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Performance Analyses of Temporary Membrane Structures: Energy Saving and CO_2 Reduction through Dynamic Simulations of Textile Envelopes

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Received: 15 May 2018; Accepted: 10 July 2018; Published: 20 July 2018

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Abstract: The aim of this research, carried out in collaboration with Maco Technology Inc., was to analyse the energy performance of temporary textile structures that are often used to host itinerant events. This paper illustrates the dynamic simulations carried on the Ducati Pavilion, designed by Maco Technology, which hosted Ducati staff during the different stages of the Superbike World Championship. Specific aspects relating to the structural/constructive system of the project were also analysed. The theme of energy saving and carbon reduction is of great importance in temporary and itinerant structures and environmental sustainability in relation to the materials used, storage, re-use, mode of transport and ability to respond efficiently to the climatic conditions of the installation sites is an important aspect. The Ducati Pavilion was modelled and analysed from an energy point of view using Design Builder software. Ways of improving performance were analysed under summer conditions. The paper focuses on the importance of optimizing the performance of textile envelopes: the methodology proposed allows visible savings in terms of energy consumption and achieves good levels of environmental comfort in temporary buildings with low thermal mass structure.

Keywords: temporary structures; membranes; adaptive envelopes; energy saving; CO_2 reduction

1. Introduction

The study presented here is the result of a long-term collaboration between the authors and their respective institutions on the theme of lightweight buildings. The outcome of this research is a new method for assessing the environmental performance of lightweight membrane structures for temporary use. A Ph.D. thesis [1] provided useful insights for this study as it focused on the social and cultural reasons behind these increasingly popular pieces of architecture [2–5]: in almost all of the cases investigated, the lightweight building was temporary in nature and would not otherwise exist in architecture [6]. The majority of itinerant structures used for events are lightweight and often made of coated fabrics which are considered the most lightweight and versatile materials currently available in the building industry [7–12].

A number of articles have been published on the topic of coated fabrics for architectural applications: these studies concern both the structural and mechanical characteristics of these materials, as well as the thermo-physical and optical properties that determine the main, critical points in their application [13–19]. In this study, these properties were considered elements to be exploited and the potential of these temporary mobile structures from an environmental perspective is illustrated.

Indeed, in recent years, lightweight architectural solutions have reflected the shift in focus to the importance of energy saving and environmental sustainability and are considered an alternative to options that use exclusively the envelope mass and therefore its thermal inertia. The European Community has also expressed interest in this theme [20]. The COST Action TU 1303—'Novel structural skins: Improving sustainability and efficiency through new structural textile materials and designs' [21], supported by several members of TensiNet association between 2013 and 2017, successfully brought together researchers and organized academic studies and research on the technological innovation of textile structures and its implications on energy efficiency. Despite the key role of the European Design Guide for Tensile Surface Structures [22], now running for 14 years, information on the environmental implications of membrane applications in architecture is rather fragmentary, sometimes contradictory and limited [23–28].

Coated fabrics for architectural use are of great potential with regards to their optical characteristics (Table 1) [22,29]. These include light transmission in a range of wavelengths, high strength, good durability compared to the life expectancy of a building and re-use, especially in the case of mobile temporary structures. This potential can be developed further by using special coatings that filter sunlight, for example, or incorporate solar and photovoltaic technology [30–33].

When looking at life cycle and energy efficiency of lightweight buildings, membrane performance is of just as much importance as aspects related to the energy consumed in the "Production" phase. In general, building performance is related to the "Use" phase of the structure (Figure 1). The state of the art shows that it is essential to consider both embodied energy and operating energy in the assessment of the overall performance of a building. The importance of this recommendation is even more evident for temporary buildings in which the phases of reconstruction and re-use imply a strict interdependence between the incorporated energy and the operative energy. In fact, the energy consumed in the transportation, related to re-construction process, depends on weight, building materials and the distance between the installation sites (for temporary structures, this is more relevant than the distance from the production site). The same occurs in the "re-use" phase, in which potential, recovery and recycling are independent of the manufacturing and the design of the structure (Figure 2).

Table 1. Typical optical properties of a sample of coated membranes [22].

Materials	Thickness (mm)	Typical Optical Properties (%)				
		Light Transmission	Solar Transmittance	Solar Reflectance	Solar Absorptance	Long-Wave Emissivity
PVC/polyester	0.6	12	10	75	15	86
	0.8	10	5	77	18	86
	1.2	8	4	77	19	86
PTFE/glass	0.6	17	17	72	11	88
	0.9	10	10	70	20	88
Silver coated PVC/polyester	0.7	3	3	72	25	35

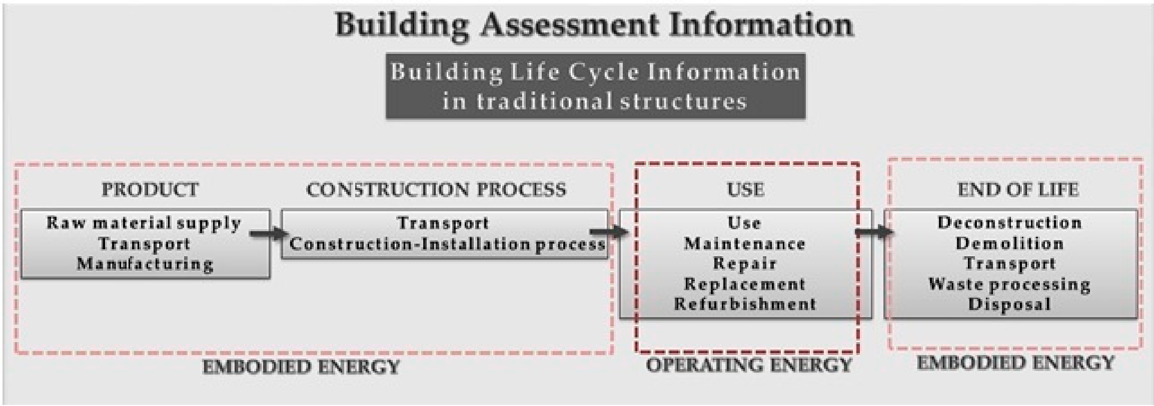


Figure 1. The life cycle of traditional structures.

The paper intends to demonstrate how temporary membrane structures have unexplored environmental potential which is linked to envelope flexibility that can be exploited by optimizing construction technology [34]. A comparison of Figures 1 and 2 shows the potential temporary, mobile structures have in the re-construction and re-use phases. The continual re-use and installation of these structures corresponds to greater energy saving but if the design process is inadequate the opposite is true leading to greater damage to the environment.

