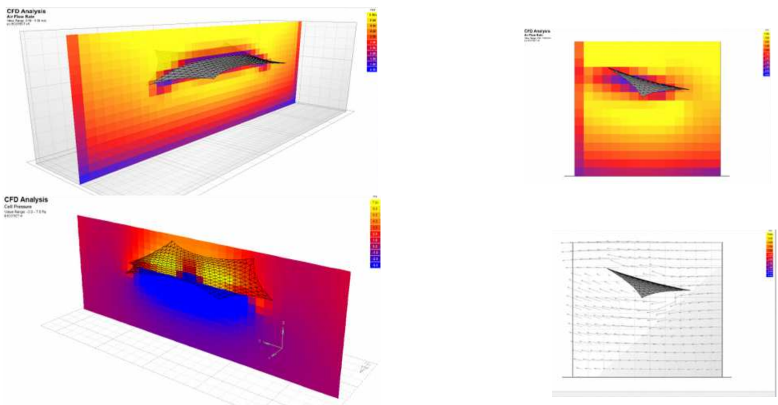


Fig. 91 CFD analysis

Tropical shelter

Location:	San Pedro, San José, Costa Rica,
Year of completion::	2010
Architect:	Students of architecture, UCR
Structural consultor:	Jan-Frederik Flor
Manufacturer:	Eurotoldos S.A.
Cover material:	PVC coated Polyester fabric
Covered area:	20 m2

The tropical shelter was designed and built during an academic workshop at University of Costa Rica, in which a group of architecture students was introduced to membrane structures. Starting from an initial design concept the project was developed in a practical way through its different design stages, which was culminated with the fabrication and installation of a real scale structure. One of the objectives of the design approach was to demonstrate that the climatic behavior of the tensile structure could enhance positive thermal comfort conditions. After the definition of space, material and climatic requirements, the form-finding process was iterated with information from shadow studies and air flow simulations. The resulting hyperbolic geometry is based on a pentagon with two low points and three high points, upheld by masts of bamboo. The full membrane was fabricated and oriented as a temporary shelter according to the optimum direction of the environmental analysis. The results from the simulations were analyzed and later compared with values on the real climatic performance from measurements taken on site.

Fig. 92 Picture: Bird's-eye view

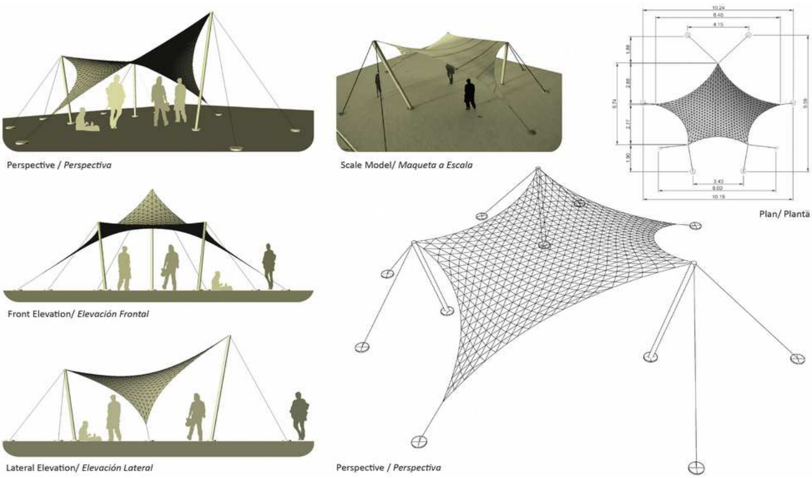
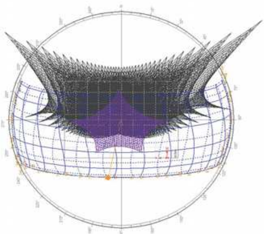
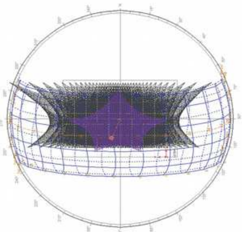


