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Study and design of a shaded area in UPC- ESEIAAT with sustainable textile structures

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Abstract

Rising temperatures due to climate change necessitate textile covers, commonly called awnings, in public spaces such as squares, terraces, and other outdoor areas that were previously optional. Although useful in various scenarios, these textile covers often present design challenges that make their maintenance, disassembly, or replacement difficult. Traditionally, they are static fixtures made of extensive lengths of fabric. If damaged, they require total replacement. Additionally, the most commonly used textile cover material is PVC-coated polyester, and its production causes a substantial environmental footprint. Nonetheless, architectural and textile engineering advancements can alleviate these issues. This master's thesis reviews the main techniques for designing and constructing shade covers and their fabrics in public spaces. In particular, we have redesigned one of the principal public spaces at UPC-ESEIAAT to provide adequate shading for its outdoor regions. Our proposal is a folding, modular textile cover grounded on eco-design principles and advances on textile engineering. The materials are locally sourced (km 0), and the fabrics are durable and crafted using sustainable techniques. These features are essential for these fabric structures to adapt to the fluctuating weather conditions induced by climate change, thereby enhancing the adaptability and resilience of public spaces.

Resumen

El aumento de las temperaturas debido al cambio climático está haciendo necesaria la utilización de cubiertas textiles, comúnmente conocidas como toldos, en espacios públicos como plazas, terrazas y otras áreas al aire libre donde antes no eran necesarios. A pesar de ser beneficiosas en una variedad de escenarios, estas cubiertas textiles a menudo plantean desafíos de diseño que dificultan su mantenimiento, desmontaje o reemplazo. Convencionalmente, son estructuras fijas compuestas por largas longitudes de tela que, si se dañan, requieren un reemplazo completo. Además, a menudo se construyen con poliéster recubierto de PVC, cuya producción tiene un impacto medioambiental significativo. No obstante, los avances en ingeniería textil y arquitectura podrían aliviar potencialmente estos problemas. Esta tesis de máster explora las principales técnicas para diseñar y construir cubiertas y sus respectivas telas para generar sombra en espacios públicos. Específicamente, hemos reinventado uno de los principales espacios públicos de la UPC-ESEIAAT para ofrecer una sombra efectiva en sus áreas al aire libre. Nuestro diseño propuesto es una cubierta textil plegable y modular basada en principios de eco-diseño y aprovechando los avances en ingeniería textil. Hemos utilizado materiales de origen local (km 0) y telas duraderas producidas mediante métodos sostenibles. Estas características son vitales para que estas estructuras de tela se ajusten a las variaciones climáticas provocadas por el cambio climático, reforzando así la adaptabilidad y resiliencia de los espacios públicos.

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1 Introduction

1.1 General Objective

The objective is to design shaded areas at the UPC-ESEIAAT using textile structures in order to adapt the public space to environmental and temperature changes, while creating comfortable spaces for versatile, recreational, and social use by the university community.

1.2 Specific objectives

Therefore, this project is divided into the following specific objectives:

1. Study the components, materials, and types of textile structures used to generate shade.
2. Identify the technical requirements of the fabric to be used as an outdoor awning.
4. Screening of potential 0 km suppliers and analysis of their products.
3. Selection of the fabric to be used.
4. Determine the eco-design parameters.
5. Design a textile structure adapted to the needs of the UPC- ESEIAAT campus.
6. Make a prototype of the new textile structure.

1.3 Scope

The scope of this project is to design and develop textile structures for shading purposes at UPC-ESEIAAT, with the primary objective of adapting the public space to environmental and temperature changes, while creating comfortable areas that cater to versatile, recreational, and social use by the university community. This will involve a comprehensive study of various components, materials, and types of textile structures used to generate shade, as well as identifying the technical requirements for the fabric to be used, including factors such as durability, UV resistance, and weather resistance.

The project will involve a comprehensive study of various components, materials, and types of textile structures used to generate shade. Additionally, the technical requirements for the fabric to be used as an outdoor awning will be identified, considering factors such as durability, UV resistance, and weather resistance.

Furthermore, potential local suppliers within a 0 km radius will be screened and their products analyzed to ensure quality, sustainability, and cost-effectiveness. The selection of the most suitable fabric will be based on performance, environmental impact, and cost considerations.

Eco-design principles [1] will be established to ensure that the textile structures conform to sustainability and energy efficiency standards, contributing to the overall environmental objectives of the UPC-ESEIAAT campus. The design phase will focus on creating textile structures that meet the adaptive needs of the campus, taking into account factors such as size, shape, flexibility and ease of maintenance.

A prototype model of the 1:25 scale textile structure will be developed to evaluate design challenges, possible modifications and improvements.

Finally, the objective of this project is to create a textile structure based on sustainability principles that will enhance the outdoor spaces of the UPC-ESEIAAT. Generating comfortable and adaptable shaded areas, to promote the multipurpose, recreational and social use of the university community, while helping to cope with high temperatures as a result of climate change.

1.4 Requirements

The research project entails fulfilling the following essential requirements. Firstly, there is a need for a strong background in architectural and textile design, accompanied by proficiency in utilizing three-dimensional modeling and design software. Additionally, it is essential to utilize stationery and layout materials to produce a sample book and physical model that visually exemplify the proposed design.

A comprehensive examination of materials and fabric types used in textile covers is imperative, encompassing an evaluation of relevant bibliographic references to ascertain their properties. Furthermore, it is crucial to assess the textile components and structures employed for generating shade while incorporating eco-design criteria. Simultaneously, careful analysis of the specific shading requirements of UPC-ESEIAAT's outdoor spaces is indispensable, taking into account factors such as size, location, climatic conditions, and patterns of usage.

Moreover, a meticulous evaluation and selection process for local suppliers will be undertaken to ensure the acquisition of suitable textile materials. The development of prototypes for the designed textile structures will be imperative in assessing their feasibility. Finally, the entire process encompassing design, testing, and evaluation will be thoroughly documented, culminating in the preparation of a final presentation containing the obtained results, conclusions, and recommendations for implementation in UPC-ESEIAAT's outdoor spaces.

In summary, the project's requirements encompass a profound understanding of architectural and textile design, proficiency in design and modeling software, the creation of samples and mock-ups, a comprehensive study of materials and fabrics, evaluation of textile components and structures, analysis of spatial requirements, supplier selection, prototype development, and meticulous documentation of the process.

1.5 Justification

Climate change refers to the alteration of temperature and other climatic factors, and it is happening at an unprecedented rate and intensity in human history. This phenomenon is primarily caused by human activities. [2].

In Spain, the impacts of climate change are manifesting themselves with greater intensity with more intense long-lasting, and frequent heat waves than before, as well as mega fires and droughts.

For this reason, the Ministry of Ecological Transition and Demographic Challenge [3] suggests the adaptation of public buildings to mitigate excessive heat and enhance energy efficiency. The priority is given to implementing passive heat prevention measures, such as shading systems and green roofs, in facilities that cater to the most heat-vulnerable groups, including educational centers, nursing homes, health centers, and day centers for the elderly.

Therefore, this work aims to create shaded areas within the public space of the campus of the UPC-Terrassa, to cope with high temperatures and improve urban infrastructure. Through the design of a structure with textile cover, versatile, modular, easy to build and adaptable to the different dynamics that take place on campus. Complying with the necessary technical specifications to be a durable textile product and with the possibility of replacing parts based on eco-design criteria.

2 Global warming and the effects of climate change

The observed global warming is undeniable and primarily caused by human activities, particularly greenhouse gas emissions. According to observations, during the period of 2011-2020, the global surface temperature increased by 1.1°C compared to the levels of 1850-1900 (Figure 1). These emissions continue to rise due to unsustainable energy use, changes in land use, and consumption and production patterns. Climate change experts highlight that the warming has been faster since 1970 than in any other 50-year period in the past 2,000 years [4].

Greenhouse gas concentrations, such as, methane, and nitrous oxide, are at higher levels than at any time in at least hundreds of thousands of years, according to scientific data. In 2019, the atmosphere reached its highest level in at least 2 million years. Furthermore, global net anthropogenic greenhouse gas emissions increased by 12% between 2010 and 2019, with fossil fuel combustion and industrial processes being the main sources. Records indicate that annual emissions during 2010-2019 were the highest recorded so far.

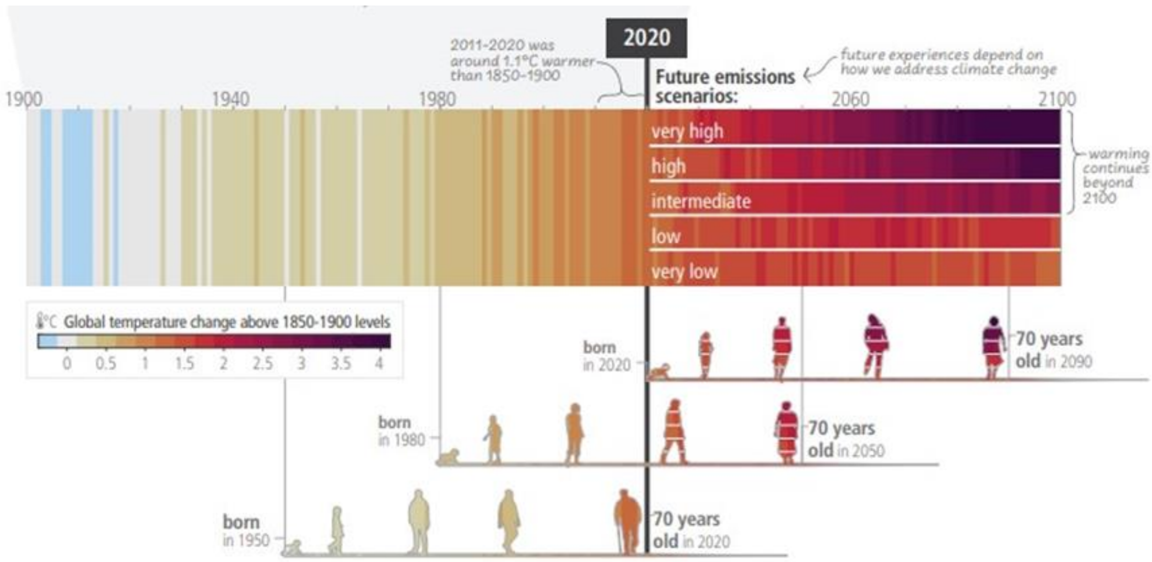


Figure 1. *The extent to which current and future generations will experience a* hotter and different world depends on choices now and in the near-term [4].

These findings highlight the critical importance of implementing substantial measures to tackle climate change and decrease greenhouse gas emissions. Experts in climate change stress the necessity of improving energy efficiency, advocating for renewable energy utilization, and adopting sustainable approaches in land use and consumption. Furthermore, they emphasize the imperative for coordinated global efforts to mitigate the impacts of global warming on the environment, economy, and society.

To explore potential shading solutions, this chapter will provide a comprehensive review of the current state of integrating rooftops into urban projects as a means of climate adaptation, energy utilization, and spatial diversification in urban design.

2.1 State of the art

2.1.1 Adaptation to climate change and energy efficiency

Architectural interventions, especially in public spaces, are essential in combating climate change. By improving energy efficiency, enhancing climate resilience, and promoting sustainable lifestyles, architecture has a significant impact on reducing carbon dioxide emissions [5]. Specifically, interventions in public spaces can mitigate the urban heat island effect by providing shade and ventilation, thus reducing the cooling demand in nearby buildings. Additionally, by creating attractive spaces for gatherings and outdoor activities, active lifestyles are encouraged, and the quality of urban spaces is improved. These architectural interventions make a significant contribution to the sustainability of our cities.

Here are some examples of architectural interventions in public spaces that collaborate in reducing the impact of climate change in cities:

<u>Campus Málaga. Ecosistema urbano studio. Málaga, Spain (2017)</u>

The Campus Málaga project of the Ecosistema Urbano studio was the winner of a public competition promoted by the University of Málaga in 2016. They developed the Landscape Management Project of the Boulevard Louis Pasteur and the main public spaces of the University Campus of Teatinos [6]. Which aims to achieve the dual objective of allowing the daily activities of university life to be carried out in public spaces, while providing a new green infrastructure for the city.

Figure 2. *Urban planning [6].*

The proposal focuses on adapting to climate change and efficiently harnessing energy. To achieve this, various strategies are implemented along the boulevard axis (Figure 2), encompassing different aspects of the campus through a unified design:

- Connected Campus: This strategy creates a comprehensive urban layout by connecting different facilities and opening up the university to its immediate surroundings as well as the entire city. It focuses on public transportation and pedestrian areas.
- Green Campus: It establishes an ecological route that, through a global strategy of sustainable management, revitalizes the space and enhances the potential of existing green areas such as the Olivar and the Botanical Garden.
- Interactive Campus: This enables users to access real-time information, interact with various elements of the public space, and customize them according to their needs. It

includes configuring bioclimatic conditioning systems to achieve optimal environmental conditions.
- Open Campus: It provides university students and all citizens with a wide variety of educational meeting spaces and devices, bringing academic activities to the public realm and making it more accessible and dynamic.

One of the key aspects of this project is its commitment to using technology as a means to enhance the interaction between people and the environment. This is achieved by implementing an application that allows users to control the conditions of the public space. Simultaneously, alongside the project's construction, the official UMA application will be expanded with open-source modules that enable access to an augmented environment of interactivity and information.

This project utilizes a network of sensors and actuators, enabling individuals to experience a new level of interactivity. They can control the bioclimatic conditioning systems, adjust lighting settings, send audiovisual content to screens and sound systems, obtain information about the atmospheric conditions in different areas of the park or scheduled events, share comments or photos associated with specific spaces, unlock lockers to access additional equipment, and even borrow books from an exterior extension of the university library.

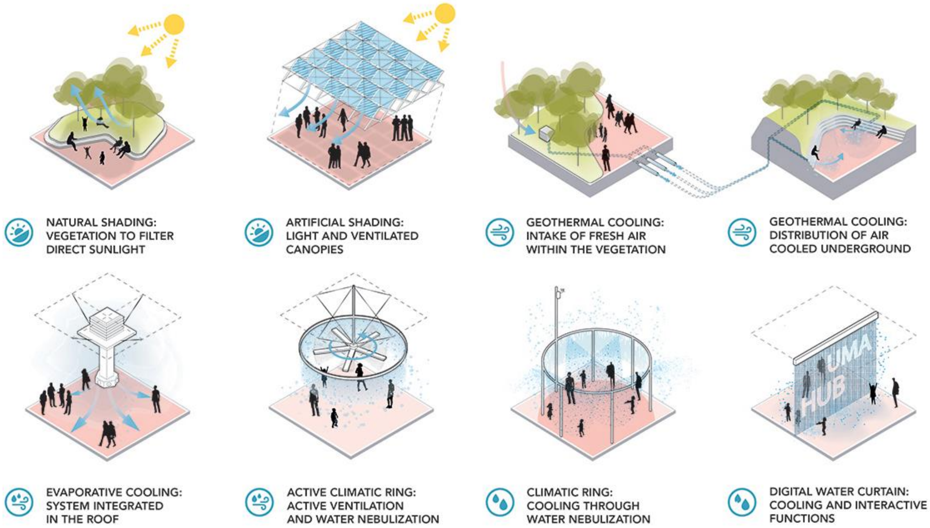


Figure 3. *Design typologies to environnement adaptation [6].*

The first phase of construction, covering an area of 7 hectares (17 acres), is organized around three main systems: the activity hubs or nodes, the large green area, and the boulevard that connects them.

The Climate and Digital Hub, serving as the primary spaces, is located next to the metro station and designed specifically for hosting large capacity events (Figure 4). These spaces are equipped with a technological roof that houses interactive screens, a digital water curtain, climate conditioning systems, and energy production systems that provide power for the entire park. Notably, advanced cooling systems such as evaporative cooling or geothermal air circulation have been incorporated into the design of the Climate and Digital Hub (Figure 4).

Figure 4.*Design and section of the climatic hub [6].*

All of the complementary electrical devices have a low level of energy consumption and are powered by solar panels integrated into the structures. These systems, together with the passive bioclimatic strategies widely implemented in the design for shade generation (Figures 5 and 6), will encourage continuous use of the space throughout the year.

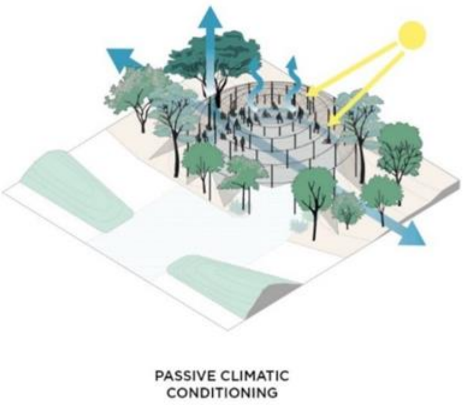


Figure 5. *Scheme for the implementation of shading structures to regulate the outside temperature [6].*

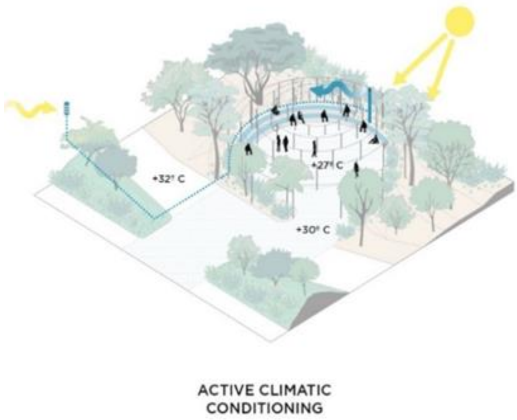


Figure 6. *Scheme for the implementation of electronic climate control systems to actively lower the outside temperature [6].*

Another important part is sustainable water management. Rainwater harvesting systems are implemented for irrigation and green spaces are designed to promote water infiltration and conservation. These green spaces not only improve air quality and the well-being of users, but also act as carbon sinks. Together, these measures contribute to reducing the environmental impact of the campus, increasing energy efficiency and fostering a more sustainable and resilient environment in the face of climate change.

