THE REPUBLIC OF TURKEY
BAHÇEŞEHİR UNIVERSITY

POTENTIALS OF PARAMETRIC MODELING FOR DESIGN AND FABRICATION OF MEMBRANE STRUCTURES

Master's Thesis

AHMAD ADHAM

ISTANBUL, 2019

THE REPUBLIC OF TURKEY
BAHCESEHIR UNIVERSITY

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Istanbul, 2019 Ahmad ADHAM

ABSTRACT

POTENTIALS OF PARAMETRIC MODELING FOR DESIGN AND FABRICATION OF MEMBRANE STRUCTURES

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Advance in digital technology has revived and empowered parametric design approach. Before the advent of parametric software, design, simulation and analysis process were mainly independent practices. The new generation of parametric applications have integrated these processes on user-friendly interfaces, resulting in a hybrid expertise that blends design, engineering and fabrication. Thus, parametric tools have altered the original sense of architecture and the process of design. Parametric tools are enabling real-time search and control over design formation, whereas analysis tools are enabling to guide the design process to reach the optimal solution. The design process can be automated by employing algorithms and establishing a feedback loop between results of simulation and initial design parameters, hence the formation can be controlled by the results of simulation and informed by efficiency indicator. Design based optimization can result in a more efficient form in terms of function, structure and environment.

This thesis covers an investigation on optimization and production of membrane structures. It aims to render traditional tent structures as efficient shading solutions for hot climates. It contains parameterizon of a vernacular tent structure, then structural optimization (form finding); functional optimization (environmental performance assessment) and the process of membrane fabrication. All workflow is carried out with Rhino and Grasshopper for parametric modelling, Kangaroo Physics for form finding and material optimization, Ladybug for environmental evaluation, and Octopus for Multi-objective optimization. It handles a case study which is a membrane structure designed via traditional CAD and installed in Erbil city. The main motivation for research derives from lack of design guidance on traditional tensile tent, which is specific to hot climate of Middle East region. The end goal is to establish a parametric workflow for designing optimized tensile membrane shading structures so that they may regain their importance and become essential features for new architectural practices.

Keywords: Tensile Membrane Structures, Traditional Tent Structures, Parameric Modelling, Form-Finding, Mult-Objective Optimization

ÖZET

MEMBRAN YAPILARIN TASARIMINDA VE ÜRETİMİNDE
PARAMETRİK MODELLEMENİN POTANSİYELİ

Ahmad ADHAM

Mimarlik Yüksek Lisans Programı

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Dijital teknolojideki gelişmeler parametrik tasarım yaklaşımını yeniden canlandırıp ve güçlendirmiştir. Parametrik yazılımların geliştirilmelerinden önce, tasarım, simülasyon ve analiz süreçleri birbirinden bağımsız temel uygulamalardı. Yeni nesil parametrik uygulamalar, bu işlemleri kullanıcı dostu arayüzlerde birleştirerek tasarım, mühendislik ve üretim süreçlerini harmanlayan karma bir uzmanlığı doğurmuşlardır. Böylece, parametrik araçlar mimarlığın kendine özgü tasarım anlayışını ve sürecini değiştirmişlerdir. Parametrik araçlar, tasarımın biçimlendirilmesi esnasında gerçek zamanlı aramayı ve kontrolü olanaklı kılarken, analiz araçları en uygun çözüme ulaşmak için tasarım sürecini yönlendirmeye izin verirler. Tasarım süreci, algoritmalar kullanılarak ve simülasyonun sonuçları ile tasarımın ilk parametreleri arasında geri besleme döngüleri oluşturularak otomatikleştirilebilir, dolayısıyla form oluşumu, simülasyon sonuçları aracılığıyla kontrol edilebilir ve verimlilik göstergeleri aracılığıyla belirlenebilir. Tasarım temelli optimizasyon, işlev, yapı ve çevre açısından daha verimli sonuçlar sağlayabilir.

Bu tez, membran yapılarının optimizasyonu ve üretimi üzerine bir araştırmayı kapsamaktadır. Geleneksel çadır yapılarını, sıcak iklimler için uygulanabilir gölgeleme çözümlerine dönüştürmeyi amaçlamaktadır. Bu doğrultuda, yerel bir çadır yapısının parametrelerinin belirlenmesini, ardından yapısal optimizasyonunu (form bulma), işlevsel optimizasyonunu (çevresel performans değerlendirmesi) ve membran üretim sürecini kapsamaktadır. Tüm iş akışı, parametrik modelleme içim Rhino ve Grasshopper, form bulma ve malzeme optimizasyonu için Kangaroo Physics, çevresel değerlendirme için Ladybug ile çok amaçlı optimizasyon için Octopus yazılımları kullanılarak yürütülmektedir. Alan çalışması, geleneksel CAD (Bilgisayar Destekli Tasarım) araçları ile tasarlanıp Erbil şehrinde inşa edilmiş olan bir membran yapısını ele almaktadır. Araştırmanın temel motivasyonu, Ortadoğu coğrafyasının sıcak iklimine özgü geleneksel çadır yapıları ile ilgili tasarım rehberlerinin noksanlığıdır. Nihai amaç, optimize edilmiş, asma germe membran gölgeleme yapılarının tasarımı için parametrik bir iş akışı oluşturmaktır, böylece yeniden önem kazanıp yeni mimari uygulamalar için önemli bileşenler haline gelebilirler.

Anahtar Kelimeler: Asma Germe Membran Yapılar, Geleneksel Çadır Yapıları, Parametrik Modelleme, Form Üretimi, Çok Amaçlı Optimizasyon

CONTENTS

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ABBREVIATIONS

ASHRAE	:	American Society of Heating, Refrigerating and Air-Conditioning Engineers
2D	:	Two Dimensional
3D	:	Three Dimensional
EPW	:	Energy Plus Weather
CAD	:	Computer Aided Design
CAM	:	Computer Aided Manufacturing
CFD	:	Computer Fluid Dynamics
CNC	:	Computer Numeric Control
GH	:	Grasshopper
Low-E	:	Low Emissivity
MRT	:	Mean Radient Temperture
NURBS	:	Non Uniform Rational B-spline
VP	:	Visual Programing
PET	:	Physiological Equivalent Temperature
PTFE	:	Polyvinyl Chloride
PVC	:	Polytetrafluoroethylene
WHO	:	World Health Organization

1. INTRODUCTION

Tensile membrane structures are one of most primitive, yet most advanced forms of building. They are continuously evolving and broadening their functional scope. In the context of architecture, tensile membrane structures system have proven their aesthetics and functionality throughout thousand years of practice. Eventually with modernity, membrane as a building material lost its importance as wood, stone, metal and glass substituted material choices. However, it did not vanish rather was utilized for non-structural purposes. As Kronenburg (2015, p.18) states: "Technological developments in material and design methodologies have enabled fabric structures to renew their legitimacy as a practical and viable method of building." Hence, they carry great potentials for design of new structures.

The world is facing higher temperatures due to global warming. Hence, thermal conditions for outdoor spaces have become unsuitable. Easy-built and sustainable design solutions have become urgent necessities for sheltering and accommodation. Tensile membrane structures have always offered shading solutions for hot climates, such as in case study area: Middle East region including the city of Erbil. They are economical and offer several advantages over other types of shading structures. Most importantly, they offer sustainable solutions through their modest responses to structural requirements. The most effective key to sustainable design is to consume less material. Require fewer materials and wasting less sources, tensile structures are efficient solutions for environmental problems. Reasonably, tensile membrane structures are likely become ubiquitous components of urban areas in hot regions.

In current practice, there exists a gap between architectural design and membrane structures' design due to their complex nature, requiring engineering skills. However, it is still architects' task to deal with site specific problems and generate suitable solutions. Hence, for dealing with environmental problems in architectural design , parametric modelling can be a panacea as it includes analysis and optimization of various design inputs. Architects may adopt parametric modelling tools, which enable computing of various design inputs through visual programming. This thesis aims to highlight the potentials of parametric modelling tools for the design and fabrication of membrane structures. By inspecting parameterizable characteristics of tensile membrane structures and available parametric tools, the thesis proposes a new workflow for architects dealing with tensile membranes.

The first chapter introduces and defines the scope of the study. The second chapter covers a detailed literature study on historical value of the membrane structures, which were mostly called as tents. It explains the incentives that gave impetus to the development of membrane structures around the world and change of their symbolic meanings and technical aspects. It concentrates specifically on black tents, which are native membrane structures of the Middle East, due to their high thermal performance in hot climates. The study re-evaluates traditional black tents' architectural qualities and their adaption for future architectural practices. Third chapter is about the concept of parametric design and possible parametrization of tensile membrane structures. The fourth chapter deals with a case study in Erbil city, where shading solutions are of outmost importance for continuity of outdoor life. The thesis aims to propose a reliable workflow for the architectural design and optimisation of tensile membrane structures through the parametric modelling which includes the structural aspects of membrane together with material properties in structural formation and climatic data. The parametric workflow consists of dynamic modelling, environmental analysis, functional optimisation, structural optimization and cutting pattern for proposed design. The final chapter contains the conclusions drawn from parametric modelling phase for design and production of tensile membrane shading structures and suggestion for future research. The appendix part contains relevant information about material properties of membranes, parametric software used in the workflow; interviews held for the case study.

1.1 AIMS OF RESEARCH

For centuries, human have deployed tent structures as shelters from extreme weather conditions. Recently climatic changes and global warming has become severe and outdoor spaces have lost their liveability and workability especially in summer. In Middle East where case study area Erbil is located, the climate is extremely hot. Temperatures rise up to 50C° hence the need for membrane structures is significant. Several projects in Erbil have employed membrane structures for shading purpose.

However, their efficiencies are yet questionable, considering that there is no clear guide for design and construction of membrane structures. Besides, the conventional process does not incorporate any environmental calculations. Its architects task to tackle the problems, and at the current state, the membrane design sector is “disconnected” from architectural design and is dominated by engineering.

Therefore, the motivation of this research is to explore the potentials parametric design for tensile membrane structure and propose a design and optimization workflow based on functional and structural efficiency. The theoretical and historical research on vernacular tent shelters are for over viewing their usage throughout history and highlighting their potentials for future. In case study, structural components of vernacular tent shelters are parametrized for form finding and linked with environmental data. General aim is to promote tensile membrane structures as functionally efficient, sensually comfortable, aesthetically beautiful and financially economic responses to extremely hot climates. Membrane design which is carried out in engineering domain in Erbil, is re-linked with architectural design. In sum, the output will be a useful design tool for all including architects and engineers working on membrane structures.

1.2 METHOD

This thesis seeks to explore the potentials of membrane structures as a practical solution for hot climates. Furthermore presents a reliable parametric workflow for designing tensile membrane structure. It puts forward a workflow in which the design of tensile membrane structure is informed by its own performance in outdoor space. The thesis text includes extensive literature study on history, development and architecture of tent; also, it contains membrane materials and tensile membrane structural logic. Before proposing alternative designs for the case study, the local traditional vernacular tent (Black tent) specific to Middle East hot region is investigated for parametrization purpose. Therefore a study on parametric concept, parametric modelling systems and simulation algorithms for structural and functional optimization of membranes are given. For case study, it deals with a tensile shading structure, built over a British international school (BISK) yard (gathering area). The chosen tensile shading is located in Erbil city, which is one of the hottest cities in Middle East region. During summer period, temperature regularly exceeds 40C, so the outdoor is deemed as unsuitable for human outdoor activities. The owner of the construction firm is interviewed to understand the design criteria and methodology; moreover, to find out the main incentives for the selection of tensile membrane shading structure.

The Erbil's climatic condition is analysed, considering the need for blocking undesired sunrays and allowing comfort wind flow in this outdoor space. A parametric model and workflow is created in Grasshopper to design alternatives based on historical references to vernacular tents and in respect to weather data representation graphs available in Ladybug. The climatic indicator set via Ladybug will control the orientation and dimensions of the structure at the initial phase. In following stage, ladybug analysis, octopus and kangaroo will be used. The ladybug will be used for analysis the performance of membranes design. Then octopus will be used to perform multi-objective optimization and present a set of semi-optimal alternative. The Optimization algorithm will interactively generate optimized shapes in an automated manner. Kangaroo physics turns the selected options from optimization process to tensile membrane by conducting form finding process. Finally, existing membrane structure and one of the optimized proposals will be compared in terms of their performances and materials consumption. The comparison will be as a critique of balance between aesthetics and performance of tensile membrane structures. The desired option will be discretised by patterning, then cut and flattened for fabrication purpose.

1.3 LIMITATIONS

The proposed parameters and structural elements of tensile membrane are derived from vernacular black tent specific to hot Middle East hot region. The thesis will not go deep to load calculation and material types, as it requires special engineering knowledge about structural system and stiffness of different materials. The simulated material is PVC coated membrane as it is the only used material for few existing projects in the city.

Parametric software usage is limited to Rhino, Grasshopper, Kangaroo physics, Ladybug and Octopus. Input data for Ladybug is Energy plus Weather file (EPW) for the Erbil city centre. Thesis will propose a workflow for tensile membrane shading.

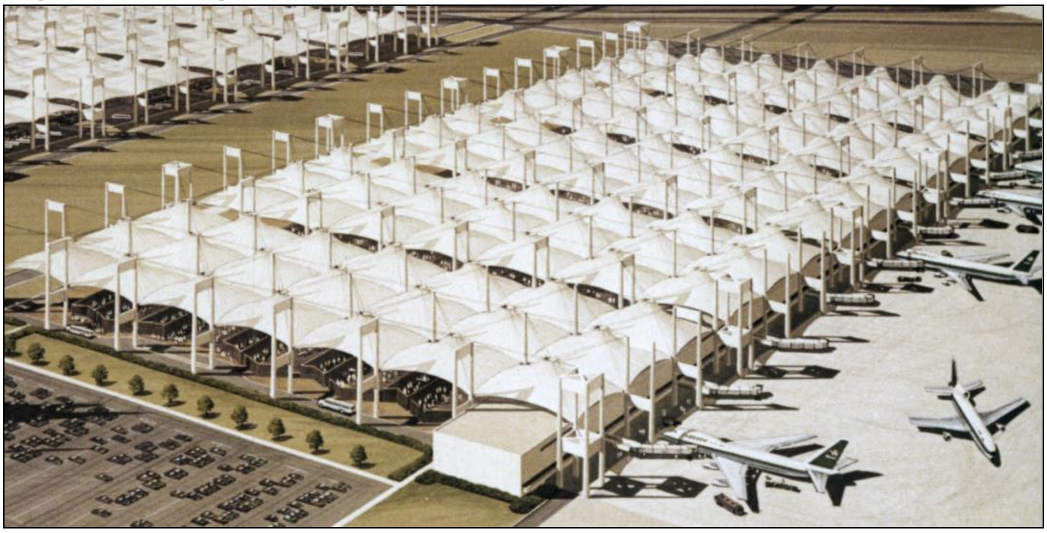
However, the workflow can be further utilized to provide indicators for membranes of different structures, materials and functional requirements and environmental inputs. Thesis will not go in details of plug-in coding as the process is complex and require advanced computational design ability, experience and proficiency in applications used. It will only provide decent explanation for crucial aspects to fully comprehend the workflow and expand applicability.

2. TENSILE MEMBRANE STRUCTURES

Tensile membrane is a spatial construction system. It consists of several co-dependent elements, in which stability and load-bearing capacity is achieved through tension stress of the main components. Deb (2014, p. 141) states: “By ensuring that the fabric membrane remains in tension at all times, these materials can act as both structure and cladding to efficiently cover large areas”. The structure is almost entirely composed of membrane, especially if it is fixed on the ground. The membrane, as the thinnest structural layer, is tied by secondary elements such as tie rope or steel wire cables, which are usually used at boundaries or edges. Furthermore, rigid, compression-based supporting members such as frames, masts, rings, arches, and edge beams, are used to elevate the membrane and convey the stress to the ground. These rigid, compression-based supports are typically made from conventional building materials such as steel, concrete, and timber.

Membrane structures have standard features such as a larger span, being more lightweight, a rapid construction speed, being resource efficient and safety. Since the material works as a cladding and a structure, its visual properties play a key role in the design, such as colour, transparency and reflectivity. They have been used to create some of the largest buildings in the world such as the Hajj terminal in Jeddah, constructed by SOM Architects in 1981 (Figure 2.1).

Figure 2.1: King Abdulaziz International Airport-Hajj Terminal.



Source: https://www.som.com/projects/king_abdulaziz_international_airport__hajj__terminal/
[Accessed 12 Dec. 2018].

Modern tensile-based membrane structures come in different sizes, scales, shapes and forms. Membrane materials can resist loads, due to membrane forces, but only in the case of small to medium structures. Larger structures need to be reinforced by a cable frame system that helps them bear and transmit heavy dead and live loads.

Membrane structural types can be categorized in two main types, which are skeleton membrane and tension membrane.

İ. Skeleton membrane: This type of membrane structure has a timber or metal skeleton frame and a covering skin. In cases where materials with high tensile strength are not available, the membrane layer is draped over the skeleton. In this case, the membrane is not structural, it is merely working as a covering. The frame provides the structural support; no outside fixtures are needed for the stability of the membrane cover.

