# Geometry Optimisation for Adaptable Lightweight Structures in Remote Areas

**Jessica FERNANDOY**
PhD (C)
University of Bath
Bath, UK
*J.Fernandoy@bath.ac.uk*

Jessica Fernandoy studied Architecture at the University of Technology Santa Maria, Chile. She worked for the University of Magallanes, Chile and is currently studying for a PhD in lightweight structures for remote areas at the University of Bath.

**Paul SHEPHERD**
Research Fellow
University of Bath
Bath, UK
*P.Shepherd@bath.ac.uk*

Paul Shepherd has a math degree from Cambridge, PhD from Sheffield and worked for Buro Happold where he set up their advanced analysis group now known as SMART. He is now Digital Architectonics Research Fellow at the University of Bath.

**Paul RICHENS**
Professor
Univerisity of Bath
Bath, UK
*P.N.Richens@bath.ac.uk*

Paul Richens studied Natural Sciences and Architecture at Cambridge and two of his research projects (Piranesi and Navisworks) have been commercialised. He is now Prof. of Architectural Computing at the University of Bath.

## Summary

This paper reviews the role of lightweight structures in remote- and pristine-areas, in particular the Antarctic and sub-Antarctic region, which can be seen as a natural laboratory for testing minimal-impact design strategies due it extreme harsh natural conditions and the environmental threat represented by the increasing human presence. The first part of the paper briefly reviews the evolution of Antarctic infrastructure and some of its characteristics. It then goes on to discuss the role of lightweight structures in the southernmost region, and to present a set of case-studies of minimal structures particularly designed for this context. Some common aspects and unique qualities are then derived from the design and construction processes of these projects. Finally, an explorative geometry-based design method is presented, which intends to respond to some of the specific problems of working with lightweight structures in remote areas.

**Keywords:** *Antarctica, Logistic, Minimum Impact, Lightweight Structures, Assembling, Geometrical Optimisation.*

## 1. Introduction

Antarctica is one of the most pristine places on Earth and at the same time, the highest, driest, and coldest continent. Its extreme energetic condition has produced exceptional evolutionary adaptations of many organisms, for which its ecological value is outstanding. These natural features, along with the lack of terrestrial connection with other continents, have been determinant in its total isolation from human civilisation until modern times. The process of human settlement has developed rather slowly, and therefore anthropic impacts have remained discrete so far. Initial explorations carried out since the late 1700s, often for sovereignty purposes, have been followed by scientific schemes from 31 different nation states. In parallel, this activity is now being joined by a rising number of touristic programmes [1]. Since the Antarctic Treaty was issued, the Antarctic territory is under a system of special protection through which it has been exclusively dedicated to 'purposes of peace and science' [2].With the adoption of the Protocol for Environmental Protection in 1991 [3] the whole continent was designated as a Natural Reserve and it was stated that everything brought to the continent should be removed after use. Thus since then, the permanent character of any infrastructure set up in Antarctica should be brought into question. Hence, Antarctica can be seen as an ideal natural laboratory on which to test zero-impact design strategies. Due the challenging nature of the Polar areas, achievements made in this context can easily be applied to other less demanding cases. In this sense, this paper is aimed at boosting the discussion and exchange of ideas and the extension of the use of lightweight structures into remote fragile areas in general.

## 2. Lightweight Structures in Antarctic and sub-Antarctic areas

The first settlement in Antarctica was established in 1899 by the Southern Cross Expedition, and since then its infrastructure has evolved extraordinarily quickly. Initial in-situ constructions, which could be classified as wooden huts, were later replaced by what were effectively adapted cargo containers, leading to a rather industrial-looking landscape (i.e. Villa las Estrellas, Chile). During recent years the Antarctic infrastructure has become of great interest to architects and engineers, thus new stations are being commissioned with more environmental friendly and bespoke design methods (e.g. Halley VI, UK and Neumayer, Germany).