The refurbishment of the La Reina square. Arq.José María Tomas and Antonio Escario. Valencia, Spain

In 1999 a competition was organized by the Colegio Oficial de Arquitectos de la Comunidad Valencia for the renovation of the Plaza La Reina, involving the transformation of a space that functioned as a double traffic circle for buses and access to the subway parking (Figure 7). The winning project was "TITOLIVIO.ES" [7] which proposed an esplanade at different levels with side access to a subway parking, accompanied by a landscape design of vegetation to provide shade (Figure 8).

Figure 7. *Ancient La Reina square [8].*

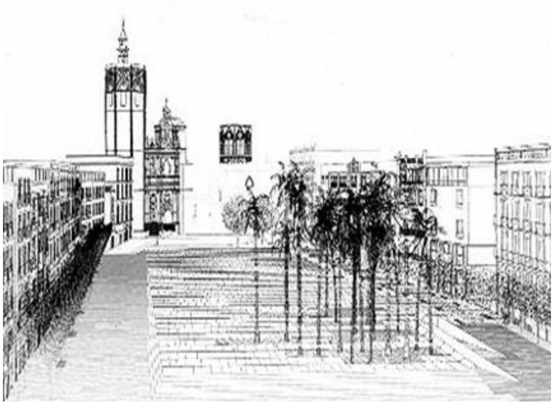


Figure 8. *Winning design of the 1st competition for the refurbishment of the La Reina square [7].*

The design proposed a complex space, with different scales, eminently pedestrian use that allows restricted traffic for resident service and even for drainage of the streets immediately adjacent to the street, defining the major pedestrian flow of the square and the historical route of approach to the Cathedral.

However, the reform was not carried out. In 2016 a new participatory competition of ideas called "Participa Reina" was held to solve the continuous complaints about the square. of which the architectural firm of José María Tomás was the winner, in collaboration with Antonio Escario as co-author of the project [9].(Figure 9).

The reason for the reform was to convert the road space into a pedestrian area, in line with the objectives set out in the Sustainable Urban Mobility Plan (PMUS) approved in 2013. The principle of the "TITOLIVIO.ES" project was maintained on limiting vehicle traffic to the perimeter of the square, allowing access only to residents, users of the subway parking lot and loading and unloading vehicles.

Figure 9. *Final project to refurbishment of La Reina square [10].*

Figure 10. *Shading system [10].*

The new project considered the climatic conditions and the high temperatures of the hot seasons of the last few years. It integrated in the design water spraying, two fountains requested by the neighbors in the participatory process and shading structures. The latter were designed as removable textile covers, under a prestressing system of the tensioned type to the support structure, which in this case are the metal tubular masts (Figure 11,12,13). These tensioning systems will be explained in depth later in the next chapter.

On the other hand, as part of the agreement for the refurbishment in 2022, the Municipal Transport Company (EMT) contemplated the assembly of the awnings in spring, as well as their disassembly and transfer to a municipal warehouse in autumn, since they cannot be folded. The tender is for two years, extendable annually for up to two more years, for a sum of slightly more than 100,000 euros [11]. The tender also includes the repair or replacement of any element of the pergolas that may be broken or deteriorated.

Figure 11. Tensioned to a support in a connection [12].

Figure 12. Tensioned to a support with two connections [12].

Figure 13. Tensioning system between awnings [12].

Adaptation to climate change was crucial, creating green spaces and landscaped areas that improve air quality, provide shade and act as carbon dioxide sinks. In addition, sustainable drainage techniques have been implemented to efficiently manage rainwater and reduce the risk of flooding.

In addition, awnings have been designed to provide shade, helping to diminish the heat island effect in the plaza. By creating shaded areas, the awnings allow plaza users to feel more comfortable, which can prolong their stay and encourage greater use of outdoor spaces rather than air-conditioned indoor spaces.

In terms of energy efficiency, energy-efficient technologies have been incorporated into the plaza's lighting and air conditioning design. Energy-efficient LED lighting systems are used and priority is given to the use of natural light. In addition, energy control devices have been installed to regulate consumption and maximize efficiency. These actions contribute to reducing greenhouse gas emissions and promote a more efficient and sustainable use of energy in the Plaza de la Reina in Valencia.

3 Introduction of tensile structure

Understanding the importance of textile roofs or membranes as a passive climate conditioning tool to reduce outdoor temperatures. The way in which the tension force is applied to generate different types of membrane systems will be studied in depth.

Compressive forces are typically the primary forces at work in many structures. They are generated by matching and opposing loads that act within the structure's interior, with the intent to reduce its length in a specified direction. This particular phenomenon is referred to as compressive stress (Figure 14).

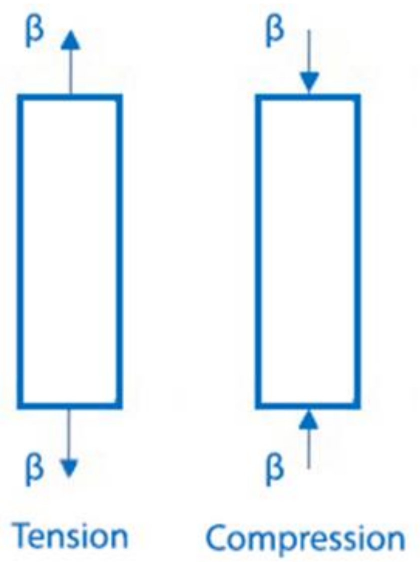


Figure 14. Axial force diagram. Beta corresponds to the applied force.

On the other hand, certain structures may only have components under tension (Figure 14), as is the case with tensile membrane structures. These are surfaces stretched by the action of cables or ropes, with poles absorbing the compression forces. In architectural terms, they are of an anticlastic nature, characterized by flexible fabric membranes held taut by cables, a structural steel skeleton, and foundations [12].

3.1 Types of tensile structure

According to the position where the tensile force is exerted, there are different types of tension mechanisms, which will be discussed below.

3.1.1 Tensioned boundary

The terminology pertains to coverings that are fastened by applying a tensile force at the extremities of the web. These force-applying components may take the form of cables or rigid frames (Figure 15). The arrangement of the tension points can influence the resultant shape, offering a vast range of possibilities - from simple flat surfaces to intricate three-dimensional forms and curvatures.

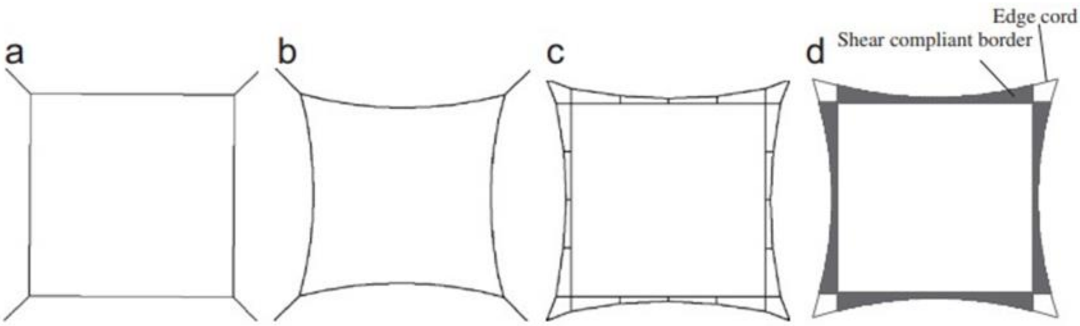


Figure 15. Existing membrane designs [14].

It is important to emphasize that the arrangement of the tension points must be carefully planned and executed. This is because the performance of the tensioned membrane depends largely on how the tensile forces are distributed. A proper arrangement will allow the membrane to distribute the forces evenly across its surface, thus ensuring its durability and strength.

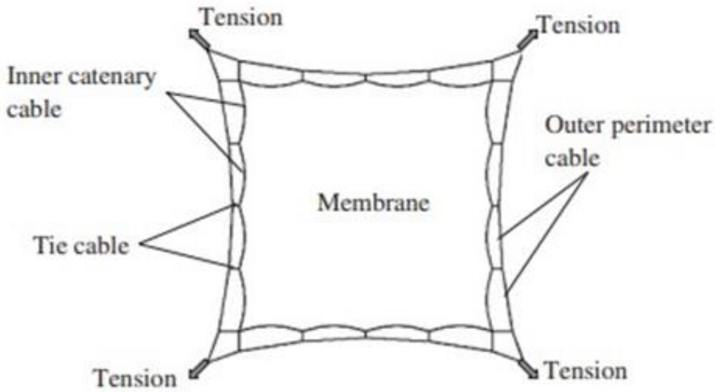


Figure 16. The design scheme of cable-tensioned membrane at edges [14].

Generally, these textile materials are pre-stretched to provide structural stability and prevent a decrease in tension. However, considering that tensions in the fabric can increase significantly with applied loads, pre-stretch levels are usually kept at 5% (1/20) of the tear strength of the fabric [13].

3.1.2 Air-supported structures

The principle of these structures is to keep the air pressure inside the fabric liner slightly higher than the outside air pressure by using a pneumatic system (Figure 18). This ensures that the fabric remains elevated and stable. Larger "domes," such as those found in sports stadiums, have a fabric roof attached to the peripheral walls. Although pneumatic or air-supported structures may bear some similarity to tensioned membrane structures and cable networks, their design and construction are considerably different.

Pneumatic structures consist of thin fabric membranes that are tensioned through internal air pressure. Since their stability depends on pressure gradients to maintain tension on the external fabric, they are highly sensitive to weather conditions, such as temperature, wind, rain, and snow [13].

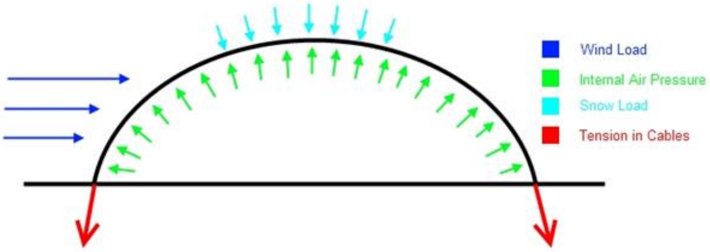


Figure 17. Force and stress diagram.

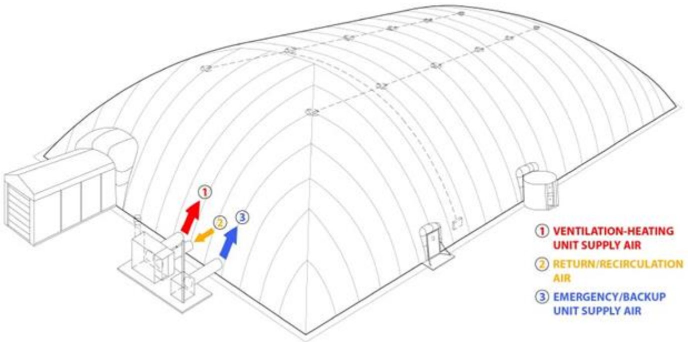


Figure 18. general principle of operation of air-supported structures [15].

Given the significant difference in pressure values, it's recommended that air-supported structures are designed with notably high safety factors, as referenced in source [16]. These structures are designed to accommodate internal pressures that range from 0.2 kN/m^2 to 0.55 kN/m^2. Yet, it's worth noting that they can also be exposed to snow loads that may fluctuate between 1.2 kN/m^2 and 2.4 kN/m^2 (Figure 17).

The main difference between boundary-tensioned membranes and air-supported structures is the method of prestressing. Although both have membrane pre-stresses for stability [13], boundary-tensioned membranes are usually mechanically tensioned, whereas air-supported structures are tensioned pneumatically with internal air. The latter has the disadvantage of air loss (Figure 18) due to the porosity of the fabric [17].

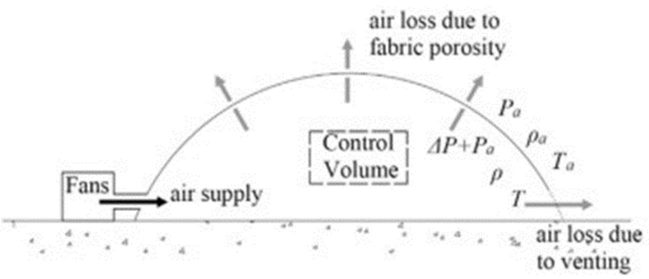


Figure 19. Air leakage diagram [17].

3.1.3 Pre-stressed cables-nets and beams

According to Lewis [17], cable networks and beams form the final category of tensile structures. From a design and construction standpoint, they bear significant resemblance to tensile membrane structures. Indeed, since the fundamental structural element of a textile membrane is the two-way cable (Figure 20), the cable network can be considered a discrete type of membrane, exhibiting similar load behavior and providing an intuitively physical foundation for analyzing such structures.

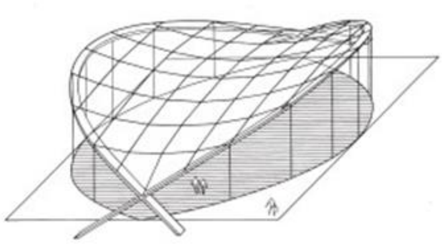


Figure 20. Raleigh Arena cable mesh roofing [20]

The primary reason for distinguishing between cable networks and textile membranes is that cable networks are unable to transmit shear stress and do not account for the interplay between closely interwoven threads, known as warp and weft threads [13]. Disregarding this effect of the threads, the distinction between cable network and tensile fabric structures is not entirely necessary.

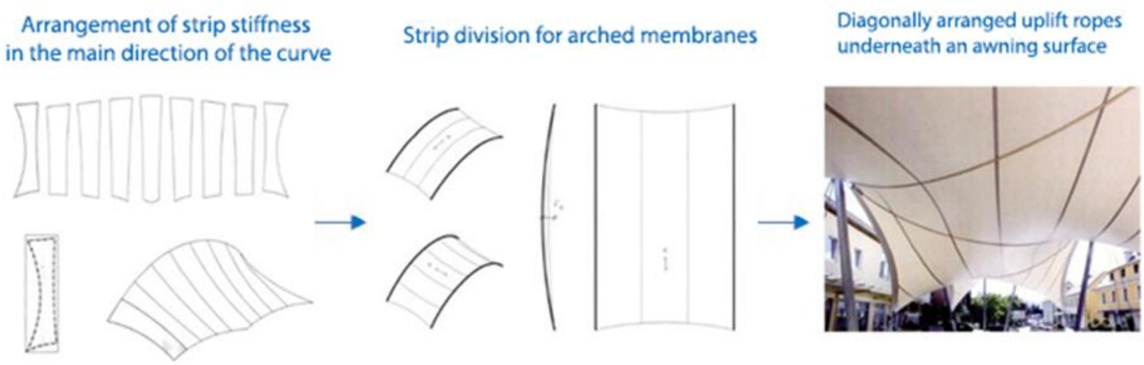


Figure 21. Membrane scheme of prestressed girder and cable system membranes [19].

3.2 Material characteristics

Understanding the types of tensile structures that exist, the following will study the types of fabrics. As well as the fiber materials, properties, finishes, finished fabrics and bonding details most commonly used in the manufacture of textile covers [21].

1.

3.2.1 Types of fabrics

Fabrics are divided into: woven, knit and nonwovens (Figure 22). Knitted and woven fabrics are made up of warp and weft yarns. Of these, the most commonly used fabrics for architectural uses is the woven fabric due to its strength and flexibility.

The weaving process can follow different patterns, resulting in different aspects and properties. During the weaving process, the yarns undergo different levels of curvature, depending on the pattern adopted, with a consequent reduction in their tensile strength [21].

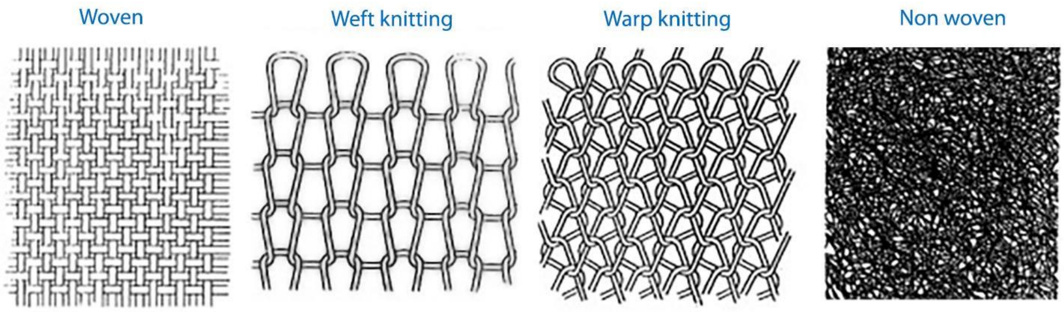


Figure 22. Types of fabrics.

3.2.1.1 Knitting

Knitted fabrics are manufactured progressively, row after row, using interlocked loops. Each time a new yarn is fed, a new loop is formed on each hook of the needle. The needle pulls the new loop through the old (knitted) loop that has been retained from the previous knitting cycle.

At the same time, the needles release the old loops so that they hang from the new loops, which remain attached to the needle hooks. In this way, a cohesive structure of knitted loops is created by combining the interlocked loops on the needles and the thread passing from one needle loop to another [22].

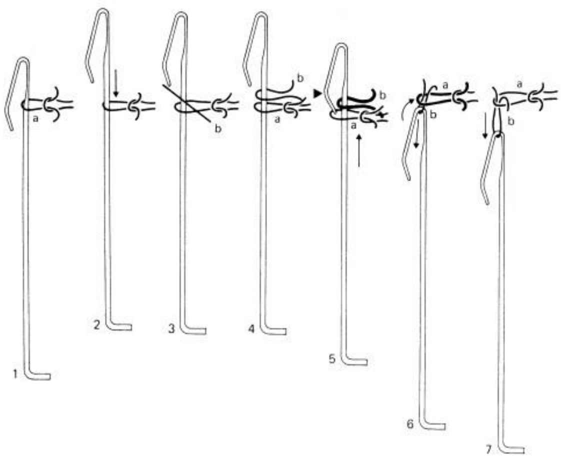


Figure 23. Basic knitting action of the needle [22].

