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Membrane structures in the Tropics: building technology and climate adaptation

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Artículo

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Abstract

Adaptation to climate has played an essential role in the history of architectural design and is becoming even more important in times of climate change. However, contemporary buildings and structures, as in the case of tensioned membrane structures, often lack the cycling process of adaptation that traditional constructions have undergone over time. The objective of the study presented in this paper is to investigate the principles and strategies that enhance the climatic performance of tensioned membrane structures in the Tropics. The study focusses on the proposal of specific design strategies for the early design stage of membrane projects. The strategies are based on passive and bioclimatic principles to create thermal comfort conditions without additional energy input. In the first part of this article, an overview of the development and use of membrane structures in the tropical regions is outlined, highlighting formal and functional requirements of geometry and material. In the second part, the climatic elements which are relevant to thermal comfort in the Tropics are addressed with specific design strategies and synthesized by schematic diagrams and drawings, showing different design solutions for geometries and details of typical membrane structures. In the third part, three case studies are presented, exemplifying the analytic processes and implemented design strategies in a real case scenario. The study concludes with passive design guidelines applied to membrane structures and argues for a climate-adaptive design approach of light-weight architecture in tropical regions.

Keywords: adaptive design; membrane-structures; tropical climate; thermal comfort.

Estructuras de membrana en los trópicos: tecnología de construcción y adaptación climática

Resumen:

La adaptación al clima ha jugado un papel esencial en la historia del diseño arquitectónico y se está volviendo aún más importante en tiempos de cambio climático. Sin embargo, los edificios y estructuras contemporáneas, como en el caso de las estructuras de membrana tensadas, a menudo carecen del proceso de adaptación cíclica que las construcciones tradicionales han sufrido con el tiempo. El objetivo de este artículo es investigar los principios y estrategias que mejoran el rendimiento climático de las estructuras de membrana tensil en los trópicos. El estudio se centra en la propuesta de estrategias específicas de diseño para la etapa inicial de diseño de proyectos de membranas. Las estrategias se basan en principios pasivos y bioclimáticos para crear condiciones de confort térmico sin aporte de energía adicional. En la primera parte de este artículo, se describe una visión general del desarrollo y uso de estructuras de membrana en las regiones tropicales, destacando los requisitos formales y funcionales de la geometría y el material. En la segunda parte, los elementos climáticos que son relevantes para el confort térmico en los trópicos se abordan con estrategias de diseño específicas y se sintetizan mediante diagramas esquemáticos que muestran diferentes soluciones de diseño para geometrías y detalles de estructuras de membrana típica. En la tercera parte, se presentan tres estudios de caso que ejemplifican los procesos analíticos y las estrategias de diseño implementadas en un escenario de caso real. El estudio concluye con pautas de diseño pasivo aplicadas a estructuras de membrana y defiende un enfoque de diseño adaptable al clima de arquitectura ligera en regiones tropicales.

Palabras clave: diseño adaptativo; estructuras de membrana; clima tropical; confort térmico.

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Introduction

Tensioned Membrane structures have undergone a rapid and successful development over the last 70 years (Llorens, 2015). Since the initial pioneering works of Frei Otto, membrane structures have been built in basically all parts of the world as well as in the Tropics. The diffusion of the knowledge on how to design and build these structures, combined with the large-scale industrialisation of fabric materials manufacturing, has led to a globally spreading building industry specialised on membrane structures. Some cultural regions were already intensely linked through their building history to the use of membrane structures. Other cultures which had given up their nomadic life were about to reintroduce this building technology for large scale sports events. However, only since the end of the last century fabric structures have gained popularity on a broader scale as the technological and regulative aspects of the building system evolved and allowed to fulfil the requirements of building standards for permanent buildings (Pohl, 2010). In the design process of tensile membrane structures, architects and engineers traditionally have been concerned with finding the correct form and calculating the structural behaviour. However, the response to climate and considerations about the thermal comfort have not received the same attention (Devulder, Chilton & Wilson, 2007), while the ongoing global success of membrane structures calls for design solutions for a variety of climatic regions. One of the regions with the most challenging climate conditions, regarding thermal comfort and limited literature record of the development of membrane structures, are the Tropics. Therefore, the question arises: 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 favourable comfort conditions in tropical climates?

A large percentage of the human population lives in tropical environments and has traditionally been dealing with the unique climate conditions of the Tropics. Sun, wind, and rain are the climatic elements that have the biggest influence on tropical climate. Intense solar radiation, high humidity levels, and heavy rain in the wet-season combined with strong winds and thunderstorms have a significant impact on human activities and thermal comfort, which need to be addressed in the design of the built environment (Stagno, 2004). In general terms, the architectural requirements in the tropical climate demand a light building envelope, allowing natural ventilation, shading from intense solar radiation, and protection from frequent and heavy rain. Membrane structures using light and flexible fabrics might, therefore, be an adequate building technology in the Tropics. In that sense, the presented study aims to provide basic guidelines for the design of membrane structures in tropical climates with the main objective to provide comfortable thermal conditions for human activities without creating negative environmental impacts and dependencies on energy supplies. The study is based on the premises that climate itself can be understood as a potential resource and source of information for the design process of membrane structures. The theoretical frame of the study relates to the bio-climatic design theory, initially introduced by Victor Olgay (Olgay, 1963), establishing an active link between climate, thermal comfort, and architectural design.

Methods

The methodological approach of this study is qualitative with a bibliographic review and a case study as the main methods of research. The study covers the current and historical use of membrane structures in the tropics comprehensively and discusses challenges and opportunities relating to specific aspects of the tropical climate and thermal comfort. The underlying physical principles of climate phenomena in the Tropics that affect thermal comfort are systematically outlined and addressed with concrete strategies for the design of membrane structures based on the findings of the literature review. The results are synthesized in a series of design principles which enable architects and engineers to make decisions during the early design stage about the climatic adaptation of membrane structures in the Tropics. Three geometric models (Figure 1) are used as a base to represent the design principles for more complex structures. The theoretic principles are contrasted with a case study which exemplifies the practical application of climatic design strategies on selected built projects, highlighting different analysis tools which were used as a source of information during the design process.

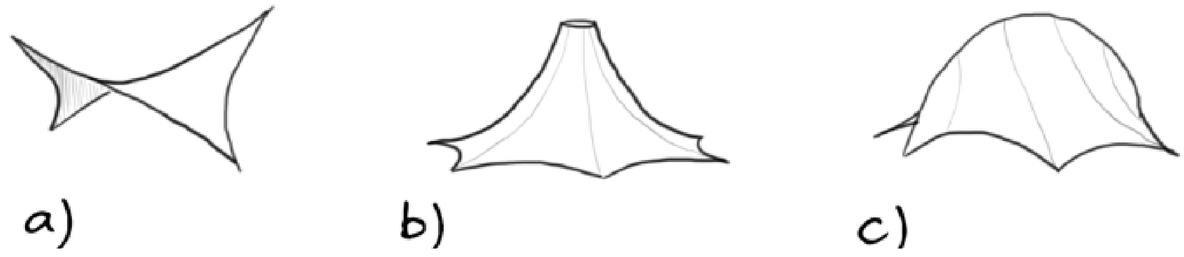


Figure 1. Basic membrane geometry models for investigation: a) hyperbolic-paraboloid, b) conoid, c) arc.
Source: (Image) elaborated by the authors.

Membrane structures in the tropics

The use of tensioned membrane structures in the Tropics as a building technology is a relatively recent development with a, however, increasing application over the last three decades around the tropical belt including Latin America (Hernández, 2015). Tensile membrane structures have several advantages, compared to other building techniques which make them very suitable to address the special conditions of the tropical climate (Mendonça, 2012). 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, covering from rainfall and natural ventilation just through an informed design of the structure. On the material side, the resistance to microorganism growth, bio-deterioration, UV rays, and ageing as well as not being susceptible to corrosion (Forster & Mollaert, 2004) make membranes an ideal building material for the use in atmospheric conditions like those of the Tropics.

The Tropics refer to a global region which is located between the Tropic of Capricorn and the Tropic of Cancer, which are the geographic turning points of the farthest possible latitude where the sun radiates vertically onto the earth at the solstices (McGregor, 1998). Due to the tilted rotation axis of the earth, these turning point positions span as equatorial parallels around the globe. At a latitude of 23,5 °, the Tropic of Cancer marks the limit of the tropical regions on the northern hemisphere and the Tropic of Capricorn on the southern hemisphere. These limits are only a geographical convention. The climatic conditions of the Tropics are not strictly contained within this zone but compare more to an amorphous belt as can be seen in Figure 2. The tropical zone further divides into sub-regions in which America, Africa, Asia, and the oceanic Islands cover the main tropical regions. These regions all have their 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). Furthermore, within each climate zone, sub-zones on a smaller scale are influenced by the topography, latitude, altitude, and distance to main bodies of water. The perceived general conditions of the Tropical climate, thus, resume to a combination of high humidity and heat, intense solar radiation, cloudiness, and heavy rainfalls during the rainy season. In meteorological terms, the elements of climate which characterize the tropical climate most appropriately are temperature, humidity, wind, precipitation, and atmospheric pressure. The climates discussed in this study are the tropical or megathermal climates in general and in specific the regions which show a climate regime that corresponds to the tropical rainforest and monsoon climate zones as defined by the Köppen climate classification system (Köppen, 1884).

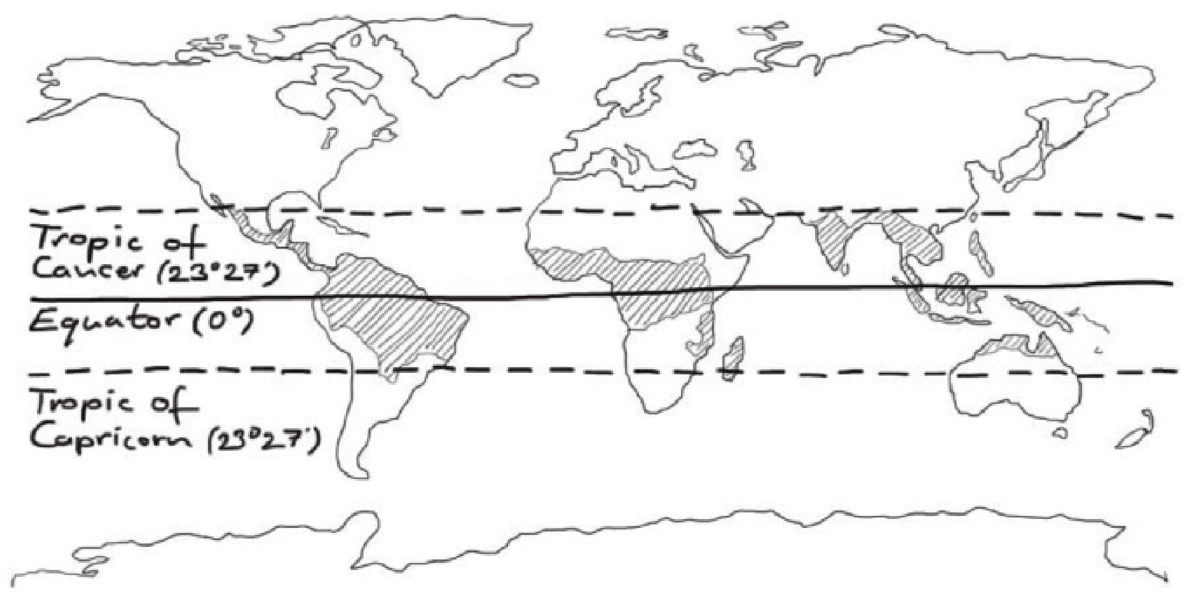


Figure 2. Tropical zone.
Source: (Image) elaborated by the authors.

Protection from the climatic conditions is of great importance for the development of human activity in the Tropics. 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 lead to developments of textile architecture in different parts of the world, beginning over a few thousand years ago with the use of natural fibres and skins for mobile shelters such as tipis, yurts, and tents (Mundo Hernandez, 2006). Fabrics and mats were woven and braided using natural fibres of different species of plants to cover the walls, roofs, and floors of temporary dwellings, providing shade and protection from the rain (Kronenburg, 2015). Nowadays, remainings of proto-textiles applications can be found in the Tropics mostly in the traditional or vernacular architecture where structures built with materials such as bamboo and wood are still covered with natural materials for roofing or screening (Waterson, 2010).

Around the middle of the last century, another architectural approach arose after many learned lessons on temporary construction and life in the Tropics during colonial and war times. Bioclimatic architecture began to address issues beyond the classical concerns of building design, which were commonly related to economy, utility, durability, and comfort. Now, the efficient use of energy and resources throughout the building's life-cycle, as well as the occupant's health, became increasingly important (Baker & Steemers, 2000). Adaptation to local climate and direct response of buildings to the natural environment would be the way to achieve thermal and visual comfort while saving energy using solar radiation (Sastre & Cuchi, 2015). Triggered by rising energy costs and awakening ecological consciousness and awareness of climate change, scholars and practitioners (Gut & Ackerknecht, 1993; Neila, 2004; Serra, 2004; Yeang, 2006) transferred the bioclimatic theory of Olgay to the contemporary architectural practice. The concept of bioclimatic architecture has been an elemental tool for architects and engineers around the world and especially in the Tropics since then.

Modern lightweight constructions, including membrane structures, have proven to be in many cases part of the solution in projects with a bioclimatic approach. The same principles that apply to conventional buildings may also be valid for lightweight structures, offering many possibilities in terms of material reduction and climatic adaptability (Goldsmith, 2008). The formal flexibility in the design of a tensioned membrane structure allows incorporating topography, local climate, sun, and wind as significant parameters in the form-finding process. The form and topology of the membrane structure might even enhance natural ventilation and cooling of spaces. Membrane structures may also be used as environmental filters, using different grades of permeability for light and air and creating an intermediate climate between the external and interior climate-controlled space of the building (Elnokaly, Chilton & Wilson, 2003). The physical properties of membrane fabrics also comprise the potential for beneficial climatic performance. Besides the capacity for high reflection and the low emission of solar radiation, the low thermal mass benefits most of the tropical climates. As a consequence of the small mass and thinness of the material, membrane structures offer almost no thermal resistance to the environment; thus, it heats up quickly under direct sunshine, but it also cools down fast as soon as it becomes cloudy or the sun sets. This effect can become even a cooling strategy for hot tropical nights when the membrane turns colder than the ambient air temperature radiating against the cool night sky.

On the other hand, difficulties or challenges with the climate-adaptive design of membrane structures are perhaps not apparent at a first sight but might result from the fact that the membrane geometry, yet flexible to some extent, is not modifiable once manufactured. The topology does usually not change much, except to load from wind and precipitation or when the structure is specially designed for geometric transformation like retractable and foldable structures. Design problems may arise because the climate conditions are dynamic , which 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 an average level to the climate conditions. In this sense, an analysis of weather data and local site conditions become the most vital tool for a successful climatic adaptation of the design itself. Other climate adaptation issues related to the fabric are on a smaller scale. According to a study conducted in Malaysia, the most common defects of membrane materials in the Tropics are deterioration of fabric coatings, fungal decay, mould growth, and dirt accumulation as well as corrosion on fixings and anchor cables (Wang et al., 2015). Encountered difficulties are related generally to material behaviour, manufacturing quality, detailing, and underestimation of the deteriorating effects of UV radiation and humidity. In this sense, it is desirable for future investigations to aim at conducting on-site real-time measurements and post-occupancy studies to obtain reliable data on the climatic performance of membrane structures in the Tropics.

In summary, tensioned membrane structures offer a promising potential for the response to tropical climates. Large open spaces are the vision in which they are self-ventilating, reflecting most of the solar radiation, providing adequate shade, and protecting from heavy rainfall with wide overhangs like giant umbrellas (Figure 3). However, challenges arising from the complex interplay between climate and structure must be accepted and addressed with innovative design solutions at all scales.

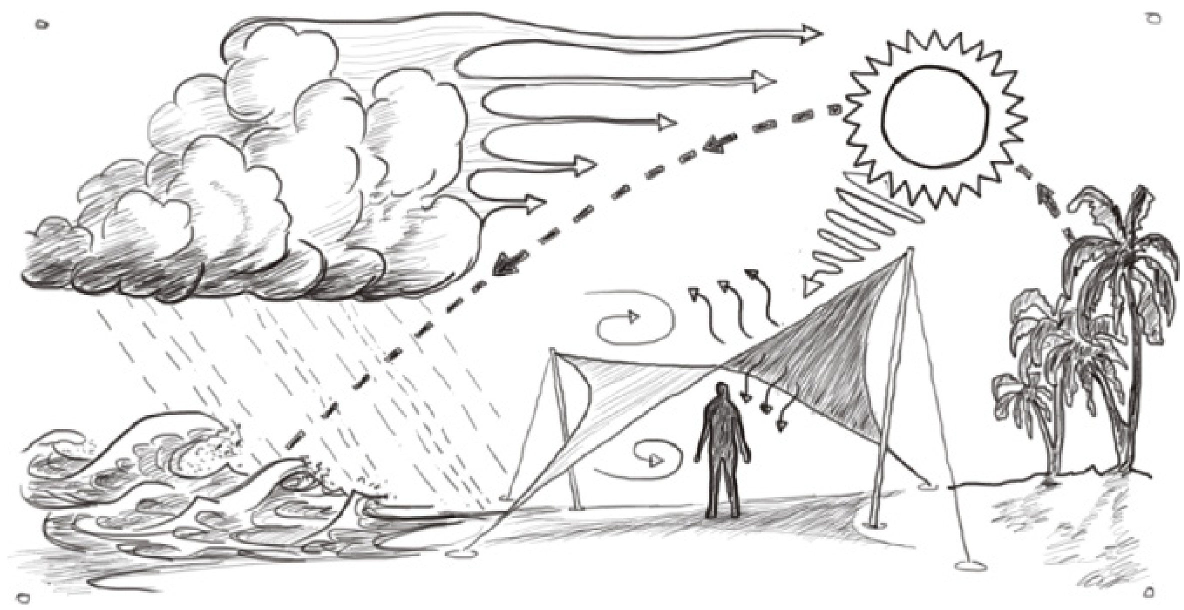


Figure 3. Membrane structure in tropical environment.
Source: (Image) elaborated by the authors.

Design Strategies

Design Strategies - SUN

Solar radiation is perhaps the climatic element with the most significant impact on thermal comfort. In this section, various strategies will be presented to reduce 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 analysed and compared as well as different shading techniques. Advantages and disadvantages of shapes and anti-clastic topology will be introduced as well as thermodynamic effects that are related to the behaviour of classical anti-clastic shapes. Furthermore, the mechanisms of heat and light transmittance will be addressed, and material and geometry requirements will be discussed.