At the other end of the Antarctic building spectrum, there is a fascinating variety of Lightweight Structures, mostly used as field camps [Fig. 1], which play an important role in the fulfilment of the aims of human presence in Antarctica, a ‘natural reserve dedicated to peace and science’. They make possible the temporary surveys in the most remote and uninhabited areas of the continent, and leave no trace once removed. These isolated structures have to face a number of constructive limitations and at the same time perform successfully under the most adverse climatic conditions with a minimum of material.  This constitutes an as yet under-recognised achievement in the literature on Polar construction. It is evident that the employment of these kinds of structures has been boosted by the development of the commercial-tent industry, nevertheless this paper presents a small digest of case studies related to lightweight structures that have been designed for the extreme Southernmost context in particular, including Antarctic and sub-Antarctic areas, aimed at demonstrating that this as an emerging novel field for the structural design discipline.

*Fig. 1: Variety of Antarctic Lightweight Structures.*

## 3. Case Studies

### 3.1 Sub-Antarctic Vernacular Technologies

The Kaweskars and the Aonikenks were the semi-nomadic indigenous inhabitants of the Sub-Antarctic regions. The Kaweswar inhabited the southern archipelagos of Patagonia, whilst the Aonikenks occupied the deep Patagonian plateau. Both groups developed technologies used for their dwellings which constitute remarkable examples of the smart use of available materials as well as efficient designs of lightweight structures capable of withstanding one of the harshest environments on earth [Fig. 2]. So far, literature does not provide any deep analysis of the structural properties of these systems; so a detailed assessment is as yet unaddressed.

In both cases, only part of the structure was meant to be transported - the drapes - whilst the principal structures remained on site to be repaired and reused by other groups later [4].

*Fig. 2: (top) Kaweskar dome; (bottom) Aonikenk shelter.*

In general terms, the Kaweskar shelter had the shape of a dome with an elliptic base. The structure was formed by a quadrilateral grid of flexible wooden bars, embedded in the soil, and reinforced with a perimeter pad for fixing made from branches. The dome was then covered with dried seal skins and attached to the structure using animal fibres [Fig.3]. As for the Aonikenks, their main challenge was coping with the wind blizzards characteristic of Patagonia. The structure had the shape of a half-dome, again using flexible wooden bars. Curved semi-arches were then attached to the main double-arch that defined the principal façade of the dwelling, always oriented to face down-wind. The structure was covered by a single membrane made from sewn pieces of guanaco skin tied to the structure [Fig. 4]. A key aspect of this construction was the extension of the membrane out from the front face. This provided an aerodynamic and effective wind-drifting effect which created a low-pressure air void inside the shelter permitting fires to be easily lit. The effective combination of the curved shape and frontal wind-stoppers make the shape highly efficient.

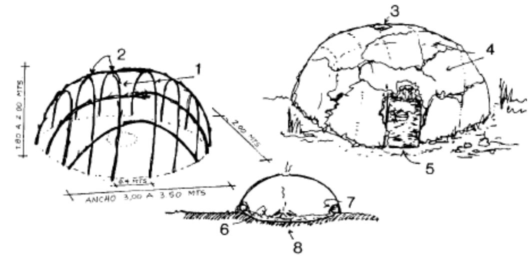

*Fig. 3: Constructive system of a Kaweskar dwelling. Baeriswyl, 1991*

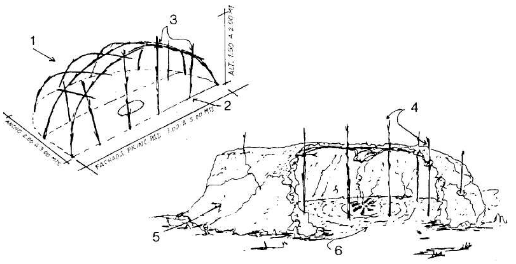

*Fig. 4: Constructive system of an Aonikenk dwelling. Baeriswyl, 1991*

Despite the fact that both structures could be classified as shells, they have rather different structural behaviour. In the first case, the structure is mainly working in compression as the heavy seal skin works as cladding and probably does not have a primary bracing role for the structure. In the Aonikenk case, the lighter covering clearly functions structurally as a tensile membrane.