This type of fabric is divided into warp knit fabrics and weft knit fabrics. Weft knit fabric involves the creation of interconnected loops of yarn across the width of the material, providing flexibility and elasticity (Figure 24). It is achieved using a series of needles in a continuous process, which can be done manually or by machine. This fabric can stretch in all directions, making it ideal for garments that need to conform to the body.

On the other hand, warp knit fabric utilizes parallel threads called warp that form vertical loops (Figure 25). This technique controls each warp thread individually, allowing for more complex and detailed designs. This method produces denser and more resistant fabrics, which are less elastic than weft knit fabric but have a higher wear resistance.

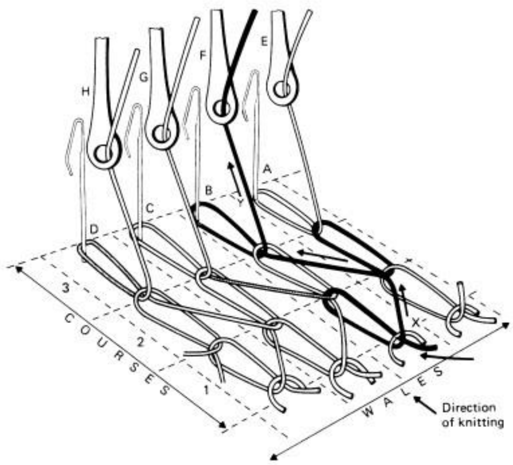


Figure 24. Warp knitting [22].

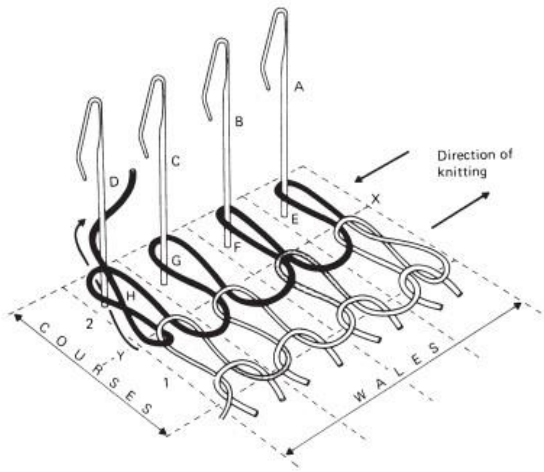


Figure 25. Weft knitting [22].

When comparing both, weft knit fabric offers greater flexibility and elasticity, making it ideal for snug-fitting garments. On the other hand, warp knit fabric produces more durable textile materials and allows for more intricate designs, thanks to the individual control of each warp thread. The choice between the two depends on the specific requirements of the weaving project.

The specific geometric structure of the knitted fabric provides a superior level of elasticity and fit compared to other fabrics. This aspect is precious when the material reinforces three-dimensional surfaces with complex geometry. However, the high curvature inherent in this geometry can induce stress concentration in the yarns of the fabric. Consequently, there is a significant reduction in the maximum tensile strength [21]. We must carefully consider these aspects when designing and selecting materials for specific applications.

3.2.1.2 Non woven

It refers to a type of textile manufactured by joining fibers through chemical, thermal, or mechanical processes instead of traditional weaving or knitting techniques. Nonwovens are materials made by fabricating and bonding threads, natural fibers like cotton or wool, or synthetic fibers like polyester or polypropylene. They are not produced using traditional weaving or knitting techniques but through chemical, thermal, or mechanical processes such as bonding (Figure 26). We will further discuss these techniques below:

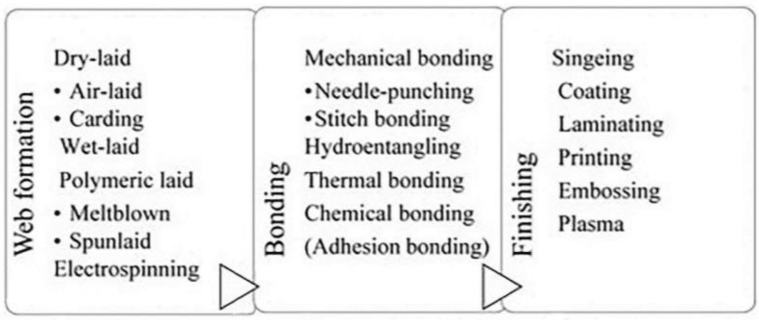


Figure 26. Non woven production of different methods [25].

Web formation: Nonwovens are produced by converting fibers or filaments into open webs using dry methods (carding and air-laid) and wet methods, depending on the specific product requirements. The dry process, which uses fibers such as viscose rayon, TENCEL, cotton, polypropylene, and polyester, creates isotropic, highly porous products with reduced cost. Another process is extrusion-based manufacturing, such as spun-bond, melt-blown, or electrospinning (Figure 27). This technique is highly efficient and cost-effective but is limited to polymeric fibers. In this process, extruded filaments are attenuated and deposited to form "isolated" fibers, with filaments of one polymer dispersed in a matrix of another.

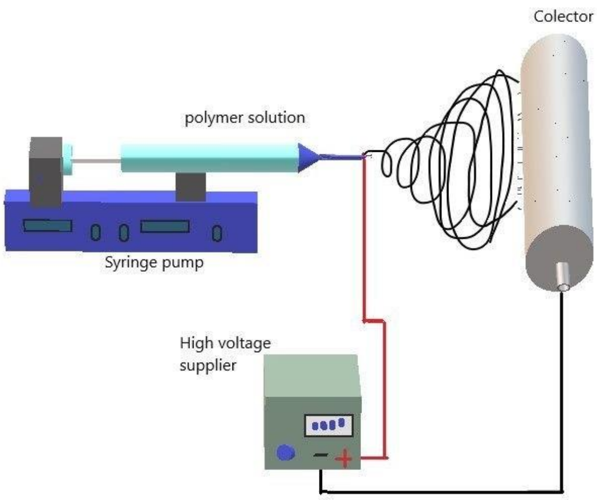


Figure 27. Schematic representation of basic electrospinning set up [26].

Bonding: There are several mechanical bonding methods in the production of nonwoven textiles, such as needle punching, stitch bonding, and hydroentanglement (spunlacing). Needle punching is suitable for heavier fabrics but may affect uniformity in lower-density fabrics. Stitch bonding is used in furniture, geotextiles, and vacuum cleaner bags. Hydroentanglement interlaces the fibers with high-pressure water jets and is applicable to all natural fibers, creating soft and durable fabrics. Chemical bonding, which uses latex, may be less skin-friendly and not environmentally friendly. Thermal bonding, suitable for thermoplastic fibers, is achieved by melting fibers or powder without the use of chemicals, but it is not compatible with exclusively natural fibers.

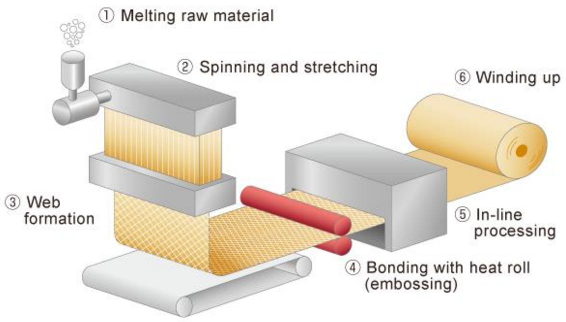


Figure 28. Schematic representation of the hydroentangling method [27].

Finishing: To improve their surface properties, nonwoven textiles benefit from finishing processes such as flammability treatment, coating, and lamination. In the medical field, these textiles must repel bodily fluids, achieved through antimicrobial and hydrophobic finishing, increasingly common in nonwoven medical products. However, traditional textile finishing methods require large amounts of water, chemicals, and energy for drying. Various gases are used during plasma treatment, and atmospheric plasma offers economic benefits by integrating it into inline production processes.

Nonwoven textiles have a wide range of uses, including hygiene, medicine, agriculture, geotechnical engineering, and filtration, due to their advantages, such as versatility, ease of production, and the ability to adjust their physical and chemical properties as needed. However, their strength and durability are often lower than woven and knitted fabrics [24].

In contrast to knitted and woven fabrics, nonwovens offer an outstanding economy and production speed but lack an organized structure, have low elasticity, and exhibit higher tensile strength due to the absence of damage caused by yarn curvature [21]. Therefore, the choice between woven fabrics and nonwovens largely depends on the specific requirements of the application at hand [25].

3.2.1.3 Woven

It is a technique that involves the interlacing of two distinct sets of yarns at right angles, creating a textile structure that can vary in terms of texture, density, and visual design. In this process, the warp yarns, or warp threads, run longitudinally along the loom's structure, providing the essential foundation for the weaving.

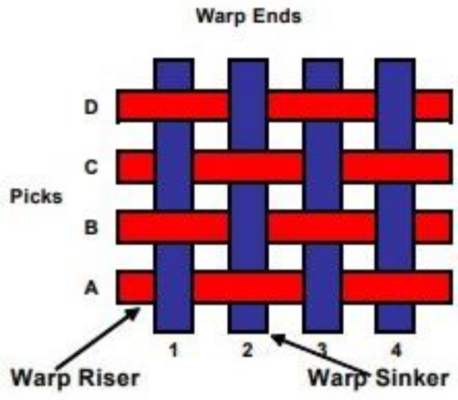


Figure 29. Scheme of woven fabric [28]

The warp threads act as the fabric's " skeleton, " determining its strength and structure. In addition, the tension of these threads is a critical factor in producing high-quality textiles, as incorrect tension can lead to deformations and other defects in the final fabric.

Transversely to the warp threads, we find the weft threads, also known as picks or fillings. In particular, these threads interlace with the warp threads, adding density, body, and, in many cases, the main visual component of the fabric. The thickness, material, and coloration of the weft threads can vary significantly, allowing for a wide range of visual and tactile effects in the finished fabric.

The interlacing process is carried out using a loom, which can be operated manually or mechanically. In both cases, the warp threads are raised and lowered in a specific pattern to allow the weft thread to pass through them, creating what is known as a shed. This process is systematically repeated, forming the fabric.

The most common patterns are the following: plain weave, twill weave, satin weave, and sateen weave. However, there are different variations, such as:

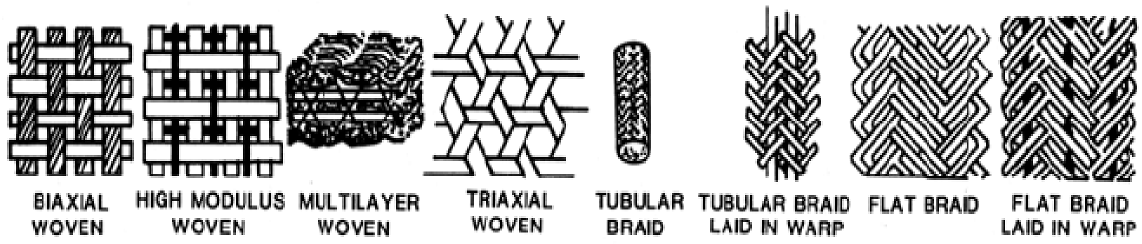


Figure 30. Types of woven fabrics [29]

Architecturally, when comparing woven fabrics to knitted and nonwoven, woven fabrics exhibit intermediate flexibility and tensile strength properties. This is because the curvature of the yarns in woven fabrics is less than that of knitted materials since they do not have loops, which reduces stress concentration in the yarns. On the other hand, woven fabrics have sufficient elasticity, making them more moldable [21].

3.2.2 Type of material

After reviewing the state of the art on tensioned structures and the types of existing fabrics, this chapter will address the most common features of membrane structures. Membrane structures are the area of research where architecture and textiles converge.

For this purpose, the technical characteristics that fabrics must have to withstand weather conditions and sun exposure will be explained. These include properties to ensure good performance under exposure [30], types of implemented fibers, coatings, and laminations [21] (Figure 32).

The fabrics used for tension structures belong to the category of technical textiles (Figure 31), as they must fulfill a specific purpose and withstand the applied force to maintain the stability of the cover.

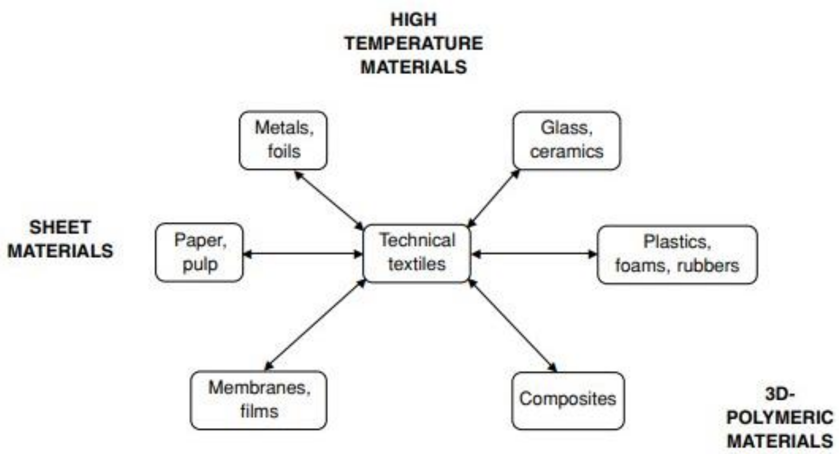


Figure 31. Scope of flexible engineering materials [25]

Textile engineering has extensively studied how to thread fabrics to enhance their performance in certain aspects or to fulfill specific functions. For this purpose, textile finishes or coatings can be applied to increase the utility of the textile product.

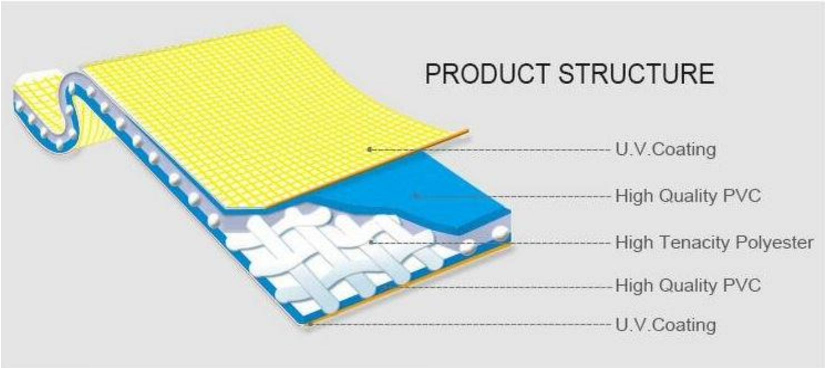


Figure 32. Example of the use of PVC lamination and UV resistant finish on membrane fabrics [31].

In the case of textile membranes, crucial characteristics include mechanical properties for structural purposes, protection against chemical and biological influences, fire resistance, weldability, impermeability, and UV resistance, which depend on the coating layer [21]. We will determine these characteristics in the following section.

3.2.3 Properties

Before addressing the types of textile finishes, we must understand the aspects under which the fabric must perform well [21]. Tensioned covers for outdoor spaces should possess solid mechanical resistance to withstand tensile forces, a low degradation index against external conditions, and adequate resistance to photochemical degradation due to sun exposure. Additionally, they need to have a good light transmission index and air permeability while also being water-repellent to prevent moisture from damaging the fiber.

3.2.3.1 Mechanical properties

Key mechanical characteristics that need to be considered for design purposes include tensile strength, which quantifies the force required to break the material, and tear resistance, which determines the material's ability to resist the extension of an existing tear. It is also crucial to consider elastic properties, such as stiffness, which relates to the relationship between the modulus of elasticity and the cross-sectional area of the fibers.

These properties are evaluated through tests such as strip tensile testing, grab tensile testing, biaxial tensile testing, seam tensile strength testing, trapezoidal tear testing, tongue tear testing, peel strength testing, and abrasion resistance testing.

3.2.3.2 Durability

It refers to the fabric's longevity, which largely depends on its resistance to degradation from UV radiation and moisture, resistance to attacks from organic matter, and seam durability. Wind load resistance and resistance to dirt exposure are also crucial factors. For newer materials, their durability can be verified through accelerated weathering tests under various environmental conditions and tests for moisture resistance and ease of cleaning.

3.2.3.3 Sun-protection

Exposure to sunlight can break chemical bonds within textile fibers, a process known as photochemical degradation. This degradation can manifest in various ways, including discoloration, increased crystallinity, and other chemical and physical changes in the fibers. Over time, prolonged exposure to sunlight can cause noticeable alterations in the appearance and properties of the textile, potentially impacting its overall durability and longevity. It is essential to consider these effects when selecting textiles for significant sun exposure applications. Additionally, protective measures such as UV-resistant coatings or treatments can be applied to mitigate the harmful effects of sunlight on textile fibers.

3.2.3.4 Light transmission and air permeability.

The design of a woven fabric structure can be customized to achieve the desired level of transparency. The prominence of stitches or the openness of the weave pattern directly impacts the transmission, absorption, and reflection of light. The fabric allows higher light transmission as stitches become larger or the weave becomes more open. This light augmentation can result in a brighter interior and increased natural daylight during winter. Conversely, smaller stitches or a denser weave restrict light passage, providing enhanced privacy and shading during summer. Therefore, the design of the woven fabric structure plays a crucial role in controlling light levels, offering functional and aesthetic benefits for applications such as window treatments, shading devices, or architectural elements.

3.2.3.5 Water-repellent

Water repellency refers to a fabric's ability to resist water, which can be either inherent or achieved through a finishing treatment. It involves the capacity to repel moisture and prevent water from being absorbed or forming a film on the surface. Unlike waterproof fabrics, water-repellent fabrics do not block pores, allowing garments to remain breathable while preventing water absorption. This characteristic helps to keep the wearer dry and comfortable by repelling water and preventing it from penetrating the fabric.