Orientation

The correct orientation of a membrane structure towards the sun is the first step towards a design that responds efficiently to the solar radiation in order to control natural lighting and heat gains. To achieve comfortable spaces in the Tropics, it is essential to create a maximum of shaded area with the membrane cover during an extended period of the day throughout the year. The orientation and proportion of a shading structure are the most effective and fortunately also the most easily adjustable parameters in an early design stage.

The surface of the membrane structure should ideally be oriented perpendicular to the sun position. As the sun moves, a geometry has to be found, which offers most of the time maximum protection from sun rays while providing a maximum shading area and offering a favourable ratio of surface to volume (Gut & Ackerknecht, 1993). Having this principle in mind, preference should be given to membrane shapes with an elongated geometry on an east-west axis. In this way, the membrane surface areas close to the lower anchorage points (L) should be designed in a way to block the almost horizontal sun rays of sunrise and dawn while keeping at the same time an acceptable ratio of volume per exposed area to minimize solar heat gains (Figure 4).

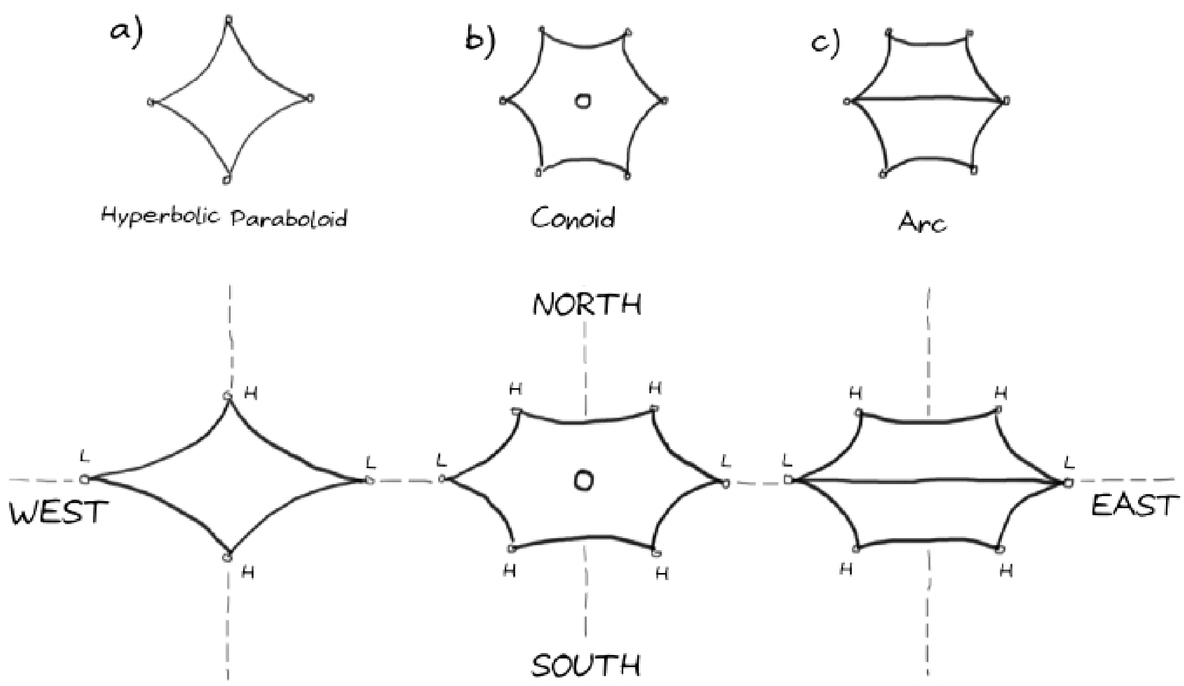


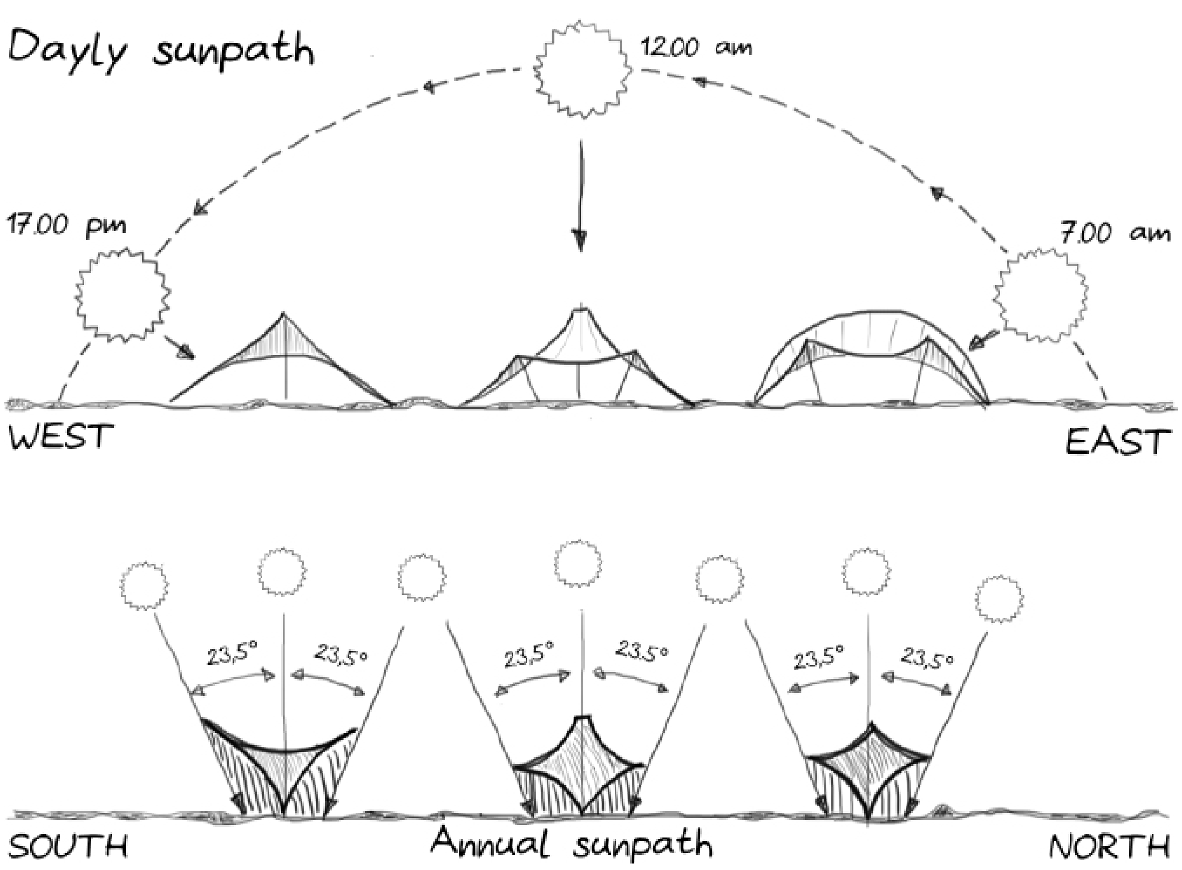
Figure 4. Solar orientation and proportion of membrane structures (plan-view), a) hyperbolic-paraboloid, b) conoid, c) arc.
Source: (Image) elaborated by the authors.

Effective shading

Shading from direct sunlight in a humid climate can considerably improve the thermal comfort of individuals in semi-outdoor spaces. On-site measurements have shown that the air temperature under membrane structures could be 2 – 4 C° lower than the ambient temperature on a sunny day with a low-speed wind situation (Goshayeshi, 2013). However, this high potential to increase thermal comfort can only be unlocked with appropriate decisions for materials and design.

While the effectiveness of a membrane shading structure depends largely on the correct orientation and geometry, the emplacement of the structure within its surrounding environment is important and requires a correct interpretation of the annual and daily solar path. Considerations about the perimeter of the structure relative to the desired shading area during certain hours of the day might also come into play. During this pre-design phase, it is vital to understand the characteristic sun angles on the solstice and equinox, which are the key dates to analyze solar exposure for any given latitude. The summer or winter solstice on the 21st of June marks the most southward oriented position of the sun during the year and the 21st of December the most northward oriented position, depending on whether the location is on the northern or southern hemisphere. The corresponding angles for the solar altitude are the lowest and, therefore, the most critical ones. The equinox at the 21st of March and September represents the mid-point of the sun-path between north and south, reaching at the equator a zenith position at midday with equal hours of day and night (Lacomba, 1991). Figure 5 illustrates 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. Three dimensional visualisations might provide additional information to the analysis, and stereo-graphic solar models enable the designer to project the shades at a selected latitude at a specific date and hour. Additionally, shade projections can be overlapped to create shadow masks for specific time frames. The analysis can be plotted out in two-dimensional solar charts for the critical dates as can be observed in Figure 6.

Figure 5. Daily and annual sun-path shade effects of hyperbolic, conoidal and arc structures.
Source: (Image) elaborated by the authors.



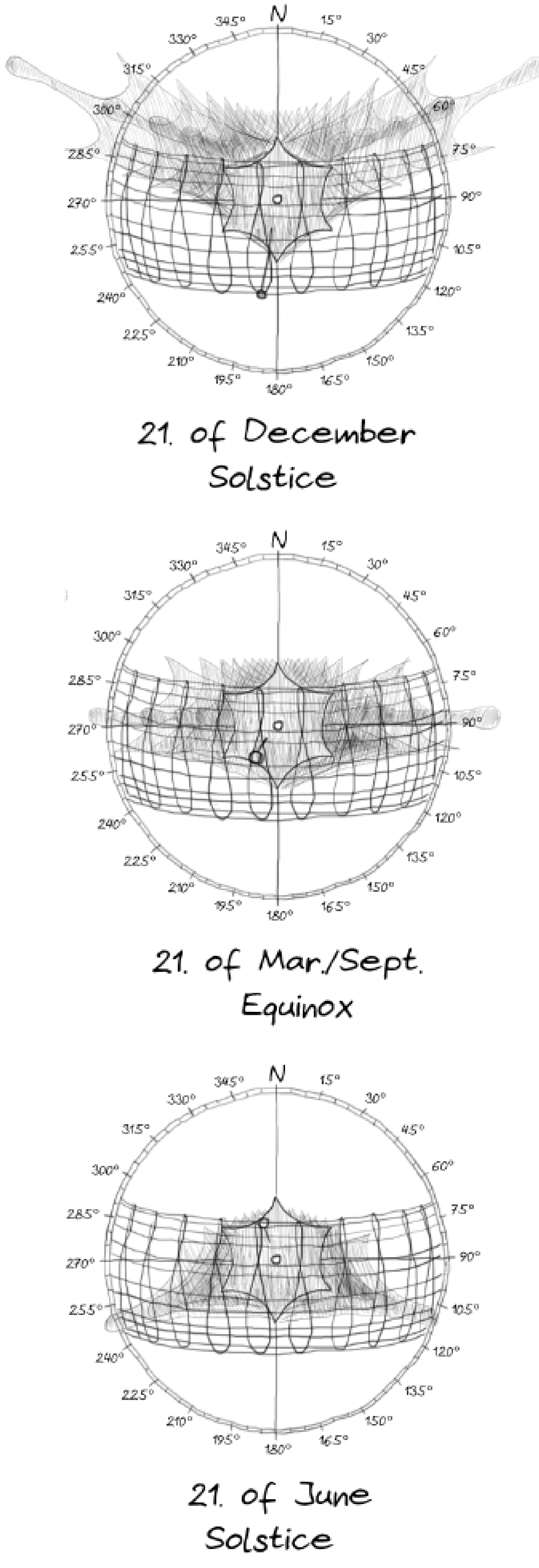


Figure 6. Solar charts with overlapping annual shade projection for conoidal membrane structure.
Source: (Image) elaborated by the authors.

As important as considering the shade projected by the structure and the shade projected on the structure by itself is the awareness of shade generated by elements in the surrounding environment. Understanding the external shading can be of advantage when shading is difficult to achieve by the design of the membrane geometry only. Analysis of the site may lead to discovering that a building or tree in proximity is already projecting the required shade. In order to carry out such an analysis, a site survey is needed, modelling all relevant elements of the immediate built environment in 3D. The shadow masks can be projected and plotted on to a stereographic solar chart for further analysis as shown in Figure 7 and 8.

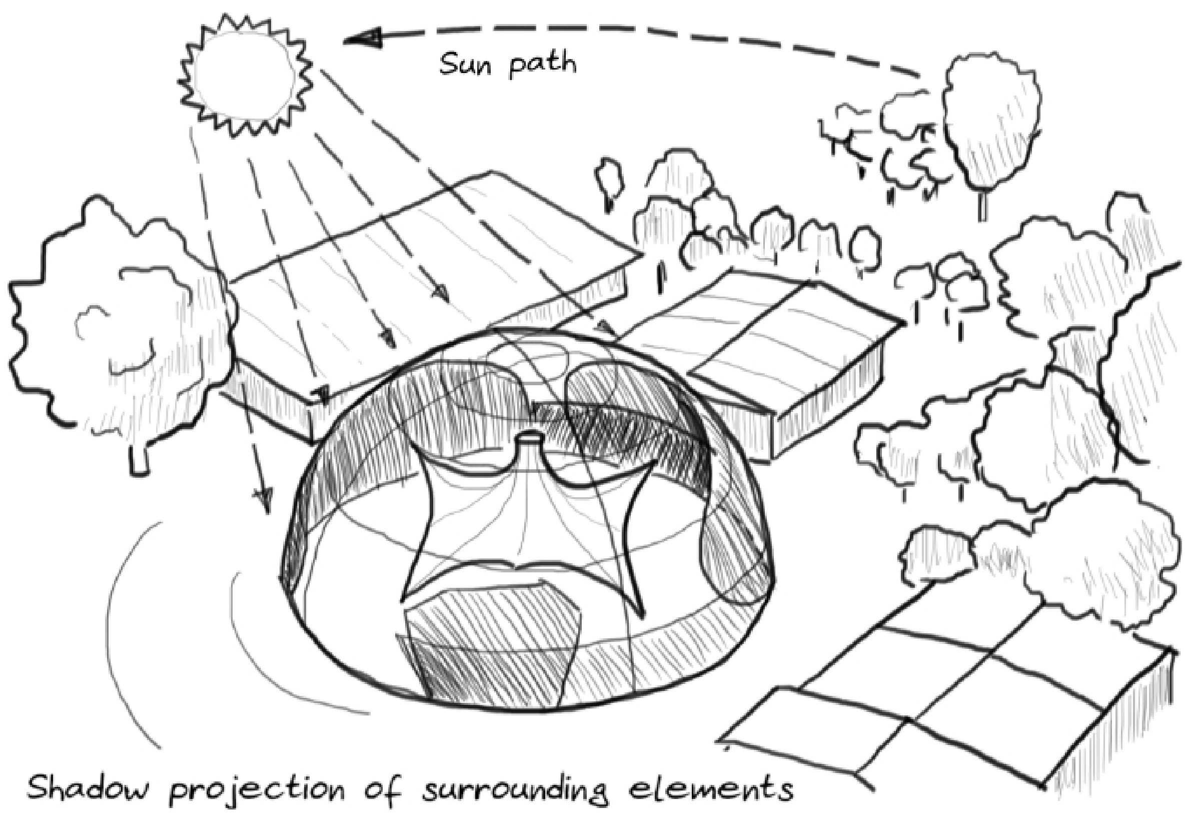


Figure 7. Shadow mapping of surrounding elements.
Source: (Image) elaborated by the authors.

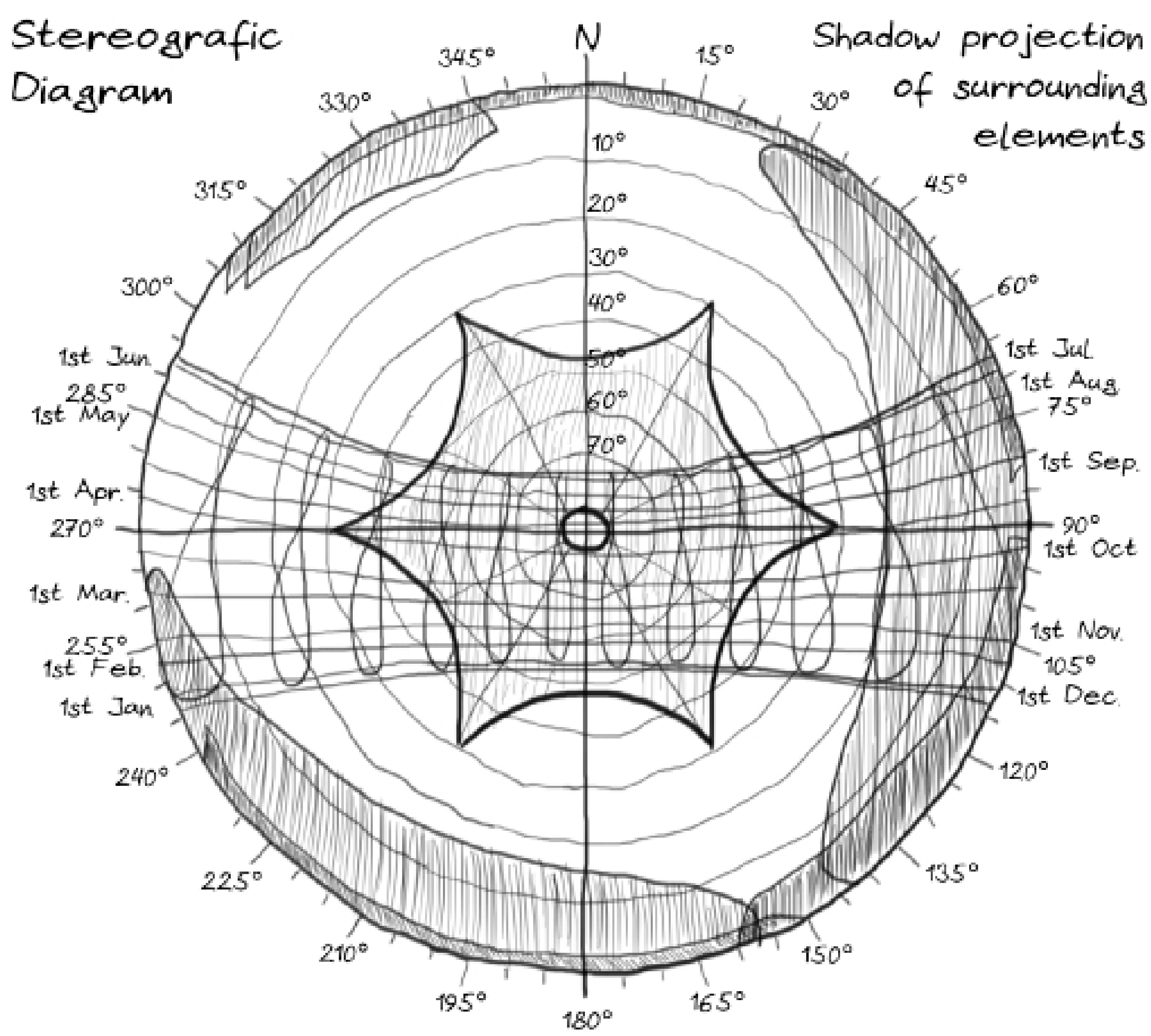


Figure 8. Stereographic solar chart with sky view factor showing visible part of the sky.
Source: (Image) elaborated by the authors.

