

11th conference of the International Sports Engineering Association, ISEA 2016

The Shaded Dome™: A smart, cool & adaptable facility for sport venues.

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Abstract

Sports are an integral part of human life and their practice is a common pleasure among people all over the world. Once nature does not provide the required climate conditions for that to happen, humans can take action. Based on that concept, a consortium of three Dutch companies (Zwarts & Jansma Architects, Royal HaskoningDHV, and Polyned) presents a sharp, cool and innovative idea that can facilitate sport's industry in desert-covered areas; the Shaded Dome™. The Shaded Dome™ is a semi-permanent facility, comprised of an air-supported dome excluding any internal supports. A very light and highly resistant outer fabric tent (the Shade) covers it, transforming it into an astonishing state-of-the-art building. A grid of cavity struts links the two layers, creating a peripheral structural system that supports the whole structure. A pleasant internal microclimate is enabled by a constant natural airflow between the dome and the shade together with the use of a custom made combination of several membrane materials. This passive design element provides protection from extreme climatological conditions like solar radiation, wind, high air temperature, humidity and precipitation. The first real-scale models are already under development and the results are extremely encouraging. The current tests show an almost 20°C temperature decline between the dome's skins, reducing consequently the need for high demanding cooling systems. Next to that the Shaded Dome™ requires limited transport volume, and can be constructed and dismantled in a matter of days. Thus, the preponderant fabrication plan promotes the sources' economy, the efficient materials' use, the reusability of the product and the self-support of its energy needs, highlighting that way a new concept on the asset management of future sport infrastructure. Moving into an era where the need for dynamic constructions is becoming more and more intense, the Shaded Dome™ can constitute an easy to build, quick and fit-for-purpose solution which can efficiently meet any sport infrastructure requirements.

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Peer-review under responsibility of the organizing committee of ISEA 2016

Keywords: Shaded Dome™; sport venues; flexible structure; semi-permanent building facility; comfortable indoor environment; sustainability; low-tech materials

1. Introduction

Sports are highly interwoven with human nature, as they constitute facets of human creativity and desire for socialization, expressed in fun, competitive and body-mind challenging activities for more than 4,000 years. The ancient Greeks even, stated that “*a sound mind fits in a sound body*”, pinpointing the great value of sports in a person's spiritual evolution and its principle role in the everyday life of people.

The practice of almost any current sport requires friendly and comfortable environmental conditions, cool temperatures and medium humidity levels, as well as satisfactory lighting and ventilation performance. Unfortunately, nature does not provide the desired conditions at any corner of the planet. Fortunately though, humans can interfere on that “natural inequity” and amend it.

Focusing mainly on areas suffering from excessively high temperatures and high irradiation levels, a consortium of three Dutch companies (ZJA Zwarts & Jansma Architects, Royal HaskoningDHV, and Polyned) came up with an innovative idea: the Shaded Dome™. That simple and clever concept, which has already been granted a European patent, is an eco-friendly, semi-permanent building facility, designed to deliver high-tech solutions and boom the sport's industry of desert-covered countries.

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Key to that challenge is the control of the indoor environment through the targeted selection of designing principles and the development of low-tech building materials.

The purpose of this paper is to describe the way the aforementioned climate control can be achieved and to reveal some of the architectural, structural and sustainability details that make the Shaded Dome™ -- SD in short -- unique.

2. The concept of the Shaded Dome™

2.1. General description

The SD originated from the idea of developing climate-controlled, indoor sports facilities in hot-dominated physical environments, in order to align with FIFA’s sport infrastructure rules and regulations. The granting of FIFA World Cup 2022 in Qatar created a strong need for developing a multitude of indoor training spaces that could protect the athletes from the hazards of long hours exposure to excessive heat. In order to prevent though that Qatar will end up with a multitude of unused sport facilities, this innovative concept was developed aiming to meet that challenge.