İİ. Tensioned membrane: The boundary tensioned membrane form is what normally comes to mind when referring to tension membrane structures. It is the lightest form of tent, and it is characteristically a tent, as well as a truly minimal tensile structure. The original tensioned tent was the desert black tent, which was formed from a relatively large, woven fabric; the warp and weft threads providing tensile strength. In the skin tent, the tear-resistance of the material allows it to be stretched over wide distances. The tensioned tents were created when the manufacturing of materials with high tensile strength became known, as the material's strength is the principle behind almost all modern tents. The new, ingenious forms of membrane are those provoked by the synthetic membrane material's strength that is confined inside boundary edge cables or rigid frames. Because their shape and size are prescribed by these boundary conditions, the edge cables dictate the possibility for interesting forms. The membranes are initially pre-stress to provide structural stability and to prevent against loss of tension due to ageing. However, because stresses in the membrane can amplify significantly with changes to the external load, initial pre-stress levels are usually set to 1/20 of the tearing strength of the membrane (Fang, 2009, p.9). In addition, membrane strengths can be undependable because they are measured using uni-axial strip tensile tests of brand new and dry membrane materials. In actuality, the endurance of membranes can be as little as half this estimated value. After exceeding the dimensional limits, it should be supported with cable net. The limits depend on material type, and anticipated loads.

2.1 PHENOMENOLOGY OF TENTS

Tensile membranes are unique structures. Their forms and physical characteristics express meanings and evoke feelings that set them apart from other structural typologies. Their quality is directly inherited from their functional roles, material properties and structural configurations. Tents represent nomadism and movement; their thin material is connoted with lightness while their curvaceous structure has a palpable sense of nature and dynamism.

Initial examples of tent structures were traditional vernacular architecture employed to shelter nomadic people from natural elements. Nomads built simple shelters that were analogous with their free roaming lifestyle. They invented membrane shelters, as a result of limited available resources in the region. The creation of shelter that was minimal, simple, and, at the same time, extremely lightweight and easily transportable. Therefore, the structure is noticeably consistent with the image of nomadism and mobility. These portable tents were not only practical responses to their construction needs, but they were also a physical symbol of complex concepts regarding shelter and freedom. Giller (2012, p. 14) stated: "Tent dwellers saw it as a shelter that provided an invigorating awareness and connection to the land that nourishes, and as a vehicle for awareness of the seasonal shift of time; watching their shelters move, change, die and be reborn". When humans advented agriculture and began farming, they settled and their lifestyle changed.

Despite their optimal forms and attractiveness, the acceptability of tents within a sedentary lifestyle, which requires permanent structures has occurred in a very limited way. For modern humans, a tent is a simple shelter and hardly the type of shelter that man would enjoy living in. This is mainly due to the perception that tents lack provisions of comfort and can not satisfy psychological needs of privacy, belonging and security. Another conspicuous reason for their neglect is that they are generally connoted as cheap and disposable. Their minimised thickness has led membranes to be vulnerable to sharp objects and flames. Furthermore, in the context of housing, home fixtures have changed, and the concept of the lightweight form of the tent containing these heavy furniture raises doubts. Thus, tents have faced several obstructions in responding to architectural expectations.

The evolution of humankind and change of lifestyle, altered the function and symbolic interpretation of tents. Portable shelters were no longer essential for long-term housing instead, they began to serve new functions as shading elements and as temporary shelters. In recent years, they have become primary solutions in post-disaster situations, as rapid and cost-effective shelters for accommodating vulnerable people for short periods of time. The availability of large number of tents at the same place may infer the presence of a refugee camp, a vacation camping or a battlefield.

During 19th and 20th centuries, technical textiles or synthetic membranes replaced traditional organic textile materials. Modern tents were governed by construction efficiency as Horst (1980, p. 127) inquired: “This raised the question if they are even architecture at all or if they are just purely engineering”. Tent fabrics continued to become even lighter and stronger, but they also lost much of their textural quality. The most efficient aspects of tent construction were preferred, and designers started concentrating on structural superiority instead of their formal aesthetics and occupants need. The tensile membrane structures built by engineers looked novel in their styles and characters; however they had recognizable historical forms.

Contemporary tensile membrane structures are very different from traditional tents. The contemporary membranes eliminated the boundary walls and increased in scale, emphasizing spatial openness and connection to the landscape. While their dynamic forms refer to movement, their structures touch the earth lightly, appearing to be floating in air. Contemporary tensile membrane structures response to structural requirements in a minimalist way and may promote use of recyclable materials. Therefore contemporary membrane shading structures are considered to be sustainable. In digital era, they have transformed from shelters to shells that are elegant and ephemeral, appearing to be images of the future yet rooted in the technology of the past. They create simultaneously organic and high-tech images As Carpo (2013) stated: “Free form represented and symbolised a new techno-cultural environment”. Throughout history, conceptual and functional interpretations of tensile membrane structures have shown major changes which will be carried on to future design and construction practices. However there are issues to be discussed upon tensile membrane structures’ authorship and originality, temporality and persistence, membrane aesthetics and emotional quality.

2.1.1 Tensile architecture authorship and originality

The design of tensile membrane structures have several problems related with authenticity and semantics. While design practice gives importance to authorship and originality, construction techniques of most tents have been developed over generations without architects and vernacular architectural design process is based on transmission, adaptation and refinement (Giller, 2012, p. 83). Along with that, membrane structures are solely composed of membrane materials. Consequently, they tend to carry strong similarities although their forms may differ. Moreover, the semantics of tents derive mainly from their materiality and inherent quality although architectural theories often postulate architecture as a body that imposes rich emotive meaning intended by the designers themselves.

2.1.2 Temporality and persistence in architecture

Human have depended on the permanence of architecture as a tool to celebrate memories and attain immortality. They exploited the durability of materials to counteract with the inevitable disintegration of architecture; however, "architectural permanence is a seemingly infeasible undertake (Roberts, 2014, p .6)".
As Marxs (1848) stated: "All that is solid melts into the air", conventional architecture is slow, unable to keep up with momentous changes in society and culture. Long-standing buildings face immense transformation of their social, political, and economic contexts. Permanent architecture is increasingly becoming wiped out and abandoned hence a shift to more temporary architecture is desired. According to Garcia (2006, pp. 10):

> *In parts of cities such as Tokyo and LA where buildings are constructed and demolished rapidly, architecture begins to take on a nomadic status. The shifting sites of architectural programmes in the accelerating cycles of economic global and sociocultural capitalist production systems leads architects and theorists like Herzog & de Meuron, Hani Rashid, Rem Koolhaas and other aestheticians of speed to conclude that conventional architecture is too slow to keep up with significant changes in society and culture.*

Lightweight ephemeral structures are better able to react to society's rapidly changing cultural and consumer demands. According to Wainwright (2015), "Lightweight architecture had been evolved exactly as a reaction against the strident monumentality of the architecture". The history of structural engineering in past millennia can be viewed as a movement towards lighter structures (Fang, 2009, p.7). In the current state of rapid population growth, fast-changing society and culture, global climate change and catastrophic incidents, temporary structures such as tensile membrane structures offer certain advantages over permanent architecture.

2.1.3 Membrane aesthetics and emotional quality

Membranes own a tactile beauty that is inherent from the materials' microstructures. The spatial atmosphere of the membrane is unlike any other structure; it is usually described as woven or knitted (fabric-formed environments.). Drew (1979) referenced the soft form of tents, suggesting that tents are feminine. This has an interesting link to the fact that, in most nomadic cultures, women were the main architects. Textile materials were woven or knitted, and tents were designed and erected by women. The tent as a shelter had incorporated a personalised layer of construction (handicraft) that granted it a personal connection, richness of beauty, comfort and meaning. However, this was stripped when its use changed (Giller, 2012, p. 14).
According to Semper (1851), as man settled, mobility was not necessary anymore; instead, security and load-bearing capacities were needed, so shelters became more refined and walls gained mass. Solid walls did not replace the use of fabric, as walls were still covered by a layer of decorative hanging tapestries; textile qualities and properties were kept firmly indoors. As such, architecture still contains a residual meaning and symbolic value that comes directly from membrane or textile qualities.

2.2 HISTORY OF TENSILE MEMBRANE STRUCTURES

The field of tensile membrane structures has evolved from traditional tents. These structures are one of the earliest forms of shelter invented by humans. Since prehistoric times, they have been the main components in man's ambition to provide shelter and shape the environment. 'Tent' is a universal term, used to classify a lightweight and transportable shelter that employs a flexible membrane as a covering skin. The forms of tents often do not differ much from each other, as they were introduced as a response to a common lifestyle and the need for mobility. Tents are rooted in diverse cultures and environments, across vast geographically separate regions from the Saharan Desert to the frozen Arctic. Their appearances diverge in response to the environment, resource availability and usage (Giller, 2012, p. 19).

Ancient tents were constructed from basic materials, such as animal by-products (skin and bone), or from textile and tree branches. Popular types of temporary shelters built by the early humans can be classified into three types: tents, yurts and tepees. The structure of these tents fall into two basic categories:

The first category is the skin tent, which is the lightest and most truly tensile structure. The skin tent was built where materials with high tensile strength could be made; it is now the principle behind all modern tent designs. The original skin tent was the ‘desert black tent’.

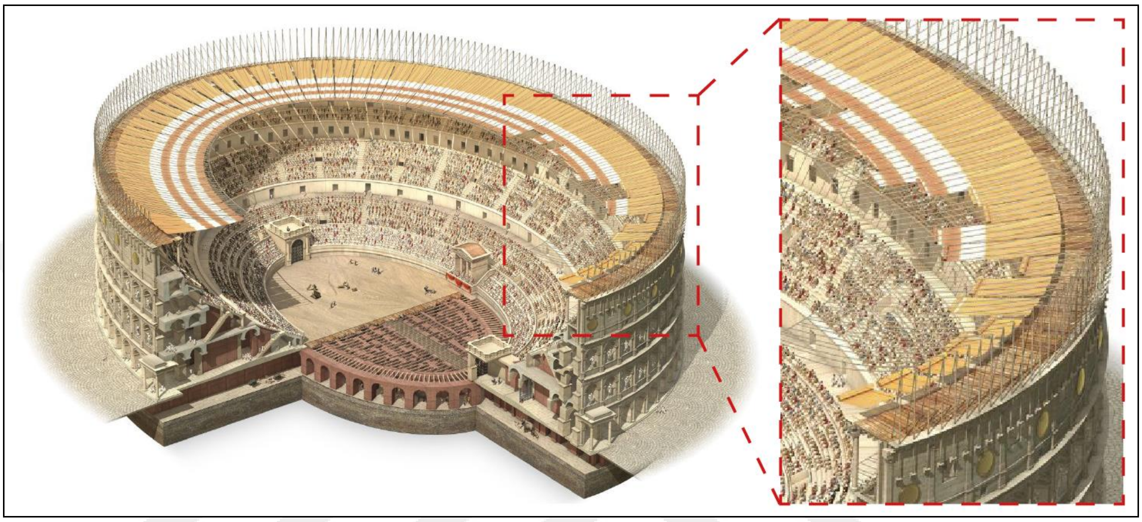
The second category is the skeleton frame tent, which was utilised in regions where materials with high tensile strength were scarce. These consist of the yurt, the tepee and some forms of the modern marquee (Figure 2.2).

Figure 2.2: Tent, Yurt and Tepee

Source: https://gulfnews.com/entertainment/arts-culture/know-the-uae-life-under-the-tent-1.1915952/ [Accessed 8 Feb. 2018].

The first nomadic society, which utilised tents as dwellings, was from Middle East and Central Asia. The earliest membrane structure discovered dates back to the middle Palaeolithic period. The remains of tent-like structures using animal hides were identified as early as 150,000 years ago (Kronenburg, 2015, p. 2). In addition, a timber-framed skeleton clad in Mastodon skins from the Mesolithic period, 13,000 years ago, were found preserved in peat bogs in southern Chile (Dillehay, 1984). Remains of sketches of Classical Roman architecture, from the beginning of the first millennium, feature temporary and retractable shading and screens. The Colosseum in Rome (AD 70-82) featured a Velarium, a tensile canvas roof that was 189 meters by 156 meters built by sailors; the experience and experimentation of making these structures transferred from nautical life to architecture (Kronenburg, 1995, pp. 27–37; Berger, 2005, p. 27; Kuusisto, 2010, p.27). The Velarium can be seen as the first attempt to scale up and explore the potential of the membrane for shading purpose (Figure 2.3). In addition, several drawings exist depicting Roman military tents from first century.

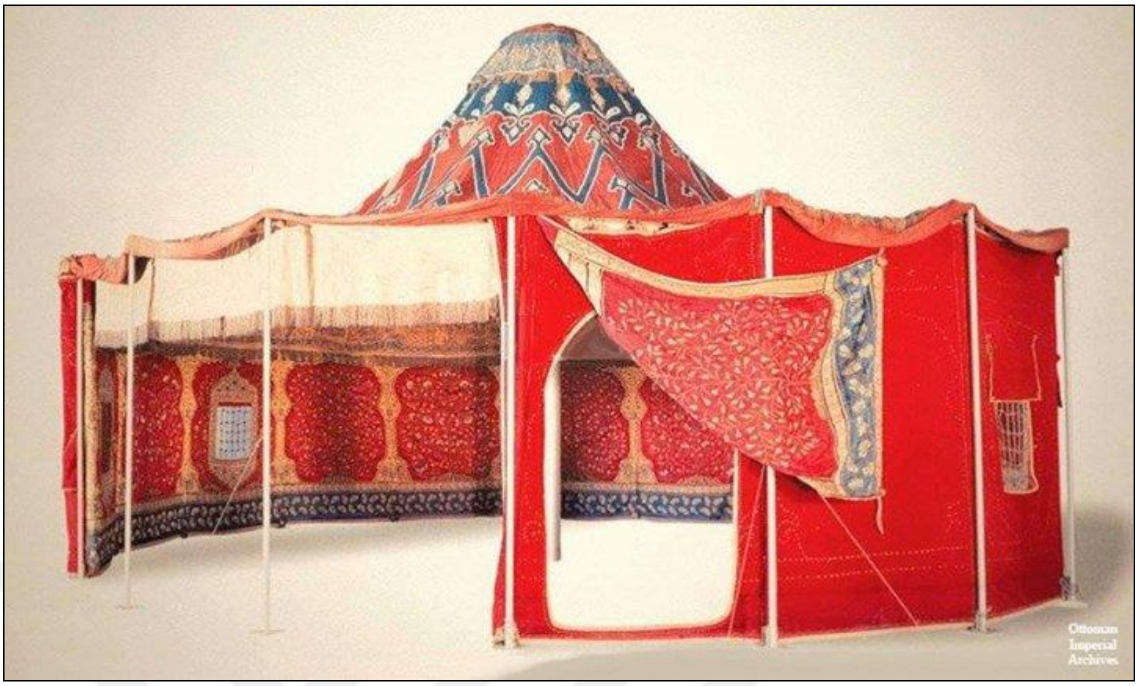
Figure 2.3: Classical Roman architecture, Colosseum tensile canvas



Source: https://wildfiregames.com/forum/index.php?/topic/20115-model-principate-romans-wonder-colosseum/ [Accessed 6 Mar. 2018].

In the Middle Eastern region, tents were familiar to the royal courts and military shelters of the Islamic empire. Ottoman royal tents were considered to be temporary palaces, intricately decorated with gold, fancy textile materials and decorated pillars; they were well-arranged in large complex layouts (Drew, 1979, p. 106) (Figure 2.4). The royal courts contributed to the development of membrane structures through exploiting properties of textile as a construction material to create huge and intricately decorated structures. After the 15th century, membranes were often utilised for royal banquet and entertainment halls.

Figure 2.4: Ottoman period tents



Source: https://www.osmanischesreich.de/kunst-kultur-1/museen-austellungen-ii/ [Accessed 12 Mar. 2018].

The ability to construct lightweight membrane structures and the availability of such materials for large constructions appears to be fragmented throughout history. Recorded membrane structures were used in remarkable monumental buildings. As explained by Garcia (2006, p. 14):

> *Many of the historical examples of textile-based architecture have perished due to the lack of durability of the materials used, and because the efforts of their makers and designers within this field were not thought worthy of recording, preserving or of scholarship, most of our early knowledge of these practices remains patchy.*

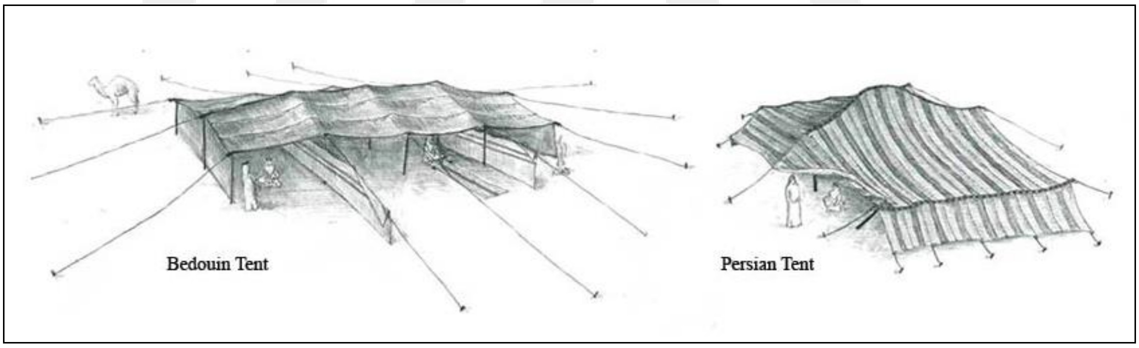
It took a long time for the membrane materials to appear in notable structural roles. In the 19th century, mobile circus tents appeared. During the 20th century, the tensile structures continued their expansion and started to be employed in public events to host large numbers of people. Temporary transportable constructions were suitable for such actions, and membranes were appropriate. These structures started to appear more often in architecture towards the second half of the 19th century, as organic membranes were replaced with synthetic membranes.