### 3.2 'In the Footsteps of Scott' Expedition Tent

*Fig.5: Antarctic Expedition Tent, Buro Happold, 1985.*

This case corresponds to a very small scale project commissioned from Buro Happold and designed by founding partner Ian Liddell in 1985. The objective was to design a deployable shelter for the commemorative expedition 'In the Footsteps of Scott' (1985-1986) led by Roger Mear with two companions. The expedition aimed to be the longest non-aided land journey (70 days), during which the team would cross Antarctica and reach the South Pole, carrying all their supplies by pulling sledges.

The scheme design was governed by the problem of optimising the classical pyramidal structure used by the British Antarctic Survey, which used wooden poles, and turned out too heavy to be carried (28 kilograms), and by the fact that no commercial tent could guarantee to support the extreme weather conditions of Antarctica [5].

The solution was to optimise the original conical volume towards a more dome-like body [Fig. 5], since spherical shapes are volumetrically more efficient and they are more capable of dealing uniformly with the characteristic shifting winds of Antarctica. Another consideration was the logistical restrictions of transport and assembly for this expedition in particular, namely the size of the sledge (2.4m). Thus, the structure was resolved as an umbrella-system that was partially deployable, an advantage over traditional total-collapsible tents. The main structure was comprised of six glass-fibre bars contained within a membrane. In this way the entire tent could be transported as a single package. The membrane was defined as a set of doubly curve faces made from Goretex fabric, an outer nylon layer and an inner PTFE skin. A thermal air buffer was achieved with a second light inner membrane, helping to avoid the loss of internal heat. The assembly process thus remained simple. The membrane was pulled down from top to bottom along the bars, which were forced under compression to form a curved shape and to meet the single base ground sheet of 2.5m diameter. Once in Antarctica, the structure proved successful during the whole expedition.

## 3.3 Teniente Arturo Parodi Polar Station (EPTAP)

*Fig. 6: The EPTAP during its assembling. ARQZE, 1999.*

The EPTAP [Fig. 6] is located in the deep Antarctic plateau at Patriot Hills (82°S). It was commissioned for the Chilean Air Force in 2000 by the University of Technology Federico Santa Maria (Chile) with the aim of providing logistical services in support of scientific activity in Antarctica. EPTAP has a capacity for 24 people. The main unit of the station is a PVC membrane tunnel, tensioned by a set of structural 2m long aluminium arches. Each section of membrane is divided into three distinct hyperbolic surfaces between arches. Along this tunnel, secondary structures can be attached through sleeve connections (so called 'plug-in ports') [6]. These permit multiple configuration options for the station. At this stage, two different types of structures have been attached. One is the so called 'igloo cabin', which is a modular rigid shell composed of 12 fibreglass panels, filled with insulation material (50mm of high density polyurethane). Seven of these units have been implemented and assigned different uses. The second type of attached structure is the 'Sastruggi Tent', a tri-axial set of nine interconnected double curvature membranes, which define a closed shape capable of withstanding the harsh shifting Katabatic winds of the area which can reach speeds of up to 150km/h. Double curvature transparent plastic panels were attached at both extreme of the tunnel. EPTAP's components are shown in Figure 7.

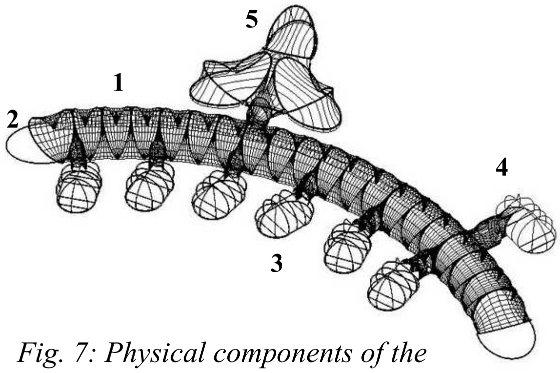

*Fig. 7: Physical components of the EPTAP: 1)tunnel, 2)visor, 3) module, 4) plug in ports, 5) Sastruggi room. ARQZE,1999.*

This case study is interesting from multiple angles, but for the purpose of this paper, it should be noted that it is the first permanent medium-scale lightweight structure used in Antarctica.