The SD thus, was designed in a way that it actually constitutes a smart, cool

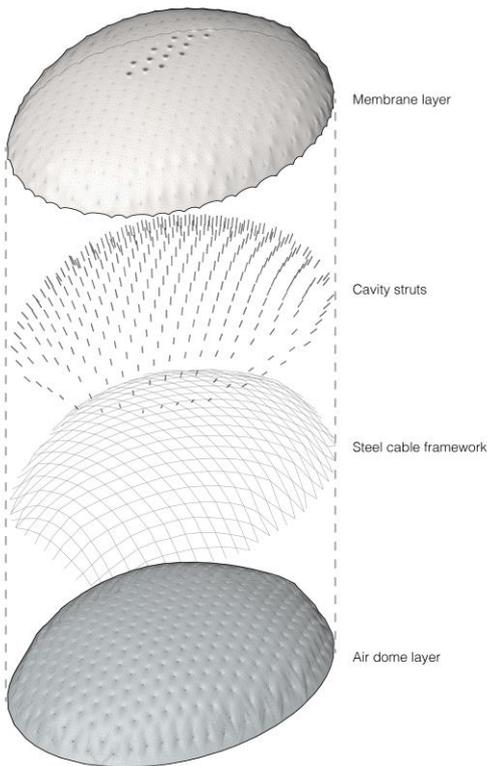


Fig. 1. Diagram exploded view

Fig. 2. Detail from a real-scale model. The cavity pins connect the Dome (lower layer) and the Tent (upper layer)

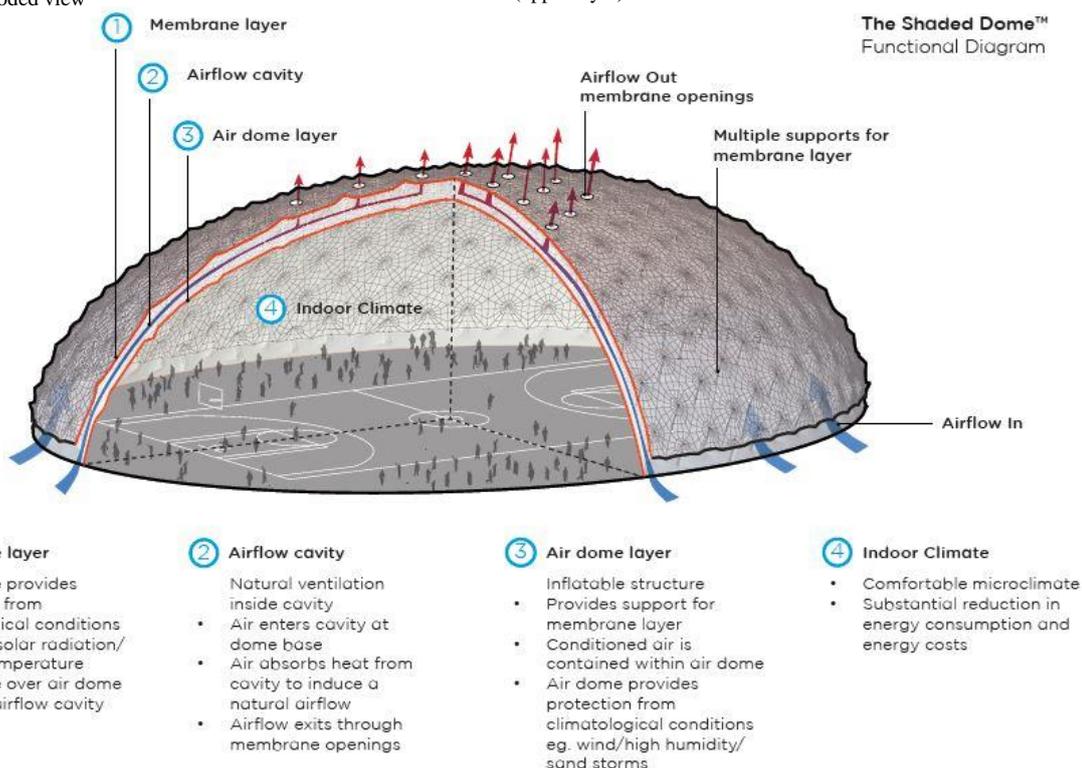


Fig. 3. Functional diagram

and adaptable facility, which meets the highest standards of comfort, sustainability, flexibility, accessibility, safety and security for both its visitors and users, protecting them from the often harsh or unfavourable climatological conditions. To add some more, it is a structure designed to shelter an area of up to 20.000m², while been constructed –on site- within just 2 to 3 weeks.

With regards to the adaptability aspect, it actually applies in a twofold way. Firstly, beside sports, the inner space can be adapted properly, in order to house instance exhibitions and fairs, adding additional light and adjusting the indoor climate, without mayor structural alterations. Secondly, adaptability lies on the concept of the SD itself. Due to the fact that the SD is tailor-made, the concept (the spatial representation) can be easily adapted to fit-specific applications and sizes when designing (see also section 2.3 for a more detailed explanation).