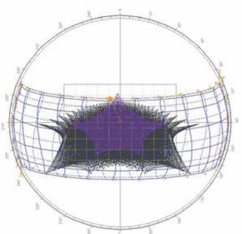
Fig. 93 Drawings and models



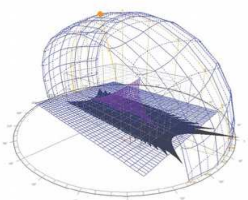
Projected Shadows, Winter Solstice (21. Dec.)
Sombras proyectadas ,Solsticio de Invierno (21. Dic.)



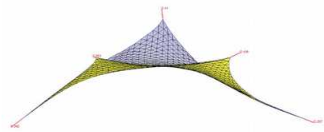
Projected Shadows, Equinoxes (21. Mar/21. Sep.)
Sombras proyectadas, Equinoccios (21. Mar/21. Sep)



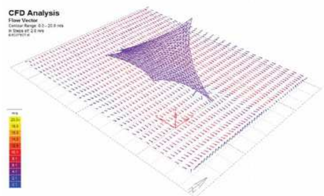
Projected Shadows, Summer Solstice (21. Jun.)
Sombras proyectadas ,Solsticio de Verano (21. Jun.)



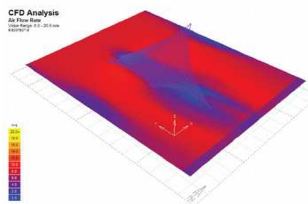
Projected Shadows, Latitude 10º, North Hemisphere
Sombras proyectadas , Latitud 10º, Hemisferio Norte



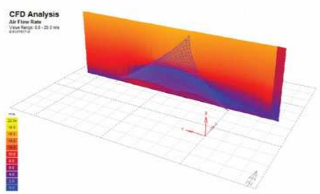
Calculation of wind loads and maximum deformations
Calculo de cargas de viento y deformaciones máximas



Air flow analysis, flow vectors
Análisis de flujo de viento, vectores de flujo



Air flow analysis, wind speed, Plan
Análisis de flujo de viento, velocidad de viento, Planta



Air flow analysis, wind speed , Section
Análisis de flujo de viento, velocidad de viento, Seccion

Fig. 94 Shading and CFD analysis

Shading sail for a tennis court

Location:	Santa Ana, San José, Costa Rica,
Year of completion::	2011
Architect:	Ronald Zürcher
Structural engineer:	Manuel Ugarte
Manufactorer:	Eurotoldos S.A.
Cover material:	PVC coated Polyester fabric mesh
Covered area:	12 m2

This small scale tensile project assignes with the request for a shading sail for a tennis court on the property of a private residence. The design brief required that the membrane cover should provide shade throughout the most critical hours of the day, when the sun is close to the zenith and the solar irradiation most intense. As the project is located in the tropics, at a latitude of 10° N, these critical hours would be around mid day from 10 am to 2 pm all year long. Sun path studies and shadow projections were carried out for the dates of solstice and equinox. After the analysis, the design of the shading sail was adapted in an iterative process to the most critical sun angles in order to provide effective shading for the resting athletes on the tennis campus. The material choice has also been considered with the idea in mind to positively modify the micro-climate and enhance thermal comfort A white, highly reflective, micro perforated mesh with an effective UV filtering capacity was chosen, which would provide both, a high percentage of translucency and permeability while reflecting a important percentage of the solar radiation.