# 4. Geometrical Features of Antarctic Lightweight Structures

By definition, the implementation of lightweight structures entails a deep integration of shape, structural behaviour and the mechanical properties of materials, in direct agreement with the environmental conditions [7]. However, when it comes to the remote contexts, further aspects must be incorporated into the very early stage of design such as logistical possibilities, transportation capacity, assembly procedure and human performance under harsh conditions. Each of the cases presented above demonstrates how these criteria can directly influence the design of a structural system, and it has been shown that Polar lightweight systems can be considered as state-of-the-art designs that are equally well suited to other, less demanding contexts. However, this section focuses on just two geometrical aspects of the existing array of minimal Polar structures, which are then addressed by the proposed structure presented in the final section of this paper.

## 4.1 Curvature

The need for transportable, light, resistant structures verifies the efficiency of curved shapes in remote cold areas. From a geometrical perspective, it is possible to find structural surfaces with either single- or double-curvature and also developable surfaces. Figure 8 shows one example of each of these cases. The configuration of lightweight structures is still dominated by extremely regular shapes, either as a single unit, such as the South Pole Dome, 1975 [Fig. 9], or as collection of independent units as in the case of the *'Patriot Hills Field Camp'*, operated by the *'Antarctic Logistic and Expedition'* [Fig. 10]. It is therefore possible to say that geometrical explorations which provide more free-form and bespoke solutions still remain unaddressed in the field of lightweight structures for Polar areas.

*Fig. 8: Structures with different curvature: a rigid module with synclastic shape from Wallhead (top left); a fabric shelter from a developable surface, Weatherheaven (top right) and the Stratuggi Room from a set of anticlastic surfaces, ARQZE (bottom).*

*Fig. 9: South Pole Dome. US Navy (1975).*

*Fig. 10: Field Camp at Patriot Hills. Antarctic Logistic & Expedition (2002).*

## 4.2 Rationalisation of Surface Components

The assembly procedure is a key aspect for the assessment of the feasibility of any construction in remote areas. Figure 11 shows two very different approaches in this respect: the rational patterning of the membrane tunnel of the EPTAP, which tries to minimise the number of different pieces, and in contrast the complex assembly process from the Amundsen-Scott Dome constructive manual, where each component is unique. Working in remote areas imposes strong restrictions on the technical resources available for construction and it must be executed on a tight timescale, since field activities are usually dependant on transport schedules, which at the same time relies on the often variable weather conditions for their operation.

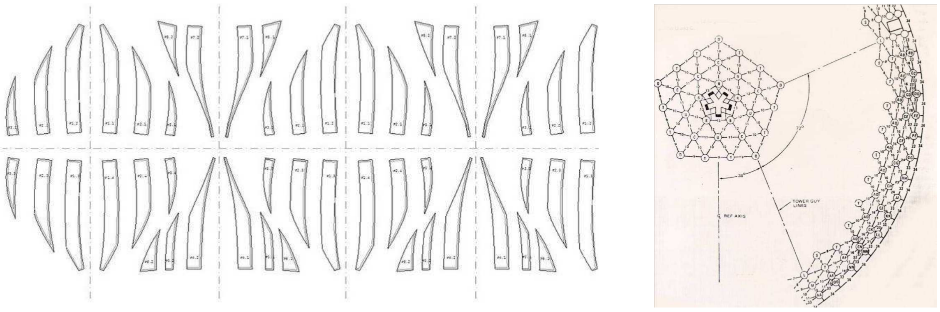

*Fig. 11: (left)Pattering of the anticlastic membrane of the EPTAP, ARQZE (1999); (right) assembly procedure of the South Pole Dome's components, TEMCOR (1973).*

In addition, it must be accepted that human performance is detrimentally affected by extreme climatic conditions. Therefore, the design of joints and the assembly procedure must be also considered in the earliest stages of design.

## 5. Geometry-Based Design Method for a Lightweight Construction System

This section describes a geometry-based method for the design of a generative lightweight structural system developed by one of the authors [8], which allows the definition of a double curved gridshell from a rational number of components. This system is aimed at addressing some of the particular challenges described earlier relating to innovative Polar constructions: the capacity of a system to define more complex shapes from a rational constructive system (i.e. reduced number of components and simple assembly procedure). In order to achieve this, a geometric-structural logic is developed.