From a morphological perspective it is a semi-permanent building, which is comprised of a pneumatic structure (an air-supported dome), also referred to as Dome, covered by a membrane-form layer (the tent), also called Shade, where the latter is fixated through a steel-cable framework of numerous cavity struts to the former (see Fig. 1 & 2). Consequently, the tent structure and the outer surface of the air-dome are spaced apart at a distance.

By providing the membrane addendum, the internal dome can be shielded from excessive sunshine, wind and precipitation loads. The existing gap between the outer covering layer and the upper part of the air-dome generates heat flow towards multiple openings in the top of the tent. That flow or -better to say- updraft, cools the air-dome externally by dissipating, the generated by sun's radiance, heat (see Fig. 3.). That membrane-like coverage is constructed from easily removable and adaptable elements, meaning that openings can easily be formed or PV-cells will not be hard to get added later on. By doing so, the tent structure can be conveniently adjusted to the desired functionality of the area that it has to cover, and more importantly to the smooth functionality of the air-dome underneath it.

Regarding Dome, it is an isolating and inflatable structure, fixedly attached to the ground through a cable supporting framework, and having a substantially concave shape with respect to its interior. It is mainly constructed by textile membranes, made of coated fibers. Examples include (combinations of) fiberglass and polyester plastics, PVC, PU, PTFE, ETFE and metals such as AISI 304, 316 and galvanized iron. The lightweight materials result in a relative light construction, which allows large spans and lower cost. The aforementioned materials can be combined to create a (coated) fabric or membrane, which is consisted of different layers in order to obtain the required performance. Printing can also applied for producing some of the needed materials.

2.2. Lightweight architecture

The architectural manifestation of the SD is determined by two main factors. The SD originated by the chain integration of architects, engineers and suppliers, taking into account the relevant technical, economic, cultural and ecological aspects that accompanied this venture.

Architecture has always been equated with density and mass, while the use of textiles has often been limited to lightweight decorative expressions; recent developments though in textile technology have revealed their relevance today. Apparently, SD can offer surprising modularity and multi-functionality. It proves to be one of the most tactile expressions, as tailoring techniques find expression in architecture by means of variety of shapes, sizes, diverse colours, textures and finishes. SD can be seen as an interface between sports infrastructure and user's comfort experience on many different levels, resulting in a new model shift in lightweight performative architecture. That new kind of architecture creates advanced possibilities, by harnessing geometric articulation, solar and wind energy, to achieve unprecedented reduction of temperature.



Fig. 4. 3D representation Birdseye view Shaded Dome™



Fig. 5. 3D representation Shaded Dome™ by night

The combination of supply chain management with the unique application of membrane and pneumatic structures provides a vocabulary of architecture with its own character and beauty. The aesthetics of the SD is determined by the rational aspects arising from the different constraints, which are at the same time structural, architectural and ecological determined forming together a whole and being also reflected in the appearance of the SD. The addressing of membrane structures (Tent) and pneumatic structures (Dome) open up new opportunities and prospects in the field of research and development, granting SD an important role to play in shaping (sports) architecture with temporary character, from a both practical and cultural perspective.

The skin of the SD has a distinctive and complex pattern that is generated by using the parametric model for manipulating and interpreting the conditions in a differentiated, varied architectural skin; the composite textile membrane.

2.3. Different Sports Applications

The SD has an unprecedented flexibility in size and shape, allowing thus for a multitude of utilizations, such as travelling exhibitions, market places, museums and entertainment halls, to be covered. It is obvious though that it is exceptionally suitable for the accommodation of various sport venues types, as well as for the sheltering of temporarily needed facilities, due to the benefits of the Dome’s large free-span interior. To make it more tangible, the SD can easily cover a single tennis court (size approx. 700m²) a basketball court (size approx. 860m²), or four tennis courts (size approx. 2740m²), but it could also exceed these numbers and cover an area as large as a football pitch (size approx. 8800 m²), or an athletic track. Its shading capacity however, can be extended even up to 20.000 m², which is large enough to accommodate two adjacent, rectangular football pitches with adequate circumference, according to FIFA standards, offering at the same time a low total cost of ownership.