Fig. 95 Picture: Front view

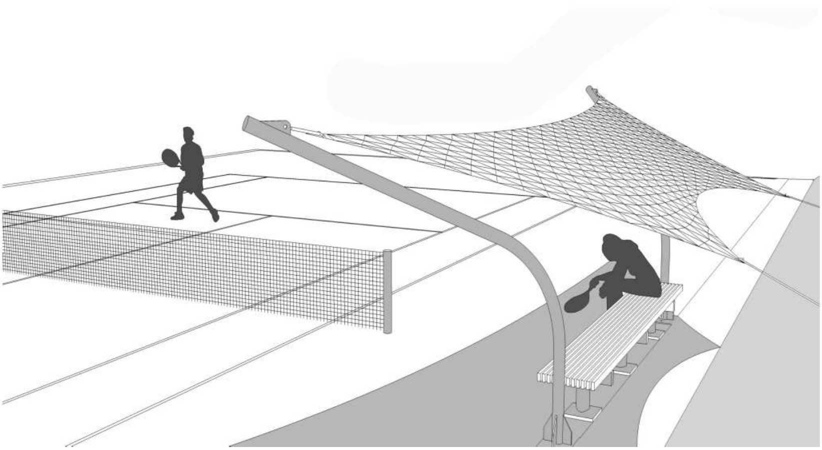


Fig. 96 Perspective view

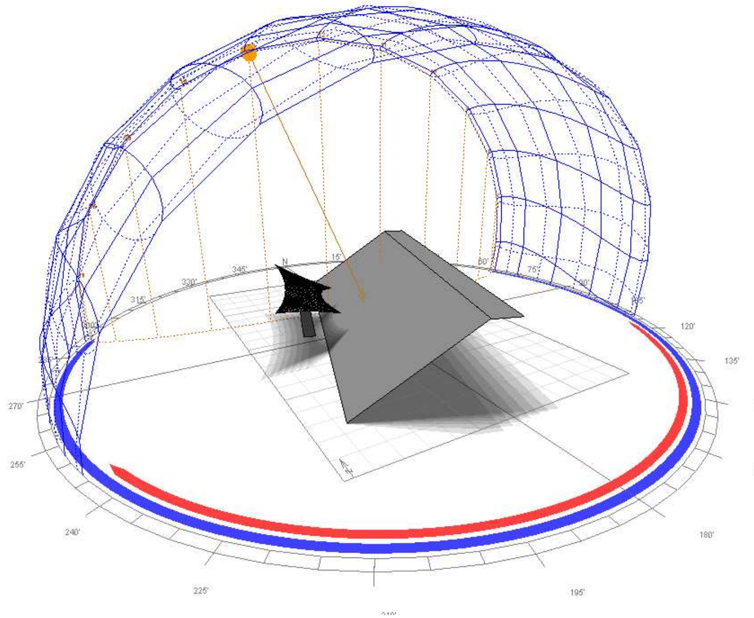
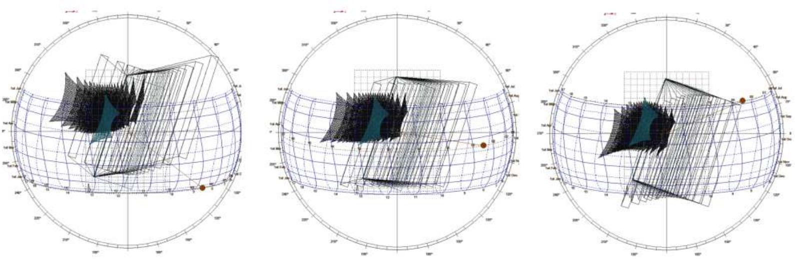


Fig. 97 3D solar projection



21. DEZ (7.30–16.00) 21. MAR/SEPT (7.30–16.00) 21. JUN (7.30–16.00)

Fig. 98 Shading analysis

Modular tent for expositions and fairs

- Design study -

Designer:	Jan-Frederik Flor
Renderings:	Javier Castro
Cover material:	PVC coated Polyester fabric
Covered area:	36 m2