Through the analysis of the solar geometry and the projection of shadow masks, it might be found that the plan of the membrane structure does not coincide with the projected shade for certain hours of the year. This issue could be addressed by reconsidering the proportions of the membrane geometry relative to the incidence angle of the sun. Figure 9 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.

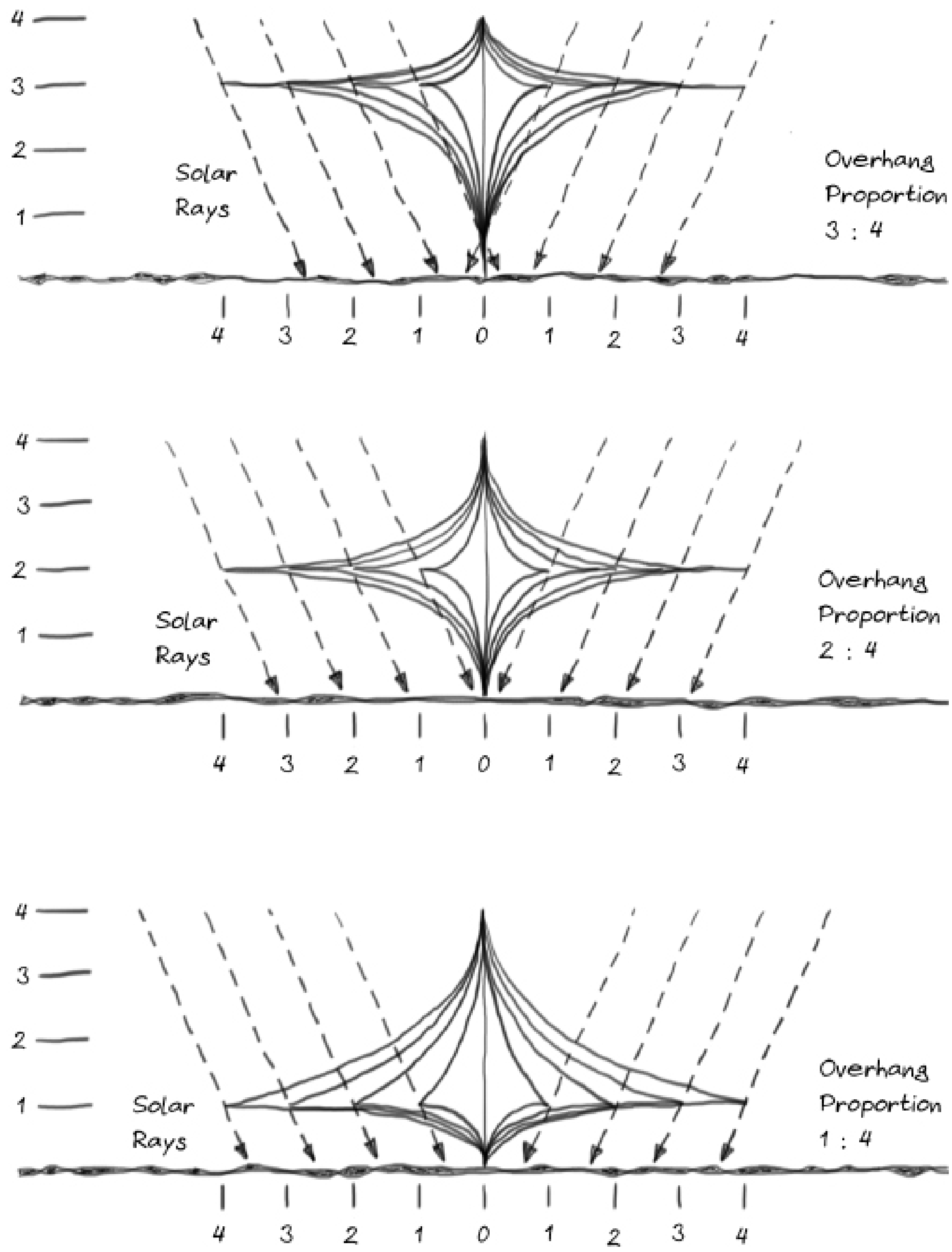


Figure 9. Relation between membrane canopy proportions and shade projection.
Source: (Image) elaborated by the authors.

Another shading design strategy convenient for covering large areas or facades is the repetition of membrane modules. Rather simple geometries on a smaller scale might provide an architecturally attractive and cost-effective solution. The following three examples in Figure 10 – 12 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, the overall shaded area increments and the solar heat gain is reduced with a direct impact on the thermal comfort sensation in spaces behind or below the superstructure.

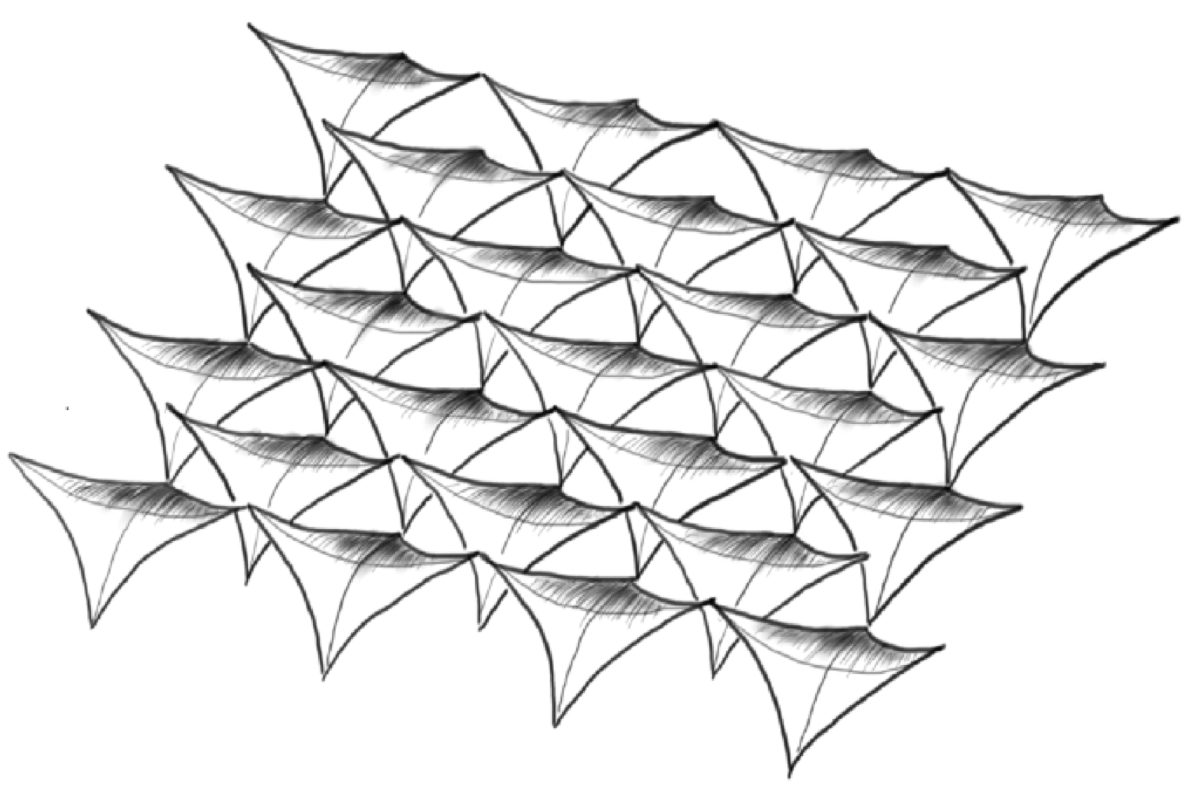


Figure 10. Repeated hyperbolic, self-shading, geometry.
Source: (Image) elaborated by the authors.

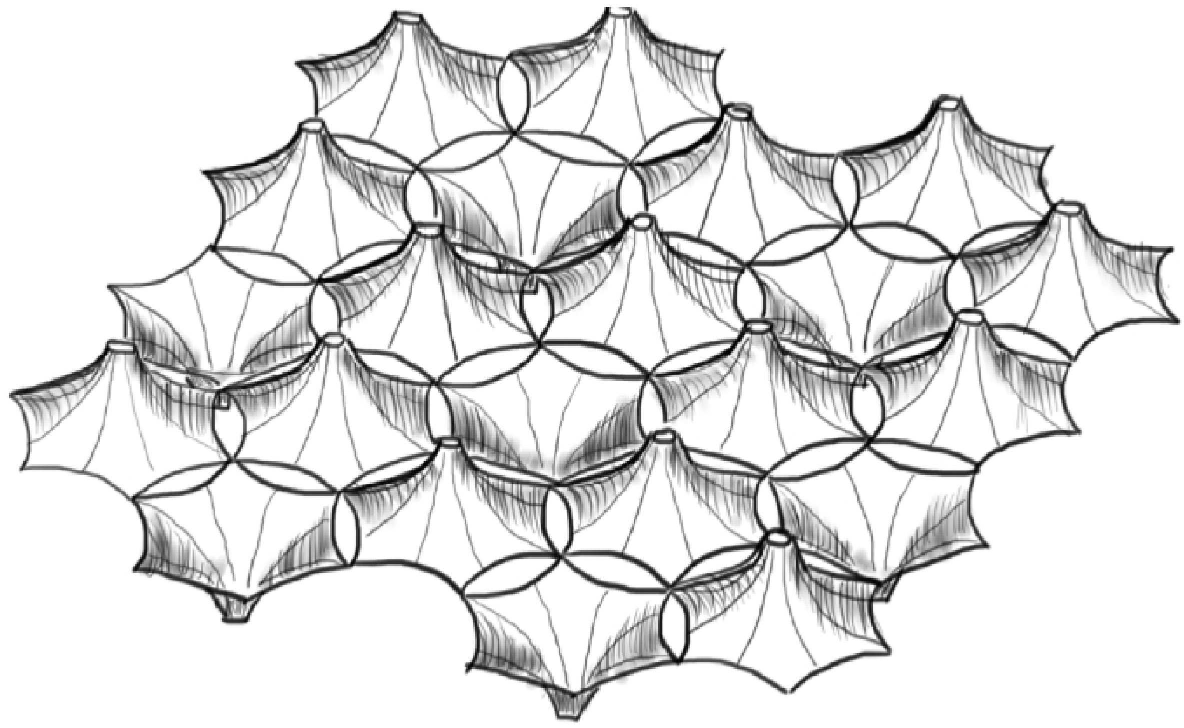


Figure 11. Repeated conoidal, self-shading, geometry.
Source: (Image) elaborated by the authors.

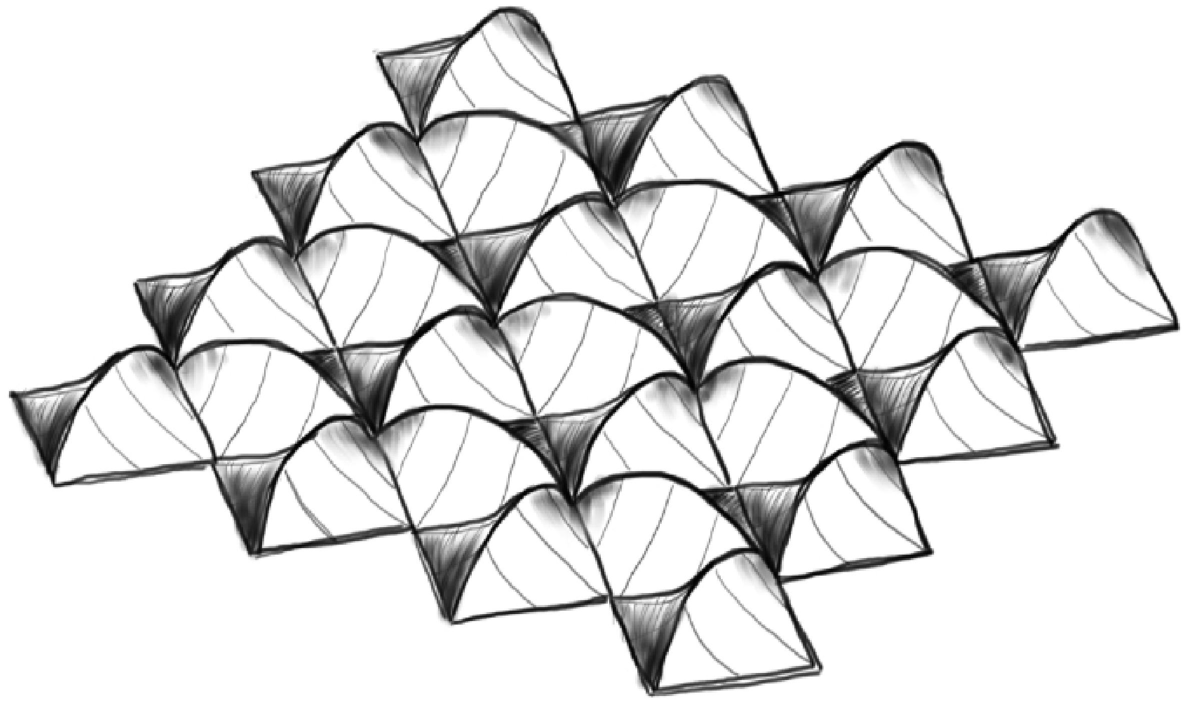


Figure 12. Repeated arc, self-shading, geometry.
Source: (Image) elaborated by the authors.

Heat and light transmittance

In building physics, the building envelope is generally 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 sufficient lighting and ventilation. Modern membrane materials open up opportunities to address these requirements, but their behaviour differs considerably from traditional building materials.

Woven and coated membrane materials used in tensioned membrane structures are, to a certain degree, translucent and provide overall good natural lighting conditions for the covered spaces underneath (Knippers, Cremers, Gabler, & Lienhard, 2011). However, due to the intense solar radiation in the Tropics, white membranes materials with highly reflective coatings on the outside and low emissivity coatings on the inside should be preferred as well as opaque materials, which can significantly improve the thermal and daylighting performance and reduce the risk of glare and overheating (Karwath, 2011). Because of the thinness and low mass of fabric membranes, the thermal resistance is minimal (Zürcher & Frank, 2014). Therefore, the characteristic thermal behaviour derives mostly from radiative and convective heat transfer mechanisms. For the calculation of heat transfer of membrane structures parameters of solar transmittance, reflectance and absorbance, emissivity roughness, thickness, and conductivity are required (Elnokaly, Chilton & Wilson, 2003). However, creating reliable simulation models for membrane structures is not a trivial task. Most of the reported models in the literature represent spaces enclosed by membrane structures (Harvie,1996; Devulder, 2004), but for the conditions of the Tropics, it can be assumed that most of the time spaces covered by membrane structures are semi-open spaces or secondary façade shading elements. Here the presented models apply only partially, and adaptation is required. A schematic model showing the heat exchange mechanisms acting on a semi-open membrane structure is shown in figure 13.

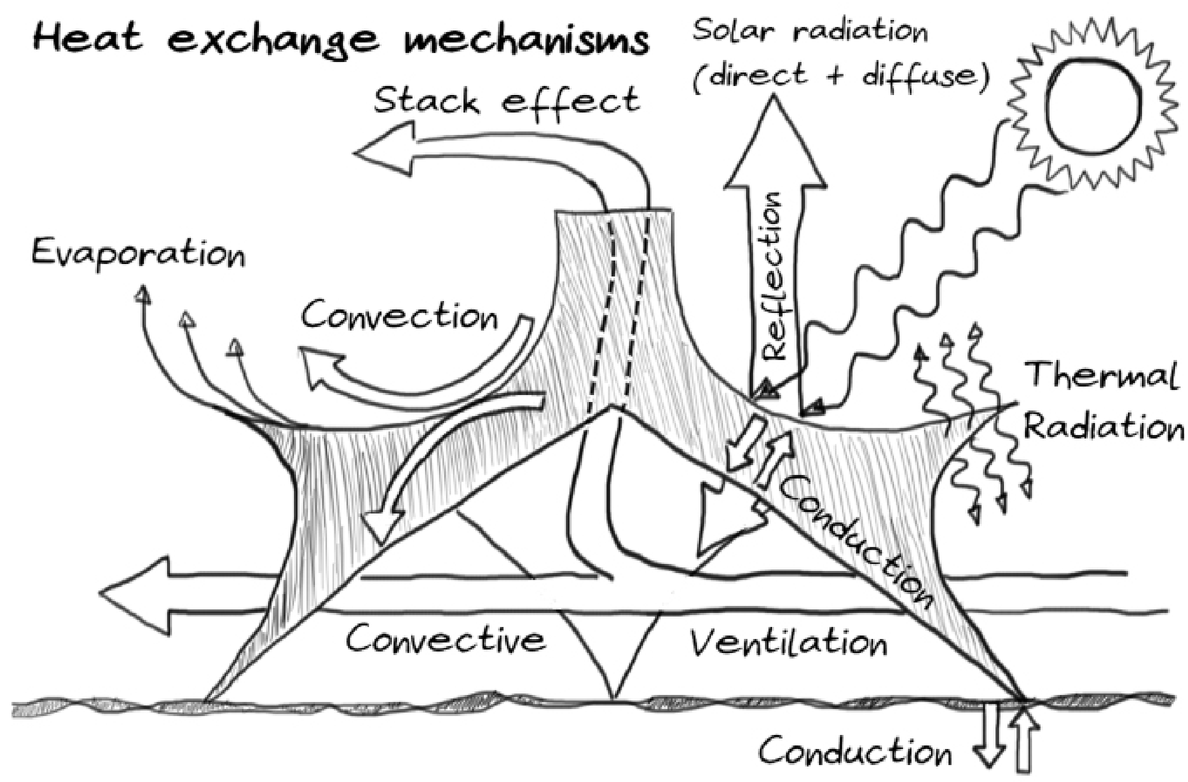


Figure 13. Heat exchange mechanisms on semi-open conoidal membrane structure.*
*Note: The size of the arrows is not representative for the magnitude of the heat exchange.
Source: (Image) elaborated by the authors.