3.2.3.6 Fire retardant

This property refers to a material's ability to prevent ignition or, once ignited, slow down the spread of fire. The material must minimize the smoke generation and, consequently, the formation of toxic gases and prevent the dripping of molten material. Fire resistance is crucial in ensuring the safety of individuals and minimizing the potential damage caused by fire incidents.

3.2.4 Fibers

This section describes the most commonly used or promising fibers for architectural membranes as part of constructing semi-permanent structures such as sports stadiums, exhibition centers, and other modern buildings. Nonwoven fabrics made of glass and polyester are widely used in roofing applications, while other fabrics are used as breathable membranes to prevent moisture penetration in walls. Metal-coated roofs and modern buildings can be covered with specific nonwoven fabrics to prevent moisture condensation and dripping [27].

Double-walled spacer fabrics can be filled with appropriate materials to provide acoustic and thermal insulation or as a lightweight composite material core. Furthermore, these fabrics are widely used in construction operations in diverse applications such as safety nets, lifting and tensioning ropes, and flexible formwork for concrete curing.

3.2.4.1 Polyester

It is a versatile and durable synthetic fiber, widely used in the textile industry. Its most prominent characteristics include high tensile and abrasion resistance, which gives it great durability, and its chemical resistance, which protects it against stains and discoloration [32]. Furthermore, polyester does not wrinkle easily and is resistant to shrinkage and stretching. Its low water absorption allows it to resist moisture, and its high thermal and UV resistance makes it suitable for applications that require resistance to heat and sunlight.

In the technical realm, polyester is the preferred material for the manufacture of non-woven fabrics for roofs and architectural membranes, due to its resistance to weathering and chemicals. It is also used in construction and the automotive industry [25], in products such as packing tapes, safety nets, lifting and tensioning ropes, flexible formworks for concrete, safety belts, and airbags.

It has been the most used fiber for architectural fabrics since the early 1960s [21] due to its reduced price, good mechanical performance, and expected lifespan. They are flexible and are very common for temporary and seasonal structures.

3.2.4.2 Polyethylene (PE)

It is a high-value thermoplastic polymer in various industries, thanks to its notable characteristics such as high impact resistance, durability, chemical resistance, and moisture resistance. It also has exceptional UV resistance, making it ideal for outdoor applications. There are several forms of polyethylene, including high-density polyethylene (HDPE), low-density polyethylene (LDPE), and ultra-high-molecular-weight polyethylene (UHMWPE), each with their specific properties and applications [32].

As for its technical applications, polyethylene fibers are widely used in the construction industry to manufacture waterproof membranes, geotextile coatings, and drainage pipes [25]. They are also employed in the safety industry, where UHMWPE manufactures bulletproof vests and protective helmets due to their high tensile strength and lightness. In the sports sector, its water resistance and ability to float make it ideal for manufacturing fishing nets and water sports equipment.

Generally, polyethylene textiles are manufactured from high-density polyethylene tapes that are woven and then coated on both sides. This material is often preferred for low-cost uses, although its durability may be lower than that of polyester. In architecture, high-density polyethylene is used in mesh fabrics to provide shade. The fire resistance and durability against UV radiation of these textiles can be enhanced by incorporating specific additives.

3.2.4.3 Fiberglass

They are notable for their robustness, as they are essential in various high-performance technical and permanent applications. This is due to their remarkable elasticity modulus and tensile strength. In addition, they have inherent fire resistance and resistance to degradation by ultraviolet (UV) radiation, eliminating the need for additional additives to improve these properties. Despite these strengths, handling glass fiber textiles with care is crucial, as they are prone to brittleness and can easily crack, particularly when repeatedly bent or with reduced curvature radii.

Glass fibers have a variety of practical applications, especially in the construction industry. They are used to manufacture wall panels, septic tanks, and sanitary fittings. Furthermore, they are used with polypropylene and acrylic fibers in reinforcement textiles to prevent cracking in concrete, plaster, and other construction materials. This is particularly useful in bridge construction. Another vital application of glass fibers is in the field of insulation, where they have become the near-universal substitute for asbestos in building and equipment insulation.

3.2.4.4 Politetrafluoroetileno (PTFE)

It is a synthetic fiber highly resistant to chemicals, heat, and extreme cold, making it useful in many technical applications. It is known for its durability and "non-stick effect," thanks to its low friction and hydrophobia, avoiding moisture absorption and facilitating cleaning. In the field of textile engineering, PTFE fibers are applied in a variety of sectors. In construction, they are used in membranes for roofs of large structures due to their resistance to weathering and UV degradation.

In the textile industry, they contribute to manufacturing fabrics resistant to stains and wear. Their heat and corrosion resistance make them ideal in the aerospace and chemical industries, including manufacturing non-stick coatings for spacecraft and chemical processes.

Architectural textiles made from expanded polytetrafluoroethylene (PTFE) are a recent innovation and are often used in seasonal or detachable structures due to their high translucency, durability, flexibility, exceptional chemical resistance, and excellent ability to resist dirt. Their high cost means their use is reserved for projects that need and highlight their unique luminosity.

3.2.4.5 Poliamida

This fiber has high tensile and abrasion resistance, which ensures its ability to withstand wear and is resistant to most chemicals, oils, and solvents. This resistance to chemical and biological factors and its flexibility makes it a suitable material for rigorous conditions.

Its technical applications are diverse and extend to several industries. In the textile sector, it is used to manufacture sportswear and workwear and is fire-resistant. In the automotive sector, it is used to produce airbags for its thermal and tensile resistance. In construction, it is also used to develop geotextiles and reinforcing materials. Therefore, polyamide 6.6 is a highly versatile material with broad applications, proving to be a valuable resource in various industries.

Polyamide 6.6 fibers are commonly used in initiatives and manufacturers that demand lightweight and notably elastic textiles but with moderate mechanical properties requirements. In this way, they are ideal for small, easily assembled, and disassembled temporary structures, indoors or outdoors.

3.2.4.6 Aramid

These are synthetic fibers notable for their resistance to heat, flames, and tension and low thermal conductivity. Their resistance to wear, most chemicals, ultraviolet light, and moisture sets them apart in technical applications.

Their use spans various sectors, including personal protection, the aerospace industry, construction, and electronics. They are found in equipment such as bulletproof vests, firefighter suits, structural components of airplanes and spacecraft, architectural membranes, electrical insulators, and reinforced tires. Generally, Aramid fibers are essential in areas where resistance to heat, tension, and wear is needed.

These fibers are in high demand in maritime applications due to their exceptional elasticity and strength against rupture. Although they are fire-resistant, they require protection against ultraviolet rays. In the architectural field, they are used in specific situations that require their unique mechanical performance, despite their relatively high cost.

3.2.4.7 Acrylic

Acrylic fibers are synthetic polymers recognized for their wool-like appearance, soft touch, and durability. They exhibit significant resistance to chemicals, microorganisms, and the damaging effects of mold, mildew, and sunlight. Additionally, these fibers can retain vibrant colors, resist deformation and wrinkles, and maintain their shape after multiple washes, attributes valued in the fashion and clothing industry.

Acrylic fibers are versatile and used in various sectors. In the automotive industry, they are essential for producing upholstery and linings. In construction, they are used for the manufacture of carpets and floor coverings, while in the field of safety, they are used to make gloves and fire-resistant clothing due to their low flammability. Acrylic fibers represent an efficient and aesthetically pleasing option in the textile industry.

In architecture, these fibers are ideal for small and portable structures such as tents and umbrellas, thanks to their flexibility and exceptional resistance to oils, chemicals, and degradation caused by sunlight. Additionally, acrylic is versatile and can be designed to mimic other fibers, including cotton.

3.2.4.8 Polyurethane

Polyurethane fibers are widely valued in the textile industry for their notable strength and elasticity. Their robustness when facing abrasions and tears gives them exceptional durability, even under conditions of intense use. They stand out for their resistance to impacts, oxidation, and exposure to UV rays, making them suitable for outdoor use or in hostile environments. They maintain their elasticity across a broad temperature spectrum, resisting extreme cold and intense heat without deforming or losing their properties [33].

Elastane, a variety of polyurethane that incorporates polyurea, is used exclusively in indoor applications that demand exceptional elasticity [21]. This type of fiber, highly appreciated for its moderate price and lesser propensity for wrinkle formation, is not suitable for wind or snow load conditions.

Polyurethane fibers play an essential role in various industrial sectors thanks to their versatility. In the automotive industry, they are used to manufacture hermetic seals and high-strength flexible hoses. In the construction sector, they are standard components in sealants and adhesives due to their resistance to adverse weather conditions. In the textile field, they are vital pieces in making underwear, swimsuits, and sportswear, providing an optimal combination of flexibility and comfort. In the medical field, their biocompatibility makes them the material of choice for implants and prostheses. Their strength and durability make them suitable for manufacturing sports shoes and high-performance equipment.

3.2.4.9 Cotton

Cotton is a prominent natural fiber in the textile industry, valued for its comfort, moisture absorption, thermoregulation, abrasion resistance, and hypoallergenic properties. This fiber can retain part of its weight in water without feeling wet and maintains a stable temperature between the body and the environment, making it an essential component in various garments. Additionally, its resistance to wear and tolerance to allergic reactions make it suitable for applications requiring durability and direct contact with the skin.

In the field of technical textiles, the properties of cotton are enhanced through treatments and blends with synthetic fibers. Mercerization, for example, improves the appearance and durability of cotton, while water and fire-resistant finishes expand their use in work and safety clothing. In addition, the combination of cotton with synthetic fibers allows its application in geotextiles and the production of textile membranes for construction, providing practical and durable solutions.

Pure cotton fiber is characterized by limited tensile strength, significantly high elasticity, susceptibility to microorganism attacks, and resulting biological degradation. Therefore, its use is largely circumscribed to recreational tents, indoor uses, and projects that do not demand high and prolonged mechanical performance [34].

3.2.5 Coating

After understanding the types of fibers, their properties, and their applications, we will now delve deeper into the most common types of finishes that improve the properties of textiles used in covers.

Broadly, the finishing processes of textiles are categorized into four main groups:

Mechanical Processes: These include calendaring, carding, shearing, and compressive shrinkage. They achieve their effects through the mechanical action of machines and often involve a heating process to enhance the results.

Heat setting: This procedure is necessary to stabilize synthetic fibers and prevent their shrinkage with heat.

Chemical Processes: These apply various substances to the fabric to bestow unique properties, like water repellency, flame retardancy, or modification of the material's feel. These chemical finishes are typically applied as an aqueous solution or emulsion. Once applied, the fabric is dried, and a fixation process, commonly baking, is carried out to ensure the permanence of the properties granted by the finish.

Next, we will present the materials used for textile coatings.

3.2.5.1 PVC

Polyvinyl chloride (PVC) is commonly used in combination with polyester fabrics. Additional additives and coatings are typically used to improve fire performance, expected lifespan, self-cleaning properties, and color.

It is generally used as plasticized PVC, forming a transparent film with high resistance to abrasion and low permeability. The film can be pigmented or incorporated with flame-retardant chemicals to produce various colors and low-flammability products. While resistant to acids and alkalis, organic solvents can extract the plasticizer, making the layers more rigid and susceptible to cracking [25].

A notable advantage of a polymer with an asymmetric chlorine atom is its large dipole and high dielectric strength, which allows coated products to be joined using radiofrequency and dielectric welding techniques. This feature and its low cost make it ideal for protective sheets such as tarpaulins. Low permeability and good weathering properties make it a very cost-effective product.

Paolo Beccarelli, in his book "Biaxial Testing for Fabrics and Foils Optimizing Devices and Procedures," said, "PVC is the most used coating for architectural fabrics due to the reduced cost, the easy weldability (high frequency, hot air), and the range of colors available. In addition, it can be easily painted or printed. In order to obtain a non-stick, self-cleaning surface resistant to UV rays, PVC is generally combined with a top-coating based on acrylic, polyurethane (PU), polyvinyl fluoride (PVF), or polyvinylidene fluoride (PVDF)" [21].

3.2.5.2 Fluoropolymer

It is the most common material for coatings when especially high resistance to UV radiation and chemical and biological corrosion is required. The range of fluoropolymer coatings is quite broad and includes PVF, PVDF, and ETFE.

Polytetrafluoroethylene (PTFE) is the strongest bond in organic chemistry and the most used fluoropolymer coatings. It is typically used in the following combinations:

- PVF and PVDF are used as top coatings for PVC.
- THV has recently been used in combination with polyester fabrics due to its extremely high resistance to corrosion.

3.2.5.3 Silicone

Silicone is a polymer that exhibits extraordinary flexibility at low temperatures. It can be used at temperatures as low as -80 °C while maintaining its properties up to 250 °C [25]. It is mainly used in combination with glass fabrics due to its high flexibility and light transmission. They also have good weather and oxidation resistance. However, its price is high.

Its disadvantage is that it tends to capture suspended particles and dirt. On the other hand, its heat-sealing process is limited since it requires other thermofusible fibers such as PTFE.

3.2.5.4 Polyurethane (PU)

Polyurethane coatings for textiles are composed of prepolymers containing isocyanate and hydroxyl polyester. These materials react at room temperature, although their crosslinking accelerates with an increase in temperature. However, the mixture has a limited shelf life, as crosslinking begins immediately after mixing. Blocked isocyanates are used to prevent premature reactions, which react at high temperatures in the presence of catalysts.

Polyurethane coatings offer excellent abrasion resistance, as well as water and solvent resistance. They also exhibit flexibility, and the chemical composition of the diol used can be adjusted to achieve the desired water vapor permeability. However, it is essential to note that these coatings tend to be yellow when exposed to sunlight, so they are often pigmented [25]. Due to their ease of welding and high tightness, they are used in special applications such as biogas plants and flexible tanks, as well as in pneumatic structures such as inflatables and vessels [21].

3.2.6 Coated fabric

There is a wide range of coated fabrics for architectural applications, their use is generally related to their performance in terms of mechanical strength, resistance to flexing and cracking, protection against the effects of weather, fire protection, light transmission, and price. Therefore, this section will expose the most used fabric-coating combinations.

3.2.6.1 PVC-Coated Polyester Fabric

It is widely used in construction due to its good balance between price and performance. Its different types of polyester fabrics offer tensile strengths suitable for structural applications. This material is ideal for tension fabric structures, both temporary and retractable, thanks to its versatility in shapes and colors [35]. The PVC polyester coating includes UV stabilizers, fire retardant additives and other elements, and its recyclability makes it an environmentally friendly option. It is used in various applications, such as insulated roofs, covered walkways, play areas and stadiums (Figure 33,34). Although it has some limitations in terms of light transmission and dirt resistance, its resistance to flex cracking makes it suitable for deployable structures.

Figure 33. Rose Bowl, Hampshire [36].

Figure 34. Soundforms by Flanagan Lawrence, London [37].

3.2.6.2 PTFE-Coated Glass-Fibre Fabric

It is widely recognized for its exceptional durability in the fabric structures industry, with an estimated lifespan of over 35 years. This fabric consists of a woven fiberglass membrane coated with PTFE. Thanks to its chemically inert coating, the PTFE fabric offers impressive tensile strength, reaching up to 1,000 pounds per inch [38], and a low-energy surface that protects it from extreme temperatures and facilitates its cleaning and maintenance. In addition, it is completely resistant to degradation caused by UV radiation.

This material is widely used in various applications, whether for permanent structures or fabric building facades (Figure 35,26), due to its outstanding fire resistance that meets rigorous fire code compliance tests. Depending on the thickness of the required fabric, light transmission varies between 12% and 17% [38]. The PTFE fabric gradually changes from beige to permanent white as exposed to the sun. It is worth mentioning that the choice of

PTFE fabric in colors other than white requires an additional cost and the purchase of the entire fabric lot.

Figure 35. the Sony Centre, Berlin, Germany [39,40].

Figure 36. Rose Bowl, Hampshire [37].

1. On the other hand, PTFE can also be used in fabric without accompanying glass fibers, as they perform well for convertible structures. However, its use is limited to large-scale projects with high prices.

3.2.6.3 Silicone-Coated Glass-Fibre Fabric

Silicone stands out for its notable set of features, which include excellent light transmission, resistance to bending and cracking, protection against chemical attacks and UV radiation. However, it is essential to bear in mind that its surface can generate static charge and attract dirt particles. Furthermore, the high cost of the raw material and the manufacturing process, which involves vulcanization or gluing of the material, add complexity and costs, thus limiting its application in architectural projects.

Silicone-coated fiberglass fabrics are primarily used in permanent applications (Figure 37). These fabrics offer balanced performance and durability, being recognized for their ability to withstand demanding conditions and deliver outstanding performance.

Figure 37. Grandstand Roof, Latvia [41]

3.2.6.4 PU Coated Poliamida Fabrics

Renowned for its remarkable flexibility and light transmission capacity, this fiber and coating combination is characterized by its versatility. Although polyamide fabrics coated with polyurethane have relatively lower mechanical properties than other high-performance fibers such as glass or carbon, they are mainly used in smaller-scale projects. The polyurethane coating allows for easy welding and provides an optimal level of hermeticity, making these fabrics an ideal choice for pneumatic products. If higher mechanical strength is needed, polyester fabrics can be used to achieve improved performance.

3.3 Connection details

After exploring the different types of membranes and fabrics in the previous sections, it is crucial to delve into the connection mechanisms between the fabric and the structures that bear the tension force. The following is an explanation of the different types of connections according to the contact of the elements involved.

3.3.1 Fabric connections

The connections between the fabric and the structure play a crucial role in ensuring the stability and resilience of the system. These connections allow the membrane to be fastened to the structural support, creating a functional and tensioned covering. The quality of these connections is vitally important to ensure the structure's durability and ability to withstand adverse weather conditions. The types of connections will be explained next.

3.3.2 End-connections

This refers to connections affixed to the edges or ends of the fabric, where the cable is attached to the membrane using a clamping sleeve or plate.