The design proposal for this modular exhibition tent was intended to create an attractive cover for temporal exhibitions and fair stands. The design requested a modular structure which would be easy to install and easy to transport. The auto-supporting structure is composed of circular steel tubes which create a continuous frame boundary, based on a triangular geometry. The membrane cover is spanned within this structural frame and tensioned up to a hyperbolic high-point. Besides the design intention to create an iconic and recognizable form, the surface shape was designed to provide the capacity for optimal shading patterns throughout the seasons in tropical latitudes. Additionally, the design required to perform as a self ventilating structure, which was achieved through careful form analysis and optimization. This led to a geometry that generates a Venturi effect in its bottleneck-like high-point geometry and enhances an acceleration of air flow, which was simulated by computational fluid dynamic analysis and. The found form not only displays formal attractiveness and an structural system which is easy to install but is also an element which modifies the surrounding micro-climate and the thermal comfort of its users.

Fig. 99 Perspective view

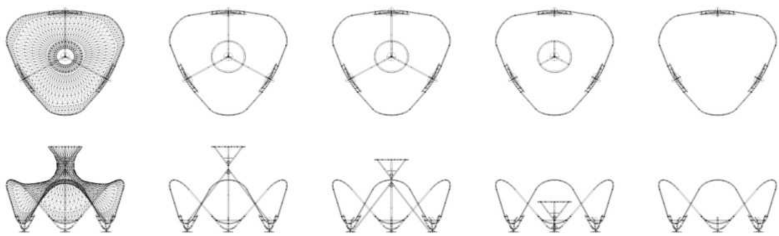


Fig. 100 Structure

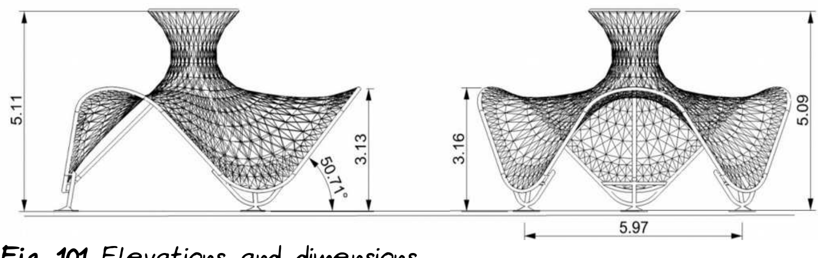


Fig. 101 Elevations and dimensions

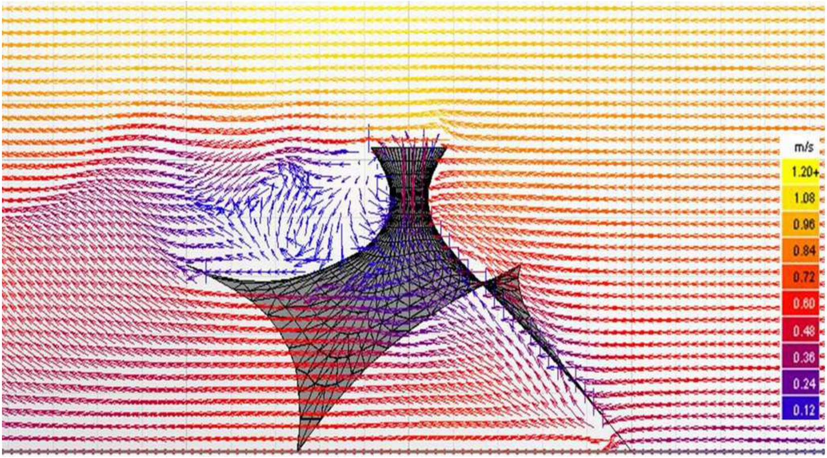


Fig. 102 CFD analysis – Air flow vectors and velocity (section)