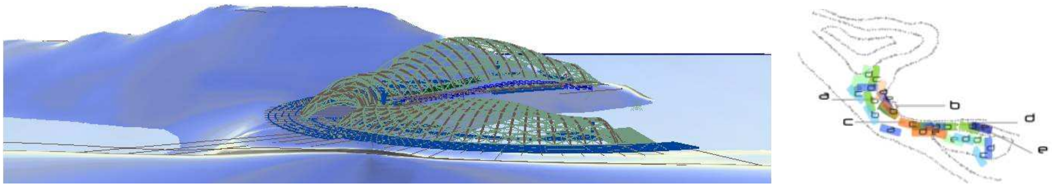

*Fig. 12: Architectural scheme of the sub-Antarctic station*

The design was based on a simple architectural brief, a small coastal touristic station located in Navarino Island (54°55'), sub-Antarctic region, which involved the implementation of both closed and semi-opened enclosures within a same station [Fig. 12]. The designed scheme had a tectonic language that allowed a generative system to be adapted to the morphology of the terrain.

The structural scheme was resolved as a lightweight membrane system supported by a set of flexible arches (so-called 'primary arches') and a double bracing system, composed of both a structural PVC membrane and tensile cables, in response to the particularly severe wind conditions. 'Primary arches' were grouped into three categories: complete (or symmetrical) arches, semi-arches and asymmetric arches [Fig. 13], in order to respectively define the closed and semi-opened surfaces. Each set of arches was parametrically defined within a range of variation.

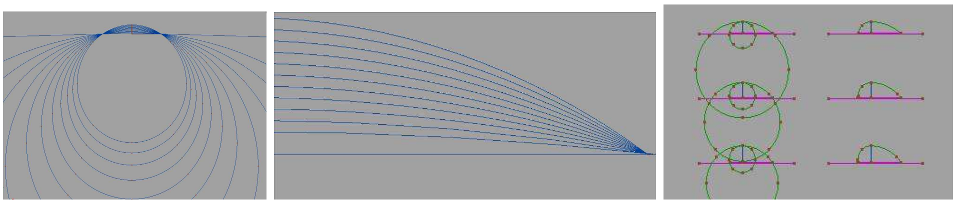

*Fig. 13: Three sets of arches: (left) complete, (centre) half-arches and (right) asymmetrical.*

In this sense, arches forming each individual structure could be progressively varied in length, which allowed the variation of the shell in its height or width (governed by minimal ergonometric constraints). As for those structures composed from semi-arches, a frontal supporting trussed arch was necessary. Additionally, each structure was provided with lateral resistance by aluminium arches [Fig. 14]. The section of these supporting elements was designed in variation according to the load diagram, in order to optimise its structural performance.

'Primary arches' were lightened by replacing the traditional single solid cross section with four flexible standard bars of carbon-fibre. In this way, the arches were optimised not only by using less material, but also because their section could vary according to the distribution of loads along the arch. The four bars were fixed with aluminium cross-shaped pins [Fig. 15].

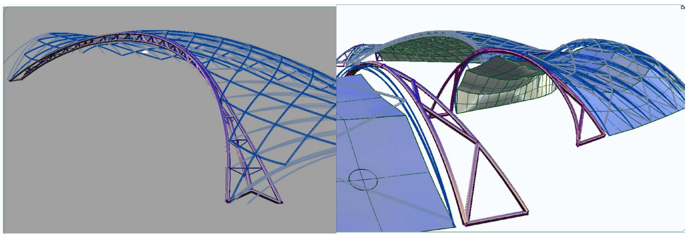

*Fig. 14: semi-open and close surfaces supported by trussed arches, (left) the storage room with frontal face open, with supporting truss at the front (right) fitting room, with lateral supporting trusses.*

It was estimated that a reduced number of different pins were necessary in order to achieve all the different sections required for the system. The arch cross sections were rationalised in order to keep the number of pins as low as possible. The same elements were used to provide a joint for the tensile cables and PVC membrane [Fig. 16].