Architectural membranes have been exploited in space exploration, as membrane habitats have been sent into space in compact forms to be inflated into large shelters (Kronenburg, 2015, p. 18). Even the initial marks made by man on the surface of Mars were imprints of the textile landing air-bags deployed by the NASA Pathfinder mission in 1997–98”. The only thing we can be sure about is that membrane structures will be as vital a component in the future development of human building, similarly as they have been in the past (Kronenburg, 2015, p. 18). These are the extreme positions of the tent or membrane structures used in society.

2.2.1 Black tent

Black tents are homes of Middle Eastern nomads. They date back to 3000 – 4000 BC (Drew, 1979). The black tents are still in use by nomads. They are identified as vernacular architecture and have evolved over time, transferred from generation to generation. The structure holds a great similarity, as they have been a response to the same lifestyle and are composed from the same components (wooden poles, membrane and rope). There are two types of black tents, Bedouin and Persian tents, as demonstrated in Figure 2.5.

Figure 2.5: Black tent types



Source: Reinventing the Tent, 2011-2012 p. 26

The primary essences of black tents are their adaptability and responsiveness to the outdoor conditions, as black tents are always placed to achieve the greatest advantage from the prevailing conditions (Qubrosi, 2013) (Figure 2.6). The aerodynamic form of the Bedouin tend is amongst the most wind-resistant forms (May, 2010 ; Faegre, 1979).

Figure 2.6: Black tent across Middle Eastern regions

Turkey

Kahraman maras turkey- dulkadir.com

A traditional tent of a Beritan family in Karliova, 2008. by : Michaël Thevenin

Iraq

K24.net-Erbil, 2016

Rawandz festival, 2018-Roj new

Persıa

Dasht-e-Lar, a traditional nomad tent Photo by: Ninara. Taken on June 20, 2009

Bakhtiari nomad home, near Shahrekord Photo by: Ninara. Taken on June 23, 2011

Morocco-sahara

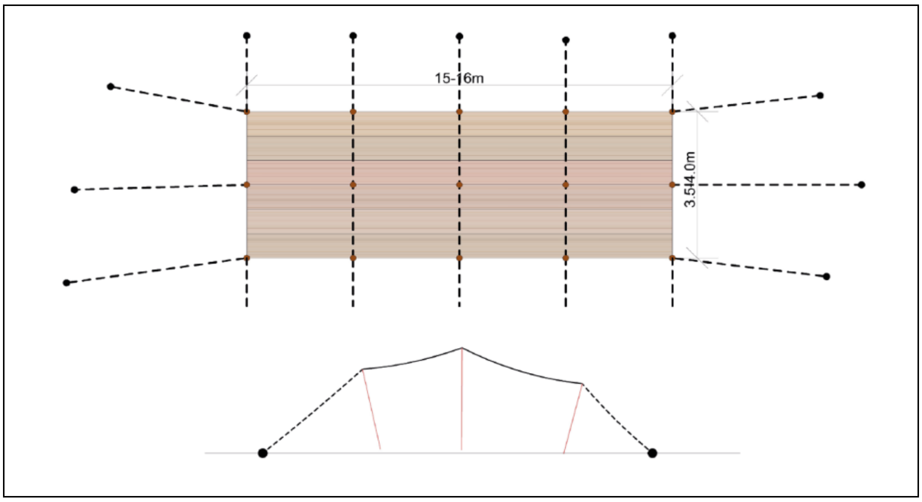
The bedouins tent in the sahara, morocco by: Seleznev Oleg

Bedouin tent 2016 By: Erg Chebbi

Source: Turkey, Left: http://hilmidulkadir.com/?sa=icerik&gr=18&ino=114 [Accessed 6 Apr. 2018].
Turkey, Right: https://link.springer.com/article/10.1186/2041-7136-1-23 [Accessed 6 Feb. 2018].
Iraq, Left: http://www.kurdistan24.net/en/default [Accessed 25 Nov. 2018].
Iraq, Right: eight Rawandz festival, 2018-Roj new. https://rojnews.news/tr [Accessed 25 Nov. 2018].
Morocco, Left: https://www.dreamstime.com/stock-images-desert-camp-image8403154 [Accessed 12 Jan. 2018].
Morocco, Right: http://chihuahuasgang.blogspot.com/2017/01/morocco-2016-2017-day-4-erg-chebbi.html [Accessed 12 Jan. 2018].
Persia, Left: https://www.flickr.com/photos/ninara/3643158773/ [Accessed 8 Jan. 2018].
Persia, Right: https://www.flickr.com/photos/ninara/5869268832/ [Accessed 7 Jan. 2018].

The size of the black tent differs in accordance with the wealth and size of the family. The standard tent is approximately 15 meters long and 3.5 meters wide (Oliver, 1997). Normally, it has a row of five poles in length and three poles in width. The longitudinal poles (which are parallel to the strips' directions) is roughly 3 meters in span, and the latitudinal poles are around 1.5 meters in span. The poles are almost 2 meters tall except for the middle ones, which are at least 15 cm taller (Abu Adel, 2013) (Figure 2.7). These middle poles are located under wooden planks attached to the roof to prevent the poles from tearing the thin layer. The top planks provide a smooth rounded outline to the tent (Drew, 1979; Abed Al Rahman 2013). The poles are responsible for providing the height and giving the volume to the tent; they are the compression-based parts of the structure, whilst the thin covering membrane is the tension part. The balance between these forces lead to the formation of tents. The interaction between directional forces freeze and stabilise the thin flexible membrane. Tents located on flat landscapes with no physical support except for the ground have the same prevailing situation and force effect scenario. Thus, this leads to an identical formal outcome. Modern tents are mainly merged into buildings or blended into man-made physical environments (steel frames, massive masts, etc.). The force balance in the new physical context results in a completely new formal configuration.

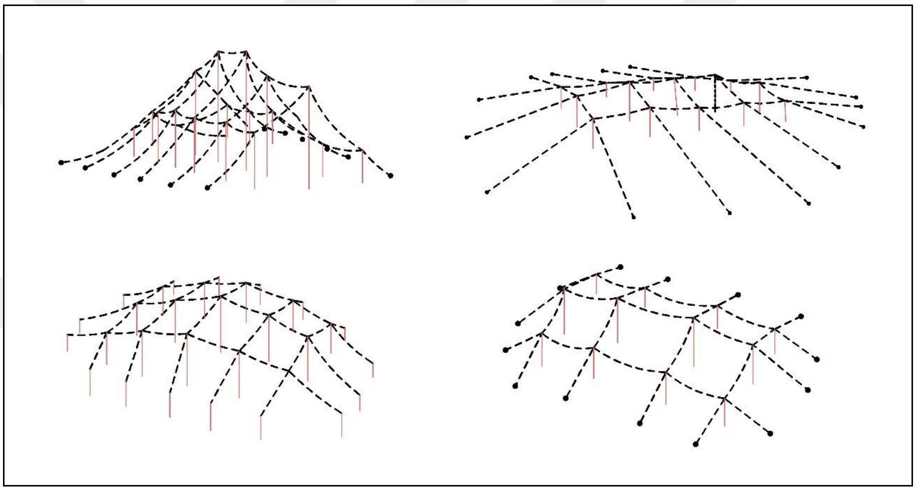
Figure 2.7: Typical black tent layout that illustrates the dimensions of the elements



Source: Re-drawn from Reinventing the Tent, 2011-2012 p. 26

The thin membrane woven from natural fibres cannot resist massive tension stress since natural fibres have a limited tension resistance. Therefore, nomads usually utilise a rope-net (or wooden beams) that ran over the poles as a support to the skin. This tension-net makes the thin woven textile roof tight and concentrates the tension on the ropes. Altogether, the tension rope-net and the wooden poles create an independent support system under the roof, giving shape to the tent (Figure 2.8). The woven textile still provides tension in a subordinate way, covering a smaller bay of 2-3 meters. The tent perimeter is tensioned and fixed to the ground (i.e. a wooden stake secured to the ground) with anchor ropes and guy ropes (Oliver, 1997). In desert regions, the black tent perimeter is buried under ground sand, and in mountainous regions, rocks are laid on the perimeter after tensioning. Similar study on analysing tent structures is given at Appendix-4.

Figure 2.8: Black tent main independent structure.

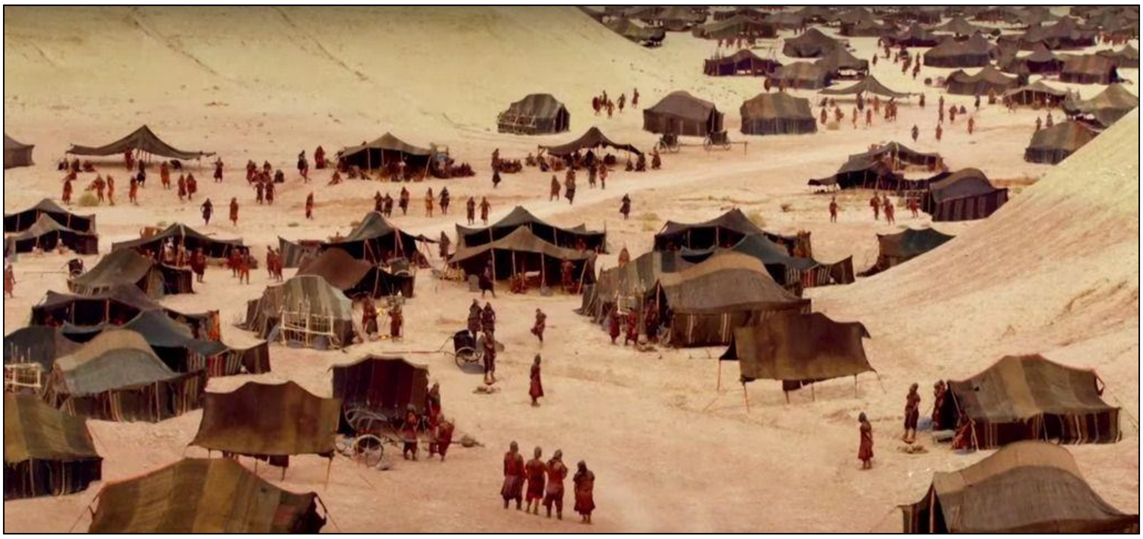


Source: Re-drawn from Reinventing the Tent, 2011-2012 p. 26

The visual characteristics of black tent are directly inherited from the colour of its fibres and the seam lines from stitching the textile sheets together.

Colour: The tent acquires its colour from black or brown goat hair. In addition to goat's hair, the tents contain decorative weaving or geometric patterns of white strips made of wool (Faegre, 1979) (Figure 2.9). The black colour is presumed to absorb heat and create an uncomfortably hot internal situation within the tent. In reality, it has a distinctive advantage over lighter coloured fibres, as the dark shades of the goat hair provide a densely shaded area and insulate against the radiated heat (Faegre, 1979). The interaction between the dark shade and the fabric weaving provides dimmed lighting and a pleasant condition (Figure 2.10).

Figure 2.9: Traditional black tent variations



*Source:*http://kissthemgoodbye.net/PeriodDrama/displayimage.php?album=405&pid=399920#top_display_media [Accessed 1 Dec. 2018].

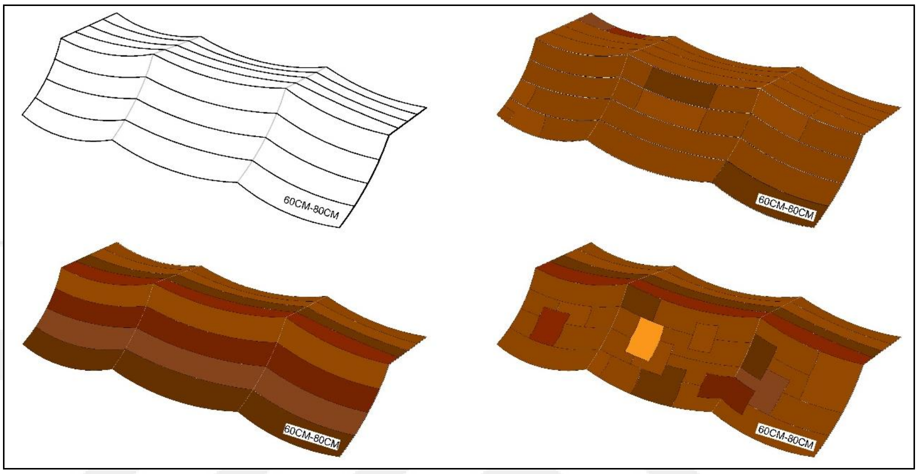
Figure 2.10: Black tent interior ambient

Source: Left interior view https://www.flickr.com/photos/ninara/4916967545/ [Accessed 12 Dec. 2018]
Middle interior view https://www.yaroslavgloushakov.com/bedouin-style-tents-image-gallery.html [Accessed 12 Dec. 2018].
Right interior view http://www.gezionerileri.com/gokceada/ [Accessed 12 Dec. 2018]

Seaming: The woven textile used for black tents has modular units. Woven strips are often between 60-80 cm in width, and their length can exceed up to 20 meters in large tents (Bahamón, 2004, 32–33: Da Cruz, 1996; Kronenburg, 1995, 17–19 2013). These strips are sewn edge-to-edge, forming a large rectangular roof (Faegre, 1979). The life span of textile is short, as the material is not durable; throughout a tent's lifespan, old and worn pieces are regularly amended. First, worn repairing is done by covering the worn areas with new pieces; after a while, the structure will start to look patchy (Figure

2.11). Even some new tents are built entirely from sewing small pieces together to have a similar patchy look. Second, the roof needed to be renewed every year due to ageing by adding new strips, pushing the old strips backward. “From the top, the strips are new, and the strips touching the ground are the oldest part and in the most worn out state (Faegre 1979, 1–25; Kronenburg 1995, 17–19)”.

Figure 2.11: Traditional black tent roof seaming



Source: Typical membrane roof Re-drawn analogous to Faegre description of nomad tent roofs

2.3 DEVELOPMENT OF TENSILE MEMBRANE STRUCTURES

The key drivers for the renewal of tensile membrane architecture can be defined as developments in material technology, design methods and engineering tools, along with new architectural theories, socio-cultural developments and functions.

2.3.1 Material technology

Until the 1970s, most membrane structures were intended to be temporary such as nomad shelters, military tents, circus tents, early Roman shadings and architectural structures including Frei Otto’s early works. Recently this has changed, and most structures that employ synthetic membrane materials are now expected to endure for decades. The scale and durability of tensile membrane structures have increased to the point where they can surpass traditional construction materials. They may also be designed to be semi-permanent, with a similar lifespan to buildings built from far more materials and much heavier ones. These materials can be used to realise increasingly complex structures, cover large spans and compose architecturally expressive forms that can enhance the physical environment. The keys to attaining an increased life span are generating the correct form and choosing the most appropriate materials.

The potential of membrane has expanded as material technology has evolved. The development resulted in an emergence of durable and high strength-coated woven fabrics and steel cables with high tensile strength. The coating of textile material first started in the 18th century, and coatings were made of different natural oils; in the 19th century, rubber mixes replaced them. The main goal of coatings was to make textiles water and wind-proof (Miraftab, 2000, p. 24–41). In the 20th century, artificial fibres were invented, and few new polymers, manmade rubbers and adhesives for coating and lamination of textiles were introduced. These fabricated materials aimed to surpass the properties of natural fibres.

A significant series of advancements in membrane materials includes the development of PVC in 1933; PTFE in 1938; nylon in 1939; polyester fibre in 1947; and PTFE-coated glass fibres in 1972 (Mewes, 1993). Modern developers have tackled with the challenge of increasing the thermal resistance of membranes, ultimately coming up with new strategies such as double-layered roofs. Thus, developments in the design of membrane structures can dramatically change the way we conceptualise permanent building construction.

2.3.2 Tensile membrane design methods and engineering tools

The design of tensile membranes is a complex task. Tian (2011, p. 4) stated: “They are, in fact, extremely difficult to structure correctly, and precise tent construction is among the most difficult methods of construction”. The complexity of the design process comes from the flexibility of fabrics, which requires an experimentational process of form finding through either analogue or digital models. The boost that elevated tensile membranes came from innovative design methods and form finding. Kronenburg (2015, p. 8) stated: “In the 1950s, Otto developed new methods for designing membrane structures based on the weighted cables and soap bubbles to produce naturally formed physical models that produced a resolved structural form”. This innovative method led to the creation of bold tensile membrane forms, also giving impetus to the structures’ usage. As such, numerous tensile membranes pavilions were erected in expos around the world.

Until the 1980s, the majority of the membrane structures were skeleton-based. Tensile membrane forms struggled to find its place on paper, as because they are difficult to design or draw in an accurate representation with precise physical dimensions of the membrane's curved surface. Otto used computational power whilst designing the roof of Munich's Olympic stadium between 1968-1972. Serebryakova (2006) stated: "The first computer simulation of a physical model was carried out by Linkwitz in 1966 on the initiative of Frei", the biggest tent roof of that time with a futuristic expression. The design team planned the construction of the roof to obtain concrete measurements for various elements. At the Institute for Lightweight Structures at Stuttgart Technical University, a wire model was constructed to simulate the stress that the roof had to withstand. Otto (2004) stated that It was a herculean task to evaluate the data. They had to solve an equation with more than 10,000 unknown factors for the first time since dimensions had been calculated by computers. The tensile membrane design and construction require high precision during design and realization processes. The advent of CAD/CAM (meshes and NURBS surfaces) brought great progress to tensile membrane development; computers are able to document and extract the dimensional properties of form, and massive computational power eases the intricate structural calculations (form finding and load analysis). Therefore, architecture began to undertake more of the qualities of tensile membranes in the 1990s. Computational analysis techniques and construction methods have come a long way since the first modern fabric structure was built in 1950s. The digital revolution that was initiated by computers and continued with computational power and new design software gave great momentum to the membrane archetype.