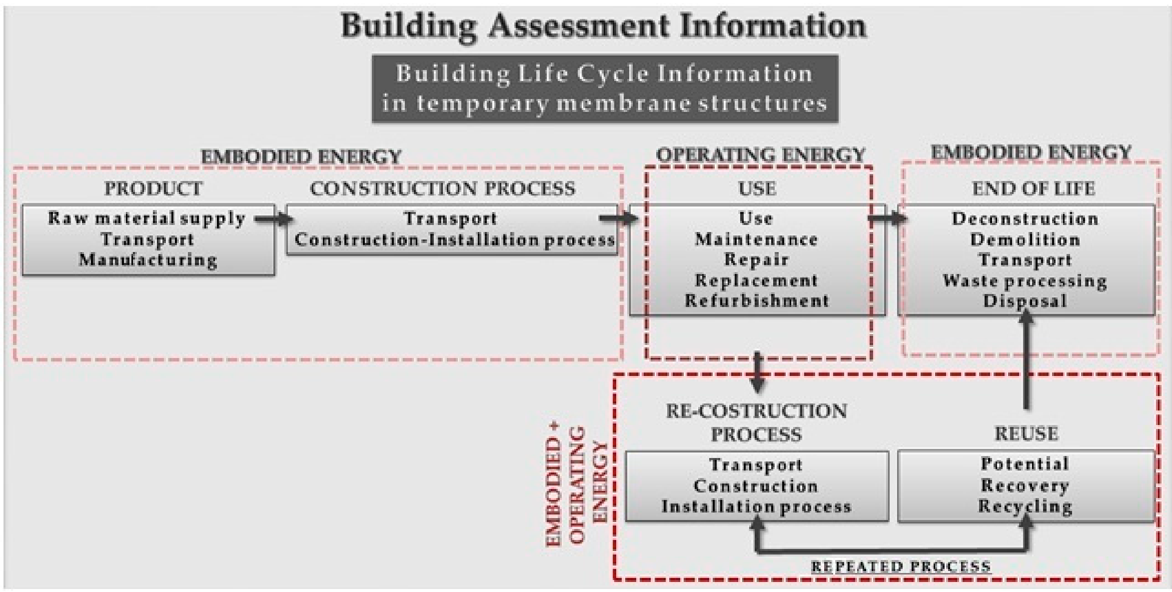


Figure 2. The life cycle of temporary membrane structures.

The design of temporary, high performance architecture involves the analysis of all the parameters that contribute to the achievement of thermal comfort. These parameters can be grouped into four categories: environmental factors (air temperature, mean radiant temperature, relative humidity, air speed), external factors (metabolic rate and clothing level), biological factors (sex, age, biological characteristics) and psychological factors (cultural background, individual expectations). Many researchers have explored ways of predicting people's thermal sensations with respect to their environment based on personal, environmental and physiological variables that influence thermal comfort. Mathematical models that simulate occupants' thermal response to their environment have been developed and most thermal comfort prediction models use a seven or nine point thermal sensation scale.

Two main models exist: the static model (PMV/PPD method) and the adaptive model. The most notable static model was developed by P.O. Fanger (the Fanger Comfort Model), the J.B. Pierce Foundation (the Pierce Two-Node Model) and researchers at Kansas State University (the KSU Two-Node Model). The adaptive model is based on the idea that outdoor climate influences indoor comfort because humans can adapt to different temperatures during different times of the year. The adaptive hypothesis predicts that contextual factors, such as having access to environmental controls and past thermal history can influence building occupants' thermal expectations and preferences [35]. In this work, the Fanger model was used to predict thermal comfort through dynamic simulations carried out with Design Builder software.

In temporary buildings, thermal comfort can be controlled through flexibility of the envelope in relation to the different external climatic conditions in temporary and itinerant buildings and this approach can also help to reduce energy consumption and the production of CO_2 [36]. In other words, temporary architectural structures are adaptable and can respond to changing environmental needs and in this lies potential. As Cremers illustrates in his work, material and building components have a direct impact on building performance and affect the operational energy use as well as the health and well-being of its occupants: the membrane industry needs to quantify these benefits in order to maximize their sustainability credentials [37].

2. Materials and Methods

The methods adopted in this research relate to the creation of textile envelope models for dynamic simulations of the thermal and energy behaviour of lightweight buildings under varying external conditions and geographical locations. The most difficult aspect of the use of Design Builder for lightweight and temporary structures was the construction of highly precise models that reflected the behaviour of the structures from an energetic point of view. This is because Design Builder is a software program designed for analysing the performance of traditional buildings and therefore envelopes of substantial thermal mass. Hence modelling textile envelopes characterized by very low thermal inertia required particular attention to detail. The textile envelope is the main thermal regulator of structures characterized by a single large interior space, as in the case of the temporary pavilion analysed in this work. One of the advantages of analysing pavilions is that it is possible to obtain a reliable prediction of membrane performance as textile envelopes have a direct effect on the thermo-hygrometric conditions of the structure.

New materials were defined for the software library in order to develop a more realistic digital model: the materials were defined starting from the data available for glazed surfaces so they had the same thermo-physical and optical characteristics of the coated membranes used in the actual envelope. Tables 1 and 2 show the characteristics of this material (data taken from the European Design Guide for Tensile Surface Structures) [22]. The software was therefore able to calculate the relevant solar radiation contribution to the internal conditions of the pavilion. The solar parameter is the one that affects the perception of comfort and discomfort the most [22]. The computer simulations investigated the key solar parameters currently used to assess the perception of comfort and discomfort inside lightweight and translucent envelopes [22,38–40]. It includes the ERF (effective radiant field), which describes the additional (positive or negative) longwave radiation energy at the body surface when surrounding surface temperatures are different from the air temperature and the MRT (mean radiant temperature) which describes the surrounding surface temperature of a space.

Table 2. Thermo-physical properties of coated membranes compared with single glazing [23].

Properties	Single Glazing (10 mm)	Coated Membrane (0.8 mm)
Surface density (kg/m^2)	25	1.72
Specific heat (kj·kg^{-1}·K^{-1})	0.72	1.2
Heat capacity (kj·m^{-2}·K^{-1})	18	2
Core conductivity (W·m^{-1}·K^{-1})	1	0.19
Core thermal resistance (m·K·W$^{-1)}$	0.01	0.0042
Total thermal resistance (m·K·W^{-1})	0.15	0.14

2.1. Coated Fabrics for Temporary Applications

Lightweight materials and efficient structural solutions that minimize the waste of resources and reduce the cost of transportation are the focus in the design of temporary pavilions. Owing to the relatively short life span of these pavilions, the use of recyclable materials or materials characterized by a reduced amount of embodied energy are preferable. Coated fabrics and foils are an efficacious alternative to more traditional materials offering more technically and environmentally as well as in terms of level of comfort and safety [19]. The coating is generally applied to both sides and can be one or several layers. The yarns can be woven in different geometrical patterns resulting in different properties, depending on the final use. Woven textiles are the type of fabric most commonly used for architectural purposes; the structure is based on two types of yarns—the warp and the fill.

The coated fabrics and foils used for lightweight envelopes have to satisfy a wide range of requirements which go beyond their basic mechanical properties for example safety, their effect on the environment and the durability of the whole system under expected weather conditions. The most relevant engineering textiles in this field are polyester, PTFE and glass fibres coated with PVC, PTFE, THV or silicone. The same fibres and coatings can be used to obtain open mesh coated fabrics which allow the modulation of the amount of radiation reflected, absorbed and transmitted through different weaving patterns and coatings in façades and roofs designed for solar protection. Finally, transparent envelopes can be easily obtained through the use of clear or fritted foils such as PVC, PE, THV and ETFE [13].

2.1.1. Membrane Envelopes Adopted in the Project: Polyester Fabrics Coated with PVC and PU

Since the early 1960s, polyester has been the fibre of choice in architecture as a result of its cost, mechanical performance and lifespan. Its progressive degradation due to exposure to UV rays and its behaviour in the event of fire are easily improved with appropriate coatings. The fibres are quite flexible and are commonly used in temporary and seasonal structures and thanks to new technology, coated polyester fabrics are now recyclable.

Structures coated with polyvinylchloride (PVC) coating were studied in this project. PVC (polyvinylchloride) is generally used in combination with additives and top-coatings to improve fire behaviour, expected lifespan, self-cleaning properties and colour stability. It can be easily painted or printed on and has a life span of over 20 years.