When using a sleeve, the cable passes through the fabric and the sleeve (Figure 38). To avoid wrinkles, small slits are cut to increase flexibility. At the ends of the sleeves, the cable and membrane are held with U-shaped clamps or attached to one end of the cable to prevent it from sliding through the sleeve once tension is applied.

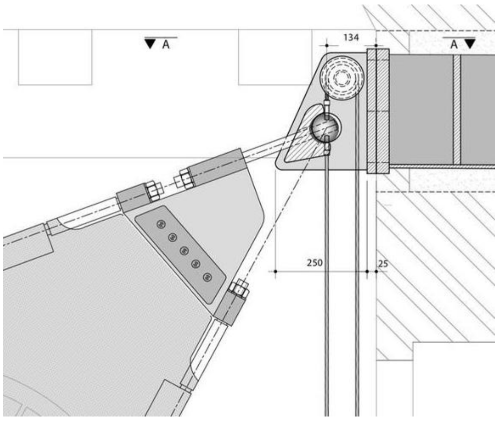


Figure 38. Connection of the cable to the membrane by using a sleeve [42].

2.

In the case of the plate, it is used to fix and stabilize the edges of the fabric. This refers to when the membrane must be joined to the support structure and the cable through the plate.

3.3.3 Cable connections

This section refers to the connections between fabric and cables, where the cable serves as the connecting element. The following will explain the two types of cable connections.

3.3.3.1 Cable to support connections

In tensile membrane structures, connecting the cables and the mast is crucial for ensuring system stability and strength. Several failure factors must be considered when designing this connection, such as pin support, plate shearing and tension, and pin bending.

A washer-type plate is used to prevent failure due to bending, and the handle can be cut in the center of the mast. In addition, a circular ring is welded around the mast to eliminate the bending force. These techniques ensure a solid and durable connection between the cables and the mast, optimizing structural integrity in tensioned membrane structures.

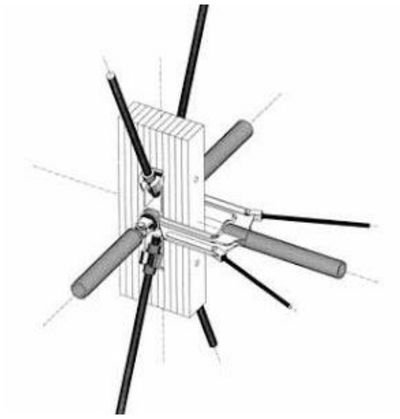


Figure 39*. Connection of mast or fixed structure with the cable [43].*

3.3.3.2 Cable saddle connections

In tensioned membrane structures, it is crucial to pay attention to details at the junction points where cables connect with other cables and supports, considering the orientation of the cable in different load states. Tension forces can vary on the sides of the support, which can cause displacements of the cable. It is essential to implement additional measures, such as securing the cables in place, to minimize slippage and ensure the stability and strength of the structure against applied forces.

Figure 40*. change of direction with rollers.*

3.3.4 Pretensioning

This method refers to the application of tension or force to secure the joining mechanism before and parallel to the connection with the fabric.

3.3.4.1 Direct tensioning

Direct tensioning is usually reserved for smaller-scale structures that do not require special or significant pre-tensioning forces to be induced in the membrane. These structures typically do not have support masts or external cables, so they rely solely on the membrane edges' tensioning. A modified version of the typical fabric-support connection includes an additional base plate with extra holes to allow for manual fabric tensioning.

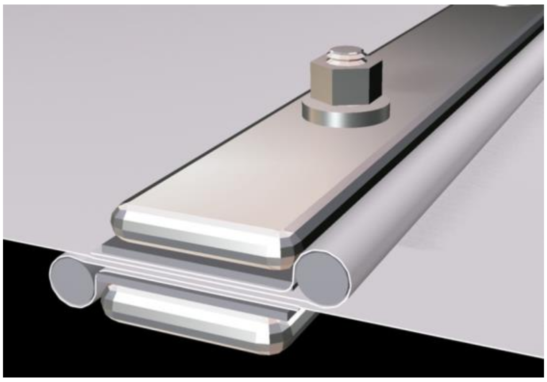


Figure 40. Direct tensioning [44].

3.3.4.2 Cable tensioning

The preferred method for tensioning the membrane is through direct tension cables. Only a few tensioning points are needed to stretch the entire membrane inside or outside the structure. For instance, adjustable turnbuckles can be used on the tie-down cables on the exterior. These turnbuckles cause the structure to contract, tightening the internal cables and the membrane. In other cases, adjustable cable-to-cable connections can be used to tension the cables at strategic points in the structure. In this way, uniform tension is achieved across the entire membrane.

Figure 41. Direct tensioning with plate and prestressed rope [45].

Figure 42. Direct connection with tensioned rope and fabric [46].

3.3.4.3 Support structure tensioning

Tensioning through masts in the support structure is highly versatile, as it can be applied regardless of the location of the catenary cables and masts. As with cable tensioning, only a few key mast points are required to achieve the appropriate tension in the membrane. Masts can be located either at the top or bottom of the structure. The main difference between these two methods lies in aesthetics and the requirements of hydraulic jacks. When using masts at the top, only one hydraulic jack is needed; at the bottom, several jacks are required. However, the tensioning of hydraulic jacks from the top is more complicated, and the construction of the masts becomes considerably complex, as cranes are required for their construction.

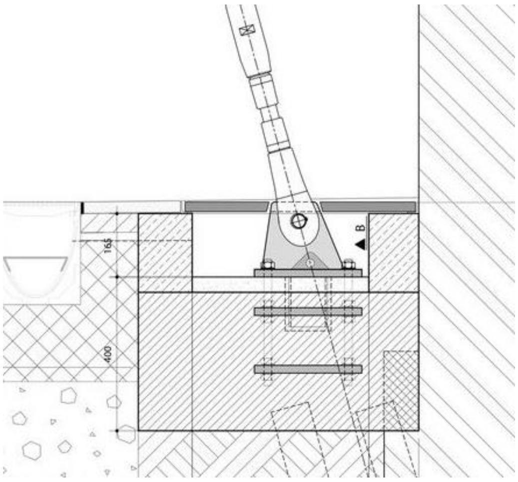


Figure 44. Prestressed rope for fixed structure [42].

3.4 Ordinance on the uses of the urban landscape of the province of Barcelona

After studying all the aspects that influence the construction of a textile cover, the regulations limiting the design possibilities should be considered as the final consideration. Therefore, the building ordinance for awnings on the ground floor in the province of Barcelona will be explained below.

3.4.1 Article 62. Awnings on ground floors

The article about awnings on ground floors [47], expose:

1. The installation of folding awnings made of canvas or similar fabric is allowed to protect the architectural openings of a building from the sun.
2. Awnings must be placed within architectural openings and, once retracted, must not obscure decorative elements of the frame. Awnings are not allowed on bay windows or enclosed projecting bodies.
3. The overhang or flight from the facade plane must be 60 cm less than the width of the sidewalk, with a maximum flight of 1.50 m.
4. The color of the awnings must match the chromatic range present in the architecture of the building on which they are arranged, and in any case, it must be the same for all awnings of the building that can be perceived simultaneously.
5. In cataloged buildings and their protection or conservation areas, the placement of awnings will be subject to the presentation of a technical and chromatic project on the entirety of the building.

6. In general and transition zones, identifying signs are permitted on the condition that the awning can display only one identifier of the establishment painted on the fabric and in only one position. The message must be unitary for the entire facade and occupy a maximum of 25% of the surface of the awning.

4 Technical characteristics selection and analysis

This section cover technical characteristics selection and analysis, which involves evaluating and choosing key features and specifications based on factors like functionality, reliability, and safety for our design. It enables informed decision-making for developing high-quality solutions.

4.1 Technical characteristics

Based on the theory previously discussed, we selected the primary characteristics of our proposal, shown in Table 1. Firstly, a plain weave fabric was selected for its tensile strength and intermediate flexibility compared to the knit fabric. Polyester fibers were chosen due to their widespread use in architectural materials, their cost-effectiveness, good mechanical performance, and anticipated lifespan. These fibers are highly flexible and commonly used for temporary and seasonal structures.

Furthermore, a polyvinyl chloride (PVC) coating was chosen to enhance fire resistance, anticipated lifespan, self-cleaning properties, and color degradation. PVC coatings can be easily painted or printed on and, when combined with suitable finishing layers, have a lifespan of over 20 years. This type of fabric is also successfully used for deployable structures, as it exhibits good resistance to flexural cracking.

Pre-tensioned cables and beams were selected for the tensile structure type to allow for component independence (cables and fabric). Saddle connections were chosen for cable joints as they contribute to the folding mechanism of the canopy. Pretensioned structures were preferred, requiring only a few tension points with external supports.

All these specifications, summarised in Table 1, were taken into account for the design of an exterior canopy structure intended for public space at UPC-Terrassa.

*Table 1. T*echnical characteristics selection

Characteristics	**Selected items**
Type of fabric	Woven
Properties	Tensile strength, durability, Sun-protection, water-repellent
Fibres	Polyester
Coating	PVC/THV
Coated fabric	PVC/THV-Coated Polyester fabric
Type of Tensile structure	Pre-stressed cable-nets and beams
Connection details	*Cable saddle connections*
Pretensioning	1. Cable tensioning

Use	Public space

4.2 Fabric selection

The fabric forms a significant part of the textile cover structure, both functionally and aesthetically. Its selection is, therefore, a critical step in the design and construction process. The chosen fabric must meet specific criteria, including durability, resistance to various weather conditions, and compatibility with the project's sustainability goals. In this section, we will delve into the fabric selection process, discussing the different considerations and options we evaluated to determine the optimal choice for our textile cover model.

4.2.1 Samples of the suppliers

We conducted a search on various websites of local suppliers who offer polyester fabrics coated with PVC for textile coverings. Subsequently, they were contacted via email to request samples and technical datasheets. After receiving the samples, an analysis of the fabrics and technical datasheets was carried out for each supplier following the sustainable methodology mentioned in previous sections.

<u>Saudela</u>

The company has its main headquarters and production center in Girona. It primarily produces technical fabrics for sun protection, offering solutions for the manufacturing of awnings, umbrellas, blinds, curtains, and other related products. These fabrics are designed to protect against ultraviolet rays, regulate temperature, control sunlight, and offer durability and weather resistance.

The samples sent were as shown in Figure 45:

MONZA SUNTEC TREND OPAK PORT M1

Figure 45. Samples of Saudela

- MONZA

El modelo de tejido MONZA tiene las siguientes especificaciones descritas en la Tabla 2. Las especificaciones expuestas no cumplen con ninguna norma estándar.

Table 2. MONZA fabric specifications.

Fabric characteristics	MONZA
Composition	100% Polyester
Weight (g/m2)	580

Thickness (mm)	0.48
Lacquered faces	1

- SUNTEC

El modelo de tejido SUNTEC tiene las siguientes especificaciones descritas en la Tabla 3. Las especificaciones expuestas no cumplen con ninguna norma estándar.

Table 3. SUNTEC fabric specifications.

Fabric characteristics	SUNTEC
Composition	100% Polyester
Weight (g/m2)	440
Thickness (mm)	0.38
Lacquered faces	1

- TREND

El modelo de tejido SUNTEC tiene las siguientes especificaciones descritas en la Tabla 4. Las especificaciones expuestas no cumplen con ninguna norma estándar.

Table 4. TREND fabric specifications.

Fabric characteristics	TREND
Composition	100% Polyester
Weight (g/m2)	± 730
Thickness (mm)	0.57
Lacquered faces	2
Fire retardant	M2

- OPAK

The OPAK fabric model has the following specifications described in Table 5. The specifications stated do not comply with any standard norm.

Table 5. OPAK fabric specifications.

Fabric characteristics	OPAK
Composition	100% Polyester
Weight (g/m2)	830
Thickness (mm)	0.60
Lacquered faces	2
Fire retardant	M2

- PORT M1

The PORT M1 fabric model has the following specifications described in Table 6. The specifications stated do not comply with any standard norm.

Table 6. PORT M1 fabric specifications.

Fabric characteristics	PORT M1
Composition	100% Polyester
Coating	PVC coating 2 faces
Weight (g/m2)	470
Thickness (mm)	0.35
Fire retardant	M1

Sedó

The company is located in the province of Tarragona and is a leading player in the textile industry, specializing in the manufacturing and marketing of synthetic yarns and fibers. Their fabrics are used in various textile applications, including architecture, sun protection, agriculture, nautical, industry, and leisure.

Sedo stands out for its commitment to innovation and quality. Additionally, the company conducts ongoing research to develop new textile solutions and improve the efficiency and sustainability of its production processes.

The samples received were as shown in Figure 46:

Figure. GAMMA-11

Figure. SED UP

Figure 46. Samples of Sedó

- GAMMA-11 WHITE 9010 OPAQUE

The GAMMA-11 WHITE 9010 OPAQUE fabric model has the following specifications described in Table 7.

Table 7. GAMMA-11 fabric specifications.

Fabric characteristics	Standard	G11 op
ligament (raw fabric)		TAFETAN
Composition	Internal method	100% polyester
Mass/unit area (g/m²)	EN ISO 2286-2	850
M2 reaction to fire classification	UNE 23727-90	-
Lacquered faces	-	2
Acrylic lacquer	-	YES
Opaque		YES

- SED UP

The SED UP fabric model has the following specifications described in Table 8.

Table 8. SED UP fabric specifications.

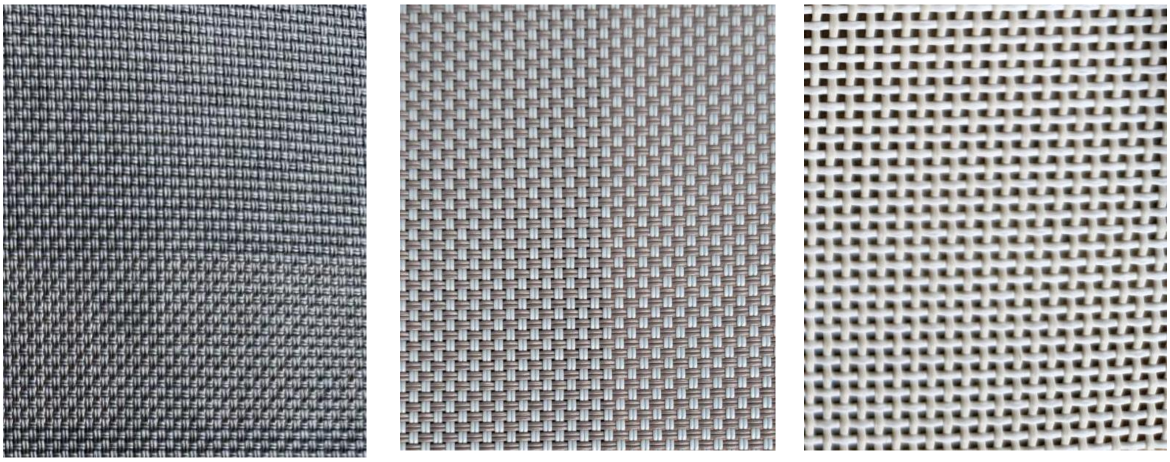
Fabric characteristics	Standard	G11 op
ligament (raw fabric)	-	TAFETAN
Composition	Internal method	100% Polyester
Mass/unit area (g/m2)	EN ISO 2286-2	650
M2 reaction to fire classification	UNE 23727-90	-
Lacquered faces	-	2
Acrylic lacquer	-	YES
UV Filter	-	YES
Opaque	-	NO

<u>Vertisol</u>

Vertisol is a textile company specializing in the manufacturing and marketing of textile products for the solar protection and decoration sectors. With headquarters in Galicia and Granollers, the company has excelled in offering innovative and high-quality solutions.

Vertisol produces technical fabrics for solar protection, such as curtains, blinds, and shades. Their products are designed to protect against UV rays, control light entry, and regulate indoor temperature while offering a wide range of designs and styles to suit different aesthetic preferences.

The samples received are as shown in Figure 47:



Elemental 1 Essential 5 Tensiline

Figure 47. Samples of Vertisol.

- ELEMENTAL 1

The ELEMENTAL 1 fabric model has the following specifications described in Table 9.

Table 9. ELEMENTAL 1 fabric specifications.

Fabric characteristics	Standard	Elemental 1
Composition	-	80% PVC ± 20%PES
Weight (g/m2)	-	508 ± 5%
Yarn diameter (mm)	Internal method	0.30
Openness factor (%)	-	1%
Thickness (mm)	-	0.65 ± 5%
Light fastness	En ISO 4892-2 (exterior) (Grey scale level)	5 4 White
Light fastness	En ISO105 B02:2002 (interior) (Blue Scale Level)	8 7 White
Fire Classification	DIN 4102 EN 13501-1:2007 EN 13773:2003 NFPA 701 C.A.C Title 19 CAN/ULC – S109-03	B1 In process Class 1 Pass Pass Pass
Recycled content	-	2% Pre-consumer

- ESSENTIAL 5

The ELEMENTAL 1 fabric model has the following specifications described in Table 10.

Table 10. ESSENTIAL 5 fabric specifications.

Fabric characteristics	Standard	Essential 5
Composition	-	85% PVC ± 15%PES
Weight (g/m2)	-	610 ± 5%
Yarn diameter (mm)	Internal method	0.40
Openness factor (%)	-	5%
Thickness (mm)		0.78 ± 5%
Light fastness	En ISO 4892-2 (exterior) (Grey scale level)	5 4 White
Light fastness	En ISO105 B02:2002 (interior) (Blue Scale Level)	8 7 White
Fire Classification	EN 13773:2003 EN 13501-1:2018	Class 1 Bs2d0
Recycled content	-	2% Pre-consumer

- TENSILINE

The TENSILINE fabric model has the following specifications described in Table 11.

Table 11. TENSILINE fabric specifications.