Digital tools for membrane design and construction, such as Dlubal, Forten-ixcube, Formfinder and Membrane NDN softwares, have been exclusively used for structural engineering. They contain a limited number of prescribed forms, such as hyper, conic, barrel volt and inflatable structures. The emergence of Grasshopper's "Graphical Algorithm Editor" in 2007 by Rutten's team offered great modelling freedom. It was introduced as an intermediary platform to link multiple softwares.

In 2011, the Kangaroo plug-in brought tensile membrane design to the Grasshopper's parametric platform. Kangaroo was capable of form finding and structural analysis, and the tools' freedom revived the experimental spirit of designing tensile membrane structures. The platform continuously developed and in 2014, it introduced Ladybug as an environmental analysis tool capable of making annual climate simulations. In 2015, a new multi-objective optimization tool called Octopus was added to the platform. The combination of the whole platform has enabled the creation of a system that incorporates multiple design aspects to tensile membrane structure design and creates a conscious design process (parametric-system) within the architect's disposal. A literature review on the concept of parametric design and plug-ins employed will be presented in following chapters.

2.3.3 New building typologies, programmes and functions

In revival of tensile membrane structures, new building typologies as well as the need for new architectural solutions with complex programmes and more intricate process-based functions emerged.

Originally, small-sized tents were built as dwellings that fulfilled the requirement of a nomadic lifestyle. Throughout history, they matured to become bigger and more complex. Membranes were predominantly utilised for shading structures; emergency post disaster shelters; car shelters; walkways; warehouses; circuses; recreational campuses; military campuses; airports; malls; pavilions; entrances; installation art; aesthetic facade finishing and stadiums. As they are the most economical way to achieve a clear span, approximately 80% of all new stadium roofs use membrane construction (Garbe, 2008). Tension membrane structures have generally been employed for free form structures, as complex curvilinear forms are more affordable and achievable with membrane materials.

The promotion and expansion of membranes mainly depend on the construction efficiency, since they are particularly effective in extreme physical conditions. Membranes can withstand dynamic forces that can result due to twisting, torsion, buckling and bending, as encountered during earthquakes, wind-directed heavy snow and hurricanes.

2.3.4 New architectural theories

Throughout history, tent structures have been present in all climates and regions around the world. Probably due to their temporality, alienation and circumstantial use, they have not been not represented adequately in architectural literature. Garcia (2006) stated: “The qualities and properties of textiles as a material group were largely excluded from most architecture theories and from architectural production itself”.

Membranes as construction materials seem to be a paradox. Conventional paradigms in material specifications are based on the concept of firmness while perceiving architectural structures as permanent, finished, durable, static, dense and compression-based constructions. However, tents fit none of these descriptions. Contrarily, tent structures are identified as temporal, never finished, ephemeral, dynamic, light and tension-based. The superiority of tensile membrane structures are their natural strength, lightness and efficiency in resource consumption. Comparing tensile membrane structures with massive compression-based ones can result in the perception that they are cheap and temporary versions of permanent structures. A consequent race to increase their performance at any cost, result in the loss of the original character. Fortunately, the advance in material technology improved the unique characteristics of membrane materials to reach their full potential. On the other hand, architecture of tensile membrane structures is relatively a new field and contemporary design has been so closely centralised on their aspects of ‘usefulness’ than aspects of ‘beauty’. Although the tent may have once satisfied Vitruvius’s definition of architecture, it is now missing the balanced realisation of his three defining features: strength, usefulness and beauty. (Giller, 2012, p. 40).

Tensile membrane architecture seems to be a paradigm shift and literally a reorientation of architecture, from the solid to the fluid and flexible states of matter. Advances in technology provoke new parametric free form trends, which envision architecture as more complex and sophisticated geometrical forms. Contemporary theories of space are dominated by dynamic, interactive, flexible, event- and process-based paradigms of space, as well as various articulated aspects of the new metaphysical and ontological definitions of architectural space. Tension membrane, as the most economical way to realise free form architecture, may become effective types for research for reorientation of architecture.

2.3.5 Sociocultural developments and functions

The end of 18th and 19th century developments formed the basis of membrane architecture. Industrial and social revolutions of the 18th century resulted in a general cultural confusion; consequently, the new situation brought about a new perspective. The old world no longer existed, and architecture was searching for new means to express the new situation; new building tasks were needed instead of the monumental architecture of churches and palaces, and new technology was required to achieve these undertakings. Large halls, office buildings and private dwellings became the new tasks of architecture (Kuusisto, 2010, p. 29-30). New theories like the "manifesto of future architecture" (Sant'Elia, 1914) promoted lightweight structures. "We no longer believe in the monumental, the heavy and static and have enriched our sensibilities with a taste for lightness, transience and practicality". In addition, other famous architects, such as Fuller (1929), made comments like, "Madam, how much does your house weigh?" as the theories of architecture pushed the field toward lightweight construction.

Until the advent of high-performance and technical membranes in the 20th century, this membrane as a building material was dismissed. The benefits of membrane materials in the construction of buildings have been accepted by society in recent years (Tian, 2011, p. 17). During the 1950s, it was standard to observe structures composed of steel and glass; conversely, Otto's membrane structure was light, slim and soft, which presented something new and fresh to the architectural field. In recent years, membranes offer significant, unique and expanding range of possibilities for innovation. The neglect of membranes in architecture is now in reversal; architects, engineers and designers are now making bold claims for the importance of its disciplinary confluence and increasing centrality in architecture (Garcia, 2006).

2.4 STRUCTURAL CONCEPT

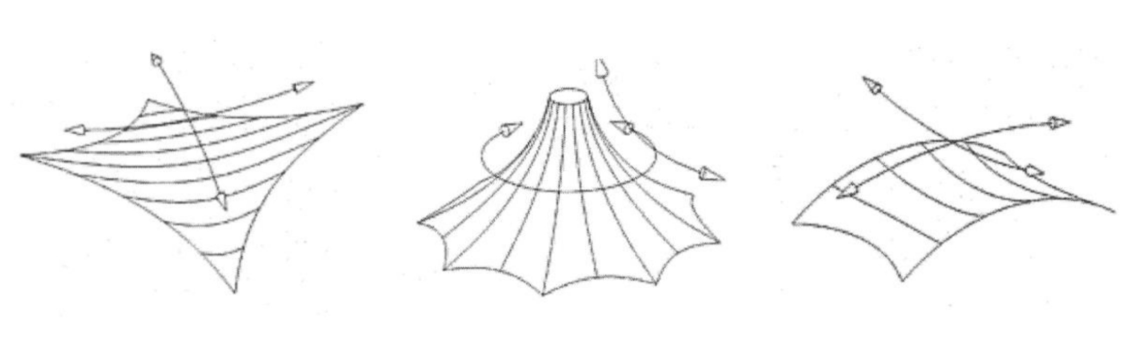
Buildings are distinguished based on their materials and structural conception. Construction that directly exploits a lightweight and flexible fabric membrane as a "structural material" is known as a "tensile membrane structure". There is a wide range of natural and synthetic materials that could be identified as membrane materials. The structural principle for tensile membranes remains the same and is directly inherited from the mechanical behaviour of membrane material; their elasticity and flexibility offer versatility of form. Designing accurate tensile membrane structures is complex and requires an understanding of the behaviour of the materials, formation process and the forces acting upon it (Henrysson, 2012). Fundamental principle of tensile membrane structures can be categorized as double curvature (Anticlastic & Synclastic) and form-finding (equilibrium) membrenes.

2.4.1 Double curved tensile membrane structures

According to Kaltenbach (2004), “A membrane material has a natural tendency to curve”. The membrane material group is identified as highly flexible and loose. For a membrane material to be structurally stable, some control should be exerted over the state of material. The double curvature will freeze structural composition and solidify the material. By forcing the membrane to take on a double-curvature, the structure will be confined, and the membrane will gain sufficient stiffness to withstand the loads it is subjected to both in upward and downward forces (Figure 2.12). To be able to make a double curved shape out of flat sheets of material, the material must allow for considerable shear deformation (Housman, 2015, P.101). According to Khan (1971), it is important to respect the quality (distinctive nature) of material that is used.

The structural concept is the membrane’s principle that the flexible material can only take tension forces. Tensile membrane translates external loading into tension forces by increasing deflection. If we want to create a stable shape under external loads, introducing extra tension to the membrane surface will work and it will increase their ability to resist external loading. It is a complex task to make a curved surface using tension, and the design process of membrane structures is dependent on utilizing the tension in a precise fashion (Kaltenbach, 2004). Detailed membrane properties is provided at appendix-A

Figure 2.12: Double curved tensile membrane forms. (Hypar, Cone and Volt)



Source: http://www.architen.com/articles/basic-theories-of-tensile-membrane-architecture/ [Accessed 17 Feb. 2018].

2.4.2 Form-finding of tensile membrane structures

Form-finding is a well-established method in Structural engineering, identified as the process of finding optimal structural shapes by using experimental tools and strategies. The process is executed using a physical or virtual model that is bounded by specific mechanical behaviour. The process is called "form" finding as during the interactive physical process, the overall form of the structure changes to many times. The main goal is to achieve increasing levels of structural performance and reduce material consumption.

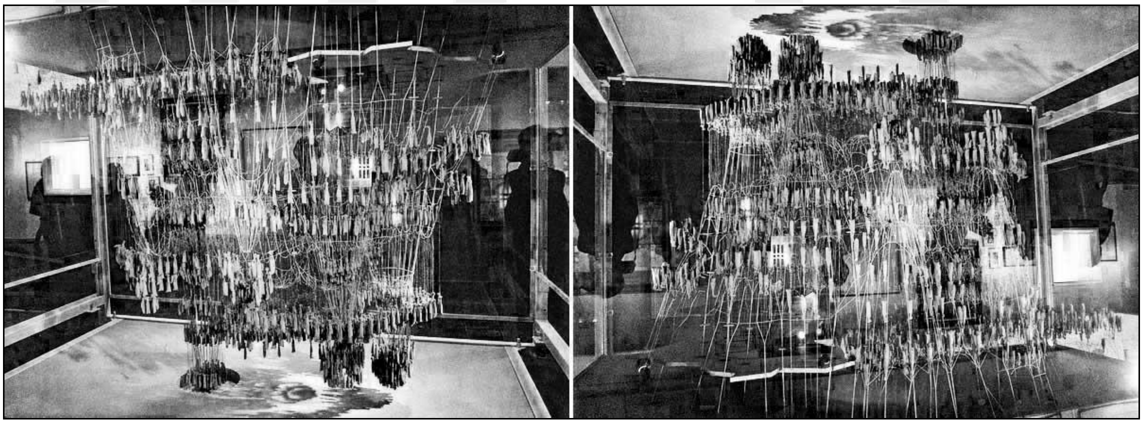
Form-finding is a kind of harnessing of the physical laws of nature to reach an optimal structure. Schumacher (2016) describes the process of form finding, as a physical setup where the form self-organises, and it is not drawn by hand, invented or pre-conceived. This method is to conceptually organize our structures based on processes in nature. Isaacs (2008, p. 3) stated, "Nature does not care about aesthetics. Her only concern is with optimal and perfect ordering". The outcome of the procedure is a rational form therefore, it is not a product of arbitrary artistic feeling. Moreover, one benefit that comes with a design process based on nature is that we have a natural feel for them, and this intuitive quality lends itself well to the design outcome (Piker, 2013).

Structures working in tension are formally and structurally distinctive from conventional buildings. They depend on a material's compression and bending resistance to gain stability: however, membrane material has no compression nor shear resistance, it has only tensile resistance. The form-finding was aimed to find pure stress states. Systems in pure tension or compression provide the most efficient way in consuming material for gaining structural stability (Beccarelli, 2015, p. 19).

There are several form-finding methods used by innovative architects during the last centuries. The structural design approach using gravitational forces to obtain structural form was first mentioned in a publication by Hooke in 1675. Hooke used the "funicular" shape to find tensile form, then inverted it to find the mechanical compression-only state (Block, DeJong and Ochsendorf, 2006, pp. 13-15).

In the 1880's, Gaudi used the same principle during designing complex double curving surfaces of Sagrada Familia. Gaudi was working with massive masonry stones, which only had compression resistance. It was important for him to find a structural shape that worked purely in compression. For understanding structural behaviour and conducting form-finding, he experimented with a scaled replica of real buildings. He implemented the hanging chain principle to find pure tension form. By inverting the shape of a hanging chain, he obtained geometry that was in pure compression and free bending from. The model in pure tension was overturned to become one in pure compression (Burry, 2016, pp. 30-35) (Figure 2.13).

Figure 2.13: Sagrada Familia hanging chain model (form-finding)

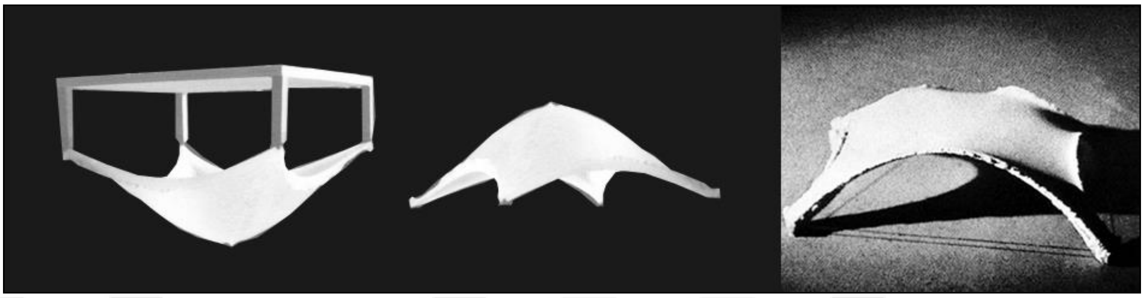


Source: https://www.flickr.com/photos/wolfgang_hammer/4664781278 [Accessed 5 Feb. 2018].

Heinz Isler in 1955, came up with another method for form-finding; a new method specific for finding the shape of reinforced concrete shells (Chilton, 2010). Isler employed the wet fabric form-finding method in his unique works such as Deitingen service station 1968 and in concrete shell for the open-air theatre at Grotzingen 1977. He basically simulated properties of concrete shells by suspending wet pieces of fabric or membrane - then derived forms were frozen and finally inverted (Pungale, 2014).

Very diverse outcomes could be obtained by changing the type of fabric used; the properties of the material used in scaled replicas played an important role in the process (Pugnale, 2014, p. 356). (Figure 2.14).

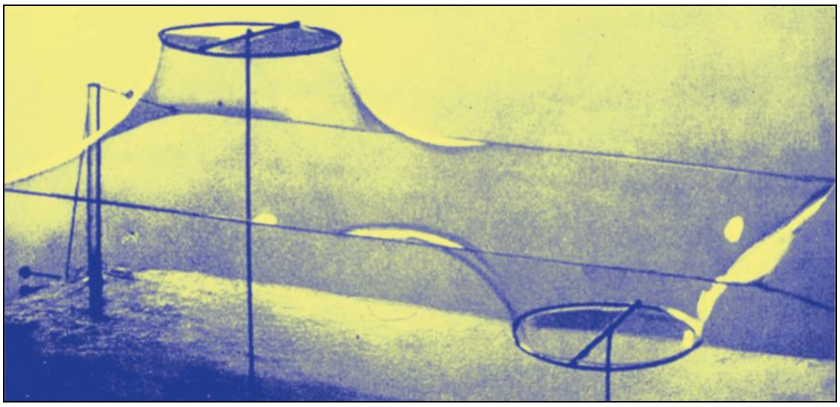
Figure 2.14: Stiffened form-finding model for compression stress concrete shell to cover the stands of the open-air theatre at Grotzingen by Isler (1995).



Source: https://n0310093.weebly.com/blog/heinz-isler [Accessed 8 Feb. 2018].

Otto, in the 1950's, invented a new method specific for designing membrane structures. Otto experimented with the soap bubble and flexible wire frames to derive various membrane forms (Pugnale, 2014, p. 357). The membrane and shell form finding were logically following different mechanical concepts. Soap bubbles tried to shrink and be as minimal as possible on the hanging chain and wet fabric hence they tried to find the optimal path curvature for transferring the load through the whole structure (Figure 2.15). Wainwright (2015) states: "Otto's ultimate quest was deducing the geometric magic of the humble soap bubble. Given a set of fixed points, he noted, soap film will spread naturally to offer the smallest achievable surface area". Soap films formed over any boundary are mathematically defined as the minimal surface that could be generated for that boundary setting (Pungale, 2014; Abbena, Gray, Salamon, 2006).

Figure 2.15: Soap bubble form-finding by Frei Otto.

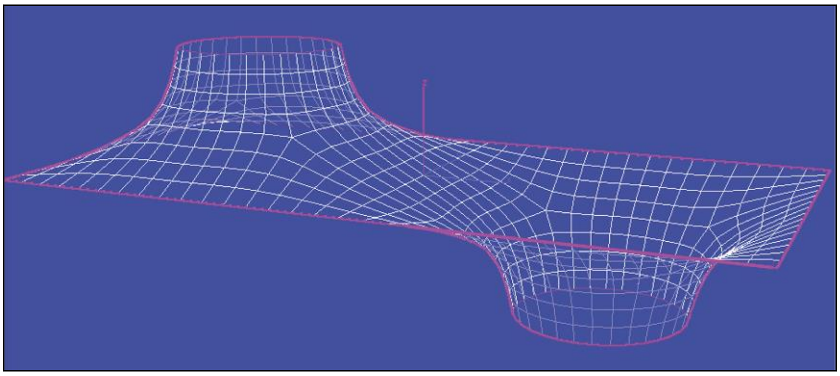


Source: https://www.archdaily.com/610531/frei-otto-and-the-importance-of-experimentation-in-architecture/ [Accessed 2 Feb. 2018].