The material used in this project was a polyester fabric coated with polyurethane and impregnated with a dirt deflecting finish produced by SIOEN. The special coating gives the fabric a distinctive textile character and outstanding technical characteristics (270 gr/mq, tensile strength equal to 230 daN/5 cm in warp and fill direction). Contrary to common PU coated fabrics for biogas and inflatable products, the PU coating in this case was relatively thin and the material had to be stitched. For this reason, the Tensairity® beams used in the Ducati Pavilion project (see Section 3), have an internal airtight bladder made with a PU foil. Due to the issues related to the durability and water tightness of the stitched connection, Maco Technology improved the original cladding with a PVC coated polyester fabric which will progressively become the standard cladding replacing the first generation of structures. For this reason, the model in Design Builder is based on a PVC/polyester fabric. The optical properties of PVC/polyester are widely covered by the current literature in this field and Table 1 shows the optical characteristics of this material provided by the European Design Guide for Tensile Surface Structures, the most reliable source currently available [22].

2.2. Models and Simulation Software

An energetic simulation of a building is a mathematical schematization of its thermo-physical behaviour and the building geometry represents the basis of the initial input data. A model for energetic simulations is simplified in comparison to the architectural model to which it refers: this often generates inaccurate results. However, in the case of the pavilion analysed in this project, the architectural model is very similar to the virtual model and so the results generated are highly reliable. It is worth underlining that curved surfaces cannot be represented in a thermal simulation that is based on one-dimensional heat transfer. Usually an object consisting of curved elements is discretized with a certain number of surfaces: this simplification is also used here. External loads, on the other hand, depend exclusively on the climatic data used in the simulation.

The main objective of energy simulation software is to compare different energy strategies with the aim of optimizing consumption and costs. Many tests have been developed and conducted by the International Energy Agency (IEA) to validate energy simulation tools. Software can be validated using three types of tests:

- Analytical: the software output is compared to the analytical solution of test cases characterized by simplified boundary conditions;
- Empirical: the software output is compared with the data from a real physical construction;
- Comparative: software is compared with itself or with other tools that have already been previously checked and tested.

Empirical validation was used for this research. The procedure chosen for validation can be summarized as follows: the model of a pressure structure used as a sports pavilion was calibrated on the data from a monitoring campaign carried out by Maco Technology in Cotignola, Ravenna.

In order to analyse and compare the effect that the configuration of the textile envelope has on the energy behaviour of a membrane pavilion, two structures, side by side, identical in size, were monitored for a whole season (from 16 November 2013 to 28 April 2014). The structures were the same geometry and orientation but one was had single membrane whilst the other a double membrane with ventilated cavity. Two black boxes (sensors) were installed in the double membrane pavilion, one inside the air space and the other inside the gaming volume. In the single membrane pavilion, the sensors were only inserted in the gaming volume. Each black box recorded data from the following sensors on a microSD:

- Air temperature sensors placed at heights of 1, 2.5 and 4 m above the ground;
- Membrane temperature sensors;
- Relative humidity sensors;
- Pressure sensors.

A weather station with a wind sensor, air temperature and relative humidity was also installed outdoors.

A comparison of the results from the monitoring campaign and the results from the dynamic simulation enabled the validation of the functioning of the textile pavilion model. The textile envelope model used to carry out the dynamic simulations was developed by the authors using empirical data from Cotignola monitoring campaign. In the construction of the model, the pavilions monitored were located in Cotignola (Ravenna), so the relative data was set to the "locality" template (latitude: 44.23; longitude: 11.56; ASHRAE climate zone: 4A; height above sea level: 19.0; wind exposure: normal). The activity template was set to "Dry sports hall," so the software imposed the following input:

- occupancy = 0.0467 person/mq;

- met = 0.90;
- summer clo = 0.50; winter clo = 1.1.

The production systems for domestic hot water were excluded from the calculation, as was the installation of additional machinery in the playing area. The "construction" template was used exclusively for setting the floor because the casing was modelled starting from glass surfaces, which can be managed from the "openings" template: in fact, in "openings" it was necessary to impose the total filling of the surfaces (100% fitted glazing, without frame). In order for the glass to be assimilated to the membranes, an "external project glass" was built. Within the tab of the physical and optical properties of the glass, the values of the designed membrane (PVC/polyester with a thickness of 0.8 mm) from the European design guide of textile structure were used (Tables 1 and 2). The lighting template is automatically generated according to the previously set "activity" template. A heating system powered by the electrical networks was set up for the HVAC template to which natural ventilation was added for the double-membrane pavilion simulation. Since it was not possible to reproduce the typical geometry of the pavilion vaults with Design Builder as it does not recognize Boolean operators, a barrel vault design was chosen ensuring that the surface area through which the pavilion exchanged heat with the exterior was identical to the real area (1195.8 m^2). The period chosen for the simulation was that of a typical week identified from monitoring: 30 December to 5 January. In order to allow a direct comparison between the data obtained through the monitoring and the climate simulation files, it was decided to launch the simulation in the same week of the year. This allowed an accurate assessment of the solar contributions on the structure.

The more relevant results from the empirical validation are given below:

- The internal surface temperature of the membrane differed, between the single membrane and the double membrane structure by approximately 3 degrees both in the monitoring and simulation results, in favour of the double membrane structure. Moreover, during the hottest periods of the day and in correspondence to maximum solar irradiation, the two temperatures of the sheets tended to decrease their ΔT. This singularity was detected in both the monitoring and simulations. This datum is of fundamental importance for the validation of the model's summer behaviour;
- The two relative humidity percentages cannot be compared numerically as the data from the monitoring is the RH% on the membrane surface, in order to evaluate the condensation, while the simulations evaluate RH% in the volume. In any case, both the monitoring and the simulations show how the double membrane achieves relative humidity values suitable for comfort (30% < RH < 70%), unlike those of the single membrane pavilion for which the relative humidity values fall outside the comfort zone both in the simulations and monitoring;
- The temperature when HVAC system is off, was stable with a difference of approximately two degrees in favour of the double membrane structure for both the monitoring results and the simulations.

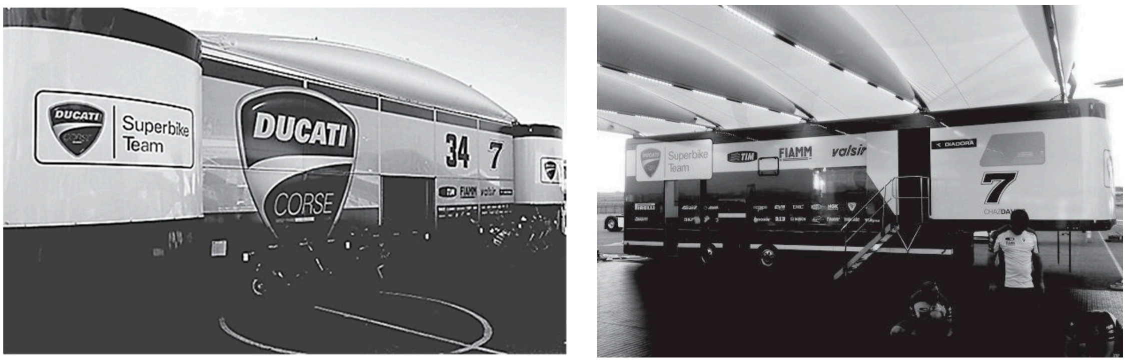
From the analysis of the results obtained during the empirical validation, the authors consider the model of textile casing reliable [1]. The relevance of this method consists in the possibility of managing the performance of these particular structures from the design phase: in fact, the performance of traveling buildings should be guaranteed whatever the weather or location. The challenge that this study presented was to be able to predict the energetic behaviour of temporary textile pavilions under varying conditions using dynamic simulation software, thus allowing the definition of an optimal envelope configuration for each condition of use. The results of this study are extremely relevant considering that the choice of envelope for temporary textile pavilions is often based on aesthetic aspects and cost whilst adaptive solutions are not yet fully envisaged.