Thermo-dynamic effects

Semi-open membrane structures cover significant volumes of air with a thin layer of material. The large surface area receives intense solar radiation, which is partially radiated to the space below, which is open enough to be affected also by the surrounding air temperature, wind and humidity. This situation leads to complex thermodynamic effects on the inside and outside of the membrane structure and influences the thermal comfort conditions of the occupants. One of the principal dynamic phenomena is the thermal stratification, which describes the vertical layering of air masses relative to temperature. Fueled by the heat gains thru the membrane fabric as well as the surrounding thermal conditions warm air raises within the membrane structure, leaving masses of air with a lower temperature at the height of the used spaces at floor level (Elnokaly, Chilton & Wilson, 2003). This phenomenon has been measured and described extensively in the literature (Harvie,1996; Devulder, 2004) and also occurs in in the Tropics whenever the membrane structures are high enough for the stratification to happen. Ventilation vents on the high points may assist in discharging the warm air and creating an additional effect denominated “stack-effect”. The warm, less dense air rises and discharges to the outside, and by that effect drawing in again cooler air to the space below the membrane, generating a self-sustaining, temperature-driven airflow (Forster & Mollaert, 2004). The increased air velocity and removal of warm air might improve the thermal comfort sensation. Double layer membranes may contribute further to improve the thermal performance of membrane structures. An added secondary membrane layer might reduce the solar heat gains of the interior space. The resulting air gap between the inner and outer membrane layer can be ventilated and warm air removed through high point outlets. The use of insulating materials, however, is not recommended in the Tropics due to high relative humidity and the associated risk of mould and fungus growth in the insulation material.

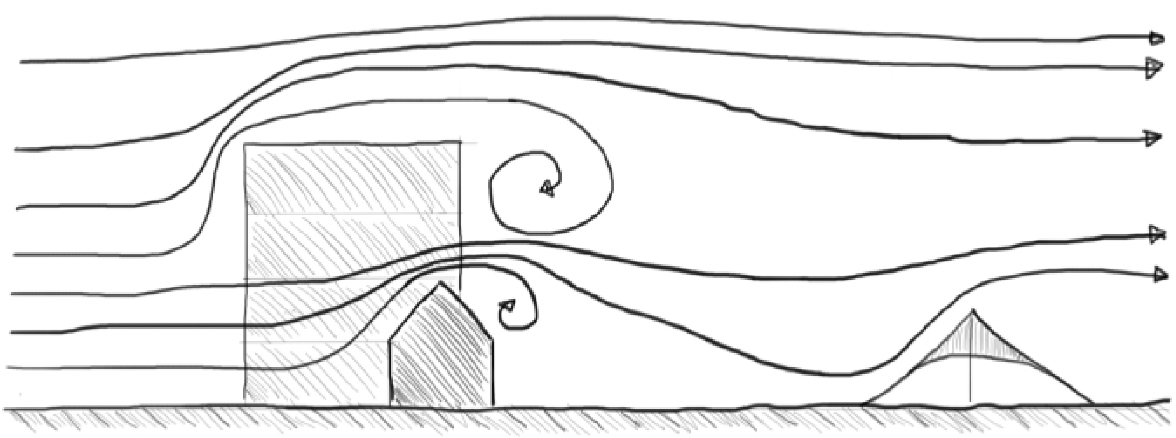
Design Strategies - WIND

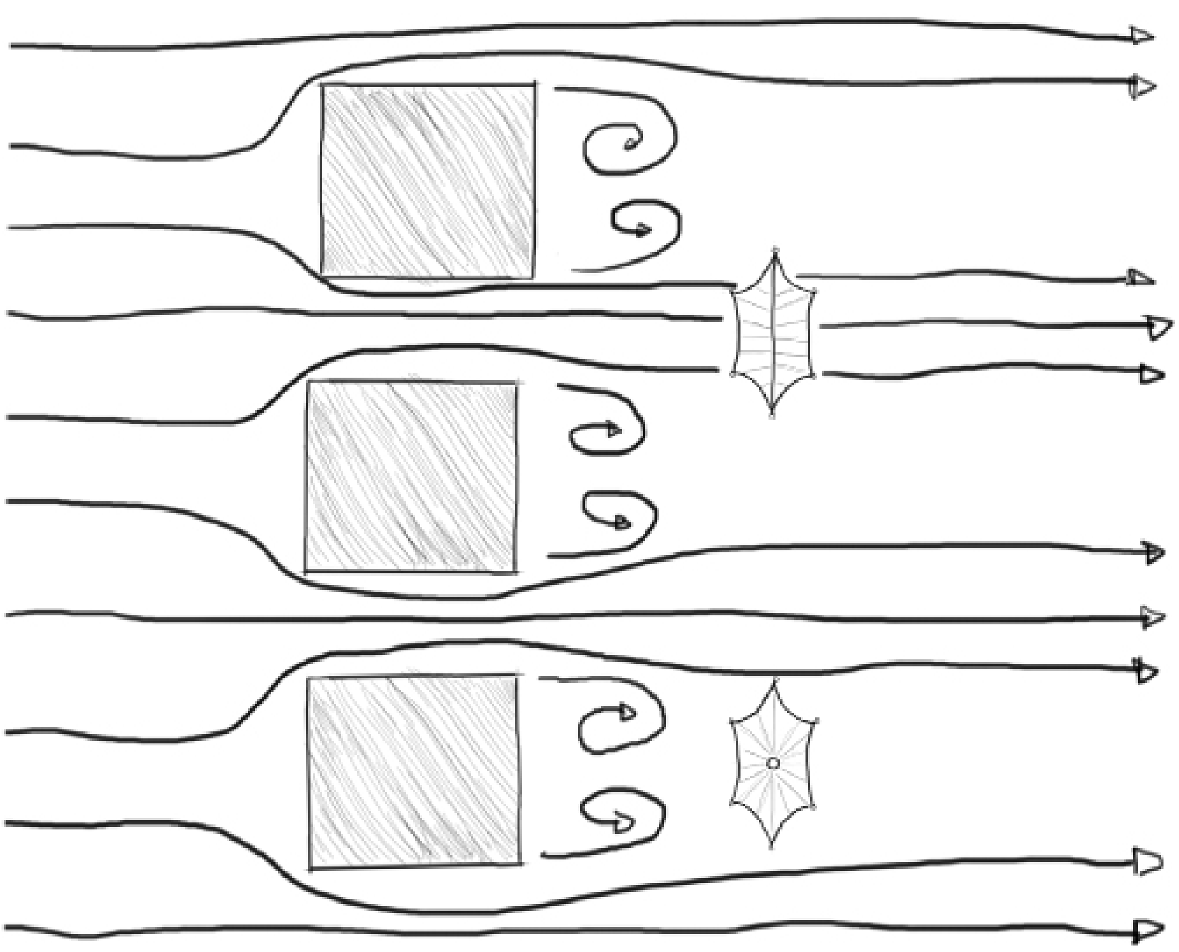
The wind is one of the most potent climatic elements and has been exploited by humanity throughout the history of civilization. The understanding of wind-patterns has been essential for human development and survival and has regained importance in recent years concerning the search for renewable energy sources. However, 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 aspect of wind, which is of importance for this study, is the positive impact on the thermal comfort in hot and humid climates. Natural ventilation for cooling has been used in architecture throughout history and is considered an effective and straightforward passive strategy for achieving thermal comfort (Elnokaly, Chilton & Wilson, 2003; Albadra, 2014). In this sense, understanding the wind and its fluid dynamics is essential when planning habitable spaces in the Tropics. Membrane structures offer, due to their light and flexible nature, opportunities to improve natural ventilation by geometric optimisation and design. Therefore, it is important to understand the airflow patterns and pressure distributions in and around the membrane structures to achieve the air-flow speed necessary for the aimed conditions of thermal comfort (Elnokaly, 2014).

Wind effects

The wind patterns in the tropical regions are dominated by the circulation of the Hadley cells, which 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 into the intertropical convergence zone (McGregor, 1998). The tropical low-pressure condition combined with an elevated water temperature of the oceans and intense solar radiation is likely to produce powerful cyclonic storm systems, which are called hurricanes in the American Tropics and typhoons in the Asian regions.

Figure 14. Urban wind shadow (section view).
Figure 15. Funnel effect (plan-view).
Source: (Images) elaborated by the authors.





Besides the seasonal global wind phenomena, wind effects on meso-scale should be taken into consideration during the pre-design phase of a membrane project. The land-ocean breeze is likely to occur in all coastal areas of the Tropics and originates in the thermal dynamics occurring between ocean and land. Another similar phenomenon which provokes local wind effects is the mountain-valley breeze, which is originated by the thermal dynamics occurring between mountain and valleys generating ascending and descending air masse on a day-night period. 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. Site aspects like the topography, roughness of the terrain, vegetation or the existence of a lake or river can influence the wind flow. 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 airspeed in narrow streets, which act like channels creating the funnel effect which can convert breezes into heavy gusts (Krautheim, Pasel, Pfeiffer, & Schultz-Granberg, 2014) as can be seen in Figure 14 and 15. 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. Knowing the site conditions prevents from having a lack or an excess of natural ventilation.

Effective Ventilation

In the Tropics, ventilation is one of the most effective strategies to improve the sensation of thermal comfort (Goshayeshi, 2013). 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 thermal comfort sensation (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. However, the limitations of natural ventilation are clear: the rate of ventilation or airspeed might not be sufficient due to low or no wind availability during the hottest periods when cooling is most needed. But even though natural ventilation is mostly dependent on incontrollable climate conditions, it is still one of the most effective strategies to enhance thermal comfort and worth exploiting by specific design strategies. For the case of membrane structures, the effectiveness of natural ventilation can be improved through the shape of the structure itself, modelling airflow speed and direction with the specific geometry and orientation of the structure (Garcia, 2005). The possibility to create aerodynamic ventilation effects with flexible free-forms or combinations of different membrane elements within the form-finding process supports the idea of climate adaptive design. Examples of this design approach are shown in Figure 16 and 17.

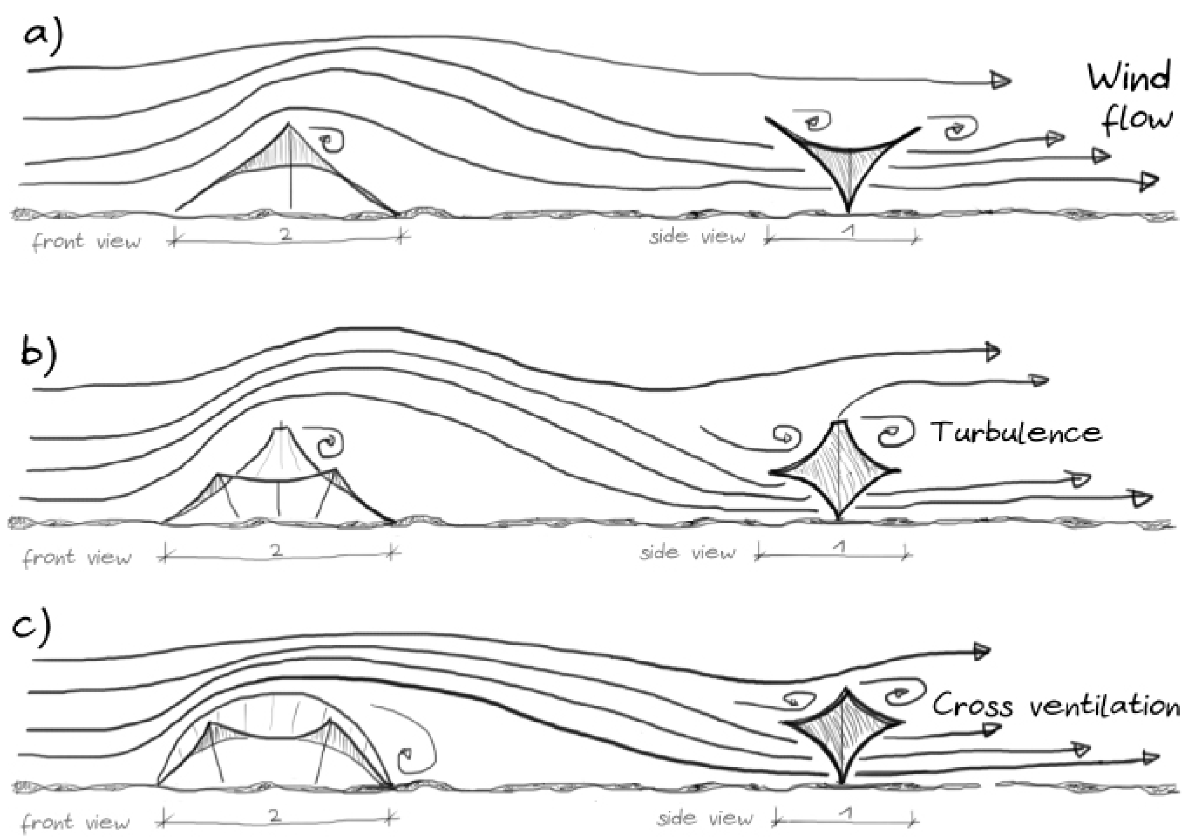


Figure 16. Aerodynamic effects on different membrane geometries: a) hyperbolic-paraboloid, b) conoid, c) arc.
Source: (Image) elaborated by the authors.

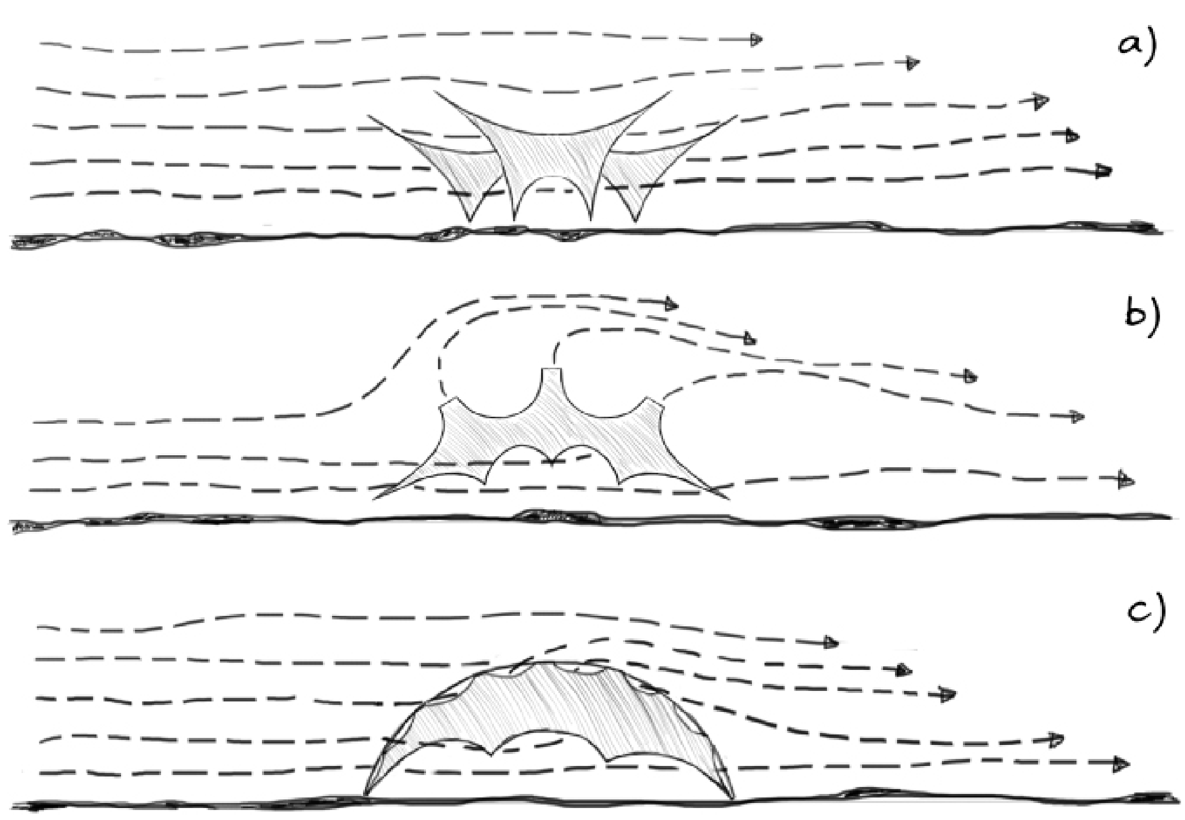


Figure 17. Improved ventilation with modified membrane structures: a) hyperbolic-paraboloid, b) conoid, c) arc.
Source: (Image) elaborated by the authors.

As a first step towards an effectively-ventilated membrane structure, the proportion and orientation of the geometry should be considered. The shallowest section of the structure should be oriented perpendicular to the wind direction predominantly during the hottest season of the year in order to allow airflow underneath the structure. The geometry should be designed in a way that even the smallest breeze can be captured and directed towards the activity areas of the covered space. Open plans and minimal obstruction of the windward facing lateral openings should, therefore, be preferred. By having openings located at high points in the structure, rising warm air can escape, creating an additional airflow. Unfortunately, this chimney effect by itself does not generate sufficient airflow speed to enhance thermal comfort; however, it is still useful for venting the accumulated hot air and thus reducing the average ambient temperature underneath the membrane (Haw, Saadatian, Sulaiman, Mat, & Sopian, 2012). High-point outlets should be dimensioned to provide sufficient ventilation regardless of wind direction (Forster & Mollaert, 2004). Details for this type of vent openings at high points for conoidal and arch structures are shown in Figure 18 and 19.

Figure 18. Ventilation detail for large scale arc structure.
Source: (Image) elaborated by the authors.