The low weight of the fabric which means that gravity or 'self-weight' is often negligible. That makes soap bubbles a perfect resemblance of membrane at small-scale models. However, in the case of large soap films, self-weight will adversely affect the form. The problem of soap models is that they are very difficult to measure, control the stress levels of the structure or determine cutting patterns.

In the case of using elastic fabric instead of soap film, the governing load for form-finding could be other external loads in addition to self-weight. Elastic membranes fixed across different edge frames can simulate the pre-stress state identical to cable nets or tensile structures. Physical models with elastic fabrics enable the designers to intervene and to experience the stiffness and flow of forces. Moreover, determining cutting patterns on elastic membranes is the most pragmatic way of using physical replica as reference for full scale realization.

Figure 2.16: Digital form finding (3ds max Dynamic relaxation)

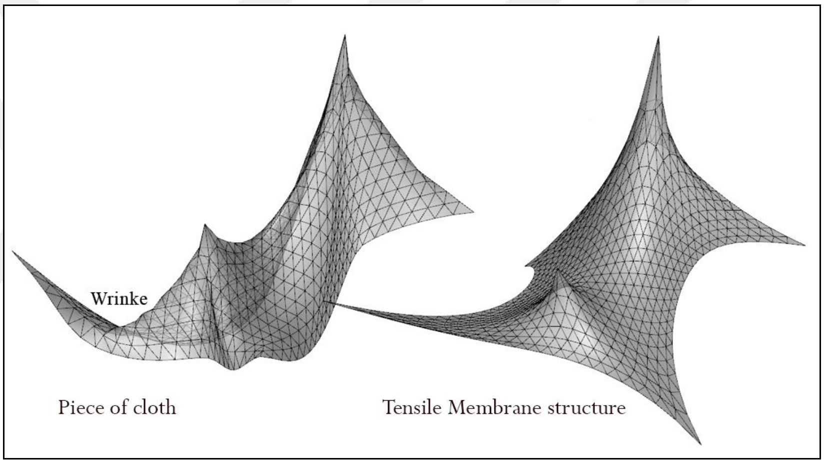


Source: 3ds max mesh modelling

The true behaviour of membrane material is highly complex and non-linear. Membrane form-finding is an attempt for finding how to achieve more with less. Olsson (2012, p.

7) states: “The other objective of form-finding for a tensile structure is to determine the geometrical configuration where the loaded membrane does not slack nor crease nor wrinkles. Also, form will not allow ponding of water” (Figure 2.17). Accumulation of water or snow can distort the membrane and lead to local failure or progressive failure of the entire structure. The high and low pitches of membrane setting should naturally prevent accumulation of water, dust or snow on the surface. Only an adequate geometry, designed with a correct level of double curvature with uniform stress level can support the downward and upward loads without ponding or fluttering problems in windy conditions.

Figure 2.17: Difference between tension (form-found) and non-tensioned membrane roof



Source: Kangaroo and Grasshopper modelling

Form-finding and analysis are different things. The first tries to find the optimal form while the latter show the deformation under the force acting upon the form. That deformation requires compensation by increasing stress. During the interview with the owner of the Supernova firm that installed the tensile membrane in the case study, Mr. Auni, stated, “We calculate for the external loads such as wind, rain and snow on site during installation and we compensate for them, by increasing tensile stress level”. Structures can be investigated under various load situations by calculating elastic deformations and stress concentrations in the membrane surfaces and the wire cables.

2.4.3 Digital form finding

Before computers, it was difficult to design double curved tensile membrane structures. The design process was based on rudimentary approximations of scale models to get the shape of equilibrium. The continuous construction and adjustment of physical models was an exhausting and time-consuming process. In addition, it was difficult to control the magnitude of the pre-stress, making the accurate form challenging. On top of that, physical models were difficult to measure, also translate it into a full-scale structure. With the initiation of CAD together with an increased knowledge of the behaviour of materials, alternative methods of form-finding have been developed.

Otto, for designing his early structures, used analogue models; however, as the scale of his projects increased and became far more complicated, he began using computers. The first use of a computer was to measure the amount of stress required to stabilise his membrane structures. In an interview in 2004, Otto stated, “I must add that since 1965 all my buildings have been calculated with the computer. This is natural and does not need to be questioned, because it’s common practice today” (Otto, 2004, A Conversation with Frei Otto (Conversations)).

Continuous increase in computational power in combination with new highly sophisticated software has created digital tools that can accurately assimilate the association between geometry and a material’s mechanical behaviour. Digital tools are helpful in finding optimum structural solutions for any given geometric parameters. Furthermore, they are capable of meticulously analysing the behaviour of materials and structures under loads. The computer can calculate the amount of membrane needed and determine the cutting patterns and the dimensions of other structural components. It also enables easy adjustment and the exploration of different possibilities (Armijos, 2008).

2.4.4 Parametric form-finding

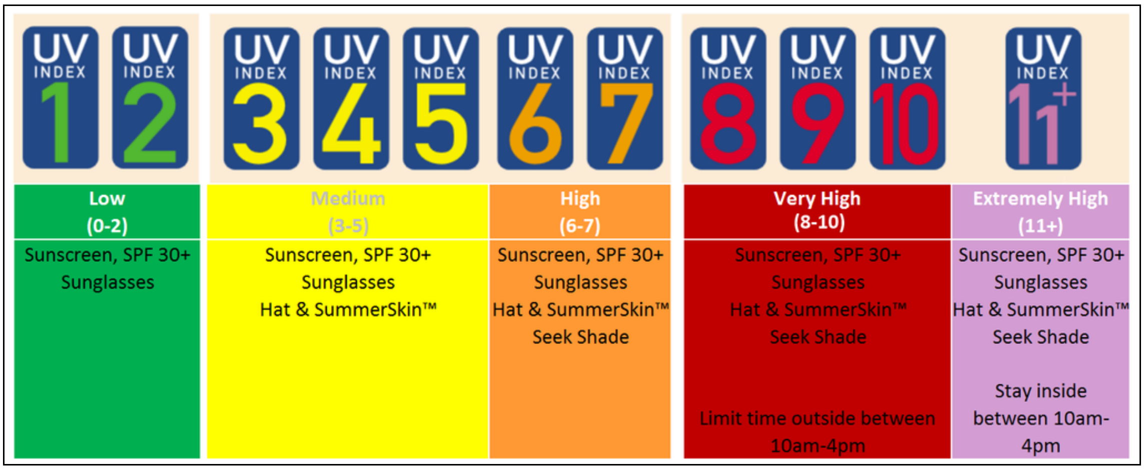
Parametric form-finding is the exploration procedure that offers solutions to the problem by using changeable variables (Kourkoutas, 2007, p. 3). Dynamically adjusting dimensional parameters, controlling the combination of forces acting on structure and real-time visualization is normally offered by membrane design applications. The parametric tool is transforming membrane's generative features into architectural design workflow by introducing a set of rules to define formal constraints. Parametric tools allow the designer to compromise the form to meet other constraints such as environmental and cultural constraints. Pugnale (2014, p. 359) said, "it can be used for form improvement" which is a new process for improving multi-criteria of an already existing spatial configuration, which does not necessarily mean reaching the optimum structure.

On the other hand, fabrication is an integral part of membrane design application. The Designer employing Grasshopper3D, can deal with issues of structural detailing, patterning, fabrication and assembly of tensile membrane structure. Grasshopper and Rhino integration can effectively lead the rationalization and fabrication of complicated architectural forms.

2.5 SOLAR SHADING

Sun radiation contains invisible radiations besides visible sunlight. Invisible radiation consists of two main components: UV radiations, which are dangerous, and infrared radiation, which provides heat. UV radiation is normally blocked by the ozone from reaching the earth's surface. However, global warming stimulates ozone depletion, which is a dangerous environmental issue that leads to increase in the levels of UV radiation. Less UV radiation is absorbed by the atmosphere and a greater amount of UV radiation will reach the ground surface (Earth observatory, 2001). According to the WHO, "The higher the sun in the sky, the higher the UV radiation level". Thus UV radiation varies with time of day and time of year, with maximum levels occurring when the sun is at its maximum elevation, at around mid day (solar noon) during the summer months". Excessive sun radiation inversely affects health and thermal comfort. As exposure to strong direct sunlight radiation is dangerous, especially for vulnerable groups such as children and elderly people, it must be blocked without any compromise (Figure 2.18).

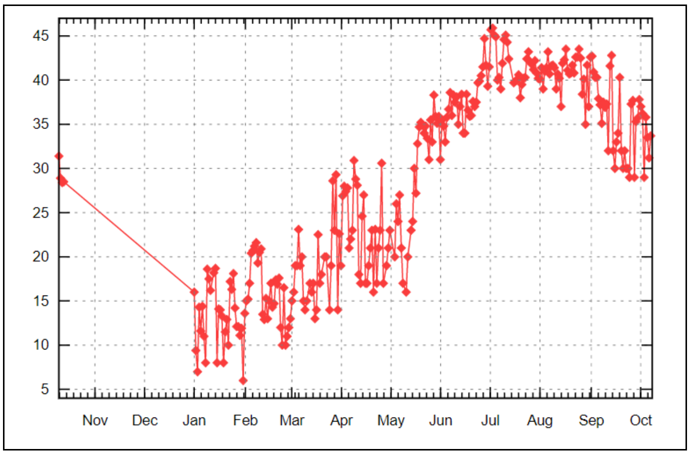
Figure 2.18: UV index and level of danger



Source: https://www.who.int/uv/intersunprogramme/activities/uv_index/en/index1.html [Accessed 5 Oct. 2018].

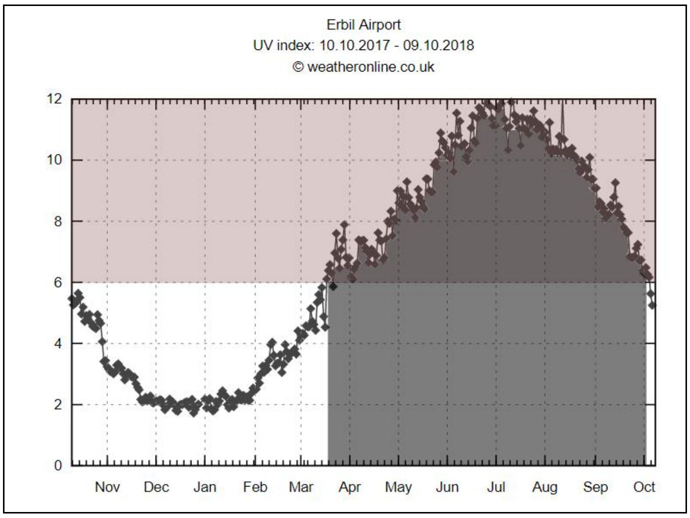
Global warming is a global phenomenon. Middle Eastern regions have for long time been facing overheating. The highest temperature recorded in Erbil city was 48 degrees on 3 July 2018, meaning that the temperature was 48 degrees in full shade (Figure 2.19). The UV index for the same day exceeded 12 degrees (Figure 2.20). The problem is real and will be accelerating in the future. According to the policymaker summary (2013), the average global temperature could rise as much as 2.6-4.8 degrees by the end of the century.

Figure 2.19: Annual temperature graph of Erbil city



Source: https://www.weatheronline.co.uk/weather/maps/city [Accessed 12 Oct. 2018].

Figure 2.20: Annual UV Index Graph of Erbil city



Source: https://www.weatheronline.co.uk/weather/maps/city [Accessed 12 Oct. 2018].

2.5.1 Thermal comfort

The presence of a tensile membrane shading structure offers comfort in physical and physiological ways. According to the ASHRAE (2010), thermal comfort is a complex science that "is the condition of mind that expresses satisfaction with the thermal environment". The key factors that influence thermal comfort determines heat gain and loss, which are directly affected by environmental or personal factors. Environmental factors encompass factors such as air temperature, mean radiant temperature, air speed and relative humidity, whereas personal factors comprise metabolic rates, clothing insulation and state of health.

Tensile membrane structures, as solar shading systems, offer a "physical sensation" of change in temperature by blocking sunrays. Mean radiant temperatures (direct sunrays) can be significantly vary in different air temperatures. Direct exposure to sun creates an uncomfortable sense of overheating. Thermal comfort determined by "psychological" factors such as one's perception play a role in thermal comfort (De Dear and Brager, 1998). Whilst outside, people are simply happy to be protected from extreme hot rays, thus shaded areas are generally perceived to be a cool escape from hot sun rays. Outdoor climate is measured by the physiological equivalent temperature (PET) – one of the most accepted models for outdoor comfort, which is dependent on the radiation exposure and wind velocity (Höppe, 1999).

2.5.2 Tensile membrane structures for solar shading

Shade is essential in outdoor spaces for any activity taking place. Outdoor spaces may become isolated due to the proliferation of temperature and UV radiation. Therefore, shading structures have become popular within the urban fabric of hot climate cities. In addition, physical configuration of outdoor spaces should be redefined as a strategy to mitigate the impact of climate change and ensure the continuity of outdoor life along with an increase in the public's awareness towards dangerous consequences of unprotected sun exposure.

Shading structures can enhance microclimate. Tensile membrane structures can provide limited protection and flexibly handle modern-day threats, including climatic fluctuations and extreme environments. Tensile membrane structures shading offer great advantages over other types of shading structures, due to their iconic forms and functionality. They are eye-catching thus more attractive to use. They can immediately provide shade for space in case of need. When compared to trees, they can shade vast areas with minimal resources. Achieving thermal comfort with low resource expenditures is another main goal for building tensile membrane structures.

Previous research on tensile membrane structures in desert climate, illustrate the effectiveness of the structures. The interior shaded space in a Bedouin tent interior can be 20 to 30 degrees cooler than outdoor conditions (Faegre, 1979). Another study about Bedouin tents in desert climates found an almost 18-degree difference between shaded sand and outdoor sand (Qubrosi, 2013). Membrane shading systems, gently block the heat whilst dimming blinding sunlight. According to SL-Rasch (2013), "The translucent membrane umbrellas of Masjid Nabawi lowered the ambient temperature by at least 8 degrees".

Temperature measurements that are recorded in shade, a SL_Rasch the air temperature is the same in both under the sun and the shade. Ray (2017) stated: "Its solar radiation [hits] our bodies, which makes it feel hotter". On average, solar radiation makes the air feel 10-20 degrees warmer, depending on radiation intensity, shading systems' properties and the wind speed. In a documentary by Friends of Tress community by Tudor (2009), an infrared surface thermometer device used to measure the surface temperature directly exposed to sun radiation was recorded to be 11 to 28 degrees hotter in comparison to shaded surface. Tensile membrane structures can also be built over entire buildings to work as a climatic envelope such as in case of Longitude 131° (Figure 2.21), it is sheltering the entire structure.

Figure 2.21: Membrane shading the entire structure (Longitude 131°)

Source: http://www.theluxurytrends.com/longitude-131-un-glamping-de-lujo-los-pies-de-ayers-rocks/ [Accessed 26 Oct. 2018].

Thermal quality of the space shaded by tensile membrane structures are determined by the structural form and characteristics of membrane material. Main formal contributors to the thermal ambience of a space are its geometry, scale, height and orientation towards sun and flow of wind at specific geographical location. To reach an ideal geometric shape for effective shading, initially the structure should be configured in a way that prevents direct radiation at overheat period and allows sun rays at cold period of the year. Secondarily, it should be set in way that projects the shadow to the right place at right time (occupation times) of the day. Finally, the topological form shall be customized to direct natural wind flow in order to enhance microclimate under by elevating edges, corners and creating wind-catching openings.

The materials used for membrane structures vary according to their properties, such as colour, translucency and reflectivity rate. A membrane material's transparency and transmittance factor effects the amount of solar radiation, that is directly transmitted into the space. Another important property of membrane material is to have low emissivity (Low-E); which reduces infrared radiation from warmer to cooler surfaces by reflecting a significant amount of radiant heat.

3. PARAMETIC ARCHITECTURE

In the past, architectural design was largely influenced by new developments. Similar to the modern, parametric architecture emanates its charge and impetus from technological development. Schumacher (2016, p.5) stated: “Parametricism is architecture’s answer to contemporary, computationally empowered civilisation, and is the only architectural style that can take full advantage of the computational revolution that now drives all domains of society”. Hence, he accentuated the role of computer in emphasising parametric architecture. Parametric can be described as a trend in architecture that gained popularity after first digital revolution, and intensified after 1990s. It is one of the most controversial themes in architecture. It is an architectural style that is connoted with cool, complex, smooth and free forms. Such perception was firstly due to architects, who implemented digital technology to produce drastic physical forms. During 1990s, several digital tools were utilised to automatically generate technical drawing of complex free forms and support their fabrication. Using computer numeric control (CNC) machineries in architecture, enabled the production of complex forms that were produced by avant-garde architects of past decades (Mario Carpo, 2016, p.1-10). The early parametric buildings were celebration of the automatized technical drawing of free forms. Secondly, the influential manifesto that was published by Schumacher in 2008, promoted the new architecture that was empowered by digital revolution as Parametricism. He advocated for a formal theme that allowed systematic adaptive variation, continuous differentiation and dynamic figuration. He proposed articulated complexity to cope with the increased complexity of post-Fordist society. He was against homogenization of architecture and advocating for heterogenization, moving from Mass-production to mass-customisation. Hence, early parametric buildings could be described as a “parametric formalism”.