In this paper, the validated model described was adjusted to look at the behaviour of the Ducati Pavilion making it subsequently possible to propose architectural and technological adjustments to improve the pavilion's performance on the basis of its location.

3. Case Study: The Ducati Pavilion

In 2014, the Ducati Superbike Team asked Maco Technology to design a new temporary pavilion to host all the events related to the Superbike World Championship races. The client requested an innovative project characterized by new technology and an end product that distinguished itself in terms of image and performance from the standard solutions currently in use. The fundamental requisites were the assembly speed of the structure, the durability in relation to the different assembly and disassembly cycles and a minimum volume of transport space. The structure had to be able to be installed as quickly as possible by a small number of people and be stored in two semitrailers and to travel thousands of kilometres.

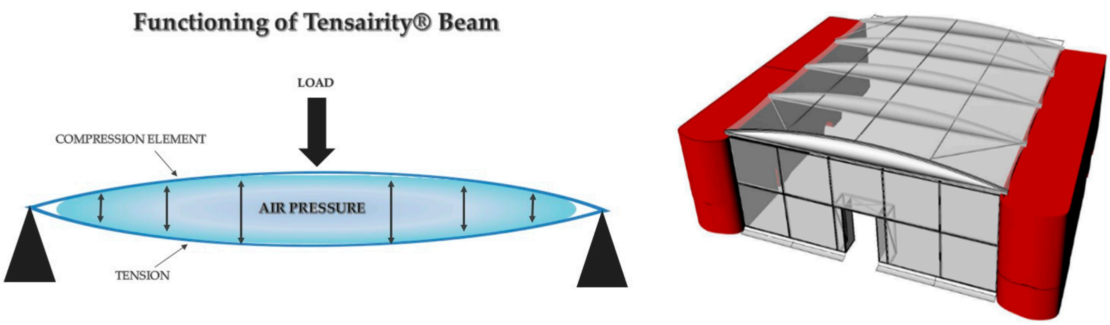
The possible use of cranes for the assembly process was excluded by the client. The first idea put forward was an inflatable pneumatic structure but this solution was discounted by the client as similar structures were already available on the market. However, the use of a pneumatic beam, made by Tensairity® (Brescia, Italy) responded adequately to the client's advanced requirements, representing a valid alternative from an aesthetic and functional point of view (Figure 3) [41–43].



(**a**) (**b**)

Figure 3. The Ducati Pavilion: (**a**) Main façade; (**b**) The internal perspective.

Tensairity® technology is an evolution of pneumatic beams. The Tensairity® principle combines a pneumatic membrane chamber with compression elements (steel, wood or aluminium profiles) and traction elements (cables or profiles that work in traction). The system, pre-tensioned thanks to the inflation of the inner chamber, also transfers compressive or tensile forces, making all the materials work efficiently (Figure 4).



(**a**) (**b**)

Figure 4. Tensairity® Beam: (**a**) The functioning scheme of a pneumatic beam [41–43]; (**b**) Example of Tensairity® beams mounted on semitrailers.

The main idea behind the Tensairity® beam is to combine the lightness and simplicity of a pneumatic beam with the load-bearing capacity of a reticular structure. The result is a load-bearing element that can weigh between 30% and 60% less than traditional trusses. With the same weight, a Tensairity® beam can cover wider spans than a traditional truss. The first Tensairity® structure developed has the shape of a cylindrical beam, where the inflated inner space is reinforced with a strut and two cables. The cables spiral around the air chamber and are connected at both ends to the strut. The air pressure holds the cables and stabilizes the strut against deformation, optimizing the use of the materials in relation to their mechanical performance. Tensairity® beams occupy a much-reduced volume compared to traditional structures for transport and are easily assembled and dismantled. The Tensairity® system can be applied to beams and pilasters but also to arches. The products that can be produced are therefore flat or curved roofs, bridges, military field tents and generally, large structures.

The Ducati Superbike Hospitality Pavilion consists of two semi-trailers and a Tensairity® inflatable roof that connects them. The five beams are made of fabric coated with polyurethane to ensure maximum translucency to light. The pavilion is designed to cover the distance between two trucks parked at a distance of 12 m (Figure 5). The roof consists of a series of 5 Tensairity® asymmetric spindle-shaped girders of 12 m span inflected at low pressure (150 millibar) able to withstand load generated from winds at 27 m/s. Standard aluminium profiles are used as tension and compression elements. The inflated hull is made of a 270 g/m^2 PU coated polyester fabric that combines good structural properties with high translucency. The beams, once deflated, can be stored in one piece, on the top of one of the semi-trailers without the need to detach the hull from the aluminium section. The 156 m^2 roof together with the front and back façade can be set up by a crew of 5 people in 6 h or less.

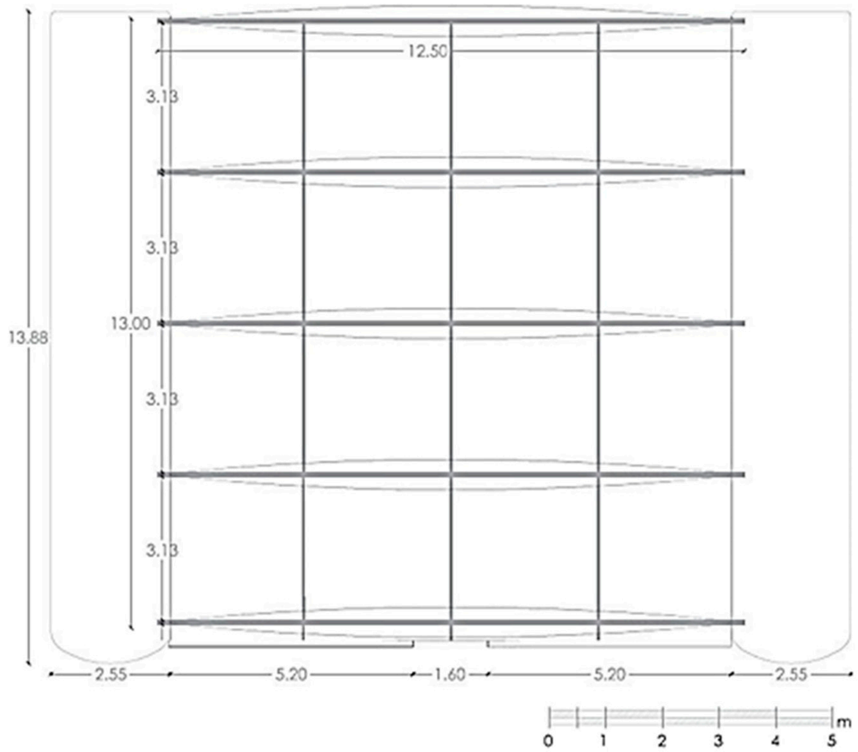


Figure 5. The Ducati Pavilion project: the plan.