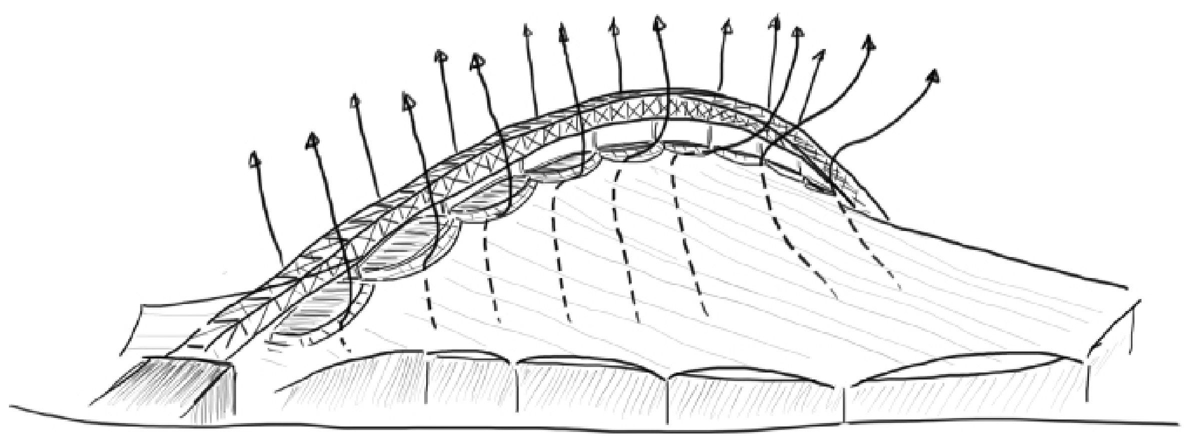


Figure 19. Ventilation detail for a high point on conoidal membrane structure.
Source: (Image) elaborated by the authors.

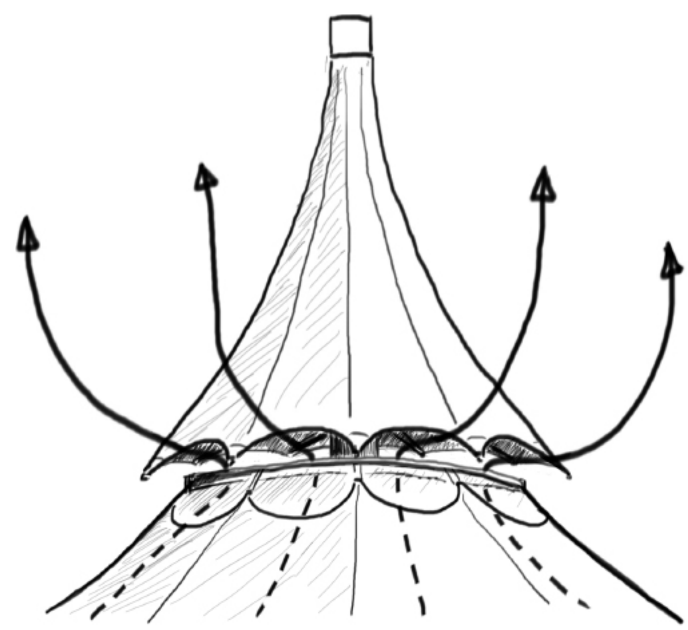
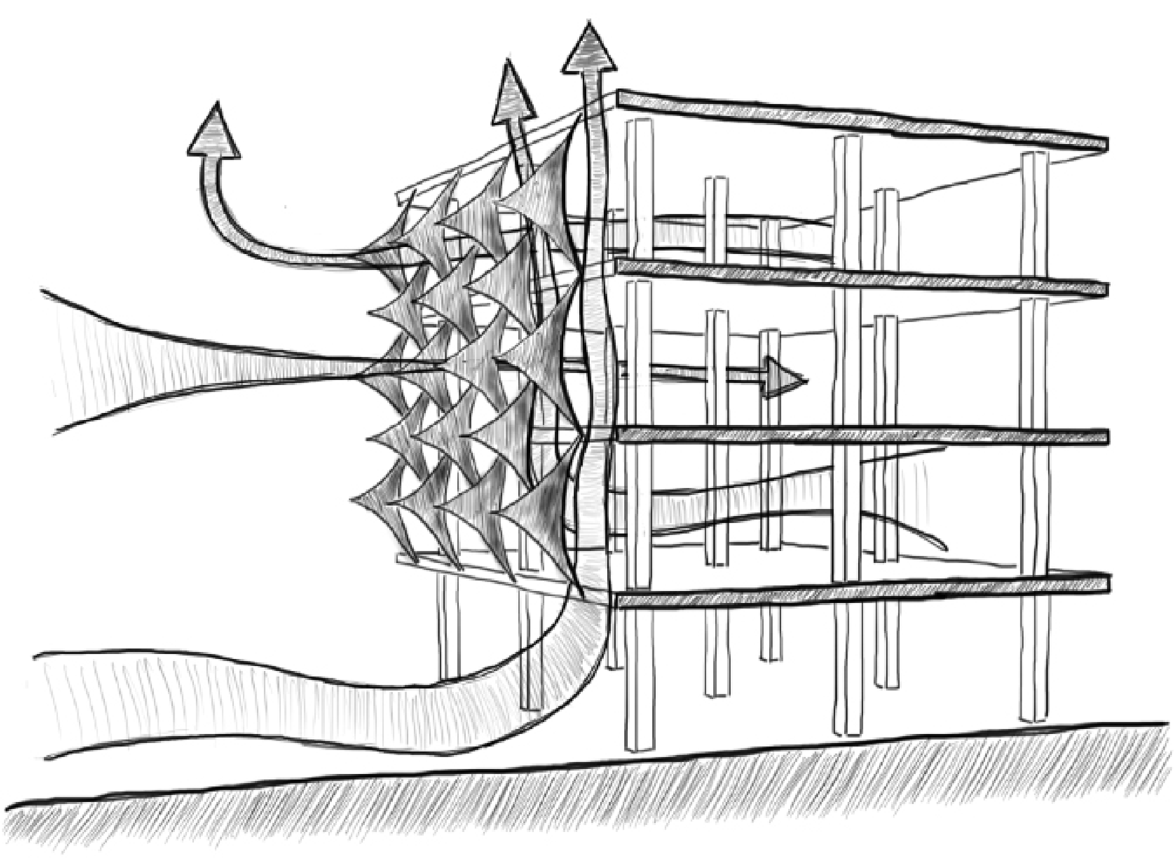


Figure 20. Ventilation strategy for double-skin-facades of a multi-storey building using modular saddle-shaped shading sails.
Source: (Image) elaborated by the authors.



A similar venting strategy for removing warm air can be applied to double-layer membrane structures. The air space between the two layers can be ventilated, removing warm air from the gap through the high-point vents while taking in cooler air at openings at lower levels. Even though this strategy does not enhance the ventilation performance, the overall thermal performance of the membrane structure can be improved (Forster & Mollaert, 2004). This is a strategy for membrane structures which has not yet been fully exploited in the Tropics when it comes to the design of ventilated double facades for multi-storey buildings in urban environments as shown in figure 20.

A more sophisticated ventilation strategy uses the wind-induced pressure differences around and across the membrane structure to generate cooling airflow. This strategy is less dependent on temperature differences between air masses and is considered suitable for the tropical climate. The geometric shape of the membrane is again of significant importance as it has a considerable influence on the airflow and pressure distribution around the structure. The part of the membrane surface facing the windward direction is compressed, generating positive pressure while the leeward facing side of the surface is exposed to lower pressure. The pressure difference across the two sides of the membrane surface induces airflow from the high pressure to the low-pressure zone, which may contribute to the thermal comfort sensation (Haw, Saadatian, Sulaiman, Mat, & Sopian, 2012). While the wind speed, which is the driving force for creating the pressure differences between opposing zones, is out of the designer's control, effective ventilation is even possible with lower wind velocities by correctly dimensioning air inlets and outlets of the membrane structure. Greater wind velocities are usually expected at the high points of the membrane structures. Therefore, these elements should be exploited to create high and low pressure zones and enhance airflow through strategic openings (Forster & Mollaert, 2004). Pressure distributions are recommended to be investigated during the design process using CFD simulation software and wind tunnel tests with scale models (Figure 20 & 21). Visualizations, generated with these types of tools, may provide a general overview of the ventilation performance of the membrane structure and assist with design decisions on the general geometry and ventilation details such as vent openings.

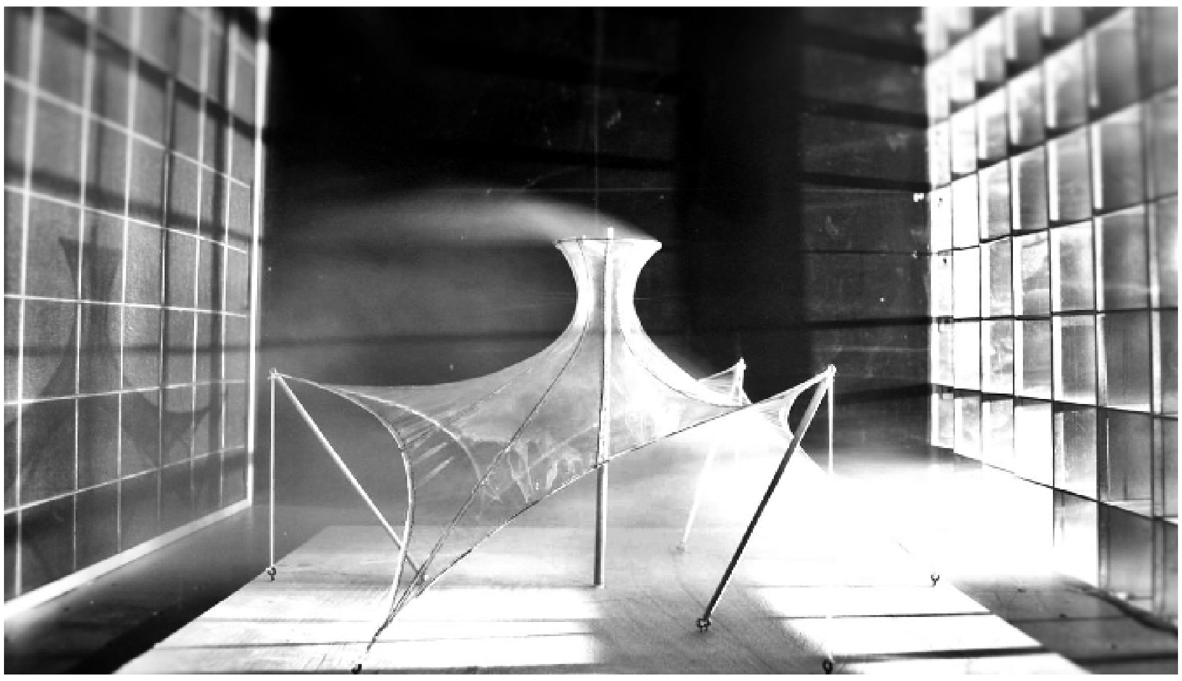


Figure 21. Wind-tunnel test with scale model of conoidal structure, at Laboratorio de Arquitectura Tropical, Escuela de Arquitectura, Universidad de Costa Rica.
Source: (Image) elaborated by the authors.

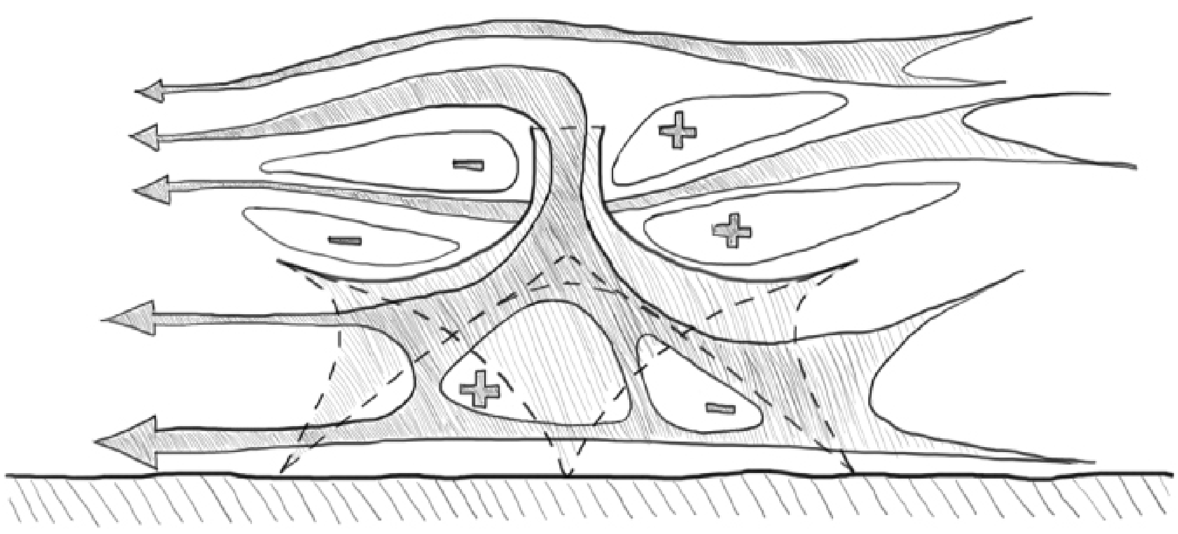


Figure 22. Diagram showing ventilation dynamics with the difference of pressure on an open conoidal high-point.
Source: (Image) elaborated by the authors.

Cross ventilation

The high humidity levels and warm temperatures of the tropics require maximum ventilation and free passage of air through the interior space, which is essential. The lessons learned from traditional architecture are that very open buildings with permeable facades and floor plans best fulfill this requirement (Gut & Ackerknecht, 1993). Cross ventilation is a well-known passive design strategy and has been used widely in vernacular architecture and proven its effectiveness for improving thermal comfort. As in the case of semi-open membrane structures, for cross ventilation and cooling effects to occur, air must move through the covered space from one end to the other. Therefore, the long axis of a membrane 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 outlets, taking advantage of the Venturi effect and increasing airspeed (Figure 23 & 24).

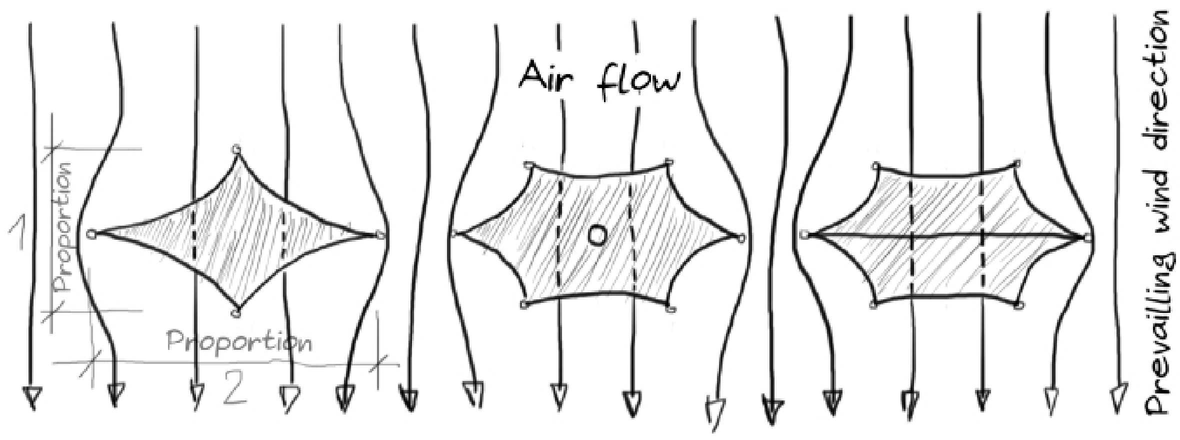


Figure 23. Orientation and proportion for effective cross-ventilation of different membrane geometries: a) hyperbolic-paraboloid, b) conoid, c) arc.
Source: (Image) elaborated by the authors.

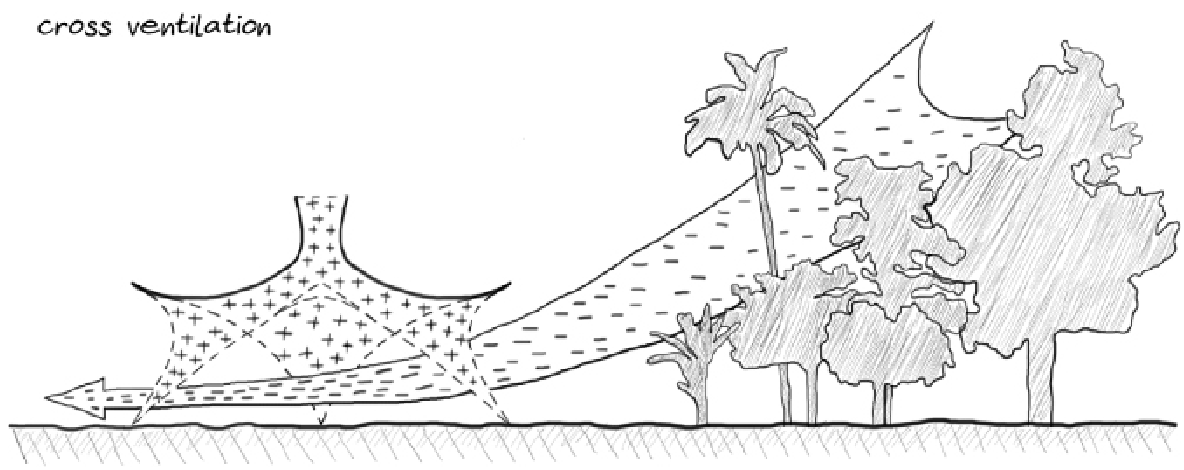


Figure 24. Cooling effect of surrounding vegetation in combination with cross-ventilation.
Source: (Image) elaborated by the authors.

Even more significant advantage can be taken of cross-ventilation when the air has previously passed through areas covered with vegetation. The air temperature around trees and vegetation is usually several degrees cooler than the surrounding ambient temperature. When such pre-cooled air flows through the membrane structure, the warmer air accumulated beneath 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 strategy.

Design Strategies - RAIN

Rain and humidity are maybe the climatic elements that most appropriately characterize the Tropics. Around two-thirds of the annual global precipitation falls 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 continuously cycling in an accelerated flow, changing state from liquid water to vapour, condensing, and precipitating in massive discharges and during elongated rainy seasons. Protection from the heavy, torrential rainfalls is a necessity and requires adaptation of architectural typologies to fit the climate: steep roofs with wide overhangs and means of ventilation to control the humidity have been employed in vernacular architecture across the Tropics. On this premise, the effects of rain and humidity on thermal comfort will be outlined and responsive design strategies presented and discussed in the following section.

Precipitation and humidity effects

The high levels of humidity in the tropical climates are the result of the intense solar radiation and the warm ocean waters, which fuel the evaporation process and allow an enormous amount of water vapour to be suspended in the atmosphere, condensing, falling, and flowing through the hydrologic cycle. In the warm and humid zones of the tropical regions, the relative humidity is always high, resulting in frequent and intense precipitation with a mean annual rainfall well above 1000 mm while the global mean annual rainfall is usually around 800 mm (Laing & Evans, 2011). The continuous presence of general cloudiness and the formation of large cloud systems like cumulus nimbus are the physical evidence of the condensing humidity in the atmosphere and often precede the typical heavy rainfalls (Koch-Nielsen, 2007). Rainfall and humidity are important quantitative indicators to characterize tropical climates with considerable variability, not only regionally but also temporally. The annual rainfall volume can vary drastically within a few kilometres and often shows significant differences from one year to another, not only in volume but also 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 unique 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).