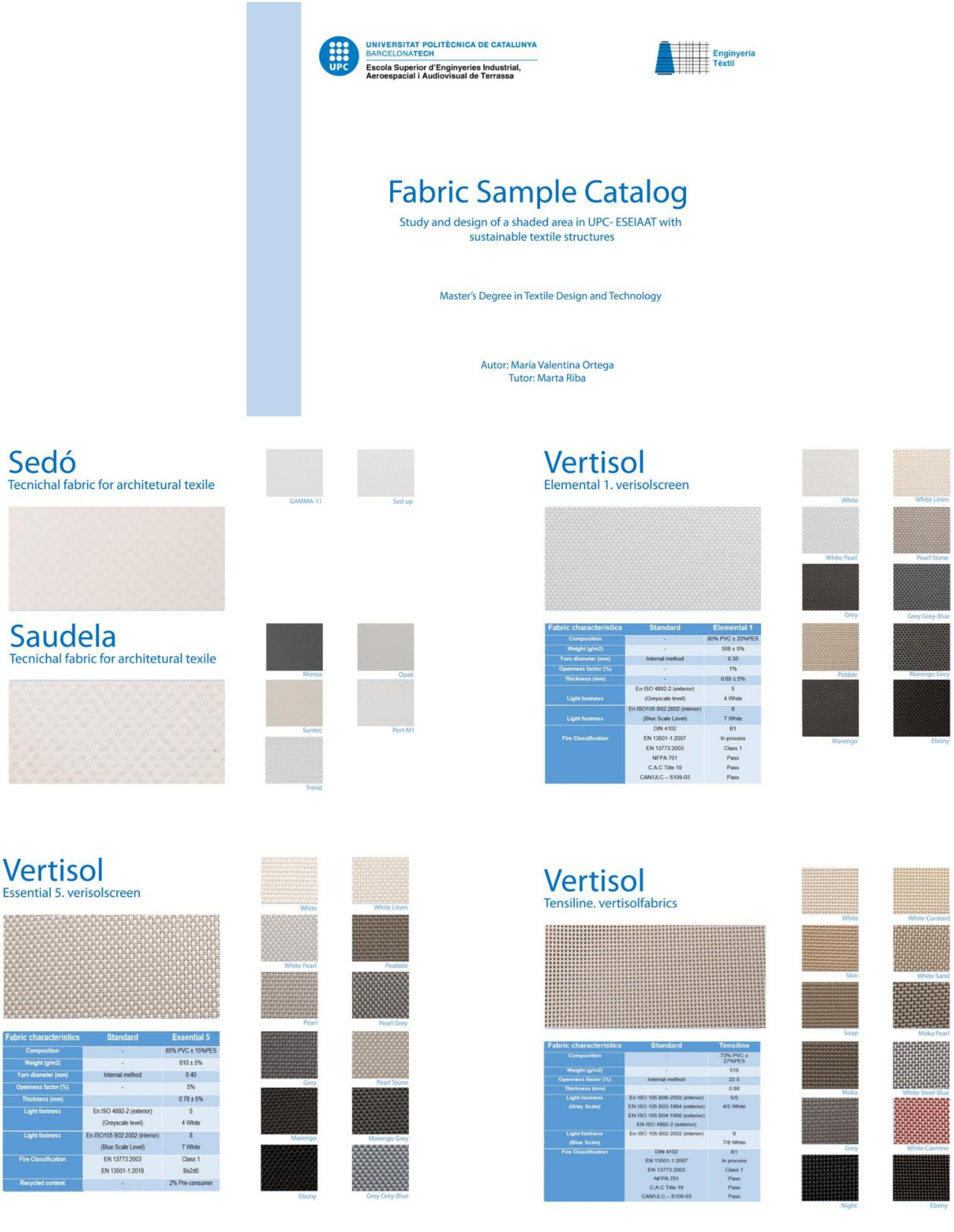
Fabric characteristics	Standard	Tensiline
Composition	-	73% PVC ± 27%PES
Weight (g/m2)	-	518
Openness factor (%)	Internal method	22.5
Thickness (mm)	-	0.88
Light fastness (Grey Scale)	En ISO 105 B06-2002 (interior) EN ISO 105 B03:1994 (exterior) EN ISO 105 B04:1998 (exterior) EN ISO 4892-2 (exterior)	5/5 4/5 White
Light fastness (Blue Scale)	En ISO 105 B02:2002 (interior)	8 7/8 White
Fire Classification	DIN 4102 EN 13501-1:2007 EN 13773:2003 NFPA 701 C.A.C Title 19 CAN/ULC – S109-03	B1 In process Class 1 Pass Pass Pass
Recycled content	-	2% Pre-consumer

4.2.2 Sampler

We have created a physical textile sampler incorporating the samples received. This sampler serves as a comprehensive display of the different fabrics and their unique characteristics. It allows us to physically examine and compare each fabric's textures, colors, and features, providing a tactile and visual representation of their qualities. This textile sampler is a valuable resource for our team and clients, enabling us to make informed decisions and showcase the diverse options available for various textile applications. These sample catalogue is shown in the Figure 48.

After analyzing all the fabrics, **Essencial 5 and Tensiline were selected** as they present a higher percentage of openness compared to Sedó and Saudela laminated fabrics. The two vertisol fabrics were chosen to generate a more varied light screening in the cover design.

On the other hand, both fabrics formed by polyester threads coated with PVC allow for the appreciation of the fabric's weave, which means that the textile forms an integral part of the entire design proposal.



Fabric characteristics	Standard	Elemental 1
Composition	-	80% PVC ± 20%PES
Weight (g/m2)	-	508 ± 5%
Yarn diameter (mm)	Internal method	0.30
Openness factor (%)	-	1%
Thickness (mm)	-	0.65 ± 5%
Light fastness	En ISO 4892-2 (exterior) (Greyscale level)	5 4 White
Light fastness	En ISO105 B02:2002 (interior) (Blue Scale Level)	8 7 White
Fire Classification	DIN 4102 EN 13501-1:2007 EN 13773:2003 NFPA 701 C.A.C Title 19 CAN/ULC – S109-03	B1 In process Class 1 Pass Pass Pass

Fabric characteristics	Standard	Essential 5
Composition	-	85% PVC ± 15%PES
Weight (g/m2)	-	610 ± 5%
Yarn diameter (mm)	Internal method	0.40
Openness factor (%)	-	5%
Thickness (mm)		0.78 ± 5%
Light fastness	En ISO 4892-2 (exterior) (Greyscale level)	5 4 White
Light fastness	En ISO105 B02:2002 (interior) (Blue Scale Level)	8 7 White
Fire Classification	EN 13773:2003 EN 13501-1:2018	Class 1 Bs2d0
Recycled content	-	2% Pre-consumer

Fabric characteristics	Standard	Tensiline
Composition	-	73% PVC ± 27%PES
Weight (g/m2)	-	518
Openness factor (%)	Internal method	22.5
Thickness (mm)	-	0.88
Light fastness (Grey Scale)	En ISO 105 B06-2002 (interior) EN ISO 105 B03:1994 (exterior) EN ISO 105 B04:1998 (exterior) EN ISO 4892-2 (exterior)	5/5 4/5 White
Light fastness (Blue Scale)	En ISO 105 B02:2002 (interior)	8 7/8 White
Fire Classification	DIN 4102 EN 13501-1:2007 EN 13773:2003 NFPA 701 C.A.C Title 19 CAN/ULC – S109-03	B1 In process Class 1 Pass Pass Pass

Figure 48. Fabric Sample Catalog.

5 Design process

The project is subject to meeting specific requirements related to the type of fabric used, the support structure, and the adoption of a sustainable design approach. We have selected a PVC-coated woven fabric for the cover, which satisfies all the necessary technical specifications and helps to contribute to local suppliers. We will use a support structure and saddle cable connections to ensure appropriate stability and resistance.

From a design perspective, we will emphasize implementing eco-design strategies oriented toward environmental protection. For this, we will conduct an urban analysis of the environment in this chapter to understand the site's peculiarities. As a result of this analysis, we identify the most suitable strategies to develop a modular and sustainable design adapted to the specific needs of the university campus.

Our primary goal is to develop a functional, visually appealing, and environmentally friendly cover. To achieve this, we will integrate sustainability criteria throughout the design process. This will help to minimize the environmental impact, in line with the primary intent of this work: to address climate change.

5.1 Urban analysis

Knowing the technical specifications required to design a tensioned structure, we will now analyze where we cover will be implemented: the Terrassa campus of the Polytechnic University of Catalonia. Specifically, we will install it outdoors for various activities and multidisciplinary events. Still, it needs more urban amenities to promote everyday use, especially during the hot summer.

Terrassa, located in the province of Barcelona, Catalonia, Spain, is known for its mountainous surroundings and the Besós River. Recognized as an essential industrial and commercial center, it has undergone economic diversification towards sectors such as technology and research. Terrassa is also distinguished for its cultural richness and heritage, with iconic modernist buildings and a notable educational offer.

Figure 49. Google earth Terrassa Map.

5.1.1 Context

Regarding the urban environment, Terrassa, Figure 49, has a rich cultural and industrial heritage. Services, commercial premises, residential buildings, and student residences surround the faculty. It is connected to the main avenue that leads directly to the park adjacent to the Ferrocarriles Catalanes station.

The faculty consists of several buildings, as shown in Figure 50, many interconnected by walkways. These include historic industrial buildings that represent the textile legacy of the city (Figure 51), harmoniously merged with modern structures.

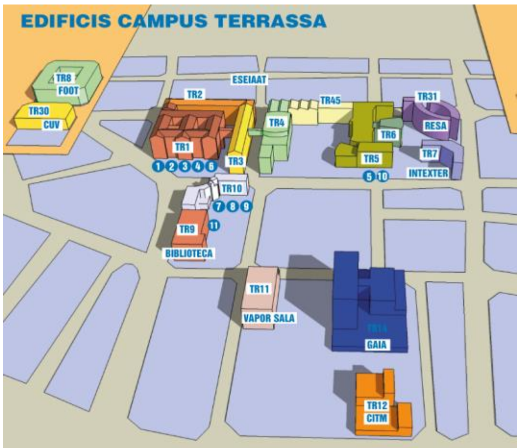


Figure 50. Tarresa Campus

Figure 51. Main building of UPC-ESEEIAT

In the midst of the buildings, interstitial spaces host various outdoor activities, as observed in Figure 51. An example of this is the main entrance of the TR1 building and the soccer field located at the heart of the campus. However, this latter public space needs more urban adjustments to promote people's stay.

Figure 52. Plane about the context of intervention at UPC-ESEEIAT.

As shown in Figures 53 and 54, the dirt plaza and the surrounding areas are used as versatile spaces for hosting various events and multidisciplinary activities. Temporary urban furniture, such as camping and ping-pong tables, is often used in this context.

Figure 53. Target public space of the project.

Figure 54. Another perspective about the Target public space of the project.

Despite the space not being conditioned, it is widely used as an outdoor dining area and workspace during the autumn and winter. However, when the hot season arrives in June and temperatures rise, its usage decreases significantly due to the lack of a shading structure. This phenomenon has become more noticeable recently as heatwaves have become more frequent. Therefore, this work proposes the design of a textile cover as a tool for passive climate conditioning.

5.2 Eco-design principles

After familiarizing ourselves with where we will design the textile cover, this section will examine the eco-design principles to identify which could be applied based on the project's characteristics, as shown in Figure 55.

Eco-design is an approach to creating products, services, or systems that consider their environmental impact throughout their life cycle, from raw material extraction to final disposal. It aims to minimize this impact by using renewable or recycled materials, energy efficiency, waste reduction, design for durability and reparability, and ease of recycling at the end of the product's life cycle. Ultimately, eco-design is vital for moving towards a more circular and sustainable economy.

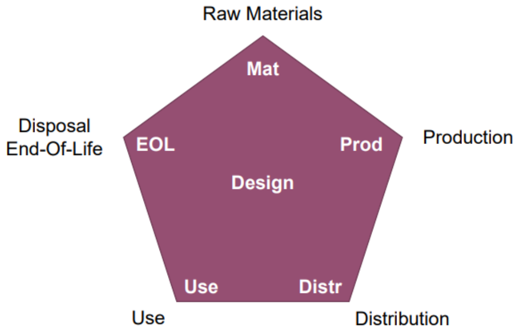


Figure 55. Concept diagram of the main eco-design principles.

5.2.1 Raw materials

5.2.1.1 Reduction of material consumption and diversity

- Minimize components: parts that do not have an important function or do not increase quality or aesthetic value
- Reuse parts or components (if possible)
- Consult suppliers: recommendations to optimise the design
- Reduce the diversity of materials in the final product: less different processes and transport stages involved in production
- Monomaterial solutions: easier to recycle

5.2.1.2 Environmentally-oriented materials selection

- Materials derived from renewable resources.
- High content of recycled material
- Free of hazardous substances
- Produced using greener processes (e.g. using renewable energy or applying energy or water-saving measures)
- With low energy intensity (low energy extraction, transport and transformation)
- Easily recyclable

5.2.2 Production

5.2.2.1 Reduction of environmental impacts of production processes

- Reduce the number of production steps: to reduce energy and materials consumption (number of different materials or components, avoid materials that require surface treatments)
- Re-introduce production waste into the production chain: defective products, production tests, off-cuts
- Choose cleaner production processes: efficient use of water and energy, low energy consumption and waste production, use of renewable energy, etc.
- Combine production processes when possible (scouring + desizing, for instance)
- Use of good quality raw materials that avoid defects

- Good definition of processes and conditions to avoid further corrections
- Reincorporation of the remnants again into the production process
- Selection of cleaner processes BATs
- Use of last generation equipment (industry 4.0), were the efficiency is connected to minimum use of energy, minimum waste of raw materials, etc.

5.2.3 Distribution

5.2.3.1 Reduction of environmental impacts of production processes

- Minimize the use of packaging
- Use environmentally-friendly materials for packaging
- Facilitate identification of the type of packaging materials: e.g. with logos
- Design the product for a maximized product per unit of volume ratio during the transport and storage
- Reduce the product and packaging weight: to reduce energy consumption during transportation

5.2.4 Use

5.2.4.1 Increase useful product life

- Allow and promote re-use of the product
- Identify and eliminate the weak points of the product: points of the product that break first, or need to be repaired frequently
- Choose adequate materials for a good resistance to continued use
- Modular design: for upgrading and repair
- Facilitate repair and maintenance

5.2.4.2 Increase useful product life

- Integration of functions: multiply product functions (consequently avoiding the need to produce other products)
- Shared use of the product: increase of the number of times that a product is used during its life time by sharing

5.2.5 EOL

5.2.5.1 Waste management optimization

- Materials use:
  - Use recyclable or biodegradable materials
  - Use as few materials as possible to facilitate recycling of the product
  - Consider materials that can be recycled together without the need to disassemble the product
- Minimize the use of finishings that difficult the recycling of the material
- Design for disassembly:
  - Minimize the number of different components or materials • Accessible joins (sews, buttons, etc.)
  - Minimize disassembly steps

  - Use joining systems that could be separated even after long use (fasteners, sewings)

Based on the principles that can be applied, the following strategies will be implemented in the project:

Raw materials:

- Reduce consumption and diversity of materials.
- Minimize the number of components.
- Consult with suppliers.
- Use local suppliers and locally sourced raw materials.
- Reduce the diversity of materials in the final product.

Production:

- Reduce the environmental impact of production processes.
- Utilize high-quality raw materials to prevent defects.

Utilization:

- Extend the product's lifespan.
- Choose appropriate materials for durability under continuous use like pvc coated polyester fabric.
- Implement modular design.
- Facilitate repair and maintenance.
- Integrate multiple functions into the design.

End of life:

- Design for disassembly.
- Minimize the number of different components with easily accessible joints.
- Streamline the disassembly process.
- Use joining systems that can be separated even after prolonged use.

5.3 Concept

Based on the selected strategies mentioned in the previous paragraph, modular adaptation is proposed as the guiding concept since both the structure type and its use should be able to accommodate different activities.

To visualize these ideas, a mood board, Figure 56, is created to determine the desired spatiality. It proposes a structure that can be adapted to different typologies based on the intended use, along with the use of fabric strips or pieces with geometric patterns to allow filtered light to pass through.

Additionally, the materials or textures chosen should be in harmony with the surrounding buildings, such as brick, aluminum, or concrete. However, this does not imply a literal use of these materials but rather the aim is to create a sense of warmth through textures and tones.

Figure 56. Mood board.

5.3.1 Architectural strategies

One of the fundamental aspects of the project is the modular design, aiming to facilitate adaptation, the use of typologies, and the replacement of parts in case of degradation due to exterior conditions.

We will briefly study two modular design projects for public space equipment to better understand how these proposals are implemented.

5.3.1.1 Modular system

3.

Urbhang BCN (2021)

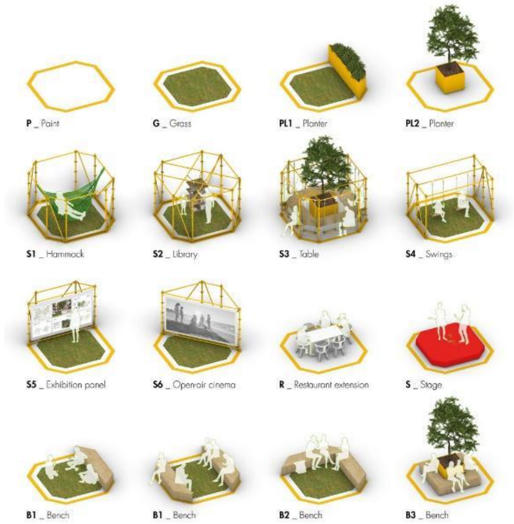


Figure 57. Urbhang BCN concept design.

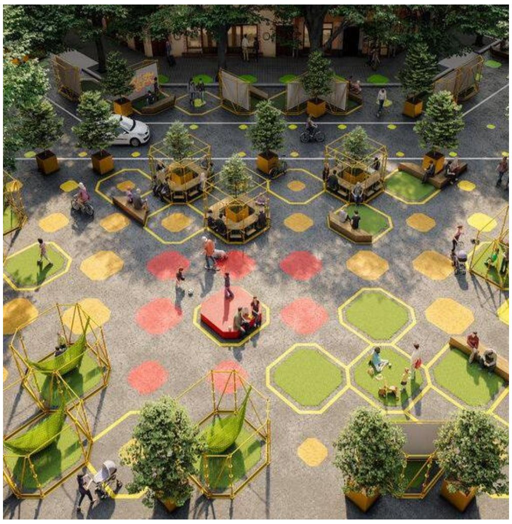


Figure 58. Urbgang BCN realistic render.