All Tensairity® girders can incorporate a RGB-LED lighting system to light the area underneath the roof but also to light up the beam itself (Figure 6). The system is controlled by an app which allows users to modify the lights through a smartphone. The blower, which compensates for the loss of air due to temperature shifts, is programmed to keep the pressure of the beam within the design pressure range. It can also be controlled remotely: in this case the hospitality team is equipped with a sim card connected to a 3 g internet network. It is possible to connect to the control panel from anywhere and modify the pressure of the beams, check the operating times of the blower and the last inflation ramp. The blower can be remotely programmed to "Standard," "Strong wind" or "Deflation" modes.

Figure 6. Images of the Tensairity® beam used in the Ducati Pavilion.

4. Dynamic Simulation of the Ducati Pavilion

This section looks at the analysis of the thermal comfort of the Ducati Pavilion and its environmental behaviour through the estimation of CO_2 production. The analyses relate to different enclosure configurations and the simulations were made considering European climate zones.

4.1. Construction of the Ducati Pavilion Model

The internal volume was treated as a single thermal zone and the following input were used:

- Localization: Oslo; Milan; Catania.
- Metabolic rate: 1.6.
- Winter Clothes: clo = 1.
- Summer Clothes: Oslo clo = 0.5; Milan clo = 0.4; Catania clo = 0.4.

The following geometrical and material characteristics assigned to the model:

- The curvature of the beam was treated as a single plane surface of 156 m^2 in coverage;
- The membranes were constructed from glazed surfaces and their properties modified so as to make the glass in the software library having the same thermos-physical characteristics as the textiles actually used for the envelope. In addition, the simulations took into account solar gains due to the translucency of the roof.

The characteristics of the PVC/polyester (0.8 mm thick) are the same as those used in the validation process described in Section 3 and shown in Tables 1 and 2. Modulating the thermos-physical and optical characteristics of the covering system allows the simulation of a range of alternatives for the configuration of the envelope: the software allows the overlap of different membrane layers and a constant air gap; it is also possible to compare performances under different climatic conditions. The optimizing process of the textile building enables the user to see the advantages of using coated fabrics compared to the more traditional membrane envelopes in PVC and to identify under which conditions the latter can be still recommended.

4.2. The Dynamic Simulations

The following outputs from the dynamic simulations were analysed:

- internal operative temperature (average indoor air temperature and the radiant temperature);
- Fanger PMV and PPD indices (Predicted Mean Vote and Predicted Percentage Dissatisfied, calculated according to ISO 7730);

- hours of thermal discomfort (the number of hours under which the combined effect of relative humidity and operating temperature are not within the comfort region, according to ASHRAE 55 2004);
- CO_2 emissions calculated from total fuels.

4.2.1. Analyses of a Traditional PVC Envelope with HVAC System

The first simulation analysed the configuration of a single PVC layer for the roof and polycarbonate panels for the façade. The walls of the pavilion in contact with the two semi-trailers were modelled as adiabatic surfaces because the air temperature is the same in both spaces (the doors separating the semi-trailers and the pavilion are always kept open and moreover, when the HVAC system is operating, it keeps the environments at the air same temperature).

The pavilion was analysed for three different European climatic zones: Catania (climate zone B and Csa according to the Köppen climate classification), Milan (climate zone E according to the Italian system and Cfa according to the Köppen climate classification) and Oslo (Dfb according to the Köppen climate classification). Clearly, the use of heat pumps to ensure comfort conditions results in different production levels of CO_2, which varies not only according to the season but also to the climate zone.

Table 3 shows how the HVAC system maintains operating temperatures in a range between 20 and 25 degrees for all the climatic zones analysed, close to the "comfort zone" for the entire simulation period. This result is confirmed by the discomfort hours values that, in the hottest months, range from 82 in Oslo to 110 in Milan and according to the Fanger Index PMV between the values +0.5 and −0.5 (Table 4). In this first simulation, the HVAC system is the main thermal regulator of the pavilion, so it was necessary to evaluate its performance in terms of comfort and environmental cost in a traditional membrane structure in PVC and then compare the performance results with the adoption of different casings.

Table 3. Comparison between the monthly average of operative temperature values and discomfort hours for the three locations analysed.

	Operative Temperature (°C) January	Operative Temperature (°C) July	Discomfort Hours_January	Discomfort Hours_July
CATANIA	20.3	24.8	250	110
MILANO	19	25.2	362	140
OSLO	20.1	23.8	363	82

Table 4. Comparison of the monthly average of the Fanger Indices values and CO_2 production for the three locations analysed.

	PMV_January	PMV_July	PPD_January (%)	PPD_July (%)	CO_2_ January (Kg)	CO_2_July (Kg)
CATANIA	0.38	0.6	8	12	1730	5950
MILANO	0.18	0.58	6	12	4150	5550
OSLO	0.25	0.25	6	6	4150	3000

Index values correspond to huge CO_2 production with peaks of over 5000 kg for the month of July in Catania and Milan. Whilst in winter, the low thermal mass of the envelope determines huge CO_2 production in the colder cities of Oslo and Milan.

From an environmental perspective, Figure 7 shows that the most critical period of the year is summer, with peaks in the production of CO_2 on the hottest days, in particular in the city of Catania. This analysis confirms the accuracy of the model and that higher levels of CO_2 production are directly related to a greater use of air conditioning systems. For this reason, it is essential to identify an energy retrofit solution for the containment of CO_2 production caused by the over-use of HVAC in the summer to maintain an adequate level of comfort in the structure.

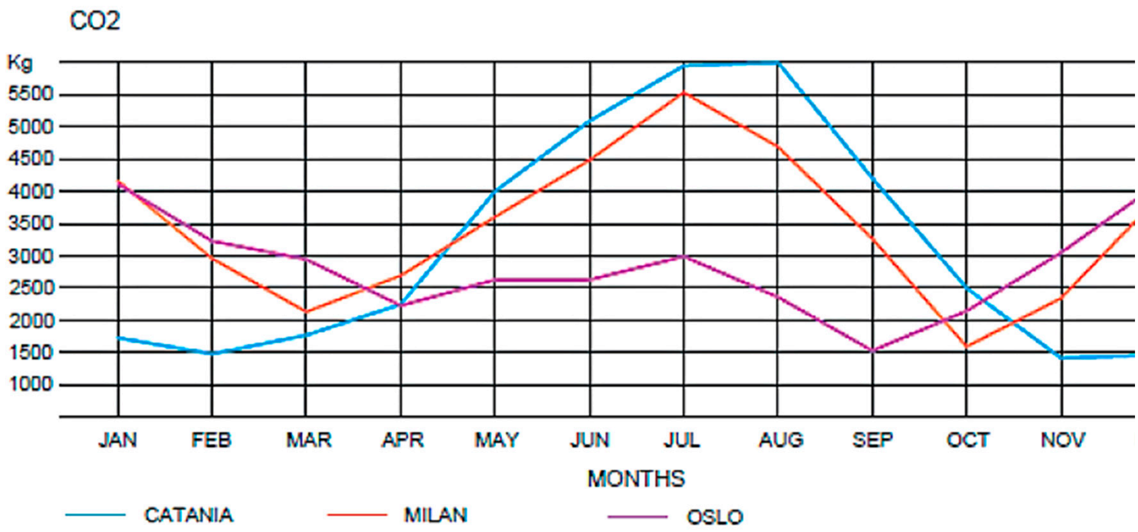


Figure 7. Graph of monthly average of the CO_2 production curves in the context of Catania, Milan and Oslo.

Figure 8 shows that in temperate climates, despite the usage of HVAC systems, a traditional membrane structure based on one layer of PVC in the hottest months does not fall in the comfort region of the psychrometric chart, according to ASHRAE 55 2004.