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 a high-tech, state-of-the-art building solution, the use of waterproof textile materials for rain protection is not new at all. Umbrellas and raincoats are of everyday use for rain protection on an individual scale and deliver the perfect concept model for tensioned membrane structures. Second, but not less important, is the mitigation of the humidity. The thermal comfort sensation is, in combination with the ambient air temperature, largely dependent on the levels of relative humidity suspended in the air. Therefore, it is a design objective to reduce the amount of humidity in and around the built environment in order to increase thermal comfort. While the control of humidity can be addressed relatively easy in enclosed buildings, semi-open membrane structures are exposed at all times to the surrounding climate conditions and humidity mitigation is only possible through the application of ventilation strategies. Whereas the protection from rain and the drainage of water, which includes the analysis and design of the membrane geometry itself, is a topic less relevant to the thermal comfort, it is yet of great importance to the primary function of the membrane structure.

The first task in the design process for rain protection and drainage is the analysis of the meteorological data and the specific site conditions. Basic data about the mean quantities of rain, which are usually documented on an annual and monthly basis, provide basic information for the design. Maximum amounts of water per square meter to be expected at a particular time will be the limiting factors for the dimensioning of drainage and gutter systems as well as slope inclinations of the membrane. As a second step, the proposed geometry should be analyzed with the criteria of rain protection and drainage in mind. Questions about possible drainage paths on the surface and drainage points on the edges should be answered. The consideration of the minimum slope inclination of the membrane surface is also of importance in order to identify areas of risk for water ponding. The projection of iso-curves onto the membrane surface reveals the drainage paths of the hydrophobic membrane on which the water is driven by gravity towards the lowest points of the surface geometry. Areas, where a risk of water ponding is to be expected, can be identified with anticipation using the graphical analysis method shown in Figure 25.

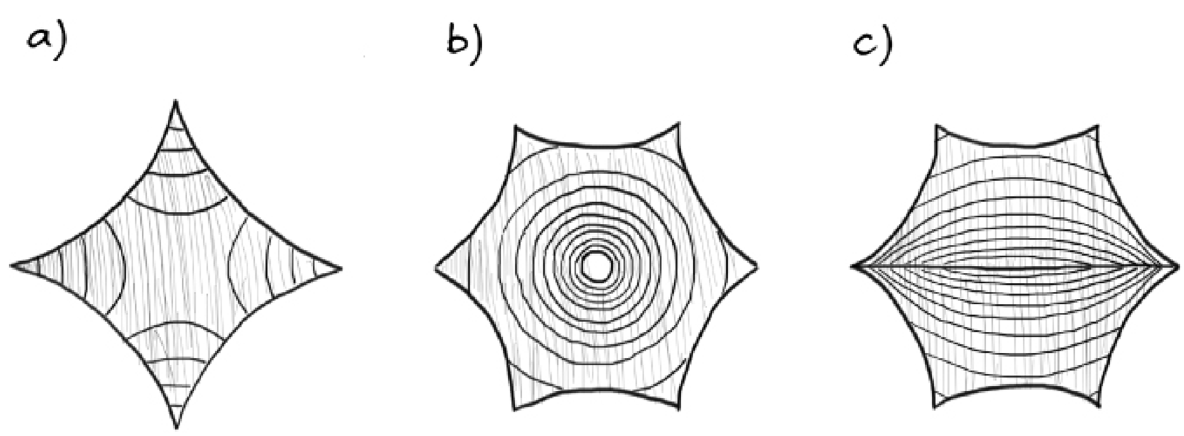


Figure 25. Isocurves of a sequence of height levels projected on different membrane geometries in plan-view: a) hyperbolic-paraboloid, b) conoid, c) arc.
Source: (Image) elaborated by the authors.

Ponding describes the situation of rainwater accumulating on a membrane area with little or no slope. The collected water deforms part of the membrane surface by its own weight, drawing more water into the deformed area. This situation may lead eventually to a structural overload and provoke the failure of the membrane. Analysis of the curvature of the surface slope is required in order to identify critical areas as exemplified in Figure 26 and 27. Even though ponding is an issue primarily related to structural considerations, it cannot be neglected in the design of efficient rain protection.

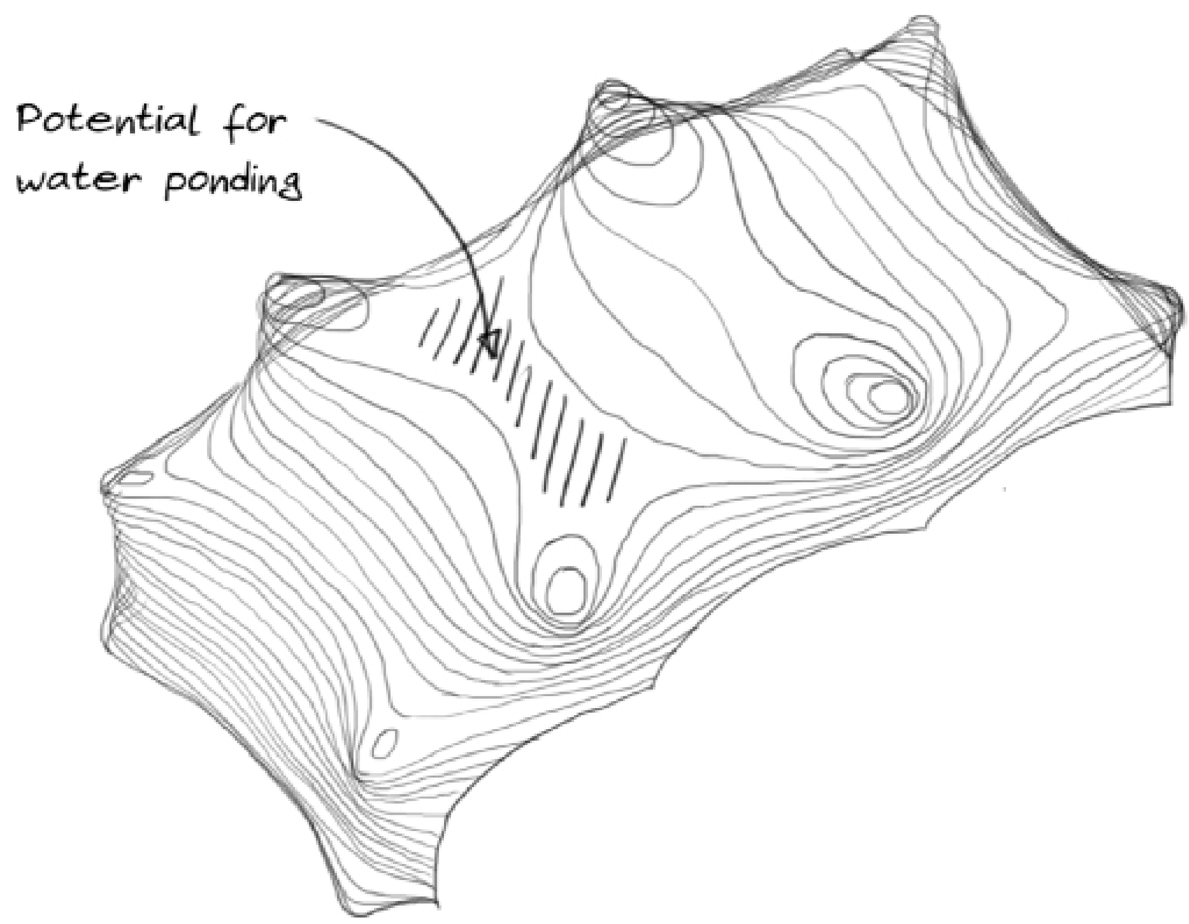


Figure 26. Analysis of drainage and potential areas for water ponding on a membrane structure with multiple high-points.
Source: (Image) elaborated by the authors.

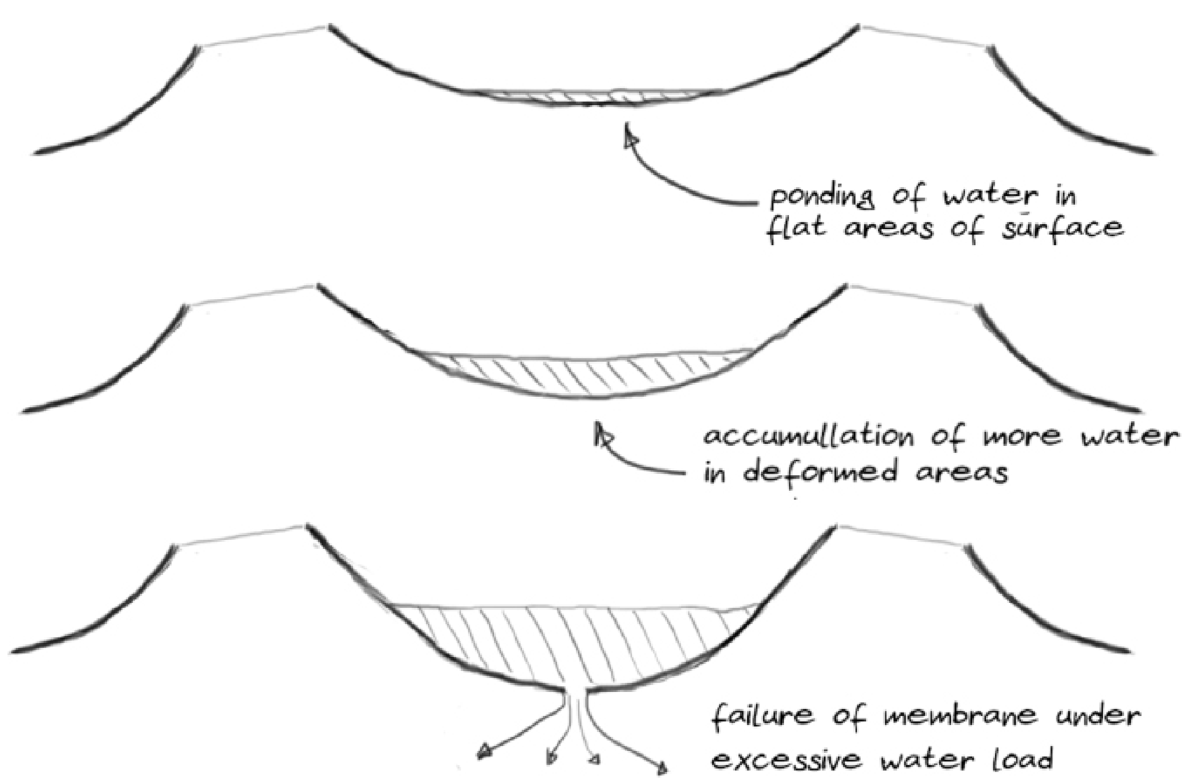


Figure 27. Sequence of water ponding on the area between two high-points: from rain-water accumulation to failure of the structure.
Source: (Image) elaborated by the authors.

Generally, rain rarely 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 inclination angle of raindrop trajectories increases proportionally to wind speed (Chand & Bhargava, 2005). During storms, raindrops may be dragged by the wind force almost horizontally and pass through the membrane structure, leaving the space underneath unprotected as shown in Figure 28.

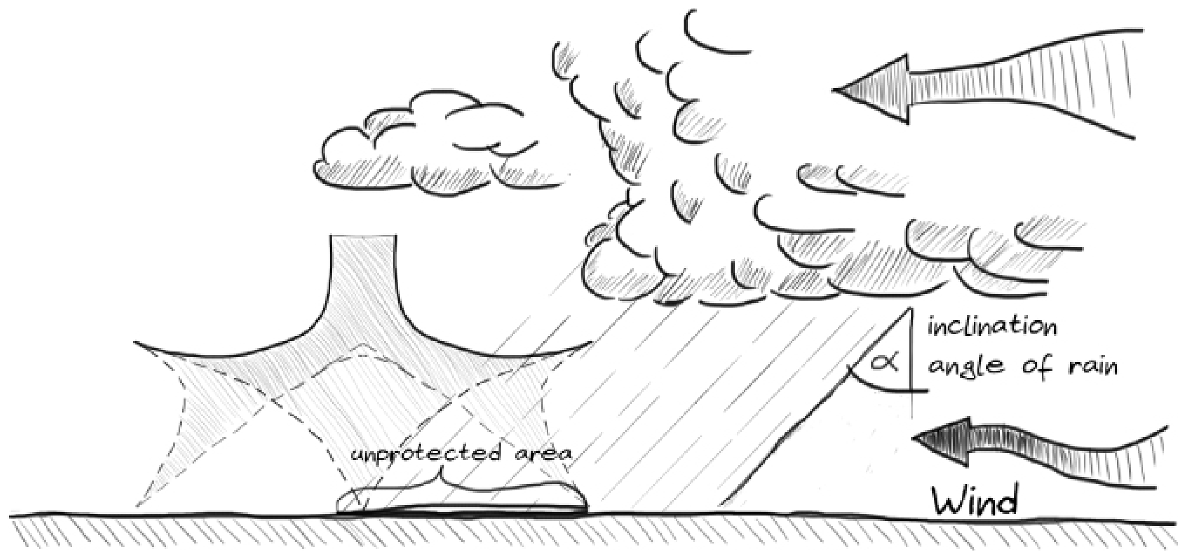


Figure 28. Inclination angle of wind-driven rain in relation to overhang projection of membrane structure.
Source: (Image) elaborated by the authors.

Although many factors influence wind-driven rain, the most critical factors are in the membrane form itself. The aerodynamic effects around the membrane strongly affect the raindrop trajectories (Choi, 1991). Membrane structures with high-points or large projecting overhangs may redirect air-flows up and over the structure at a distance further away from the limits of the perimeter and, in this way, reduce the deposition of driving rain beneath the membrane cover (Straube, 2010). However, the opposite effect is possible when the rain protected area is significantly reduced due to poor aerodynamic design of the membrane geometry. Careful analysis is in all cases recommended.

A consideration of the design to take into account regarding the humidity is the high potential for condensation. During the rainy season, the air in the Tropics is highly saturated with water. A minimal drop of ambient air temperature might lead to condensation, resulting in rain or dew. Condensation on membrane structures is likely to happen under these conditions and may lead to problems when not dealt with in advance. In open space membrane structures, the surface temperature might drop below the air temperature when the membrane radiates against the clear sky at night. The surrounding warm and humid air contains much water in the form of vapour, which condensates when the air gets in contact with the cooler membrane surface. Droplets built up and run down on the inside of the membrane skin until they encounter a dripping edge or low point, leading to issues within the space below. The susceptibility of membrane structures for condensation is linked to their thermal mass and the poor insulation behaviour of the membrane material itself. The membrane is unable to compensate temperature swings of the environment or absorb any humidity due to the hydrophobic nature of coated membrane materials (Forster & Mollaert, 2004). While the climate conditions are mainly responsible for the abundance of condensation, the use of the building also has much influence on the quantity and timing. For example, a membrane roof covering a sports centre where large groups of people gather, increasing the relative humidity underneath the cover by their transpiration, it is more likely for condensation to occur than in structures which host other activities with fewer people. When condensation is expected to occur and cannot be mitigated employing ventilation, the best strategy is to anticipate the issue during the design stage by foreseeing the possible pathways of draining condensation water and planning 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 collect and drain the condensation water (Forster & Mollaert, 2004). Although condensation is not very likely to occur in semi-enclosed spaces, humidity should be considered in the design phase and be taken into account during the analysis of environmental factors.

Drainage details

The force of gravity generally solves the drainage of water from roof structures. Tensioned membrane structures are not different from that. Their three-dimensional geometries and large curvatures are beneficial for adequate drainage. However, due to the complexity of the geometry, it is also necessary to calculate how much water per area will be collected at different drainage 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 at the main access points of the structure. If neglected, there is the risk of having rainwater draining in freefall along the perimeter edge of the membrane roof, becoming unpassable for people during heavy rainfall. As a solution to this issue, water-barriers can be welded onto the outer membrane side with a defined offset from the edge. A schematic section of this detail is shown in Figure 29.

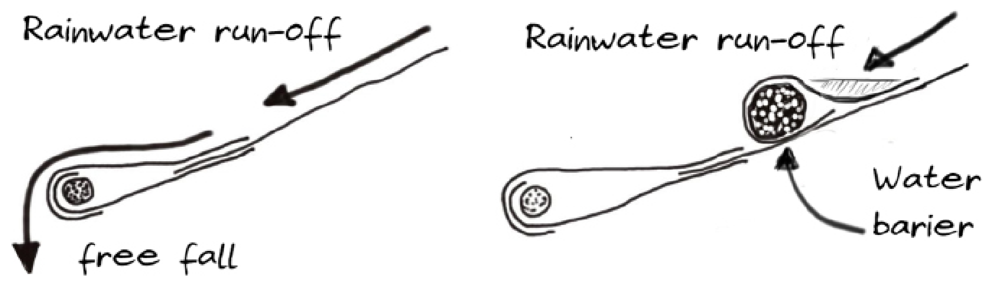


Figure 29. Draining barrier for borders and edges of the membrane.
Source: (Image) elaborated by the authors.

The design and dimensioning of the draining details is the most critical part of the total drainage strategy. The excessive amount of water which can fall in just a few minutes during a tropical thunderstorm makes 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 employing checkpoints and removable meshes, which act as filters. Details of typical drainage gutters for membrane structures are shown in Figure 30 and 31.

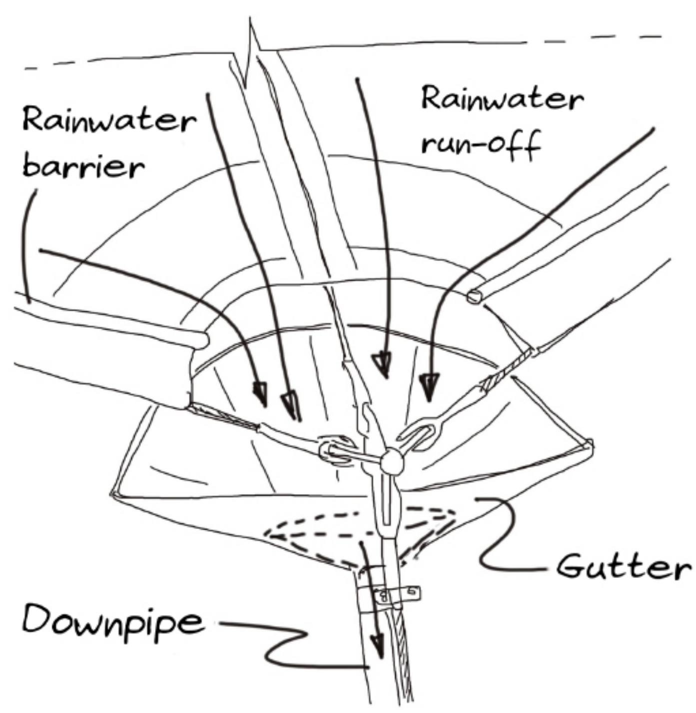


Figure 30. Drainage detail for water collection at membrane vertices with a large gutter.
Source: (Image) elaborated by the authors.