In opposition to Schumacher’s manifesto, architects such Mario Carpo, Mark Foster Gage, Alfredo Andian and Mark Burry promoted parametricism as a method of design. It utilised digital tools to create optimised buildings using dynamic models (link or relational systems) and automated processes (analytical and generative). According to Gage (2016, p.128-133), being parametric was merely a contemporary digital condition it was not a style and any building could be parametrised. They conceived parametric formalism with an imitating and faking nature. Instead they advocated for understanding the inner principles of nature. They perceived digital tools as empowerment of "parametric workflows".

Today, the term parametric is generally related to the computational world: however, according to Swaiti, In essence, architecture has always been parametric practice, It comprises of wide and dynamic range of variables (Swaiti, 2015). The nature of architectural design has always been a reflection of a wide and dynamic range of conflicting forces that shape our buildings. The major influential architectural design forces are clients' needs, site constraints, aesthetic, society, culture, economy, ecology, environment, technology, structural and material limitations. They diversely contribute to design objectives. Chokhachian (2014, p. 1) states, "design is in the role of a platform" which is meant to set and organise the relation between design forces; prioritise specific design aspects; define different bounds and constrains to attain design objectives. The way in which architects translate all physical and non-physical parameters, and then balance the interplaying design forces, will affect the body of final physical form and its ability to achieve the intended design goals. Here the parametric platform (such as platforms provided by Grasshopper and Dynamo) can be linked with basic architectural design practice. Parametric platforms allow digiising the designing process by quantifying design aspects and systemizing their relations and interactions. The process of designing is a complicated procedure hence digitalising and defining relations are all complicated tasks.

Architecture discourse is complicated as it addresses many aspects, most of which are extremely complex. Hence, the procedure, which is managing these complexities, needs to be integral and multi-disciplinary. Since the beginning, architecture has been grappling with the complexity of the design process; therefore, to confront the complexity of different theories and procedures introduced. Such as the classic theories prioritizing geometric and organisation schemes, gothic prioritizing structural logic, modern prioritizing function and mass production and sustainable architecture prioritizing environmental aspects. All theories indeed aimed to bring contextual design factors together and propose solutions based on physical or theoretical issues. According to Chokhachian (2014): "Design processes in different periods have had a variety of definitions and clarifications". Traditional architects have had to consider these forces and follow their own intuition and design theory; in addition to their personal design parameters based on experience, which enable them propose a feasible design. In this principle, parametric theories utilising computational power can deal with complexity of the design process, by taking into account almost all design aspects.

Parametric design enables the design process to be conscious, logical, intelligent and coherent by means of bringing qualitative and quantitative parameters into a systematic design procedure. Without a systematic approach, a designer cannot handle the multiplicity of the design aspect; moreover, without computers they cannot handle the massive calculations required to achieve the specific design effect, especially in the case of structural or energy efficient designs. Swaiti (2015) states:

> *Within the parametric system, architects can scientifically and creatively dive into explorations in an attempt to address emergent challenges of an ecological, social or economic nature while optimising resources creatively, improving performance and manifesting beauty.*

Such kind of dynamic relations between design inputs and needs improve design. Within the parametric platform, architects are able to design their project and justify it in its context. Designers can make decisions and test them with proofed results rather than accessing projects by rule of thumb.

The introduction and development of digital technology to the design field has provided a new way to perceive and interact with design parameters. Phillips (2010) said, "The computer did not invent parametric design, nor did it redefine architecture or the profession; it provided a valuable tool that has since enabled architects to design and construct contemporary buildings with more appealing qualitative and quantitative conditions." To design parametrically means to design a "parametric system" by using parametric platforms to translate architectural design thinking into computer language. Andia and Spiegelhalter (2015, p.23) stated: "Parametric allows for the coding of human reasoning." This process of "scripting design thinking" is mainly to harvest massive computational power in dealing with the complex nature of architectural design. The design script embodies rules and instructions that generate final forms. Scripts and involved algorithms can be set to increase the potential of outcome to reach a "good solution".

Parametric design is a system that demands input, output and mechanisms to generate designed spaces that arrive at a suitable solution (Chokhachian, 2014: Gehry, 2004). Setting the parametric system first requires choosing an appropriate set of parameters with the most sufficient correlation to fulfil the design objectives and then setting up the model definition so the architect can then explore the solution space (Kilian, 2006).

Explorations via deviation of the design parameters or variable values will assist in reaching the ideal project proposal, and exploring the potentials inherent in an idea. What is meant by mechanism or model definition is the whole script "that enables the coordination of parameters and rules that, together they clarify, encode the relationship between design goal and design response" (Jabi, 2013). We can use relationships between elements to manage the design process of complex geometries and structures. Parametric scripts are live and responsive. The relations are maintained overtime. They are capable of presenting the outcomes of parametric equations instantaneously, thus design variations are effortless in parametric environments. In a dynamically responsive system, design components become linked and will automatically influence each other in a chain reaction. The most beneficial feature of a parametric system is its ability to quickly change variables and visualise how it affects the design. All physical properties in a form could be varied. This process allows the designer to investigate a variety of possible resolutions. Further, with the help of analysistools, the designer can run a series of trials through which they analyse the various design proposals. In parametric design, main decisions are mostly made by the "aid" of computers.

Exploration can seem as a play that is equally aimless and ungrounded, if it was not guided or if the objectives were not clear. The tools can guide the solutions to reach the goals however they are not capable of making final decisions autonomously, in regard to aesthetics. Aesthetics is a subjective phenomeneon that a computer can not understand, and a computer can never replace the human sense of making an artistic judgment. It is important to mention that the designer has to imagine all possible solutions before the computer program starts calculation; otherwise, the parametric can easily get stuck or deliver non-rational results.

3.1 HİSTORY OF PARAMETRİC ARCHİTECTURE

Roman and Greek architecture could be examples that formulated mathematical and proportional relations in addition to organisational schemes in architectural design. In Roman architecture, mathematical rules were consistent despite the variation in scale of the buildings. In describing Roman temples, Gage (2016, p.128-133) stated "These parameters that intricately and algorithmically link components to each other proportionally in order to produce predictable yet variable wholes." Maher (2011, p. 10) states, "The word parameter derived from the Greek para, meaning beside and metron meaning measure" also from (OxfordDictionary, 2019, en.oxforddictionaries.com). The concept and use of the term parametric architecture, pre-existed the feasibility of using actual computational processes. Italian architect Luigi Moretti initiated it in the 1940s when he used the term 'Architettura Parametrica'. Moretti investigated the connection between architectural design and parametric equations under the topic 'Architettura Parametrica' (1940) initially without the benefit of computers (Frazer 2016, pp. 19-20). A parametric equation is a combination of parameters / variables and mathematical algorithms that enables the designer to iteratively manipulate and reform the outcome of the equation or system. The parametric model or system can be simple and formed from just one variable of input bounded between few options ; moreover, it can be complex with a great number of parameters and relations. Parametric architecture as a style, first launched in 2008 at the Venice biennial, yet, it is now a global movement. Davis (2013) states, "During the last decade, parametric tools have become part of the standard 'design workflow' in architectural practice".

Constraints in parametric architecture

Architects are using parametric methods as a way to efficiently attain design goals. In order for a goal to be feasible, it should be bound by realistic project constraints such as gravity, material properties, structure limitation, site boundaries, budget, solar access etc. Design constraints are found to be imposed by the limitations of the physical world. In addition to the limitation of physical world they are often the 'desires of designers or the needs in the projects. While considering the constraints an architect must have a sense of realistic expectations (Heath 1993, p. 12). In reality, design intentions are usually constrained.

In fact, the process of parametric manipulation could create endless discovery, if not constrained with limits. These limits could be in the form of bounding each variable or constraining them. According to Woodbury & Gün (2010 p.50), a variable is a container that holds a value. Cross combinations of a variable's possible value is described as a 'design space', and the variable limits determine the space's flexibility (Maher, 2011, p.10). Design constraints have the effect of limiting the number of possible alternatives therefore giving boundaries to design space.

The concept of 'constraint' in a parametric system, is the relation between elements that can be bound by geometrical or algebraic relations. Geometric constraints are the most conspicuous constraints between objects in parametric modelling software. In a 3D digital modelling environment, a constraint explains The relation between two or more objects.

3.2 PARAMETERIC TENSILE MEMBRANE STRUCTURES

Determining parameters or variables of a design requires a deep understanding of its formation and realization process. Those iterable elements that will contribute to enhance certain qualities are selected later. "Parameters are things or variables that computational design manipulates to generate an optimally functioning architectural forms" (Benjamin, 2017). Schumacher (2012), referred as the pioneer of parametric style, states that "In general description, Parametricism means that all the elements of architecture become parametrically variable". According to Oosterhuis (2012, p.412), "building elements must be designed to be active actors, components can't be seen as passive objects". The parametric architecture is elementary, and it is evolved from the iterative manipulation of building elements. We might be able to replace the term 'elements' with 'variables'. Black tent, as a traditional vernacular example and predecessor of contemporary tensile membrane structures, holds a great set of structural elements that could be varied interactively. Its sizing, spacing and orientation, as well as geometrical properties such as structural composition, could be turned into parametrical variables which could further be linked to influence each other.

Parametric protagonists are greatly impressed by the innovative work of Otto. "His works are recognised as pre-digital precursors" (Schumacher, 2016, p. 13). Indeed, membrane form-finding has a lot in common with parametric systems. The experimental model used for form-finding utilises a responsive system that has an input of natural algorithms (equations) and an output. The boundary condition or metal wires Otto used to frame the soap bubbles were easily adjustable. Each iteration or alteration to the basic input triggered instantaneous reconfiguration of the whole system, and generation of a new physical output.

On the other hand, engineered tensile membrane structures appear as simple structures for having a limited number of components and a well-established structural engineering process. The case is completely different for a tensile membrane's architectural design within a parametric platform. Architects have their own design considerations while the parametric platform allows a great number of previously neglected aspects of tensile membrane design to be incorporated within the design process; such as structural limitations, performance, fabrication and environmental, social, cultural, historical aspects.

3.2.1 Structural Limitations

At first glance, "tensile membrane structures are formed from a fabric of membranes confined and tensioned between a boundary of rigid structural elements, flexible cables or a combination of both (Lewis and Gale, 2016, p.112)". Despite their minimal traits, they are very difficult to build correctly due to material properties and geometry of structure. In order for a membrane setting to be considered as a tensile membrane structure, it should first reach a state of equilibrium for the given stress and downward gravity affecting on form. Second, it should have the smallest possible surface area with uniform tensile stresses throughout the entire surface. Therefore, the obligatory consideration for a tensile membrane structure is form-finding. Burry (2016, p.33-34) in describing the analogue form-finding process adopted by Otto and Gaudi states, "They were inspired to call on gravity, one of nature's ultimate parametric design inputs, to inform rather than plan architectural form as an essential physical determinant within the design process". According to Lewis and Gale, (20016, p.112) "The surface of tensile fabric structures cannot be defined geometrically by the designer, but must be generated through form finding." Structural form finding is a process of architectural volume, following the shape that gravity imposes on materials in use.

A designer may regard a membrane's form-finding as a way of tackling problems in structural engineering rather than an efficient conceptual method for form generation and testing of design alternatives. Structural engineering deals with forms and their structures according to forces and moments present in geometry. A tensile membrane can only be designed with a structural logic in mind. The formation process follows the law of physics and the nonlinear structural behaviour of material. This makes the structural type sound very restricted and purely an engineering question. It leaves no room for creativity in design of tensile membrane structures. This view has declined over time upon experience with parametric design of membrane structures.

"It was lately found out that despite the fact that the curved surface is subject to strict mechanical requirements, there is still potency for manipulation on the boundary of the surface area (Tian, 2011, p. 11)" . Boundary conditions determine the structural shape and stress distribution within its surface. "To achieve uniform pre-stress, the membrane must take the form of a minimal surface (Deb, 2014, p. 141)". A tensile membrane structure is stabilised by stressing the boundary edges. As explained by Bridgens, Gosling, and Birchall (2004, p. 21):

> *Minimal surface can be developed for a fabric membrane by accepting increased stresses in the region where the soap bubble would have failed. This reduces the limitations on the forms that can be created. However, as the desired shape moves away from the minimal surface form, the stress variations increase, and the structure becomes less efficient.*

Therefore, in forming tensile membranes, there must always be a close relationship between architect and engineer, as the possible shapes are limited by the boundary conditions of the fabric.

3.2.2 Performance

Designers use performance as a justification for formal exploration or generative strategy; moreover, they use it to analytically ground design decisions. Performance is a key driver behind form finding simulations (digital or analogue). Over the past few decades, computational power enabled digital simulation, and it has helped designers to deepen their understanding of the performance aspects of buildings. The first use of computational simulation was in 1966 by Linkwitz, he employed computer for calculating membrane's structural stress (Serebyakova, 2006). From the beginning, performance simulations were dictated by specialised engineers not architects. Only recently, it was introduced to architectural practices. first Realised in 2007, Grasshopper is one of the platforms that enable dynamic modelling, simulation and optimisation all at the same time. It has become an indispensable toolsfor parametric modeling.

Parametric form-finding based on performance is inspiring since it extends beyond structural criteria into environmental criteria, energy and shading. Bechthold (2012, p. 49) states: "Compared to the narrow pursuit of performance in the engineering context, performance in architecture remains extremely broad, encompassing almost too wide a range of design approaches". Schumacher (2016, p.10) states, "Taking the performance conditions seriously almost inevitably leads contemporary architects to Parametricism". A parametric platform allows a wide range of process to be performed continuously, furthermore enables integration of performance with other design requirements. Performance simulations are conducted to make functional enhancement, and performance optimisations exhibit true parametric architecture.

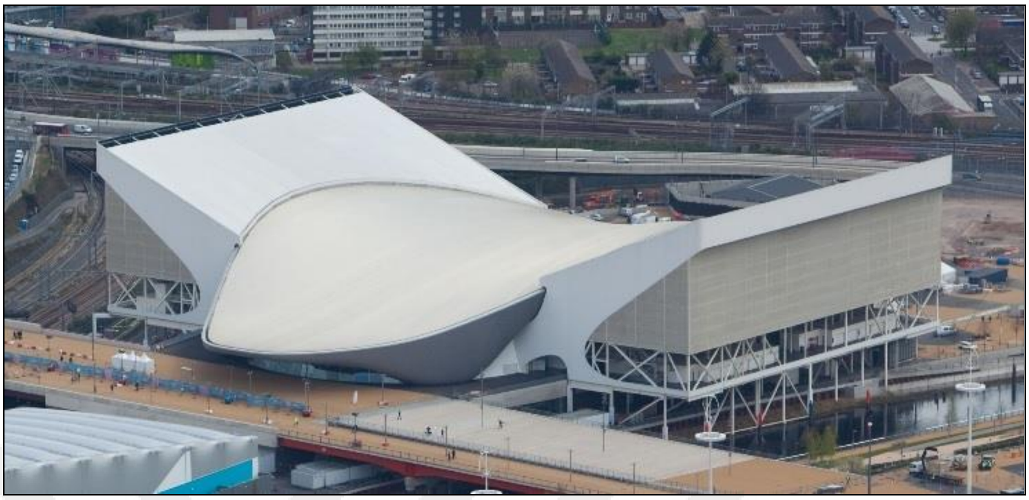
Morphology emerging from performative response to the structure can be easy; however, it is not applicable with environment, cultural and social interaction, as they are far too complex to be driven by a simple script. Parametric scripts and algorithmic procedures most often have demonstrated to be rigid and incapable of smoothly engaging the complexity of wide range of design aspects at the same time. Still there is optimisation that an algorithm can support the design of a multi-criteria design. New trends in Parametricism concentrate on addressing the environmental issues. Complex parametrically designed forms typically responded to fabrication and aesthetical principles, without making careful consideration for users' comfort and the project site's climatic condition. According to Bakos (2017), who is one of the fierce advocates of Parametricism, "Parametric design should be used to ensure buildings respond to and enhance the environments that they are in". Naboni (2014) states, "Parametric design must be released from the constraints of 'Parametricism' applied without any variations to all climates and exploited to produce intelligent designs that embrace the full complexity of the environment". Parametricism demonstrated the possibilities to become more than a matter of generational technique or scripting geometrical variation; in fact, they are a powerful mean to addressing wider environmental issues (Frazer, 2017).

Previously, the only reasoning for tensile membrane formation was purely structural engineering. However, if the main objective for structure is providing protection from sun radiation and contributing to outdoor comfort, it should fulfill the design objective in an optimal way. Bakos (2017) states, “parametrically determined solutions shouldn’t be conceived by one experience it as arbitrary every one of those components should be there and in the precise orientation for a reason.” In other words, climatic information should be imprinted on the surface of tensile membrane shading structures. Hence, parametric platforms have resulted in an expansion of computable parameters by architects. The climatic data is a new parameter for the tensile shading structures. This new approach will manipulate the design variable according to climate data as a formal generative strategy. “Parametric design process in general, is a kind of interaction between the parameters which are going to shape the solution for the problem, and the effect of solution on the parameters” (Schodek, 2005). Thus, parameters for the desired shading effect can be found. To mention, Parametric workflow aiming successful optimisation requires expertise in three areas: architecture, engineering and computer programming. Therefore parametric workflows are usually laborious, time consuming and mostly project specific.