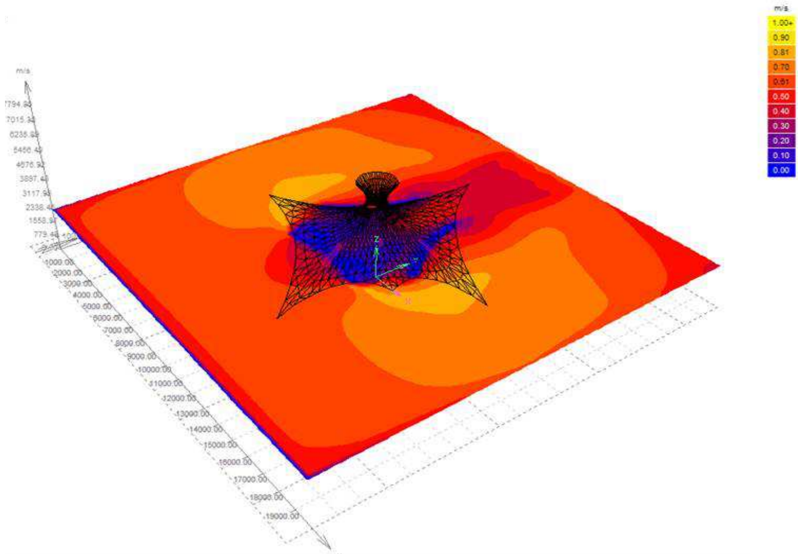


Fig. 103 CFD analysis – Air flow vectors and velocity (plan)

9. Conclusions

The study was set out to explore how tensioned membrane structures can be designed in a way that they adapt to the special conditions of tropical climates and enhance positive thermal comfort conditions. The main goal of the research was to identify design strategies which have the potential to employ the climatic elements themselves as a resource for the thermal control of semi-open membrane covered spaces. The emphasis in this research was put on passive design strategies which do not require any additional energy, other than from natural processes. Many of these strategies and physical principles are already well known, and have been widely employed in the vernacular architecture, and investigated in other fields of research. But they have not yet been analyzed and evaluated as design concepts for membrane structures in tropical environments. In this regard, the investigation correlates membrane structures, tropical climates and thermal comfort as the main topics of the theoretical framework, which serves as a basis for the analysis and evaluation of the different design strategies. The strategies are presented in a didactic manner and exemplified by different case studies, intended to provide practical guidance for architects and enginees involved in the early design stages of membrane structures.

The research was further subdivided into three main parts, starting with the description and analysis of the characteristic elements of tropical climate, followed by the correlation with thermal comfort, and the implications which the humid and hot conditions of tropical climate have on the human well being. As a third step, different design strategies to enhance thermal comfort were outlined, addressing climatic elements, where solar radiation, wind, precipitation and humidity were identified as the ones which have the most important impact on the thermal comfort. The design strategies are based on various physical principles from the field of aerodynamics, as for example the Venturi effect; thermodynamics, with the stack effect and thermal stratification; and atmospheric conditions of humidity and precipitation. The design strategies where applied to three basic geometry models which served to exemplify the possibilities and limitations, of both, the design strategies and the different geometry typologies they could be applied to.

The results of this exercise allow to resume the following conclusions:

- The comfort conditions of spaces covered by semi-open membrane structures are largely influenced by the climate elements.

- Adaptation of structures, materials and spaces to climate is a necessity in the tropical regions.

- Analyses and understanding of climatic patterns is essential to design membrane structures, which give favorable response to climate and satisfy the need for thermal comfort.

- Membrane structures have the potential to modify their immediate micro-climate through their geometry configuration and orientation in the environment, and make use of climatic elements as a design resource.

- Case studies of semi-open membrane structures from all around the world, and different regions of the tropics show that they are a suitable building solution as a response to the hot and humid conditions of tropical climate, because of their adaptability to different climate conditions.

- It has been proven that many passive design strategies and physical principles, known already from the tradition of vernacular architecture, can be transferred and adopted to tensioned membrane structures.

- Further studies and investigations are required in order to analyze the presented strategies in more depth, perform simulations and compare them with site measurements, in order to understand the relevancy of the different strategies in relation to the improvement of higro-thermal comfort conditions.