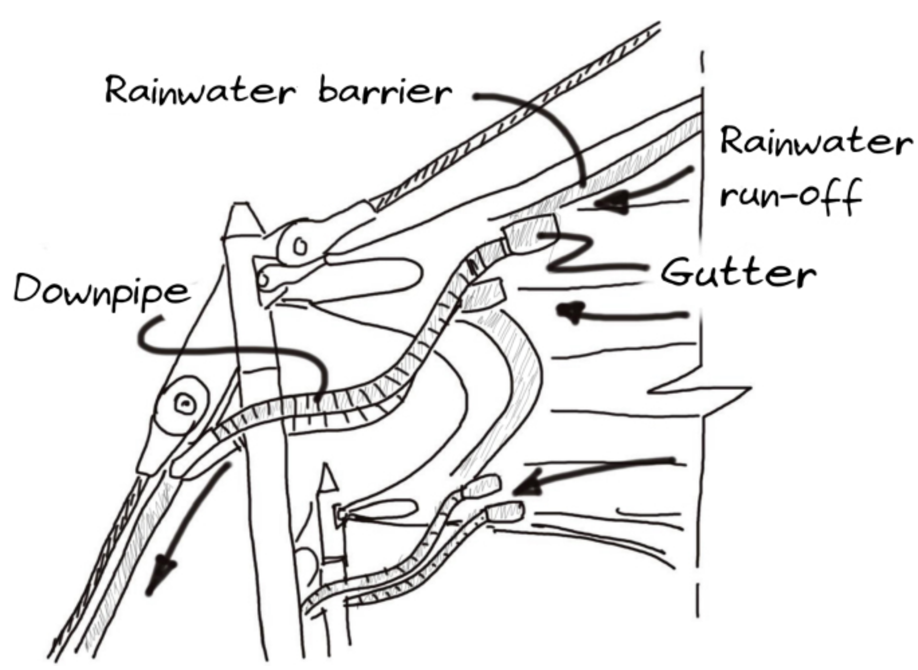


Figure 31. Drainage detail for membrane vertices with split gutters and flexible downpipes.
Source: (Image) elaborated by the authors.

Case studies

The following case studies are a selection of membrane structure projects which have been designed and built in Costa Rica (10° N, 84°) from 2008 to 2011. Costa Rica's predominant climate is defined by meteorological patterns typical to the hot and humid Tropics. The presented projects exemplify a 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 images show the finalized projects and extracts from the simulation results of solar radiation and wind effects, which were considered during the early stage design process. The preliminary performance studies were carried out using Wintess form-finding and Ecotect environmental simulation software. While the simulation results lack validation with post-occupancy data from on-site measurements, they provide valuable information of the climatic interpretation of the presented projects and serve in the context of this study as an example for the application of climatic analysis in a realistic setting. The selection criteria for the presented projects was limited by location, the similarity of scale, and the semi-open character of the structures as well as the availability of images and data.

Membrane cover for a shopping-centre

This tensile structure, completed in 2008 in San José, Costa Rica, was designed to provide formal hierarchy and a cover for the main entrance area of a shopping centre. The efficient shading and rain protection were a substantial requirement of the design brief, which was achieved using a PVC coated polyester fabric material covering an area of 182 m^2. The geometry is based on the outline of the existing building structure and has an irregular polygon-shaped footprint in plan view. 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 like topography. The upstanding, prow-like peak opens up in height and marks the entrance to the shopping centre's main avenue. The membrane structure creates a covered plaza that offers a space for different activities in a semi-outdoor environment. Adequate rain cover, shading, and ventilation was a strong requirement. A CFD analysis was carried out to determine whether natural ventilation would improve with the high point vents. Results suggested that the geometry of the membrane increased the natural airflow by thermal stratification and pressure differences thru the conoidal vent openings sufficiently (Figure 32 - 36).

Figure 32. Picture showing front-view of the project.
Source: (Image) elaborated by the authors.

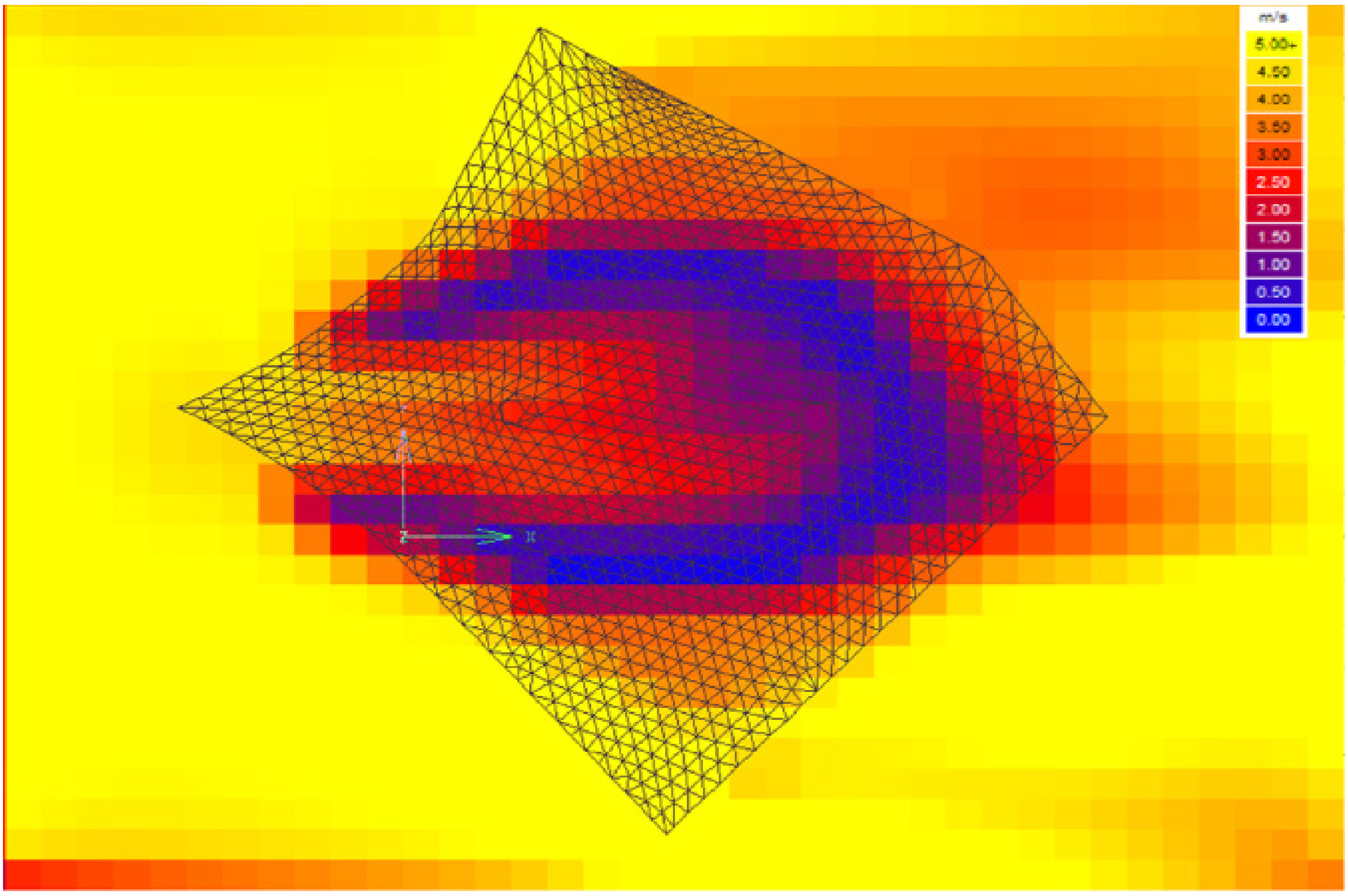


Figure 33. CFD airflow analysis showing air velocity membrane height in plan-view.
Source: (Image) elaborated by the authors.

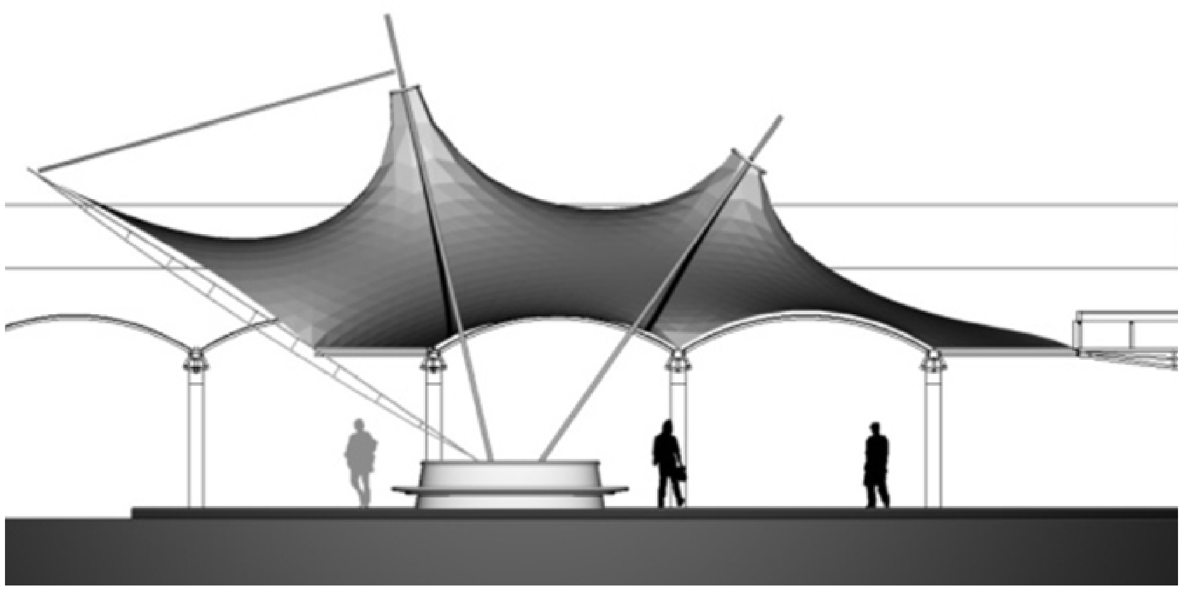


Figure 34. Schematic section.
Source: (Image) elaborated by the authors.

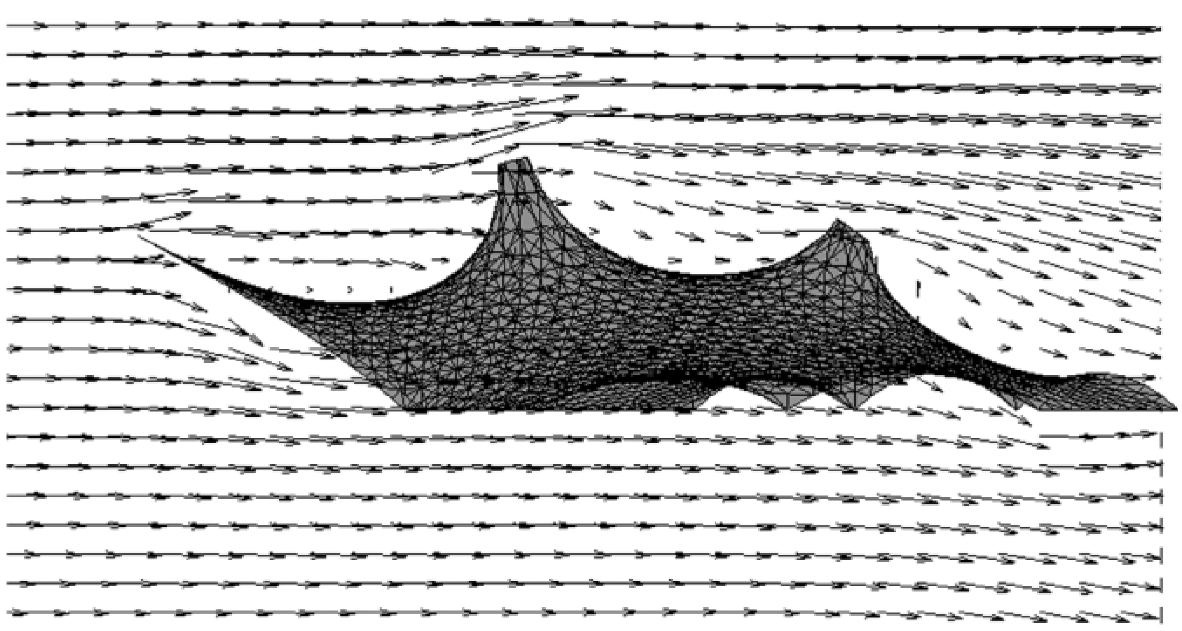


Figure 35. CFD airflow analysis flow vectors in section-view.
Source: (Image) elaborated by the authors.

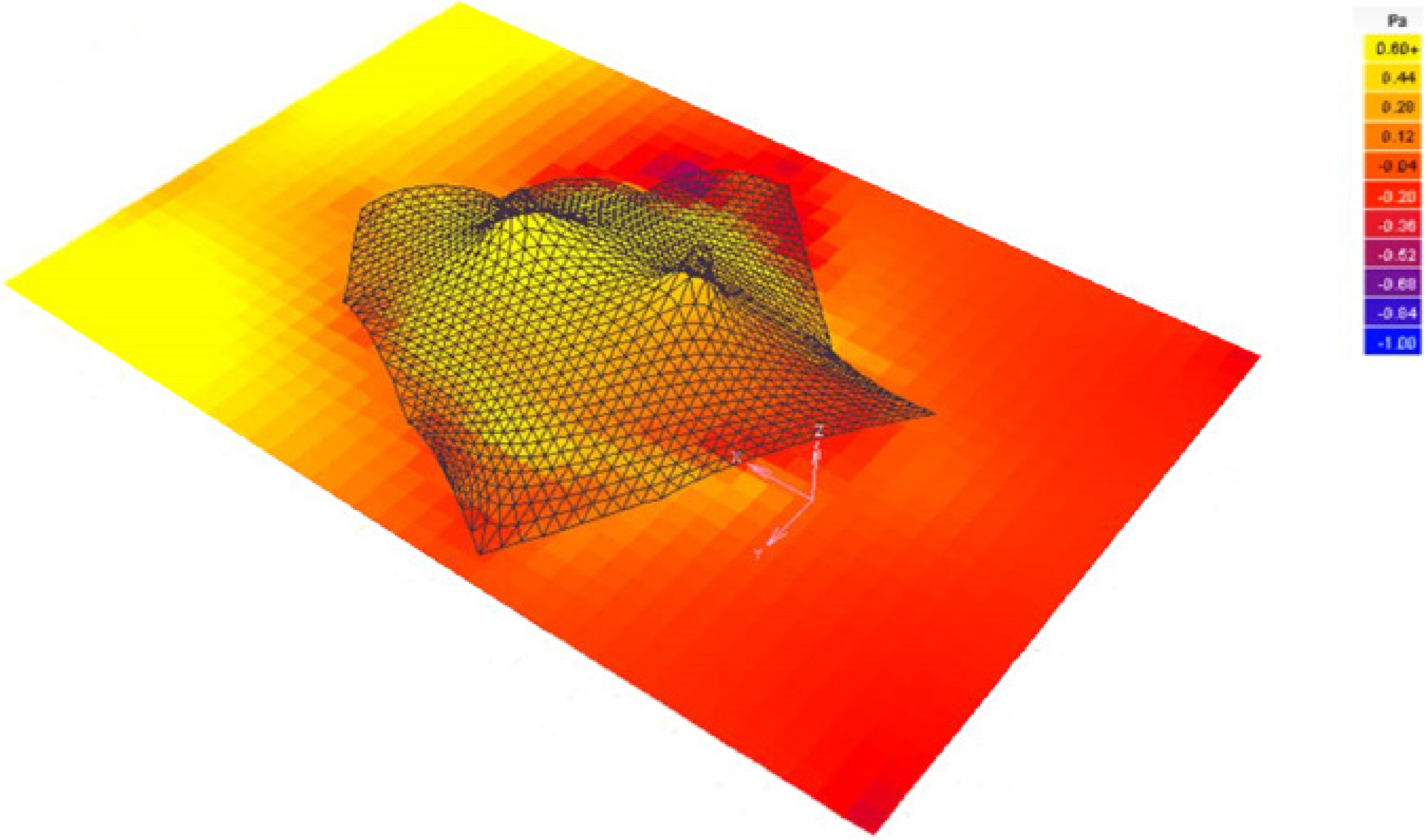


Figure 36. CFD airflow analysis showing air pressure at membrane height in perspective-view.
Source: (Image) elaborated by the authors.

Shading sail for a tennis court

This small scale tensile project (Santa Ana, San José, Costa Rica, 2011) with a coverage area of 12 m^2 was designed as 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 to the resting area 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 10º N, the critical hours would be around mid-day from 10 a.m. to 2 p.m. 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 tennis players. A white, highly reflective, micro-perforated PVC coated mesh material with an effective UV filtering capacity was chosen, which would provide both a high percentage of translucency and permeability while reflecting a considerable percentage of the solar radiation (Figure 37 - 39).

Figure 37. Picture showing perspective-view of the project.
Source: (Image) elaborated by the authors.