3.2.3 Fabrication

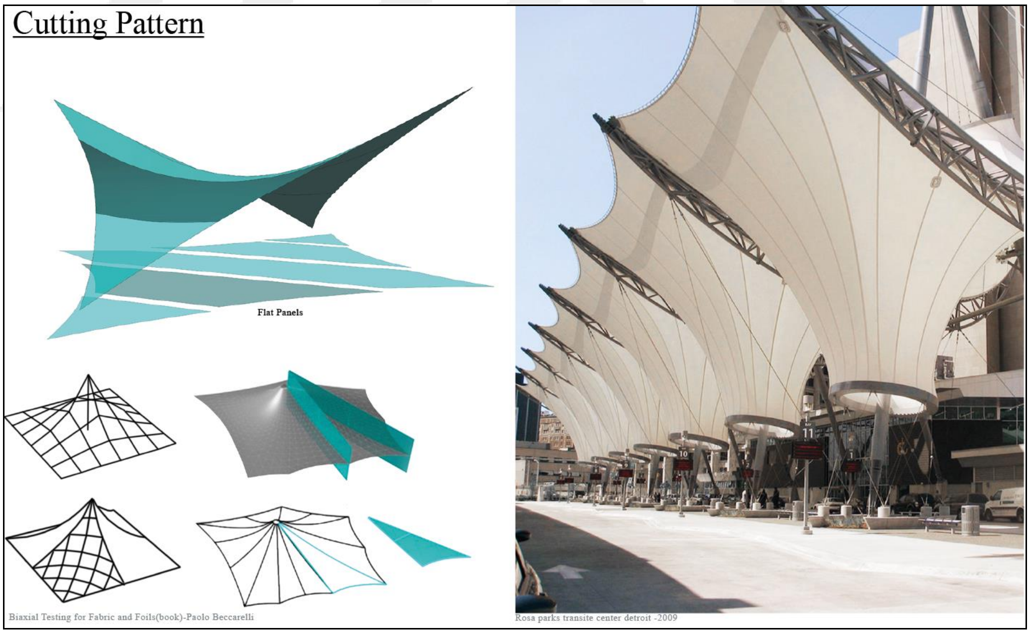
For a constructible form, the structural and material limitations shall be introduced to the parametric model. The dimensional properties greatly depend on the membrane’s type and strength. Tensile membrane structures are manufactured with typical membrane sheet traits; which have a typical width of 2 to 3 metres and a maximum width of 7 metres. In the case of the London Aquatic Centre (Figure 3.1), designed by Hadid in 2004, the roof membrane panels measured 40 metres long by 7 metres wide. In the model definition, each cutting strip should not pass this limit; furthermore, the width of strips and places of grips or fixed points should be consciously set. The rationalisation of the membrane structure has a great effect on the form’s appearance. Rice (1994, p. 97) states, “The shape of a smooth, white fabric structure is visually defined primarily by the seam lines” (Figure 3.2). The membrane’s fabrication is interlaced with an aesthetic considerations on the configuration of cutting patterns and their orientation. Structural joints are important part of aesthetic consideration and an explicit architectural requirement. Furthermore, seam lines and joints also affect a membrane's structural strength.

Figure 3.1: London Aquatic Centre



Source: http://www.internimagazine.it/news/people/a-zaha-hadid-la-royal-gold-medal-for-architecture-per-il-2016/ [Accessed 28 Aug. 2018].

Figure 3.2: Cutting pattern and seam line on facade



Source: Biaxial Testing for Fabric and Foils (book)-Paolo Beccarelli & Rosa parks transite center detroit -2009 [Accessed 4 Jan. 2019].

3.2.4 Environmental, social, cultural and historical aspects

A design approach that prioritises technological superiority rather than consideration of multiple design aspects may be problematic in architectural design. Schumacher in his manifesto (2016), Parametricism 2.0, stated the kind of architecture that was based on technological superiority or exuberant play with tools, held a kind of vacuum at its core. The vacuum could not express or convey anything. That vacuum could be filled with awareness of environmental, social, cultural and historical aspects.

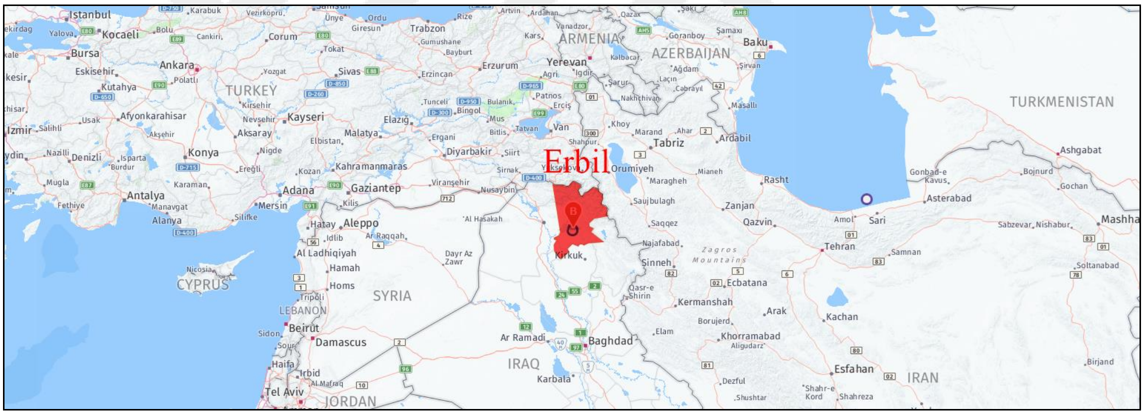
Advanced computational tools are capable of generating architecture purely from an efficiency standpoint. However, “Environmental or structural performance couldn’t be the end game, it is a constrain. We first formulate how to live and communicate and enhance our creativity then ask how we can make this in more light footed and resource efficient way. Sticking to structure or environment at first can prevent us from sustain productivity gain” (Schumacher, 2016). That is not to recommend the neglect of performance as a design parameter. Bechthold (2012, p. 52) stated that an efficient way of building is “an ethical obligation to the profession and to society”, especially at the age of global warming and diminishing natural resources. There is a growing awareness towards efficiency in parametric architecture, hence it is critical keep that consciousness maintain a position that proposes efficiency as an integral part of the architecture. The problem is that pure pragmatic morphologies can not distinguish themselves or remain relevant to context. Buildings, stuck with structural logic and efficiency aspects, lead to a loss of meaning, philosophy, expressiveness, identity and aesthetic value. The pragmatic workflow does not sufficiently understand the sociological, cultural and historical issues.

Architecture is a complete symbol of human culture, and it is assigned to keep the values and beliefs of culture in itself. Architecture is perceived as a realization of cultural background. Ettehad, Azeri and Kari (2014 p. 410) states: “architecture as a social phenomenon was originated from the culture and its effects”. Individual cultures do not have the same impact on architecture. With some cultures, it is easy to identify their influence on architecture and with some it is difficult. Moreover, due to their simplicity, membrane structures have some of the least apparent cultural manifestations. During the development of tensile membranes, the increased scale and loss of textile quality of modern tensile membrane structures resulted in the common opinion that these structures are inhuman and therefore do not reflect our culture. It can be said that these structures have lost their traditional genius. It is crucial to reinstate the cultural values of the tensile membrane structure. Culture is an instrumental life necessity and no single society has survived without distinguishing itself from others (Schumacher, 2016). The cultural products, without the necessity to be rational or efficient, are heavily dependent on the way of life, experience, historical background symbols and design language. In achieving a localised cultural identity parametric, architecture has exhibited promise in re-evoking cultural identities. They were able to redefine and creatively synthesise local traditions with sophisticated computational design techniques. Parametric design may start with a conventional design or pre-conceived shape that favours humanity, culture and history. By changing the parameters, alternative designs may emerge, which may be adapted to the same objectives. The result will be unique structures that utilise contemporary technology and materials to achieve forms that have historical precedents and original design ideas at their core.

4. THE CASE STUDY

The aim of this thesis is to propose a tensile membrane solution that is customized for Erbil's hot climate. Erbil city is located in the northern Iraq and it is capital city of the Kurdistan semi-autonomies region of Iraq figure (4.1) with (Latitude: 36° 11’ 33.25” N, Longitude: 44° 00’ 38.23” E). Despite the climatic conditions and potentials of membrane structures, yet there are only few tensile membrane structures built around city. The project handled as the case study Figure (4.3), is the biggest project in the city, in terms of utilising a membrane as a shading structure. The referred membrane structure has been built in 2016 over the British international school's yard (BISK). The project was commissioned to a small production and construction firm based in Erbil. In order to understand the design process that was followed, an interview was handled with the owner of the firm.

Figure 4.1: Geographical location of the Erbil city on the world map



Source: yahoomap.com [Accessed 18 Feb. 2019].

(The detailed interview is locate at the appendix-B page 120).

The application used for design and production is specialized for membrane engineering. The main deigning consideration is tensile stress. The designing application does not calculate for sun radiation. The shading performance prediction is done by rules of thumb. Auni stated, “If we have 100m^2 membrane in average it will give us around 50m^2 shade on the ground.” During hot summer days, people prefer to remain inside. Main perceptions toward membrane structures is that they are decorative elements (Stylistic) not shading solution.

It is the only school in the city, which uses membrane shading. The structure has 1400m2 of membrane surface; it consists of seven section of hyper shaped membranes Figure (4.2). The span is 24.5m. The lowest points are 80 cm and the highest points are 250 cm above the school's roof.

In the light of the interview results, the need for reviving the traditional black tent concept for solar protection and developing a new design tool for membrane structures is explicit. The tool will be handling local environmental data for providing shadow while preserving some openness for the public space.

Figure 4.2: Erbil British International School (satellite image)

Source: googlemap.com [Accessed 18 Jan. 2018].

Figure 4.3: Case study Erbil British International school

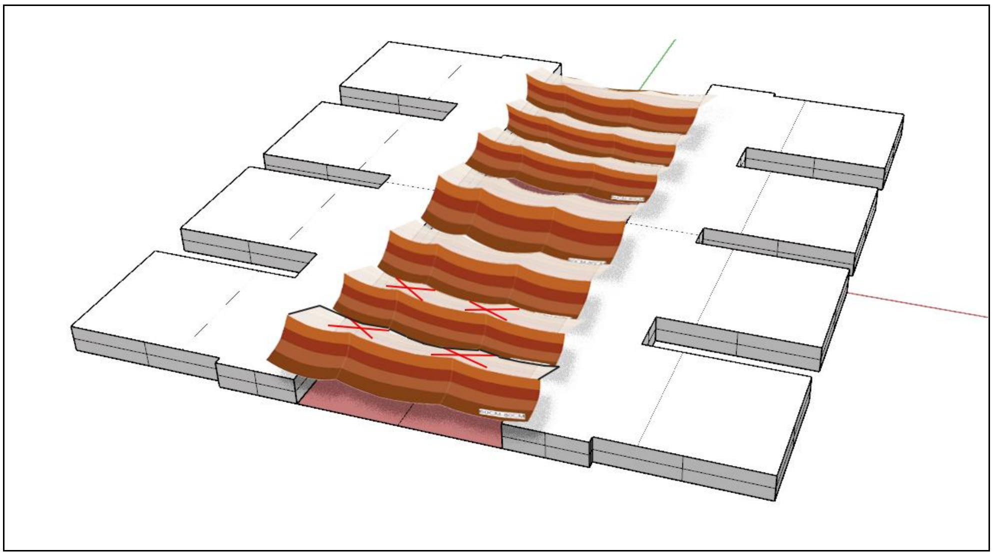
Source: Imaj membrane.com [Accessed 22 Jan. 2018].

4.1 DESIGN CONCEPT (PROPOSAL)

The aim of the thesis is to develop a workflow, which contextualizes design of tensile membrane structure to a selected site with its cultural and environmental aspects (Figure 4.5). In case study, original spirit of a black tent is referred due to its formal, visual and tactile qualities, and economic optimality (Figure 4.4). A customized design workflow, utilizing up-to-date parametric tools and concepts have been proposed. The design preserves and enhances structural optimality by using a digital form-finding process and reducing the membrane area as much as possible. Originally, whenever a black tent has been set up, it has always placed to receive the greatest advantages from the prevailing conditions (Qubrosi, 2013). Therefore, environmental optimization is considered as the main design aspect in the proposal.

In case study, the roof is proportionally scaled up in order to fit the width of the yard, which is 25m. This scaling is necessary to eliminate the excessive repetition of elements, as well as to establish some synergy between the size of the tent and the yard. The owner of the school required the preservation of the openness feature of the yard while providing a measure of protection from the sun. Therefore, half of the roof is removed to provide the required openness, and the wooden poles spots or meeting points with the roof are converted into parametric variables in (X, Y, Z) directions. This will make it easier to compare the outcomes with the existing roof.

Figure 4.4: proposed Design (Concept)



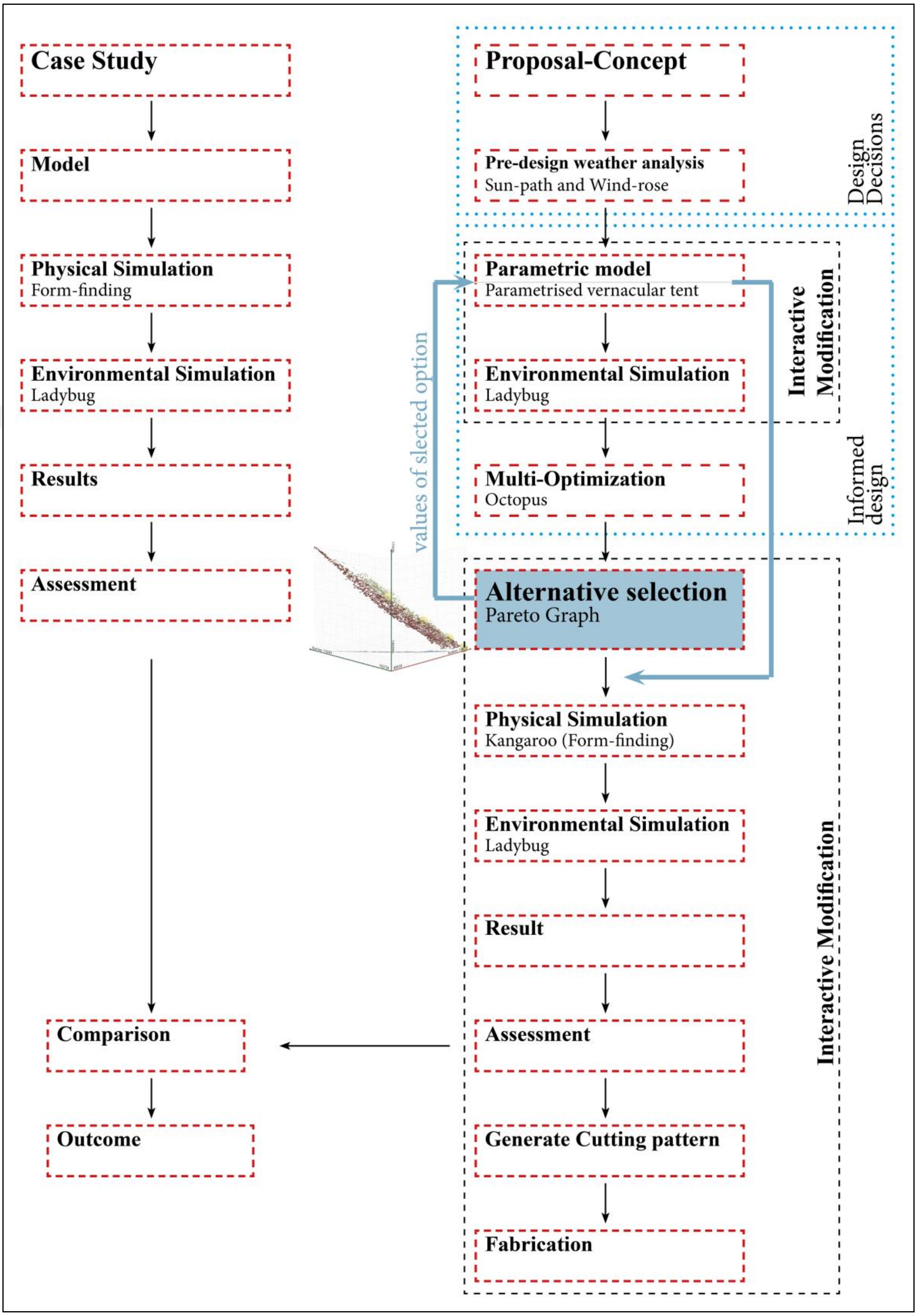
4.1.1 Design workflow

A new tensile membrane shading is proposed for covering school's yard. The fixing points of proposal is turned into variables. This parametric variable are dynamic, and will be automatically manipulated throughout the designing process aiming at reaching the design goals. In predesign process, variables are limited by dimensional constraints in order to avoid obvious non-fit alternatives and reduce the computation time. Determining variables are sort of preconceiving possible design outcomes. In the workflow, environmental data (sun-path and wind-rose) is customised according to outdoor comfort model for helping pre-design decision making process.

In design process, the existing membrane structure is analysed corresponding to radiation hours; in order to initiate the informed design. All variables are fed to the optimization engine as design genes. The optimization engine creates possible alternatives from a given set of parameters in an iterative manner. At first, algorithm tests the outcomes against the design goals, afterward it follows an evolutionary principle to find next generations. The tested alternatives are then projected to three-dimensional Pareto graph. Selected options from Pareto graph are instantaneously converted to membrane through a form finding process. Their data are then used in cutting pattern script for generating seems and fabrication process.

Throughout the optimizaiton process, the output membrane forms are environmentally analysed and compared to each other. Several optimised options are picked and compared to the existing membrane structure. The optimization (Pareto-graph) is the central stage of the workflow. Whenever a currently selected option is replaced by another membrane form from Pareto graph, its numerical values (dimensions) can be automatically assigned with parametric variables sliders. Any change in dynamic model's parametric values will intrigue instantaneous change in the membranes form (reform finding), which also will be reflected on the final cutting pattern (cutting strips of membrane form).