The project, exposed in Figures 57 and 58, uses a framework whose spatiality is limited to the marked floor space, which guides the integration of furniture components. These components range from benches to masts for hanging hammocks.

Urban Gatherings

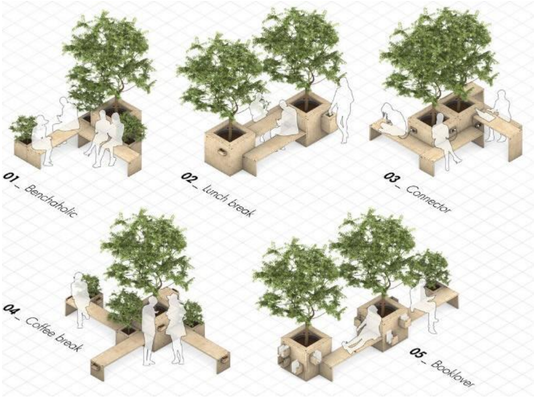


Figure 59. Urban Gatherings concept design.

Figure 60. Urban Gatherings realistic render.

This other project, Figures 59 and 60, was conceived based on two planters that function as anchors to fit and move the furniture pieces. This main structure has small holes where the edges of the wooden strips fit, which, depending on their height, serve as tables or chairs.

5.4 Color palette

Based on the design concept and the implemented system, the colors to be used in the textiles can be determined. In this process, the shades that the cover could have are identified by using the colors from the university logo (Figure 61) as well as the tones found in the surrounding context (Figure 62). Adobe Color platform was employed for this purpose, which also provides the corresponding Pantone numbers.

Figure 61. UPC branding colors.

Figure 62. Main public space project colors.

However, considering that the cover will be exposed to the degradation caused by sunlight as an exterior textile, it was decided to implement light shades based on the color chart of Essential 5 and Tensile fabrics by Vertisol.

6 Design

After exploring all the technical and design variations involved in the project, it is time to begin designing a textile cover with a modular and detachable structure to facilitate mobility and multi-functionality.

There are four critical components to develop the piece, which are as follows:

1. Cover fabric: geometric shapes integrated by metal joints, using two types of textile materials to diffuse the light rather than completely blocking it.
2. Fabric-cable connections: movable hooks that allow the fabric to be held in place and folded along the cable.
3. Pulley system: to provide mobility to the cover and prevent it from being fixed in one position.
4. Structural connections to link different modules together.

6.1.1 Process

Taking into account the specifications, initially, it was proposed to have the fabric pieces stretched across two levels to create a dynamic design that allows for adjusting the amount of light passage (Figure 63f). However, having two levels and the ability to fold the fabrics on both levels would require fixed anchors, four pulley systems, and dismantling would become overly complex for an adaptable structure (Figure 64).

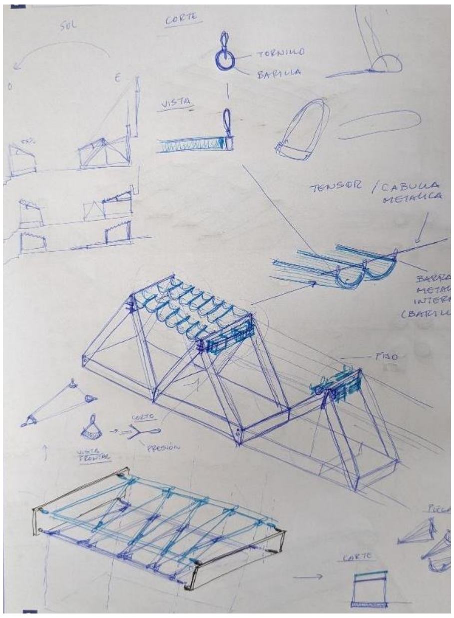


Figure 63. Design first sketches I.

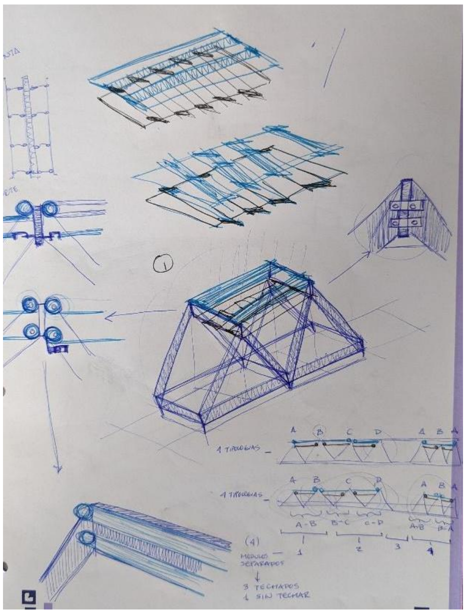


Figure 64. Design first sketches II.

Later on, we proposed a single-level cover segmented into triangles and connected by two pulleys on each side. In the sketches, we explored the possibilities of joining the triangles with hooks and fixed tensioners and the option of leaving gaps (Figure 65). However, the latter option would decrease its protection against sun exposure (Figure 66).

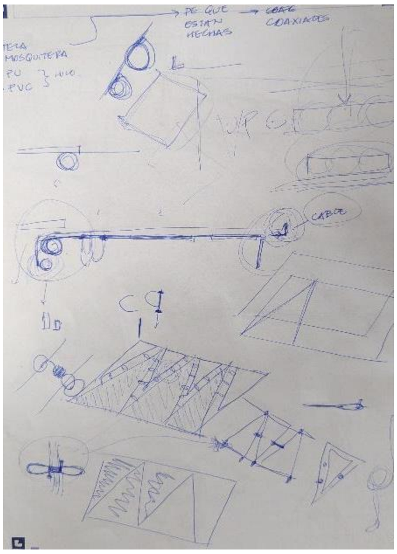


Figure 65. Design first sketches (III).

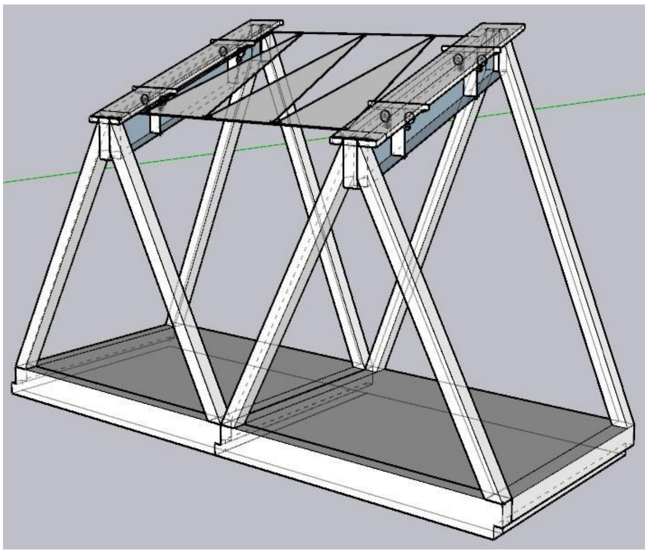


Figure 66. Textile cover proposal 3D model.

Then, we decided to simplify the design. It would be better to fix the ends with the possibility of detaching the cable (Figure 67) and have the pulley only in the middle between the modules to aid in folding the cover when not in use or in case of wind (Figure 68).

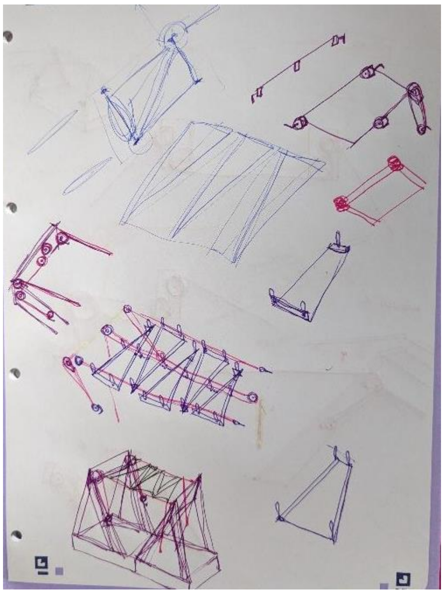


Figure 67. Design first sketches (IV).

Figure 68. Textile cover proposal realistic render.

4.
5. Finally, we decided that the triangles would alternate between closed-weave fabric (Essential 5) and open-mesh fabric (Tensile). We choose to create a more dynamic effect regarding light diffusion and design.
6.

7.

6.1.2 Plans

At the urban level, it is proposed to intervene in the open area by implementing vegetation in specific zones and distributing the modules to the sides of the roadway. This arrangement allows for vehicle passage while making use of the residual spaces.

Two typologies are proposed: one consists of two modules connecting the canopy to tension, while the other involves platforms without textile structure. This approach allows the creation of two types of spaces that can later be adapted for everyday use with furniture or serve as platforms for event areas.

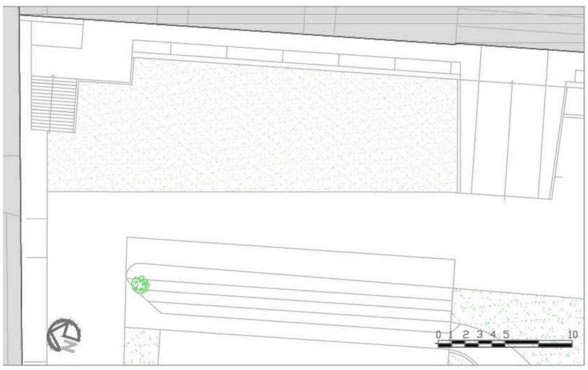


Figure 69. Plano del terreno a intervenir

Figure 70. Plano de la propuesta intervenida

6.1.3 Planimetry

Knowing the overall design and its implementation in the public space of UPC-Terrassa, this section will focus on the dimensions and structural details of the project.

The structure consists of two triangular frames made of wooden slats with a thickness of 10cm, connected by a wooden beam measuring 10x42cm (Figure 71,72). The wooden frames have varying heights to maintain a slope of 15 degrees, which helps provide shade and prevent water accumulation on the fabric (Figure 73).

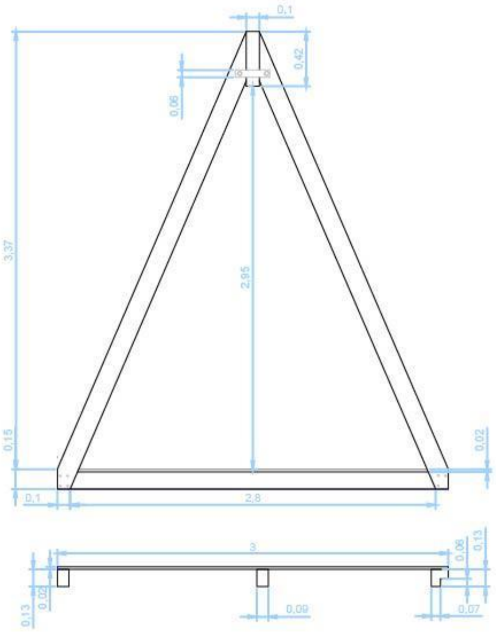


Figure 71. Back Piece

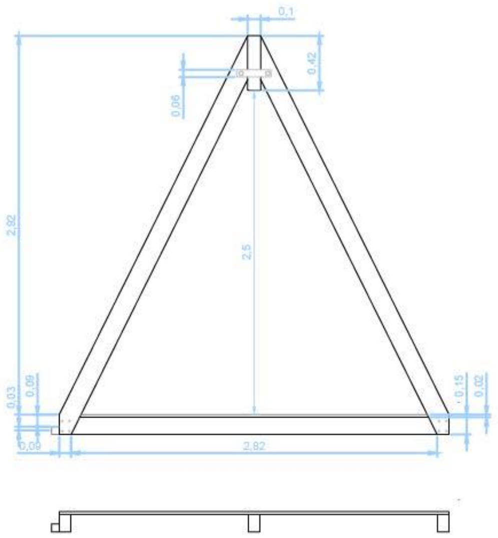


Figure 72. Back Piece

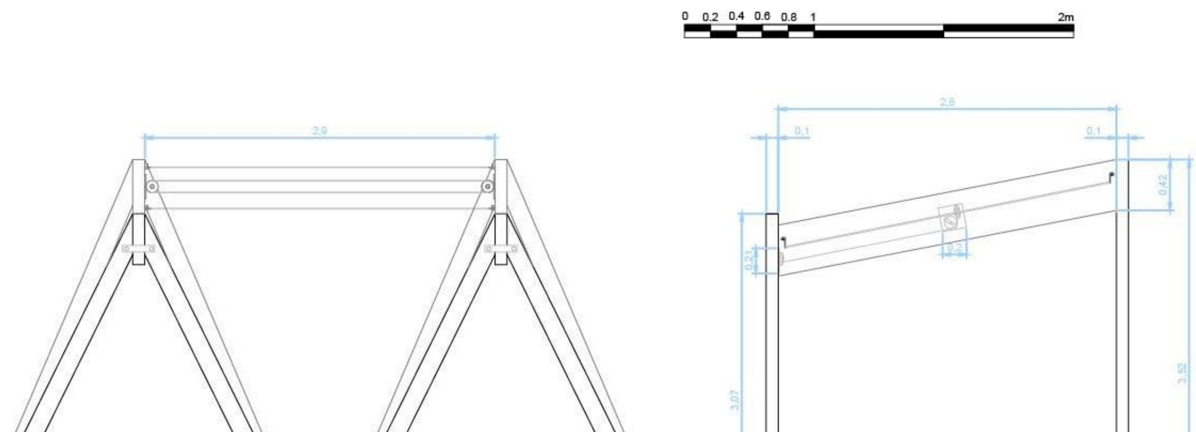


Figure 73. Textile Facade and section.

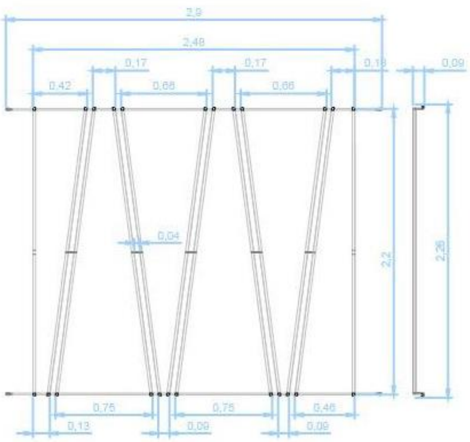


Figure 74. Textile roof

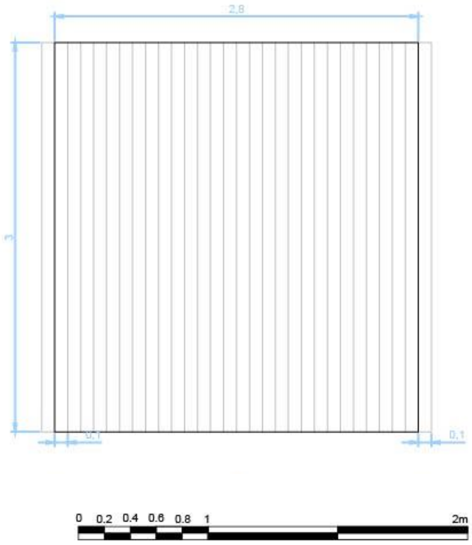


Figure 75. Floor.

6.1.4 Constructive details

The most important connection is the pulley system used to fold the cover. This system consists of two pulleys on one side, each with opposite directions to change the cable's path and direct it towards one of the sides where the mechanism for pulling and winding is located (Figure 76).

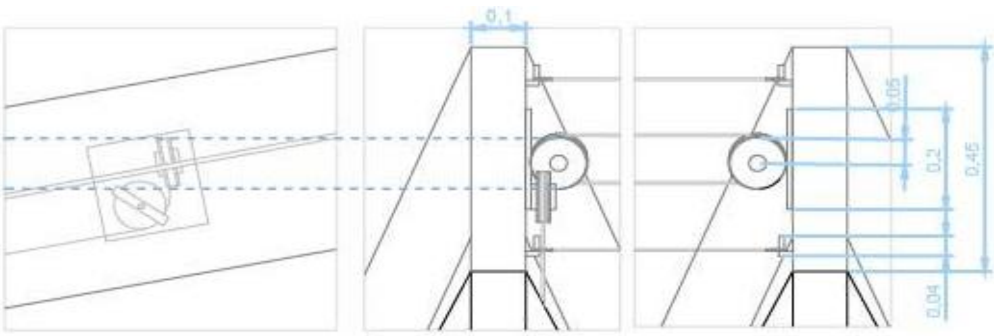


Figure 76. Connection between the elements of the structure.

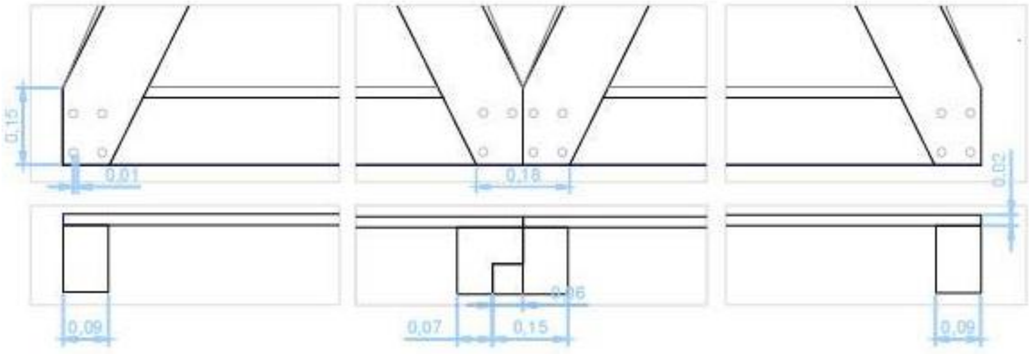


Figure 77. Structural details of the floor fixings.