While the great potential of the bio-climatic strategies to improve comfort conditions in architectural spaces has been put in evidence by bibliographic research and case studies, only general rules of design could be established for the application of these strategies in membrane structures. This limitation is owed to the great variety of possible geometry configurations and climate conditions, as well as the lack of data from site measurements which could validate the efficiency of the strategies to improve comfort conditions. While several attempts have been made by other researchers in this direction, there is a lack of data for semi-open structures in tropical climates. Therefore there is a great potential for future research projects in this field, which will gain further interest, when, in the advent of climate change, the consideration of climate adaptive spaces, which are independent from mechanized climate control systems, becomes an indispensable necessity.

The attempt to elaborate a compendium of design principles which will help to take decisions at an early stage for climatic adaptation of membrane structures in the tropics is aiming to add tools towards the progress of this development. It is furthermore the intention of this study to contribute to a reconsideration of the design approach towards a more site specific and climate related consciousness where the main functions of architecture, which are linked to the physical well being of its occupants, are in a energetic equilibrium and fluent harmony with the environment.

Bibliography:

[b] Baker, Nick and Koen Steemers, *Energy and environment in architecture a technical design guide*, (London: Taylor & Francis Group, 2000).

Basham, Wright, Ferguson and Moy, *Cooling buildings by natural ventilation*, (USA: Department of Defense, 2004).

[c] Chand, Ishwar and Bhargava, P. K., 'Estimation of angle of deflection of rain at driving rain prone stations in India', http://www.researchgate.net/publication , 2005.

Choi, Edmund C. C., 'Velocity and impact direction of wind driven rain on building faces', http://www.bath.ac.uk/cwct/cladding_org/icbest97/paper69.pdf, 1991.

[d] Devulder, Thibaut, 'The thermal response of textile membrane constructions', (Nottingham: University of Nottingham, unpublished PhD thesis, 2004).

Devulder,Thibaut, Chilton, John and Wilson, Robin, 'The thermal behaviour of buildings incorporating single skin tensile membrane structures', International Journal of low carbon technologies, 2/2 (2007) pp 196-213.

Diaz Botero, Angela Bibiana, 'Analisis del comportamiento termico y luminico de una fachada compuesta por multiples capas textiles', (Concepción: Universidad del Bio-Bio, unpublished master thesis, 2013).

[e] ElNokaly, Amira, Chilton, John and Wilson, Robin, 'Environmental behaviour of tensile membrane

structures', (Nottingham: University of Nottingham, 2002).

ElNokaly, Amira 'CFD Analysis of Tensile Conical Membrane Structures as Microclimate Modifiers in Hot Arid Regions', http://www.hrpub.org/journals/article , 2014.

ElNokaly, Amira, Chilton, John and Wilson, Robin 'Environ mental performance of spaces enclosed or semi-en closed by fabric membrane structures', http://eprints.lincoln.ac.uk/8521/ , 2003.

[f] Flor, Jan-Frederik, Criterios climaticos para el diseno de tensoestructuras en el tropico humedo, (Monte video: IV Simposio de Tensoestructuras, https://sites.google.com/site/simposiomontevideo/, article, 2011).

Forster, Brian and Mollaert, Marijke, *European design guide for tensile surface structures*, (EU: Tensinet, 2004).

[g] Garcia Chavez, J. R., *Viento y arquitectura: el viento como factor de diseno arquitectonico*, (Freixanet V.F., 2005)

Givoni, Baruch, *Man, Climate and Architecture* (Sydney, Elsevier Architectural Science Series, 1969).

Goldsmith, Nicholas, 'Climate effects on lightweight structures as a design tool', http://www.ftlstudio.com/climate.pdf , 2008

Goshayeshi, Shahidan, Khafi and Ehtesham, *A review of researches about human thermal comfort in semi-outdoor spaces*, (European Online Journal of Natural and Social Sciences, 2013)

Greenwood, Soulos, Thomas, *Under cover: Guidelines for shade planning and design* (Wellington: NSW Can cer Council and NSW Health Department Sydney, 1998. adapted for New Zealand use by the Cancer Society of New Zealand, 2000).