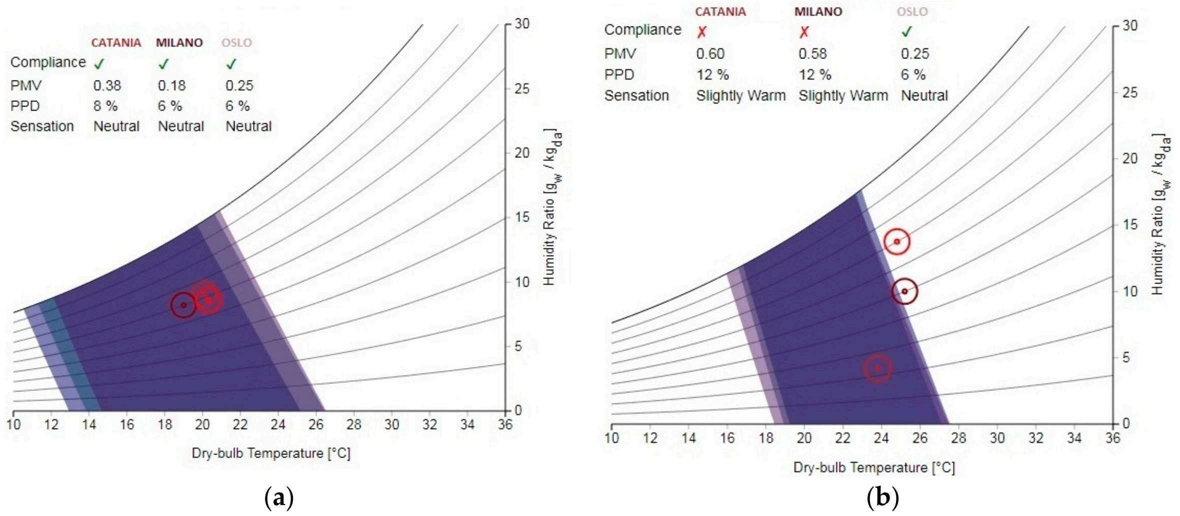


Figure 8. Psychrometric chart of Ducati Pavilion based on one layer of PVC and operative HVAC system: (**a**) January behaviour; (**b**) July behaviour (charts produced using CBE Thermal Comfort Tool).

The purpose of this work is to evaluate the changes in the structure's behaviour from an environmental point of view with the modification of the envelope configuration (different materials and/or multi-layer casing). Given the results of the simulations on the environmental behaviour of the structure in different envelope configurations, it is possible to choose, in accordance to location and season of use, a solution to optimize the building performance in terms of internal comfort and energy saving.

4.2.2. Temporary Retrofitting Solutions: Model Construction and Dynamic Simulations

The next step focused on how to find a solution to the complex problem of how to prevent summer overheating thus guaranteeing ideal comfort conditions at minimal environmental cost. Envelope solutions were designed for the period between April and October, the period when these structures are also most typically used. Simulation outputs covering the entire year were also studied in order to obtain feedback on the behaviour of the structure even in the colder months.

Two different scenarios were analysed:

- Case 1: the pavilion is equipped with an air treatment system (the Design Builder HVAC template is completed), so the energy performance optimization must necessarily focus on sustainability issues related to CO_2 production;
- Case 2: the pavilion is not equipped with an air conditioning system (the HVAC template of the software is left empty), the optimization of environmental performance focuses on achieving adequate levels of thermal comfort.

In each case, the behaviour of the envelope was simulated using a single and then a double PVC/polyester coated fabric layer with a steady air gap (Figure 9).

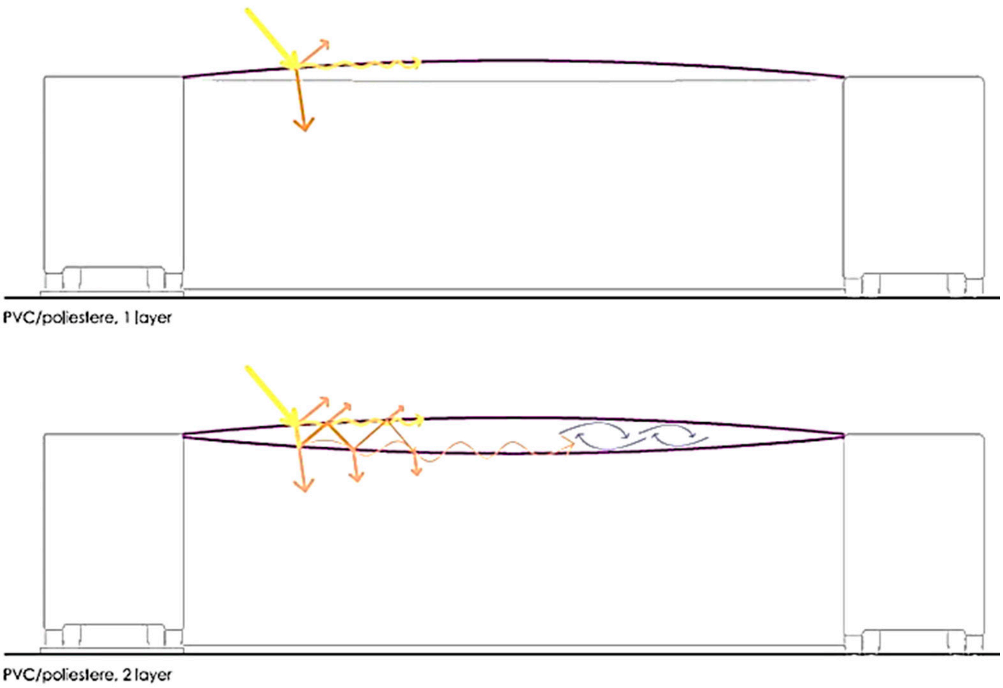


Figure 9. Diagram showing heat transmission modes in the coverage configurations analysed: orange lines relate to solar transmission toward the membrane, blue lines represent the steady air gap.

The following simulation outputs were analysed for the two cases described above:

- Case 1: Fanger Index PMV and CO_2 production to evaluate the environmental impact of HVAC systems;
- Case 2: Operative temperature, hours of discomfort and Fanger PMV and PPD indices to evaluate in the absence of air conditioning systems, how different envelopes configurations impact on thermal comfort.

To tackle the issue of summer overheating, simulations were carried out in the most problematic climatic zone-the city of Catania. The first simulation performed in this second series of analyses focused on the performance of PVC casing, a double PVC membrane with a 50 cm chamber of steady air, a single PVC/Polyester membrane and a double PVC/Polyester membrane with a 50 cm chamber of steady air. These analyses clearly demonstrate that the variation in CO_2 production depends not only on the season but also on the type of membrane chosen for the envelope. As expected, the HVAC system provided a good level of thermal comfort for each configuration analysed, as Figure 10 shows.