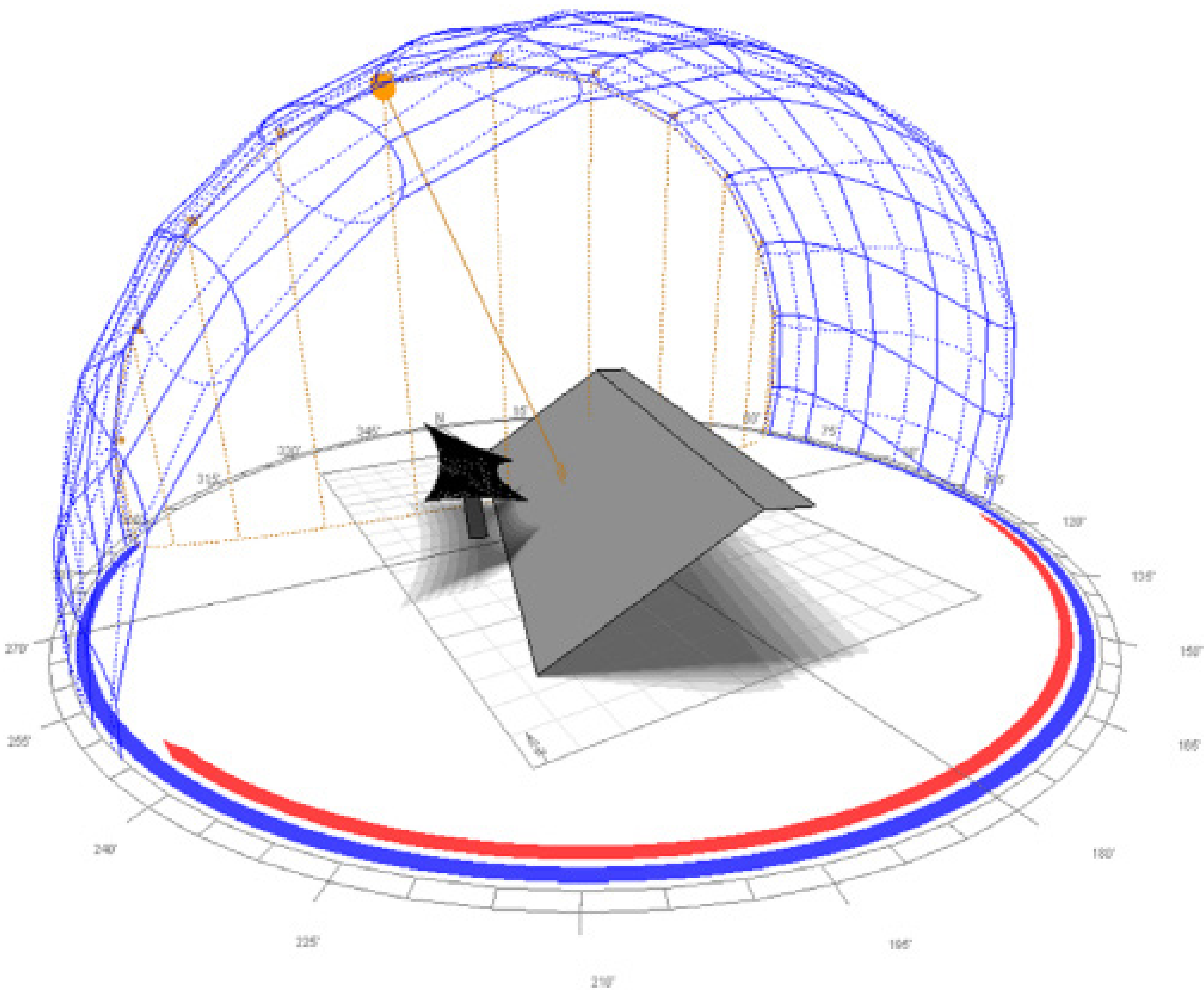


Figure 38. Three-dimensional solar sun path diagram with hourly shade projection. Source: (Image) elaborated by the authors.

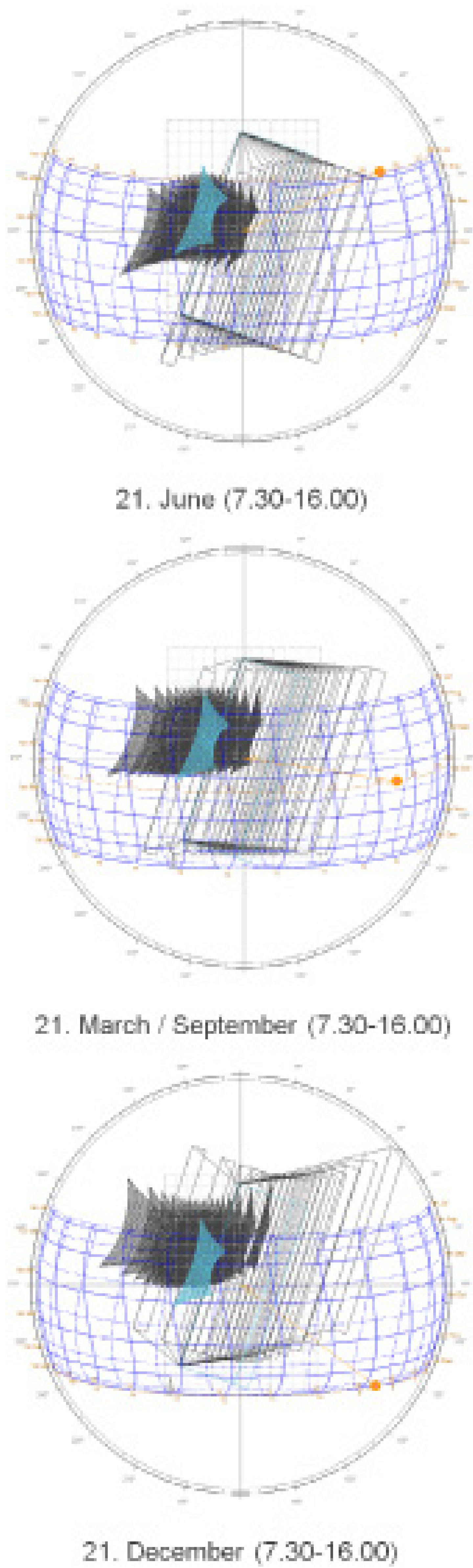


Figure 39. Annual Shading analysis, Solstice and Equinox.
Source: (Image) elaborated by the authors.

Modular exposition booth

The design proposal for this modular exhibition tent was intended to create an attractive cover for temporary exhibitions and fair booths. The design requested a modular structure which would be easy to install and transport. The self-supporting structure is composed of circular steel tubes, which create a continuous frame boundary based on a triangular geometry. The membrane spanned within this structural frame and was tensioned up to a hyperbolic high-point, covering a total area of 36 m^2. Besides the design intention to create an iconic and recognisable shape, the surface geometry was designed to provide optimal shading patterns throughout the seasons in tropical latitudes independent of the orientation. Additionally, the design was required to perform as a self-ventilating structure, which was achieved through an iterative process of analysis and form optimization. The result led to a geometry that enhances an acceleration of airflow through the highpoint cone, which was simulated by computational fluid dynamic analysis and validated in a wind-tunnel study. The found form not only displays formal attractiveness and a 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 (Figure 40 - 43).

Figure 40. Rendering.
Source: (Image) elaborated by Javier Castro.

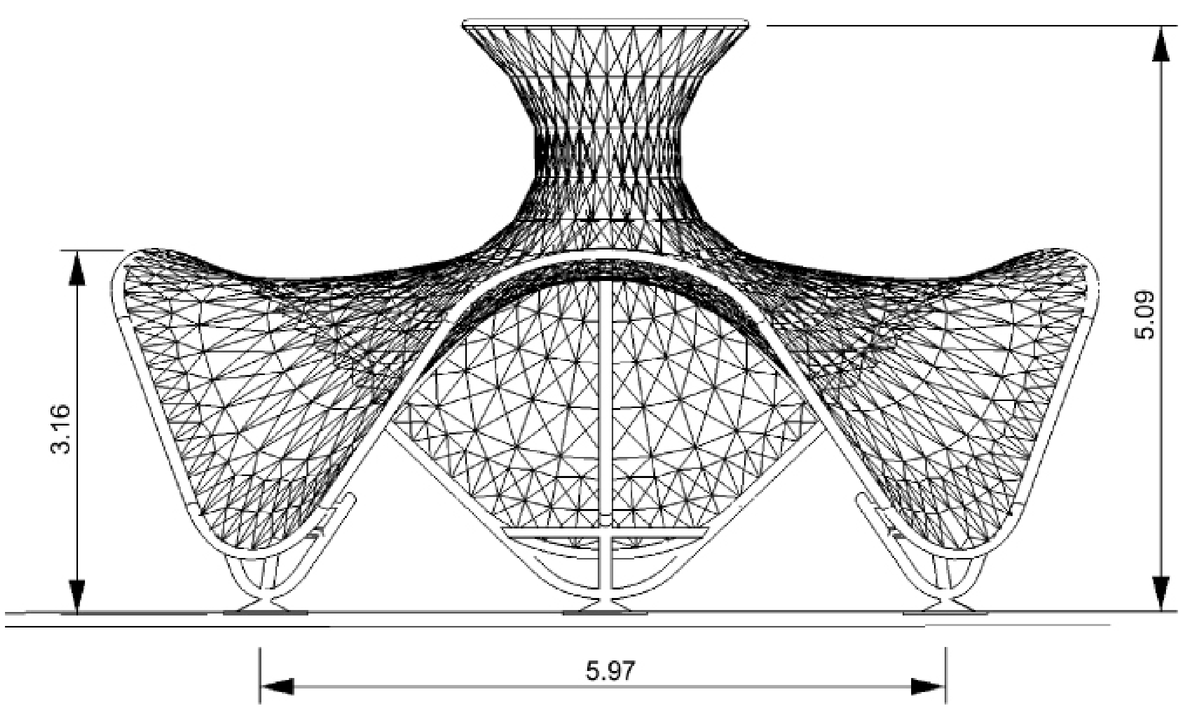


Figure 41. Model dimensions.
Source: (Image) elaborated by the authors.

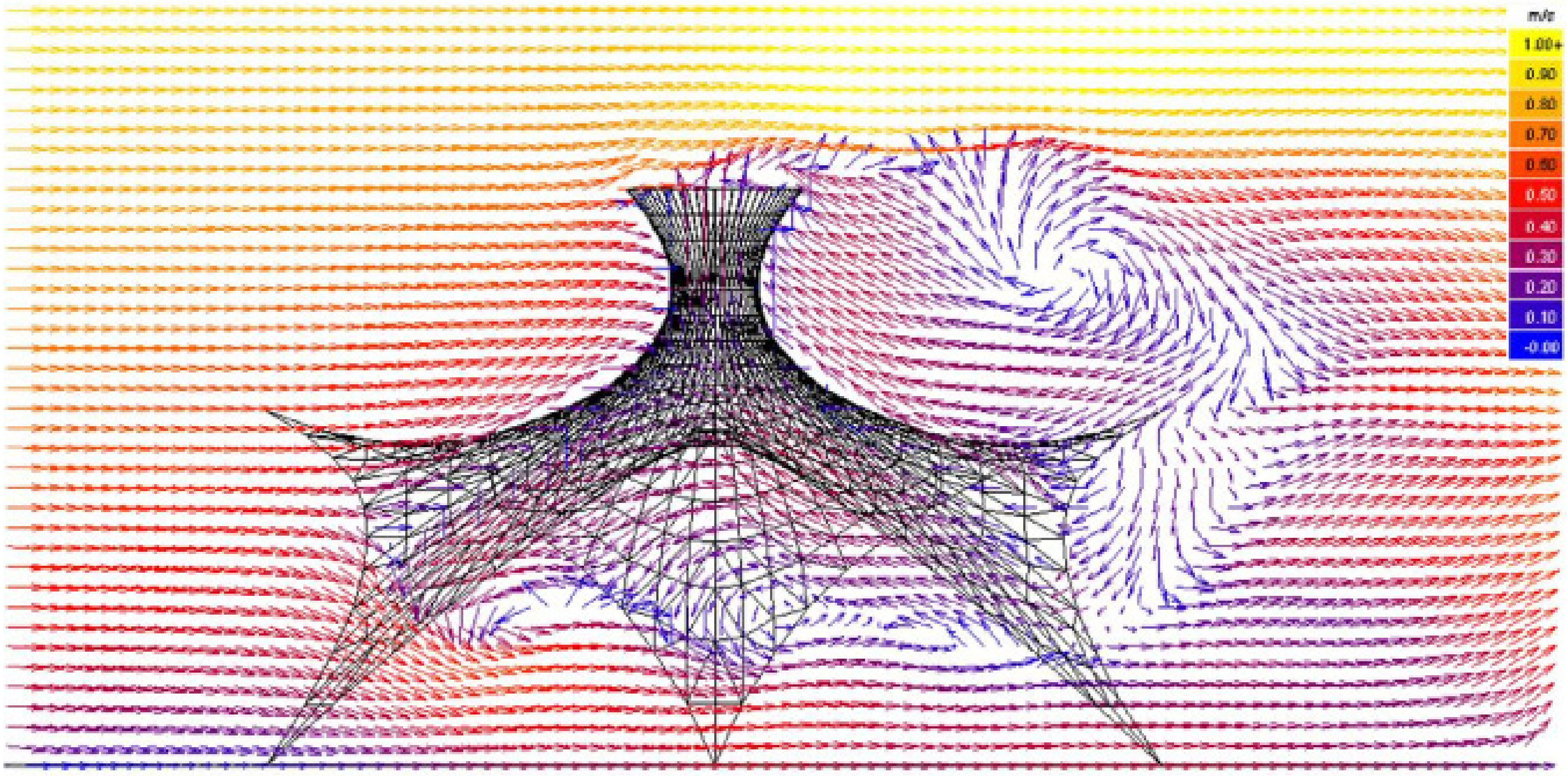


Figure 42. CFD analysis Air flow vectors and velocity (section view).
Source: (Image) elaborated by the authors.

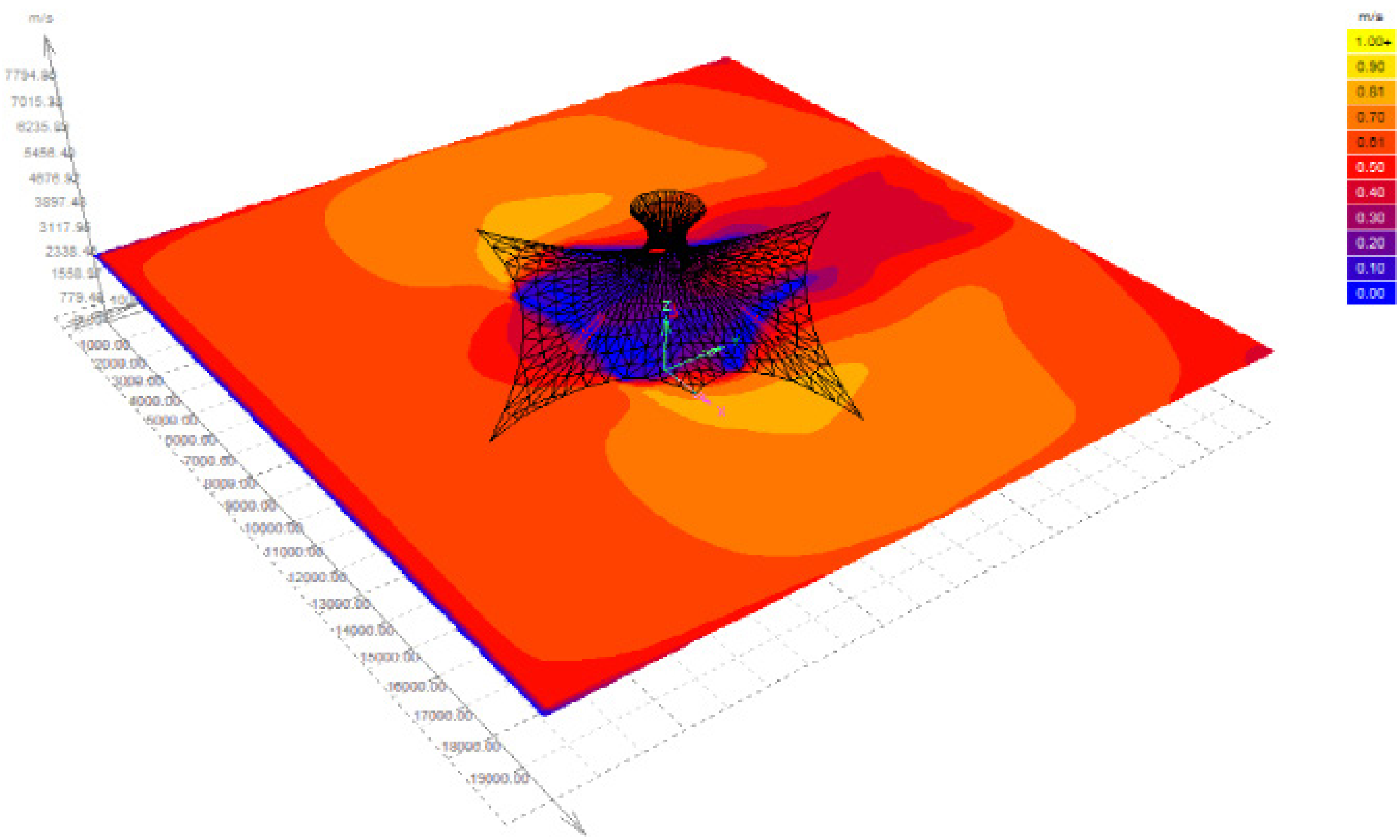


Figure 43. CFD análisis showing air velocity at membrane height (perspective view).
Source: (Image) elaborated by the authors.

Conclusions

This study set out to explore how tensioned membrane structures can be adapted to the conditions of tropical climates and enhance thermal comfort. The main goal of the study was to identify strategies that have the potential to employ the climatic elements themselves as a design resource for the thermal control of spaces covered by semi-open membrane structures. The following conclusions can be drawn from this study:

- Analyzing and understanding climatic patterns in the Tropics is essential to design membrane structures, which are able to satisfy thermal comfort conditions.
- Membrane structures have the potential to modify their immediate micro-climate through their geometry configuration and orientation in the environment using climatic elements as a design resource.
- Passive design strategies, known from the tradition of vernacular architecture, may serve as design principles to be transferred and adapted 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 relevance of the different strategies concerning the improvement of thermal comfort.

While the 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 geometric configurations and climate conditions. While the proposed strategies in this study were based exclusively on passive design principles, future research might explore as well novel developments such as actively responsive or switchable membrane structures, aiming for greater flexibility and effectivity of climate adaptation. Expanding research beyond the current focus on mechanically tensioned membrane structures using standard woven and coated materials, such as polyester PVC or glass PTFE fabrics, may also be a route to consider for future studies. By the time this article is written, new materials and technologies such as extruded ETFE foils and inflated multilayer structures are introduced to the Tropics and will most likely require adaptation to the climatic conditions to achieve thermal comfort in and around buildings and structures.

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