The other essential connections in the design are at the base, where the wooden slats are connected to the platform, extending diagonally toward the ground (Figure 77). On the other hand, there is a joint groove between the media of each module. It involves creating a small section in the wooden foundation of one module and fitting it by adding a slight edge on the lower edge of the other module.

6.2 Prototype

As the final section of the design of this master's thesis in textile engineering and architecture, we developed a prototype for a shading cover structure measuring 20 x 8 cm. This model has been constructed using a range of materials, including balsa wood, insect screen, Fliselina Vilene C/White de 90cm as testing textile, beige torzal yarn bobbin, UHU universal glue, Adedul plywood (1.2mm), galvanized cable, nickel eyelets 10/0L, and corrugated micro flute cardboard. In the following lines we explain with visual examples the prototype.

Figure 78 shows how the fabric pattern shows the triangular piece and how to sew the sides. Figure 79 presents part of the cable modeling to realize a cable-fabric joint . Figure 80 provides a test of how the selected Essetial 5 and Tensiline fabrics look on the piece, offering an exciting insight into their contrasts within the design.

Figure 81 shows the wood structures of the prototype, allowing the viewer to appreciate the model's intricate detailing and structural integrity. The wood roof fixation of the prototype is further examined in Figures 82 and 91, providing a detailed understanding of this critical element of the construction.

Figures 83, 88, and 89 offer a close look at the prototype's pulley and awnings and the change of cable direction, revealing the intricate mechanisms that enable the structure's functionality. Figure 85 showcases the joining of the beam and triangular form, a crucial aspect of the design, contributing to the prototype's stability and aesthetic appeal.

Lastly, Figures 86 and 87 depict the front and lateral facades of the prototype, respectively, giving the viewer a comprehensive view of the prototype's exterior. Figure 90, a shadow projection study, illustrates the effective shading capabilities of the prototype, underscoring its potential utility in outdoor spaces.

.**Figure 78.** Test piece pattern and sewing of the canal.

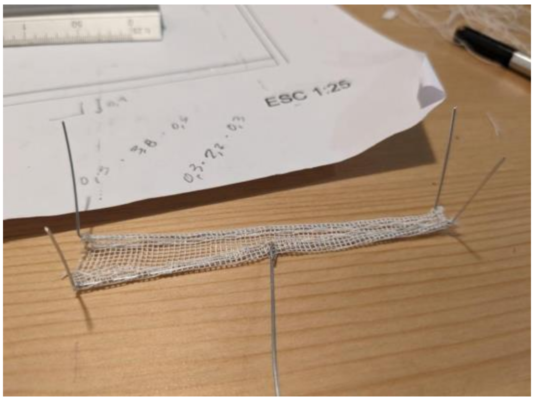
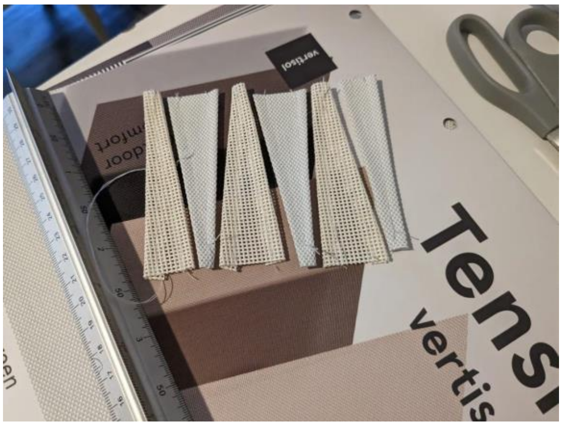
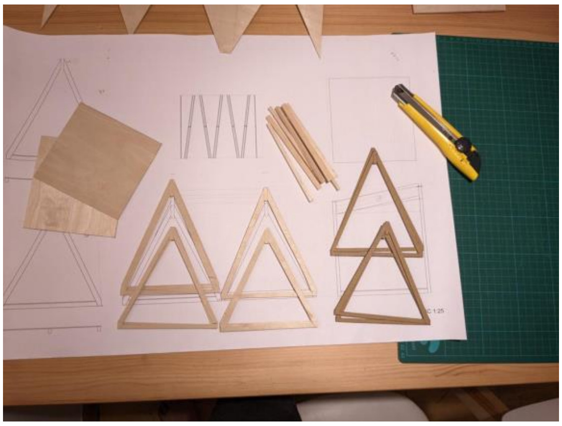


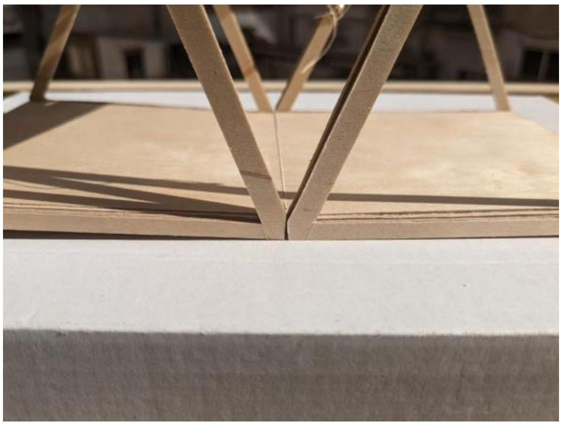
Figure 79. Handmade modeling of the wire to make the joint piece between fabric and cable.



.**Figure 80.** Image of the both types of textiles toguether.



.**Figure 81.** Wood structures of the Prototype.



.**Figure 82.** Wood roof fixation of the protoype.

Figure 83. Detail of the prototype on the pulley and awnings

Figure 84. Wood roof fixation of the protoype.

Figure 85. Joining of beam and traingular structure.

Figure 86. Front facade of the prototype

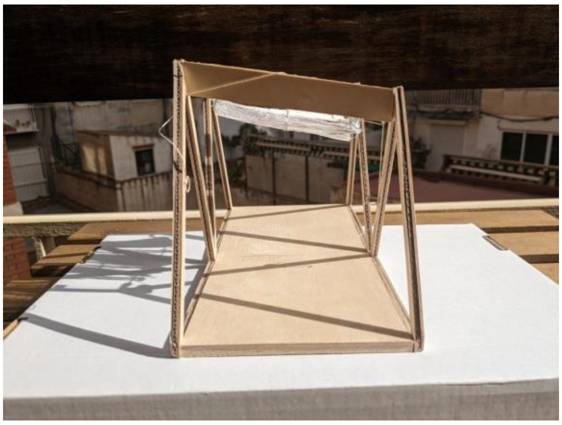


Figure 87. Lateral facade of the prototype

Figure 88. Detail of pulley and change of cable direction (I).

Figure 89. Detail of pulley and change of cable direction (II).

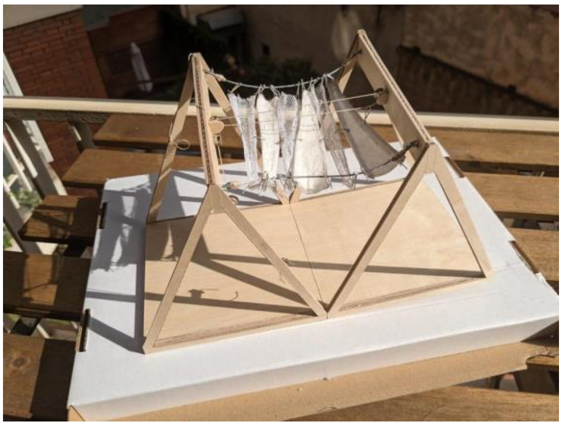


Figure 90. Shadow projection study (I).

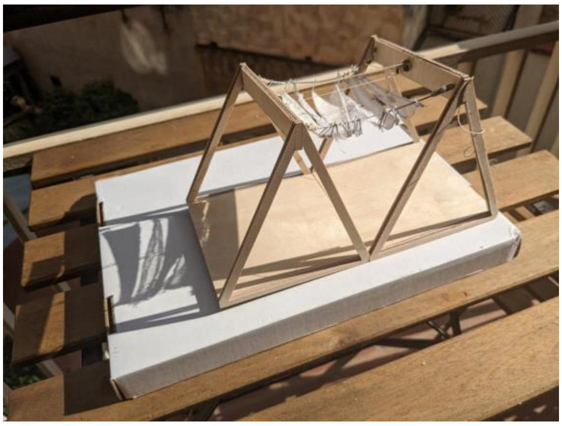


Figure 91. Wood roof fixation of the protoype (2).

7 Budget summary and financial feasibility study

We have divided the budget into four main sections: staff expenses, model materials, model tools, and global budget.

7.1 Staff expenses budget

The project's financial feasibility relies primarily on two key components: research development and project management, as shown in Table 12. In the following paragraphs, we describe the global budget table.

Research development is assigned to an architect intern, costing €8 per hour for 300 hours. This results in a total expense of €2400. The intern's responsibilities include researching, developing the design, and identifying the materials and methods to design textile covers.

Project management is handled by a PhD holder in chemistry and textiles. Their role, costing €70 per hour for a projected 100 hours, sums up to €7000. This role oversees the project, ensuring it stays on time, within budget, and meets performance targets.

The initial budget for these two components amounts to €9400. While this upfront investment may seem high, the durability and sustainability of the proposed textile covers can lead to long-term savings in maintenance and replacement costs. Thus, the overall financial feasibility of the project appears promising, despite the substantial initial investment.

Table 12. Staff expenses budget

Role	Category	Price (€/h)	People	Working hours	Total (€)
Research development	Architect intern	8	1	300	2400,00
Project management	PhD in chemistry and textile	70	1	100	7000,00
				TOTAL	9400,00

7.2 Budget of the model materials

The proposed model for the textile structure cover involves several materials, each contributing to the overall functionality and durability of the cover. As detailed in Table 13, the budget for this model is quite economical, further enhancing the project's financial feasibility.

To start, 0.5 meters of Insect screen material will be used, priced at €4.2. The exact quantity of Fliselina Vilene C/White material, which costs €2.28, will also be included. Next, one unit of Beige torzal yarn bobbin will be required for the project, costing €4.2, and one Balsa wood board measuring 10x100cm, costing €8.6. Additionally, a unit of UHU universal glue, priced at €4.5, will be utilized to assemble the structure. Two units of Adedul plywood, each 1.2mm thick, costing €23, will also form part of the model. A galvanized cable will be used, priced at €3.1, along with 25 units of eyelets, priced at €3.7. Lastly, a corrugated cardboard microflute measuring 600x1000mm crafted from Kraft material will be used, priced at €2.65.

The total cost of materials for the textile structure cover model comes to €56.23. This budget-friendly approach not only adds to the project's financial feasibility but also reflects the project's commitment to sustainable and economical design practices.

Table 13. Model materials budget

Quantity	Materials	Price (€)
0,5m	Insect screen	4,2
0,5m	Fliselina Vilene C/White de 90cm	2,28
1und	Beige torzal yarn bobbin	4,2
1und	Balsa wood board 10x100cm	8,6
1und	UHU universal glue	4,5
2und	Adedul plywood 1,2mm	23
1und	Galvanized cable	3,1
25und	Eyelets 10/0L. Nickel S/A S/Toquel. Diam.4,5mm	3,7
1und	Corrugated cardboard microflute 600x1000mm Kraft	2,65
TOTAL		56,23

7.3 Model tools budget

In addition to the materials, specific tools will be required to construct and assemble the textile structure cover model, as shown in Table 14. These tools are necessary to ensure precision, efficiency, and safety during construction.

A pair of flat pliers is needed, priced at €4. This tool helps grip and manipulate materials during assembly. Diagonal cutting pliers are also included, costing €13.5. They provide the capability to cut materials precisely and safely. A cutter, priced at €8.3, is another essential tool for accurate material cuts. A scalimeter, costing €8.6, will ensure precise measurements throughout the construction process. Finally, a cutting map with dimensions 450x300mm is necessary for protecting surfaces during cutting tasks. It is priced at €12.7.

The total cost of these tools amounts to €47.1. The selection of these tools was made to ensure the efficient, safe, and high-quality assembly of the textile structure cover model. While these costs contribute to the initial project budget, these tools can be reused for future projects, providing value over time.

Table 14. Other model tools.

Tools	Price (€)
Flat pliers	4
Diagonal cutting pliers	13,5
Cutter	8,3
Scalimeter	8,6
Cutting Map 450x300	12,7
TOTAL	47,1

7.4 General budget

The overall budget for the textile structure cover project includes several categories: the cost of tools, materials, and personnel, an activity budget, energy supply costs, and a contingency allowance, as detailed in Table 15.

The cost of tools necessary for assembling and constructing the textile covers is €47.1. The materials required for the project amount to €56.23. The largest budget share is allocated to personnel, including research development and project management, totaling €9400.

The activity budget, which includes all other costs associated with the project activities, is estimated at €9503.33. This budget accounts for additional expenses that may be required to ensure the successful execution of the project.

10% of the activity budget, which amounts to €950.333, is allocated for the energy supply. This provision accounts for the cost of water and electricity required during the research and production phases of the project.

The subtotal for the project, not including contingencies, stands at €10453.663.

Given the potential for unexpected costs or overruns, including a contingency allowance in the budget is prudent. An amount equivalent to 3% of the subtotal, which equates to €313.60989, has been set aside for this purpose.

Therefore, the total projected cost of the project, accounting for all factors and contingencies, is €10767.27289. This comprehensive budgeting approach ensures that all potential expenses are considered, promoting financial feasibility and successful project completion.

Table 15. General budget

Cost type	Total price (€)
Tools	47,1
Materials	56,23
Personal	9400,00
Activity budget (P.A.)	9503,33
Energy supply (10% of P.A.)	950,333
Subtotal TFM	10453,663
Contingencies (3% of Subtotal TFM)	313,60989
TOTAL	10767,27289

2.

8 Analysis and assessment of environmental and social implications

Environmentally, the textile covers offer a range of potential benefits. First, the choice of locally sourced materials and more sustainable manufacturing processes could decrease the environmental footprint of these structures compared with traditional practices. This approach might lead to fewer carbon emissions, less waste, and more efficient resource utilization. Also, the design of the pieces like a modular system allow to replace the piece without trashing all the meters of fabric and the material selected have a high resistance with large durability.

Second, the resilience of these textile covers to varying weather conditions makes them a potentially effective response to the challenges of climate change. Their adaptability could ensure they provide shelter and shade amidst fluctuating weather patterns, highlighting their role in enhancing climate resilience.

Socially, the textile covers could improve public spaces by providing efficient shade and shelter, making these spaces more inviting and conducive to social interaction and community engagement. In addition, the visible application of these eco-friendly covers could raise public awareness about sustainability and climate change. Such sustainable structures in public spaces might encourage individuals to consider the environmental impact of everyday items, potentially inspiring more sustainable practices within the community.

Lastly, the production of these sustainable textile covers could stimulate local economies. As demand for locally sourced materials and sustainable processes grows, new employment opportunities could arise in sustainable textiles and other related sectors. This approach will benefit local economies and encourage more sustainable industry practices.

9 Conclusions

The implications of climate change, such as rising global temperatures, have highlighted the need for more adaptable and resilient textile covers, such as awnings, in public spaces. The traditional approach to these covers, predominantly static fixtures made from PVC-coated polyester, could be more common in the market with good performance. Their high resistance to weathering conditions makes them durable, which avoids continuous material change or disposal. This small decision in choosing fabric can make a big difference in the long run regarding considerable maintenance, disassembly, and replacement challenges.

The innovative design strategy presented in this master's thesis represents a substantial step toward resolving these challenges with simple design strategies. A modular and foldable textile cover has been created by incorporating eco-design principles and leveraging recent advancements in textile engineering. This design presents a marked departure from the traditional static models and paves the way for new, more sustainable practices in public space design.

Significantly, the strategy includes using locally sourced materials and sustainable manufacturing techniques to produce the textile covers. Combined with the flexible and modular design, these aspects further reduce the environmental impact associated with the textile covers and demonstrate the potential of textile engineering in fostering sustainable practices in public spaces.

The practical application of these principles has been demonstrated through successfully redesigning one of the primary public spaces at UPC-ESEIAAT. This tangible example illuminates the potential for developing more sustainable and adaptable public spaces with textile architecture structures, giving us a glimpse of a promising future.

10 Further proposal

The first step in future research should be to perform a comprehensive study on load and tension. This step is an integral part of refining the design and manufacturing of the textile covers. Understanding these physical characteristics allows the textile covers to perform well under various environmental conditions. These characteristics also provide insights into the durability and stability of the covers under different weather conditions and usage scenarios.

The development of a detailed strategy for cable attachment is a crucial next step, given the modular and flexible nature of the textile cover design. If planned and executed meticulously, this process could significantly enhance the structural integrity and adaptability of the covers. It could also contribute to the ease of assembly, disassembly, and replacement, making these covers more user-friendly and practical for public spaces.

Exploration of potential materials for the textile covers could also become a key focus of future research. Conducting an in-depth analysis of various materials' sustainability, durability, and other essential properties could enable future researchers to provide a broader range of options for textile cover production. This approach could help ensure that the textile covers are environmentally friendly and tailored to suit specific environmental and usage conditions.

Although the current study focused on the specific location of UPC-ESEIAAT, it could be beneficial to extend the scope of research to other geographical areas and climate conditions in future studies. This research might help to establish a more comprehensive understanding of these textile covers' global applicability and adaptability. Consequently, this could ensure the solutions are universally effective, accommodating various environmental and climatic conditions.

Lastly, future research might explore the potential integration of these textile covers with other environmental systems. This integration could include strategies for rainwater collection or solar energy production. Exploring such synergies could yield significant ecological benefits, further enhancing the sustainability of public space design. This is a step towards a more holistic and sustainable approach to public space design, where different elements work together to achieve common environmental goals.

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