Gut, Paul and Ackerknecht, Dieter, *Climate Respon sive Building - Appropriate Building Construction in Tropical and Subtropical Regions*, (St. Gallen: Swiss Centre for Development Cooperation in Technology and Management, 1993).

[h] Haase, Klaus, Knubbe, Mielert, Neuhäuser, Schmid and Sobek, 'Adaptive Multilayer Textile Building Envelopes', Stuttgart: Institut für Leichtbau Entwerfen und Konstruieren ILEK Universität Stuttgart, 2011.

Harvie, Gregor, 'An Investigation into the thermal behaviour of spaces enclosed by fabric membranes', (Cardiff: University of Wales, unpublished PhD thesis, 1996).

Haw, Saadatian, Sulaiman, Mat, Sopian, *Empirical study of a windinduced natural ventilation tower under hot and humid climate conditions*, (Selangor, Energy and buildings, 2012).

Hooff, Blocken, Aanen, Bronsema, *A venturi-shaped roof for wind-induced natural ventilation of buildings*, (Building and environment, 2011).

[i] International Organization for Standardization, *ISO 7730:2005(E) Ergonomics of the thermal environment -Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*, (Geneva: International Organization for Standardization, 2005).

[k] Karwath, Michael 'Membrane structures with improved thermal properties' Eugenio Onate, Bernd Kröplin and Kai-Uwe Bletzinger (eds), *Textile Composites and Inflatable Structures IV*, (Barcelona: International Center for Numerical Methods in Engineering CIMNE, 2011) pp 312-319.

Knippers, Jan, Cremers, Jan, Gabler, Markus and Lienhard, Julian, *Construction manual for polymers + membranes*, (Basel: Birkhäuser, 2011).

Koch-Nielsen, Holger, *Stay cool a design guide for the built environment in hot climates*, (New York: Earthscan, 2007).

Krautheim, Mareike, Pasel, Ralf, Pfeiffer, Sven and Schultz-Granberg, Joachim, *City and wind climate as an architectural instrument*, (Berlin: Dom Publish ers, 2014).

[l] Lacomba, R., *Manual de arquitectura solar*, (Mexico D.F., 1991).

Laing, Arlene, Evans, Jenni-Louise, *Introduction to tropical meteorology*, (Boulder, National Center for Atmospheric Research, 2011).

Lengen, Johan van, *Barefoot architect a handbook for green building*, (Bolinas: Shelter Publications, 2008).

Llorens, Josep Ignasi, *Fabric structures in architecture*, (ed.), (Cambridge: Woodhead Publishing, 2015).

[m] McGregor, Glenn R., *Tropical Climatology: An introduction to the Climates of the Low Latitudes*, (UK: John Wiley & Sons, 1998).

Mollaert, Marijke, 'Environmental aspects in textile architecture',presentation, http://www.tensinet.com/files/Environmental_Aspects_of_Tensile_S tructures/envaspectsTR2002-1-1.pdf , 2003.

Mollison, Bill, *Handbuch der Permakultur Gestaltung*, (Stainz, Permakultur Akademie im Alpenraum, 2012).

Monroy, Manuel Martin, *Manual de calor, calidad ambiental en la edificacion para las Palmas de Gran Canaria*, (Las Palmas de Gran Canaria: Ayuntamiento de las Palmas de Gran Canaria, 2006).

Mühlberger, Jörg, 'Zur Bauphysik und zur Konstruktion von mehrlagigen gedämmten Membranbauwerken', (Stuttgart: Institut für Leichtbau Entwerfen und Konstruieren ILEK Universität Stuttgart, unpublished diploma thesis, 2005).