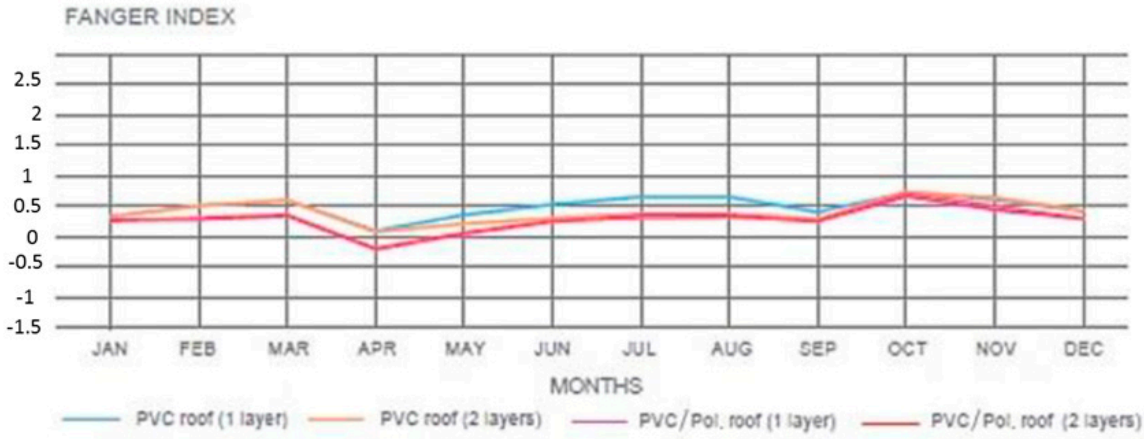


Figure 10. Case 1: Monthly average Fanger Index curves.

From Figure 11 and Table 5 it is clear that the PVC double-membrane solution is a net improvement to the single membrane, reducing the peak of CO_2 production in the summer months by more than 20%. Whilst the configurations with coated fabrics show a reduction in CO_2 production of over 50% in the case of the double membrane and of 50% in the case of the single layer. The use of a double layer of coated Polyester represents the optimal solution for covering in summer months.

Figure 11. Case 1: Monthly average CO_2 production curves.

Table 5. Case 1: Comparison of the monthly average of PMV Index values and CO_2 production.

	Fanger Index_January	Fanger Index_July	CO_2 Production_January (Kg)	CO_2 Production_July (Kg)
PVC (1 layer)	0.38	0.60	1730	5950
PVC (2 layers)	0.35	0.28	1125	4150
PVC/Pol. (1 layer)	0.30	0.40	2420	2050
PVC/Pol. (2 layers)	0.25	0.30	1600	2250

The graphs in Figures 12 and 13 show the results of the analyses relating to case 2. The impact of different cover configurations on internal comfort without HVAC systems was assessed as this is typical of temporary-mobile pavilions including the Ducati Pavilion. These analyses confirm that the use of a multi-layered configuration is desirable in summer: in fact, a marked comfort improvement was observed in both the case of the single-component fabric and that of coated fabrics such as

PVC/polyester (the Fanger Index approached the zero value). In general, during the summer months, the multi-component fabric proved to be more effective in bringing the Fanger index very close to the relative comfort zone, while in winter the index approaches the zero value for traditional PVC envelopes whether single or double layered (Figure 14).

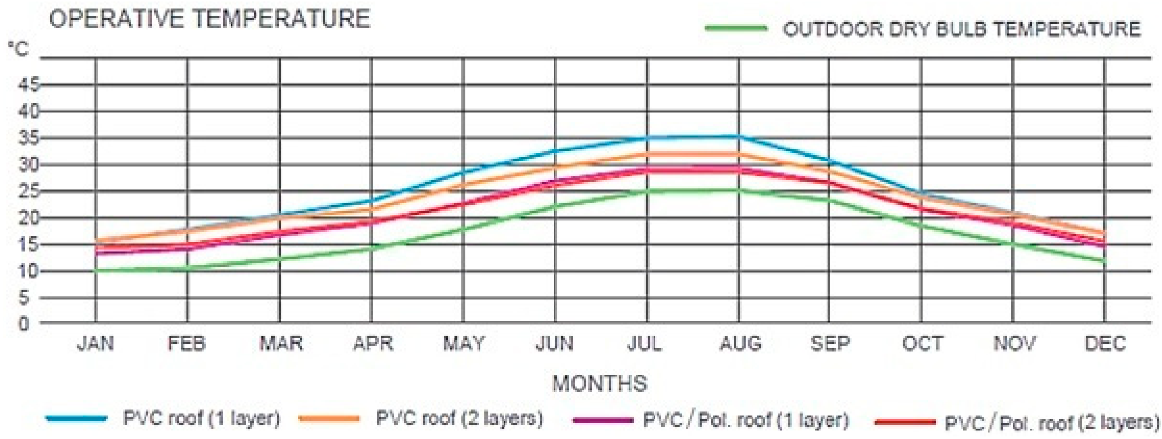


Figure 12. Case 2: monthly average of the operative temperature for the four envelope configurations analysed.

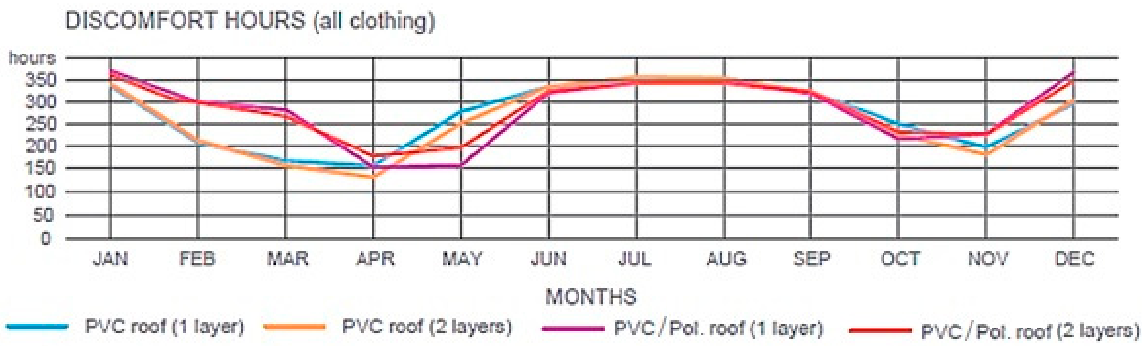


Figure 13. Case 2: monthly average of the Discomfort Hours for the four envelope configurations analysed.

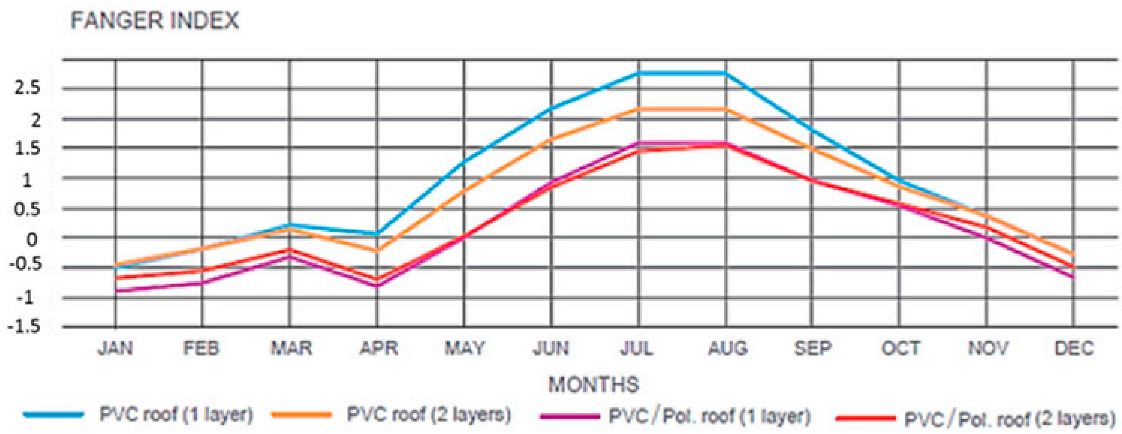


Figure 14. Case 2: monthly average of the Fanger Index for the four envelope configurations analysed.