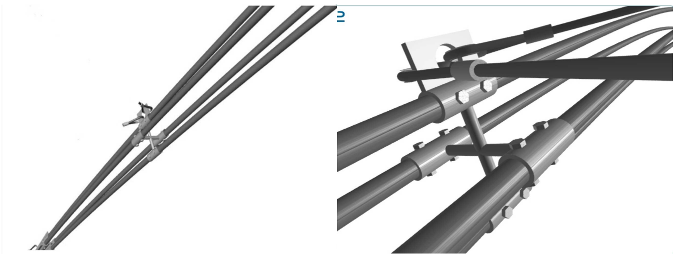

*Fig. 15: Cross-shaped pins joining the four flexible bars which compose a 'primary arch' of variable section.*

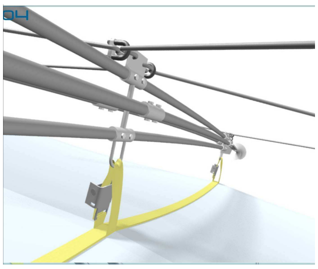

*Fig. 16: Pin joints serve as a support for the two bracing systems: tensile cables supported with a plaque, and fasten buckles for the PVC membrane*

The membrane could be easily patterned as rectangular pieces [Fig. 17]. The cable system was defined under the same triangulation principle as geodesic tents, which supposes the formation of a regular triangular grid from two perpendicular sets of cables in collaboration with the arches. The definition of the regular grid meant that every arch had a different length, so using equal distances to define the pin joint's position was not a solution. Instead, they were positioned by an equal angle measured from the centre of curvature of the arch. Hence, each arch has the same number of pin-joints, joined with the cables [Fig. 18].

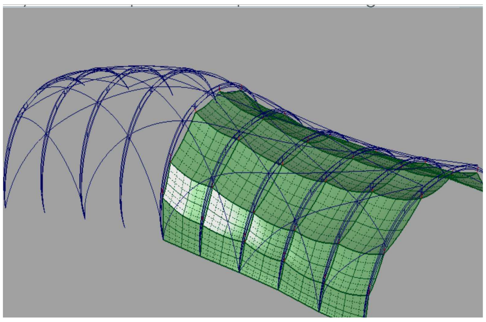

*Fig. 17: Rectangular pieces of PVC fabric forming the membrane.*

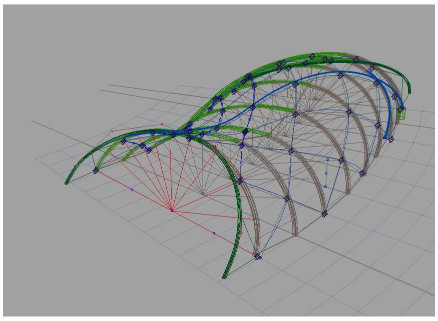

*Fig. 18: Equally degree distribution of joints along the arches.*

The versatility of this system, capable to handle a free range of different shapes, is achieved by a complex coordination of its different components. Thus, two groups of components can be recognised: standard components such as pin joints (previously adjusted for the particular position), flexible bars, tensile cable; and a second group of specifically-designed components like membranes and trussed arches.

## 6. Conclusions

This paper has shown how the complex problem of building in the harshest and most remote natural environment under the highest standards of environmental protection has transformed Antarctica into an exciting platform for the development of minimal impact design strategies. A fascinating spectrum of zero-impact solutions are being utilised, including some novel attempts at bespoke lightweight designs, some of which have been briefly described in this article. In that sense, it is possible to say that lightness has proved to be the natural answer to the harshest environments, either from the southern-most vernacular technologies to the latest novel attempts to implement minimum impact infrastructures.

The intrinsic relation between environment, geometry, structure and material properties which are seen in the implementation of structural surfaces needs to be taken into account when working in remote harsh environments such as Polar and sub-Polar areas, where a much more integrated design process is required. This implies the integration of all the stages of the construction process in the earliest stages of design, including logistics, transportation, assembling techniques, maintenance. The tectonic lightweight system proposed in the previous section is responsive to some of these particular restrictions imposed by the Polar context, in this case related to its geometry and constructability, and aims to suggest that the singular challenges imposed by extreme contexts can be a source of innovative constructive solutions in the field of lightweight design.

## 7. References

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