Fig. 6. 3D representation interior athletic track

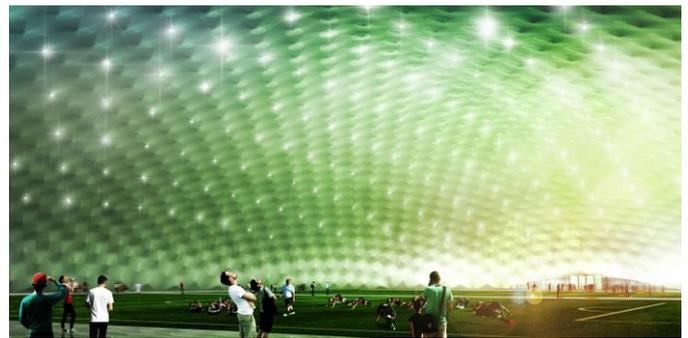


Fig. 7. 3D representation interior football pitch

Of course different combinations of provided sport fields, regarding the nature of the accommodated sports or the number of the necessary courts and pitches are possible. Less demanding sports though, with respect to their needs for temporary covering, such as swimming pools, cycling tracks, baseball pitches or even golf training driving ranges can be also included among the possible applications of the SD.

One of the greatest advantages of the combined air-dome and membrane structure is that no use of heavy rigid elements is needed, That way the SD requires limited transport volume, while at the same time it can be constructed and dismantled within a matter of days, making it particularly suitable for short-duration tournaments and season related activities, especially during summer when the climate can be extremely ferocious.

2.4. Structural concept

The structural concept of the SD operates similar to that of a genuine air-dome, allowing air pressure to act as the main load bearing system, an inner air dome layer covered by a steel cable framework to be responsible for the equal distribution of the arising forces, and multiple tension anchors to undertake the role of its foundations. In addition, the main air-dome’s principle states that an ideal curved shape, with a constant radius, is formed by an air pressure level that is slightly higher than the outer (atmospheric) one.

The double façade system, considering the tent structure and the cavity struts as a unified additional layer, creates a hybrid structural configuration in which both the Dome and the Shade collaborate in search of equilibrium in the forces’ distribution. The curved steel cable framework behaves much stiffer than the outer membrane, compelling the cables to take up the majority

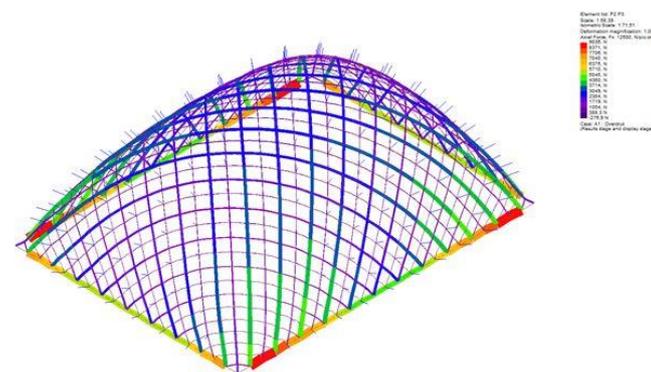


Fig. 8. Forces in the steel cable framework

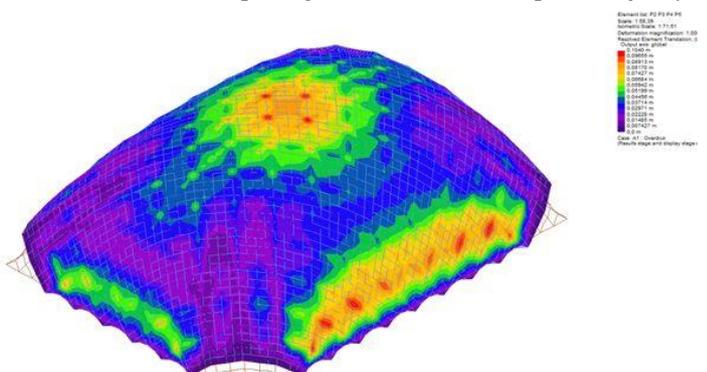


Fig. 9. Deformations of the membrane layer (corner results are removed for calculation purposes)

of the forces and transforming them consequently into the main load bearing system.

The outer skin spans among the cavity struts. The latter are simple pins, hinged connected between the two layers in order to ensure the required cavity width. A wide variety of materials can be used for the production of struts, such as steel, wood, aluminium or fibre reinforced composite.

A double curved shape of the outer membrane layer is realized through specific confectioned cutting patterns, creating thus a certain pre-tensioning in the tent. This technique ensures not only sufficient stability for the struts, but it also prevents the membrane layer from wrinkling or rattling.

Among various load cases (i.e. inside LED lighting, sand), the critical load case for the SD is the wind load, due to its limited mass and its excessive bumping surface. This load case eventually dictates the membrane thickness and cavity strut profiling. The membrane stresses and forces that act in struts and anchors are calculated for a range of wind loads, according to various international standards, making the SD location independent.