Tables 6 and 7 show the numerical results of the monthly average simulation outputs relating to Fanger Index PMV, PPD, Discomfort hours and Operative temperature, both in winter and summer period. It is worth highlighting that in January the PVC solution improves the operative temperature by approximately 1.5 °C while in July this improvement ranges from 3 to 7 °C with the coated polyester solution. These results are confirmed by the PPD data: in January, the PVC casing guarantees the lowest percentage of dissatisfied while in July the double layer of PVC/Polyester represents the best envelope solution.

Table 6. Case 2: Comparison of operative temperature values and discomfort hours for the 4 envelope configurations analysed.

	Discomfort Hours_January (Hours)	Discomfort Hours_July (Hours)	Operative Temperature_January (°C)	Operative Temperature_July (°C)
PVC (1 layer)	340	350	15	35
PVC (2 layers)	345	352	15.5	32.5
PVC/Pol. (1 layer)	370	350	13	29
PVC/Pol. (2 layers)	360	349	14	28

Table 7. Case 2: Comparison of Fanger PMV and PPD indices for the 4 envelope configurations analysed.

	PMV_Jan.	PMV_July	PPD_Jan. (%)	PPD_July (%)
PVC (1 layer)	−0.5	2.75	10	97
PVC (2 layers)	−0.45	2.20	9	85
PVC/Pol. (1 layer)	−0.9	1.6	22	56
PVC/Pol. (2 layers)	−0.6	1.45	13	48

5. Discussion

In light of the fact that the Ducati Pavilion which hosts the Superbike World Championship Races, is used most frequently between March and October, the most significant problems relate to the summer period. The analyses show that the level of environmental comfort in these warmer months can be improved with the sapient use of coated-fabric layers. The study analyses the advantage of a double layered membrane structure, where a layer can be added or removed. Double membrane and adaptive covering are systems that are already used for comfort purpose in textile structures. This work offers a methodology that allows designers to quantitatively estimate—using reliable models and a simulation software-the improvement in performance of a double-membrane envelope on the basis of the type of textile used and climatic conditions.

Figure 15 shows potential optimization of the Ducati Pavilion performance. The graph allows us to identify the best covering solutions on the basis of the period of use and in the presence or absence of air treatment systems. A global evaluation of the results also allows us to conclude that in order to use the structure year round, the envelope needs to be adaptable, allowing the installation of a double PVC/polyester covering system without the support of any air conditioning system (Figure 13 and Table 5). The transition between these two solutions is relatively simple involving the removal of the second inner layer in the intermediate seasons or, vice versa, to the assembly of the latter in the warmer months.

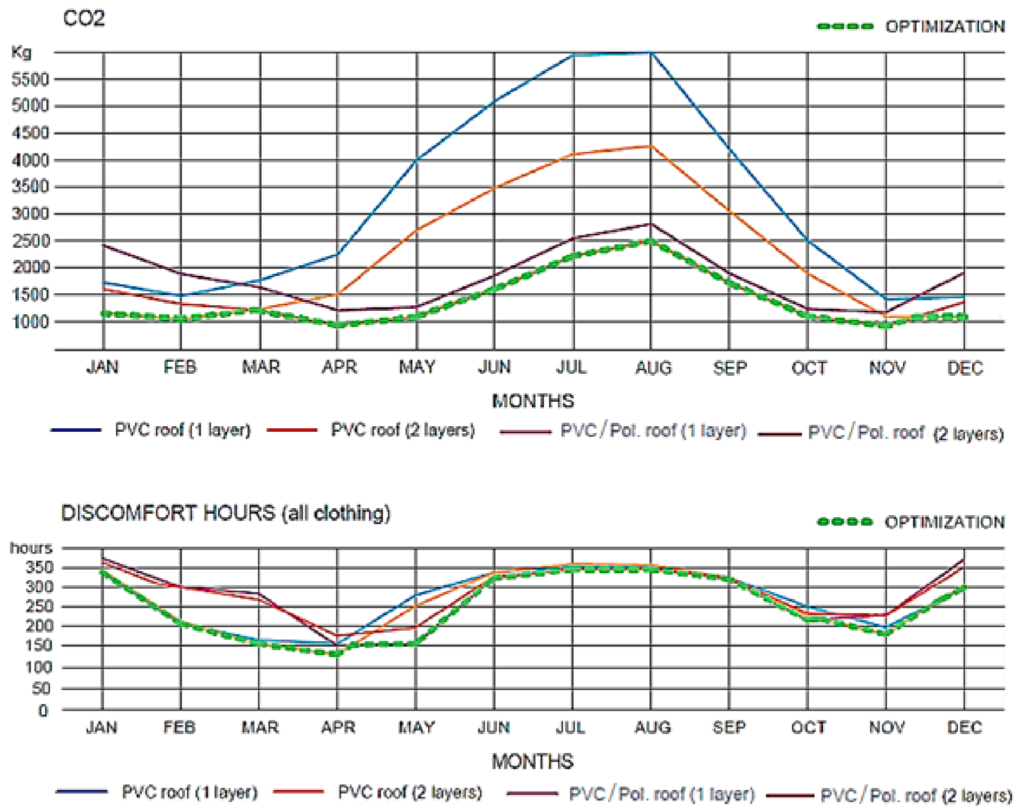


Figure 15. The envelope performance optimization: CO_2 and Discomfort Hours reduction.

From the analyses carried out it is also clear that if the pavilion was equipped with an HVAC system, the use of a permanent double membrane would be the best solution as it considerably reduces the production of CO_2. It is also interesting to note that during the winter season two layers of PVC are recommended, while in the summer optimal conditions are achieved with a two layer PVC/polyester covering system. This difference is due to the different translucency characteristics of the two materials which result in different solar gains within the structure (see Table 1).

Changes in envelope configuration are facilitated by the fact that not only is the structure disassembled and reassembled at each stage of the Superbike World Championship but also and perhaps more importantly, by the fact that the section of the aluminium profile of the pneumatic beam that allows the second membrane to be housed without difficulty, also guarantees an air chamber (approximately 50 cm^2 span between the membranes). The design method outlined here can be used for different locations as the performance of the pavilion varies in relation to the climatic zone.

6. Conclusions

Based on the results of the dynamic simulations presented in this work, we conclude that:

- The use of coated fabrics and membranes that are easily interchanged allows an optimization of the performance of temporary buildings;
- In the case of seasonal use, the design phase can incorporate additional features that favour the period in which the structure will be used;
- The methodology proposed allows visible savings in terms of energy consumption and reduction of CO_2 production;
- The methodology proposed achieves good levels of environmental comfort in temporary buildings with low thermal mass structure.

It is evident that having an adaptive envelope allows buildings that remain in the same place for more than one season, the possibility of changing envelope configuration according to the climatic needs and in respect of the environment.

Author Contributions: M.D.V. designed the research, constructed the models, performed the simulations and wrote the paper; P.B. performed the monitoring campaign and wrote Sections 2.1, 2.1.1 and 3; E.L. wrote Section 1 and produced Psychrometric charts with M.D.V.; P.D.B. supervised the research.

Funding: This research received no external funding.

Acknowledgments: Maco Technology was founded with the aim of incorporating the most up-to-date research into its products. This work arises from a close collaboration with Maco Technology, which provided its products that coincided with the objectives of this project for analysis. The work carried out on the Ducati pavilion, which involved the design of temporary retrofit solutions on an existing structure, was the result of a dialogue between the two parties (academic and business) and the sharing of experiences and ideas.

Conflicts of Interest: The authors declare no conflict of interest.

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