Mundo Hernandez, Julia J., 'Fabric membranes daylighting control systems in buildings', (Nottingham: University of Nottingham', unpublished PhD thesis, 2006).

[n] Nachtigall, Werner and Pohl, Göran, *Bau-Bionik, Natur Analogien Technik*, (Heidelberg: Springer, 2013).

Neila González, F. Javier, *Arquitectura bioclimatica en un entorno sostenible*, (Madrid: Editorial Munilla-Leria, 2004).

[o] Olgay, Victor, *Design with climate*, (Princeton, Princeton University Press, 1963).

[p] Pohl, Göran, (ed.), *Textiles, polymers and composites for buildings*, (Cambridge: Woodhead Publishing, 2010).

Pöppinghaus, Hubertus, Kühle Schattenzelte, 'Sommerkomfort und UV-Schutz in Spanien unter zug beanspruchten leichten Flächentragwerken', (Innsbruck: Fakultät für Architektur der Universität Innsbruck, unpublished PhD thesis, 2011).

[s] Sastre, Ramon and Cuchi, A., 'Tensile structures & sustainbability', Espazio, *Handbook for sustainable construction with tensile structures*, (2015) pp 4-18.

Serra, Rafael, *Arquitectura y climas*, (Barcelona, 2004).

Stagno, Bruno, 'Harnessing comfort through climate', (San José: Institute for tropical architecture, 2004).

Straube, John, 'Simplified prediction of driving rain on buildings', (Westford: Building Science Press, 2010).

[t] Tainturier, Francois, *Wooden architecture of Cambodia, a disappearing heritage*, (Phnom Penh, Center for Khmer studies, 2006).

Turrin, Buelow, Kilian and Stouffs, 'Performative skins for passive climate comfort, a parametric design process', http://www.elsevier.com/ , 2011.

[v] Viquez Quesada, Mora Ramirez, Flor, Gonzalez Es pinoza, Obando Robles and Rodriguez Mora, 'Diseno de la envolvente y sus implicaciones en el confort higrotermico', (San José: Escuela de arquitectura Universidad de Costa Rica, unpublished thesis, 2011).

Visitsak, Sopa, An evaluation of the bioclimatic chart for choosing design strategies, Texas A&M University, Texas, 2007).

[y] Yannas, Simos, 'Adaptive Skins and Microclimates', (Eindhoven: Conference on Passive and Low Energy Architecture, article, 2004).

Yeang, Ken, *A manual for ecological design*, (London: Wiley Academy, 2006).

[Z] Zhang, Lingyun, 'Untersuchung zu mehrlagigen Membrankonstruktionen im Hinblick auf unterschiedliche Funktionen von Gebäudehüllen', (München: Technische Universität München, unpublished PhD thesis, 2007).

Zürcher, Christoph and Frank, Thomas, *Bauphysik Bau & Energie*, (Zürich: VDF Hochschulverlag ETH Zürich, 2014).

Figures:

[51] Mountain - valley breeze, (page: 91, source: Chavez, 2005. modified by the author)

[52] Urban wind shadow, (page: 93, source: Author)

[53] Funnel effect, (page: 93, source: Author)

[54] Geometry and airflow, (page: 95, source: Author)

[55] Topology enhanced ventilation, (page: 96, source: Author)

[56] Ventilation detail for arc structure, (page: 97, source: Author)

[57] Ventilation detail for a high point, (page: 98, source: Author)

[58] Ventilation by difference of pressure, (page: 99, source: Author)

[59] Wind tunnel test, (page: 101, source: Author)

[60] CFD analysis – air flow rate, (page: 101, source: Author)

[61] Ventilation strategy for facades, (page: 102, source: Author)

[62] Cross ventilation – orientation and proportion, (page: 103, source: Author)

[63] Cross ventilation and vegetation, (page: 104, source: Author)

[64] Venturi effect - theoretic principle, (page: 105, source: https://de.wikipedia.org, 2015. modified by the

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