The structural analyses are partly executed by self-programmed FE (Finite Element) software for membrane elements and they are part of the in-house computational design strategy. For validation purposes, full 3D analyses are executed to aim for accurate results in terms of stresses, forces and displacements of each unique SD case.

2.5. Computational approach towards design of The Shaded Dome™

Architecture nowadays involves constant evaluation and development of the design, addressing it best as design processes. Designers need constantly to adapt and redesign elements in order to express more effectively the requirements of a particular brief. The computational design approach provides the architects with much greater freedom, in terms of form research and shaping, granting them simultaneously a constraint-based environment to work into. In addition, the design itself can be subjected to structural, environmental and cost valuation with an increased level of certainty as it matures. Most importantly though, the computation design can aid both the client and the designer to explore a far broader solution space as quickly as possible within a specific requirement, having a wide range of engineering aspects already worked out simultaneously.

This approach makes design process considerably more streamlined and efficient. The design is evolved by using in-house developed parametric software scripts that can produce various digital schematics. Following that method the designers can acquire and maintain complete control over the manipulation of complex geometries produced for the SD. Parametric approach also allows the former to simultaneously generate multiple iterations of the SD within a single digital model, based on functional requirements to be housed within. The digital generation of these parameters permits the design to be sufficiently malleable, allowing the smooth adaptation of the dome to contrasting typologies, which can range from sport fields to public expos and museums.

Each iteration effort can be easily and quickly tested, adapted and optimized, in order to meet all necessary functional requirements, environmental performance and structural criteria, singling out thus, the design that can be the most suitable. Once the designer is satisfied with the outcome, on the pressing of a button, he can generate the specifications of strut elements and textile's cutting patterns for both the inner inflatable dome and the outer tent. By doing so everything is ready to be tailored, uniquely numbered and tagged for fabrication and on site assembly.

3. Climate and sustainability

3.1. Climate and thermal principle

The concept of the SD is to create a shade with a passively ventilated air gap around the tent. The sun heats the tent and the air gap. Hot air rises to the top and this draft strengthens, taking much of the thermal energy out. This creates a temperature on the tent surface which is similar to outside temperatures. During cold nights, on the other hand, the air flow slows down and acts as an insulating layer, reducing heating needs. This is an ancient principle of cooling, but has thus far never used in larger (air-supported) tent structures.

Most of the energy used in buildings in the Middle East is used for cooling. The outside fabric consists of a metallic layer which reflects and absorbs 80-90% of the solar energy and the updraft in the cavity removes the heat produced. This combination makes the SD a highly energy efficient system, reducing required cooling capacities by 150-200W/m² compared to a conventional tent with metal coating¹. The cooling loads of the SD are calculated to be in the order of 75 to 200 W/m²² – depending on the size and number of people that have to be accommodated and the exact climate conditions– without compromising on construction speed and form flexibility. And this is low enough to make a cool and comfortable SD, even in the hottest climates.

¹ Transmission & absorption tent: 10-20% * 1322W/m² (solar load) = 130-260W/m². Reduction by 2nd layer according to CFD-calculations 80-90%: 100-230 W/m²

² Transmission: $R_{c,tent} = 0.36 \text{ m}^2 \cdot \text{K/W}$, transmission: $1/(0,36+0,17) \text{ m}^2 \cdot \text{K/W} * (39-25)\text{K} = 26\text{W/m}^2$
 Fresh air ventilation: Enthalpy outside: 103 kJ/kg; enthalpy inside: 56 KJ/kg. 10m² per person, 60m³/h.person.
 Cooling capacity ventilation: $60[\text{m}^3/\text{h.p}] / 10[\text{m}^2/\text{p}] / 3600 [\text{s/h}] * 1.2 [\text{kg/m}^3] * (103-56)[\text{kJ/kg}] = 94\text{W/m}^2$

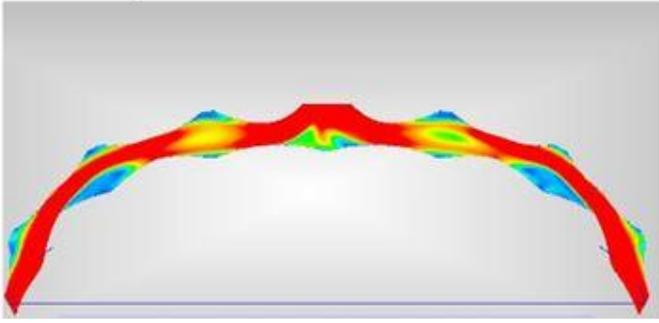


Fig. 10. Results of CFD calculations: air velocities (between 0 and 1 m/s)

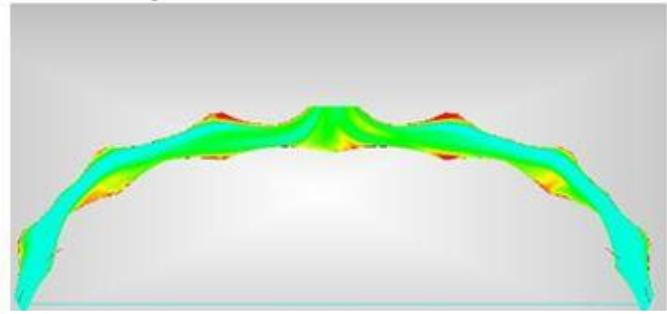


Fig. 11. Results of CFD calculations: air temperature (between outdoor temperature of 38°C and 50°C)

The air-gap principle has been optimized using CFD-calculations and is fully integrated in the computational design approach. With little effort, the thermal performance of new shapes and patterns of openings can be evaluated and optimized.

To support the dome, air is supplied to the dome at a pressure of 200-250Pa. This creates the structural stability, but also provides fresh air and cooling. To avoid draft, this air is supplied to the dome using textile mixing ventilation ducts at the sides of the wall. For larger domes, this will not provide enough mixing for a comfortable climate at 15-20m from the ducts. Therefore, tests have been performed using an unconventional method to ventilate the OpenBalance ventilation control system. A varying amount of fresh air was supplied to the tent from one opening and it was tested if a comfortable climate conditions and low air speeds could be reached inside the dome. The idea is that this system creates differences in pressure and different air speeds at a molecular level, which aids the thermal mixing. The initial results were very positive: reaching a very good indoor climate with very low air speeds, while achieving fast mixing and low stratification.

3.2. Sustainability

The SD is at its core a very sustainable concept as it combines low-tech material inputs with high energy efficiency and flexibility in resources' use and re-use.

The inner and outside membranes are built of extremely light materials, which is a necessity for air domes. This minimises the efforts for transport and construction significantly. The lightness also ensures simple foundation elements (i.e. steel soil anchors) that can be simply removed after usage, limiting the SD's ecological footprint. The membrane materials as well as the steel anchors, cables and struts are very suitable for reuse, exceeding the technical life span of the SD.

The SD's efficient energy use is a direct result of the cavity between the layers that passively takes out the radiation heat before it reaches the dome. Less energy is then needed for cooling purposes. This is enforced by the chaos ventilation system, which reduces the required air volumes needed for cooling and ventilation. In addition, several add-ons and optimizations are possible, in order to make it even more sustainable. The following examples are currently under thorough investigation and might become the cornerstones for the next generations of domes: translucent aerogel insulation for daylight transmittance and advanced insulation; radiant cooling in the floor; desiccant cooling to cold fresh air for ventilation by using solar heat; integrated thin-film photo voltaic cells on the shade to produce its own electricity.

4. Conclusion

The SD can constitute an extremely valuable solution for the promotion of sports and the wider cultivation of the athletic spirit in areas, which are not used to experience the benefits of fitness in large scale, due to unfavourable climatic barriers. The simple, smart and natural way of obstructing heat from reaching the building's interior, diminishing the indoor temperatures with only limited use of auxiliary cooling systems, combined with the unhindered use of the total internal space, due to the lack of indoor supporting elements, can establish a new –building and athletic- reality in desert-covered regions of the world. The factor of temporality, as well as the high delivery speed of the project, constitutes a couple of extra strong points of that venture that cannot be unnoticed.

Consequently, the SD is more than just a sport building facility, as it can do a lot more than simply ease and improve the sport's industry in such areas. The creation of a pleasant fitness environment will also influence positively the social web of local societies. By providing a comfortable environment for people to meet and interact with each other, new cores of social interplay and personal interrelations will be developed, transforming each SD in a wider exchange cultural centre.

The successful realization of that concept can also create new perspectives regarding sport facilities in other places of the world suffering from unfavourable climate conditions. The delivery of cosy and friendly environment to areas of extremely low temperatures, heavy snowfalls or intense rain incidents can follow, using as input the already gained knowledge of the first version of SDs. Although a lot of factors and parameters will need to be changed, adjusted, redefined or replaced in that case, the innovative design, fabrication and installation processes that are currently been promoted through at specific concept, can be used as the basic pattern to step on.