Figure 4.5: The Framework suggested for conducting thesis (experimentation approach)



The chosen software to design tensile membranes is Rhinoceros since; it has endless modeling capabilities, exclusively used for complex free forms. Second, its data interoperability accepts the vast majority of file formats used in the design industry. The Rhino and Grasshopper combination enables models created in Rhino to have full interactive interoperability throughout the design process. Third, integration with third party plug-ins, such as Grasshopper, Ladybug, Octopus and Kangaroo Physics, expands its modeling ability to embrace parametric modeling. Furthermore, simulation and optimisation are allowed within the modeling platform. Detailed information on the used application and their working systems is provided at appendix-C.

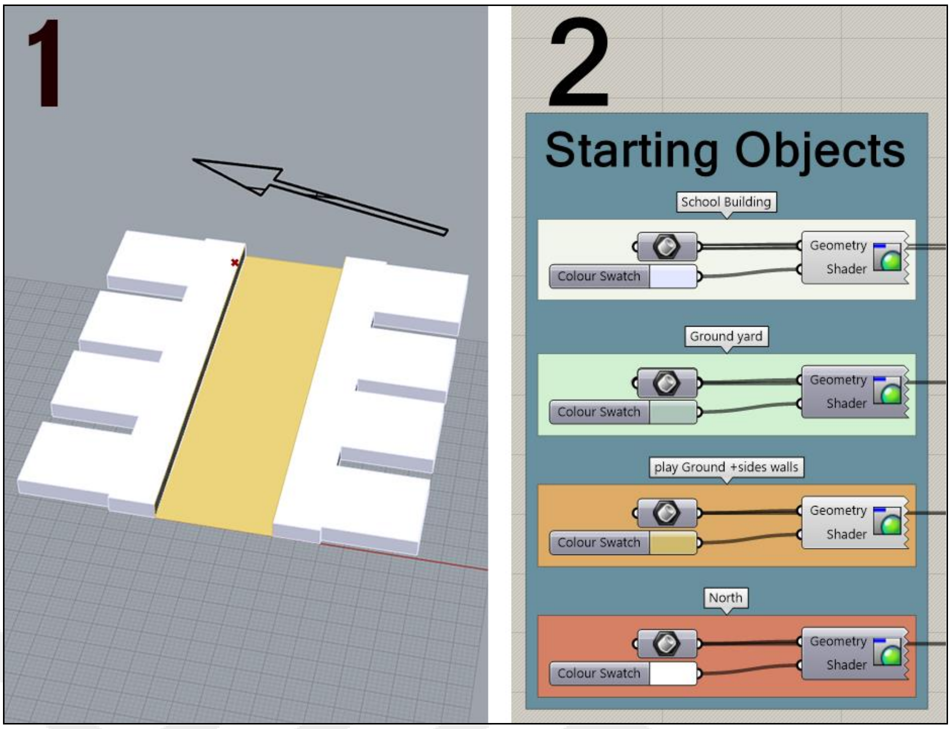
4.2 MODELING

The existing site is modeled using CAD application, and then imported to visual programing application. For creating the existing membrane structure above the playground, a script is written to divide the base yards geometry realted to a bunch of anchor points. The generated membranes are to be formed between those extracted points, which are controlled by individual sliders. The separate control over the anchors are critical as any membrane roof can shade adjacent membrane roofs. In the case of area optimization, individual control can help in area reduction without compromising shading performance.

The first step of the workflow is remodeling the existing site and surrounding buildings Figure (4.6). By using Rhinoceros, the school building, the playground and surrounding walls of the playground were modeled. The school buildings are two rectangular blocks accommodating classrooms. They are set symmetrically across the main playground. The class blocks are 90m long, 30m wide and 4 m high. The rectangular playground is 90m long and 25m wide. The north is forming a 14 Ddegree angle with the playground’s short side, and 76 degrees with its long side.

For importing geometries into Grasshopper, inside Grasshopper VP interface, <Brep> component is used to assign Rhino geometries to the components. Right click on <Brep> offers the possibility of internalising data, and embeds geometries into <Brep> instead of linking. The physical surrounding is modeled via direct modeling method since they are fixed and will not be manipulated through design process.

Figure 4.6: Modeling and importing building into grasshopper



Source: Rhino + grasshopper print screen

4.2.1 Membrane surface modeling

To represent the membrane's geometry, a plane directly above the playground is required. The yellow geometry in the Figure (4.6) is used as the starting point for generating membrane geometry. The playground geometry <Brep> is streamed into <Mesh surface> component. The component converts surface to mesh and allows increasing the surface subdivision. The ground area that is covered by membrane is around 80m in length direction. The original design membrane roof consists of seven hyper shaped membranes. Therefore, proposal with a similar configuration, was created for an easier to comparison with the existing membrane. In the yards, short direction is divided into three segments (U count=3) (four anchor points as traditional black tent) and the length into thirteen segments (V count =13) (fourteen vertices).

For extracting vertices, the subdivided mesh is fed to <deconstruct mesh> component, vertices output is the form of flattened data as (56 vertices). A structured data is needed to generate membrane faces. The restructuring data is done by streaming the 56 points that were attained through <deconstruct mesh component> into list input of <partition list> component, and size input, is U value plus one (number of vertices of surface in U domain). It will rearrange the data by packing each 14 points(U+1) in one tree branch. As a result it creates four branches with fourteen points each. Output of <partition list> component is linked into <flip matrix> component which flips the branches with item indexes. The output is a fourteen branches of four points (items) (Figure 4.7).

For design genes (variables), the points from <flip matrix> output are addressed as {x}[y]. The x are the branches and the y are items. The X values are between (0-13), and Y are between (0-3). Based on mesh subdivision, the specific point structure helps in picking and separating the design anchor points and setting movement bounds (Figure 4.8).

For picking points, points from <flip matrix> output are feed to data input of <split tree> component in simplified mode. The component allows specific point to pass through components' positive output and nulls all others points. For the component to filter a specific point, it requires a mask, which is the point's address. There are 56 dynamic points hence the easiest way to pick a point is to write a script instead of manual writing of the point address for masking purpose (Figure 4.9) and (Figure 4.10).

Figure 4.7: Extracting anchor points

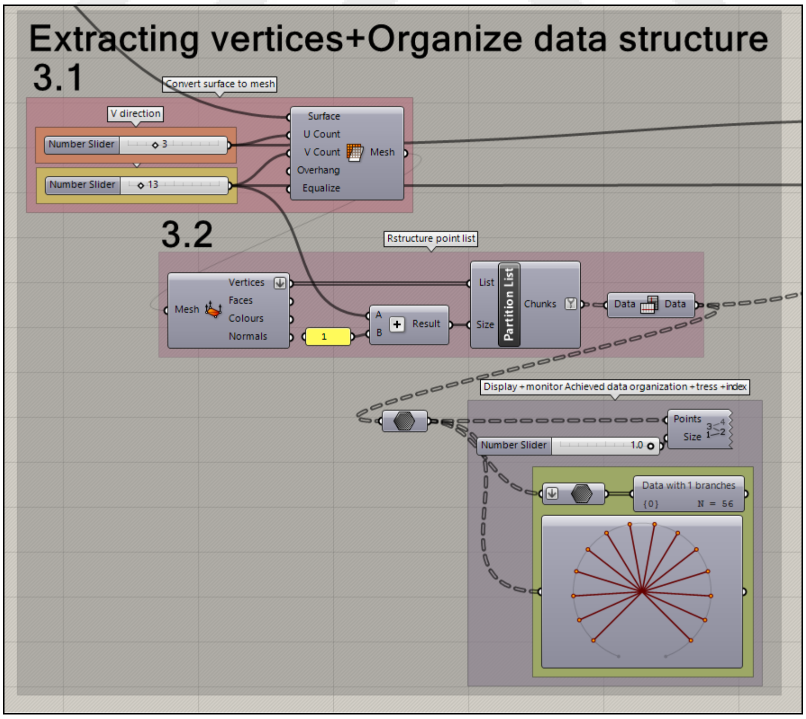


Figure 4.8: Anchor points (scripts) organized corresponding to membrane form and anchor locations

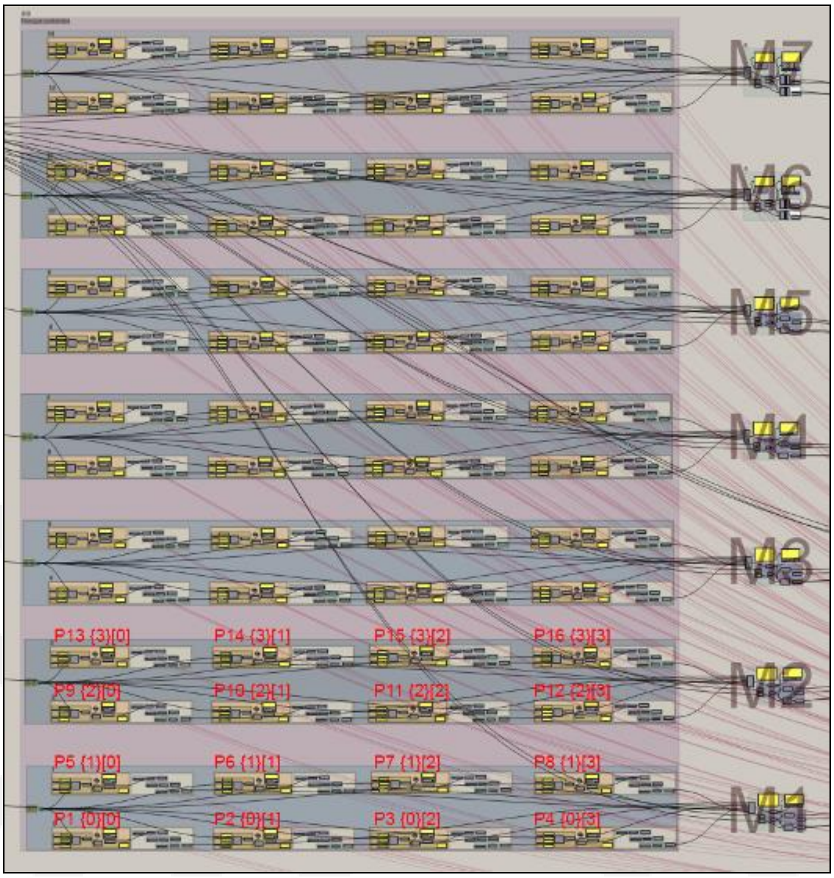
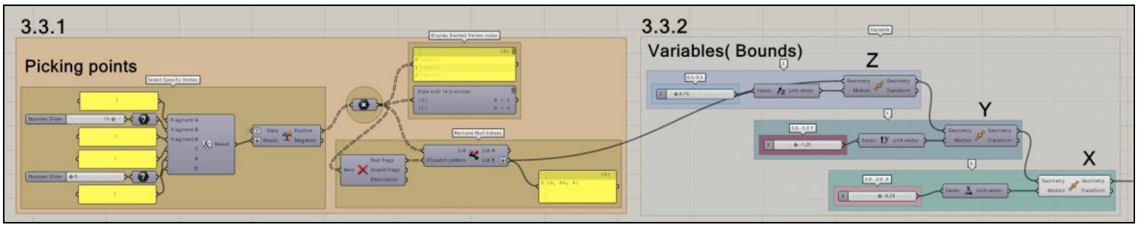


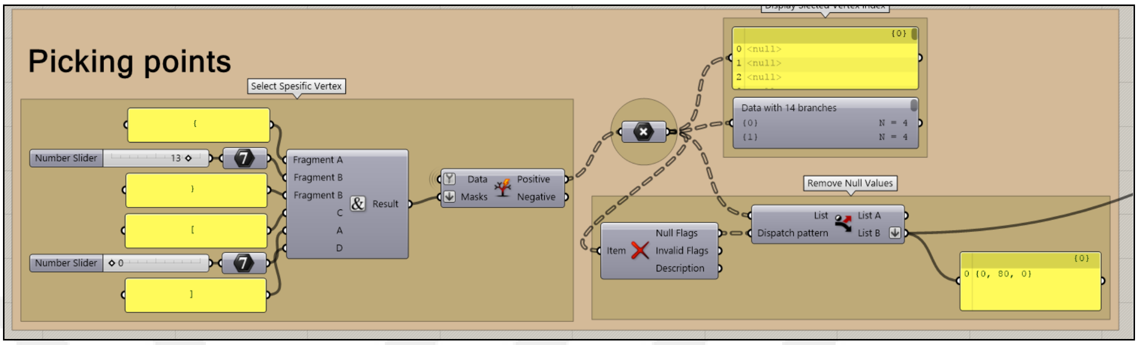
Figure 4.9: Picking point and adding variable Script



A <concatenate> component is used to arrange inputs in a sequential way and outputs in the other end. The first input is ({); Second, slider ranging between (0-13) streamed through integer to eliminate zero after coma; Third, is (}); Fourth is ([); fifth is a slider ranging between (0-3) passed through integer and finally the (]). The output of component will be as following {x} [y], both x and y are dynamically altered by sliders. Beside positive values, <split tree> allows the passage of fifty-five null values. All nulls have to be removed.

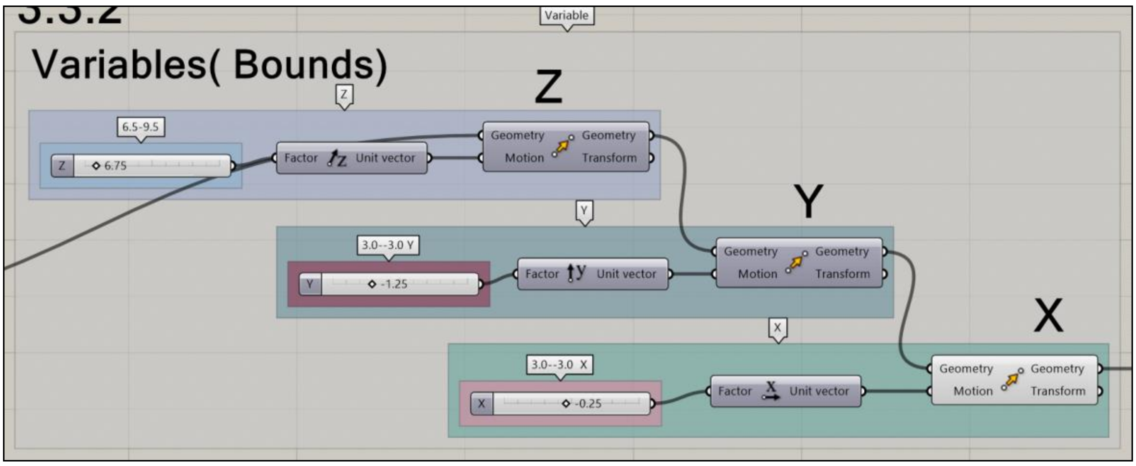
The positive output of <split tree>component is streamed into a list input of <Dispatch> component. The dispatch pattern input is obtained from the <Null item> component. It takes the point from positive output, then eliminates nulls and feeds the null flans to dispatch pattern. List B output is the point's data used for following steps (Figure 4.10).

Figure 4.10: Picking individual points from 56 anchor points



For setting movement bounds (search space), results in independent points, are suitable for adding movement slider for all X, Y and Z directions. Movement of points is done by feeding the point into geometry input of <move> component. For the motion input <Unit X>, <Unit Y> or <Unit Z> are used. The vectors input are fed with value from <slider> component. In the model, the bound of X and Y slider is set between 3.0 to minus 3.0 but for Z value, pre design weather data analysis is set. Through the script, data component is used as a container in order to organize and clear the components linked with each other (Figure 4.10).

Figure 4.11: Design bounds or search space bounds



4.2.2 Visualization and analysis of weather data for setting up design variable

In their essence, traditional black tents were environmentally (wind and sun) responsive structures. The wind and sun directions were important aspects in the formal configuration of Bedouin tent. The tensile membrane employed for sheltering humans and anticipate in users' comfort conditions need to be responsive to environment data. Indeed, human have zero control over outdoor climate condition. Thus for concerning human comfort, moderation of harsh climate is possible by protection from heat radiation (infrared) during summer and exposition to sun in the winter. Also, undesired wind that adversely effects the comfort situation shall be avoided.

Understanding climatic condition for project site is an essential step prior to design decision-making. In this respect, Ladybug offers very impressive custom graphical representations of climate data including sun path and wind rose. The graphs are helpful in decoding the relation between the sites' climate conditions and intended projects. They can be used to inform the design and contextualize climatic architecture. In case of automated optimization, using climatic indicators before design can reduce simulation time as well as skipping obvious unfit design options.

Preparing sun path graph

In this phase, environmental data are analysed for decision making purpose. A sun path is created and colour coded using outdoor comfort model (Figure 4.12). The required data for outdoor comfort model are dry bulb temperature, mean radiant temperature (MRT), wind speed and relative humidity. The output is in the form of thermal stress hot, cold and comfort. Stress state is used as the specific input for customising the sun path as well as wind rose. At the end, a set of decisions will be made considering the environmental data of the site.

Sun radiation analysis in Ladybug components are done in Python scripting language. Therefore Rhinoceros5 /Grsshopper0.9.0076 require installing Python plug-in before using Ladybug tool kit. However, the Rhinoceros6 has Python built-in.

For Initiating the Ladybug, the first step of utilising the plug-in is to find the Ladybug-ladybug component, which it is located in Ladybug panel. Dropping it into Grasshopper viewport will start the plugin (Figure 4.13).

Figure 4.12: weather data analyzing visual script (sun-path and wind-rose) using ladybug

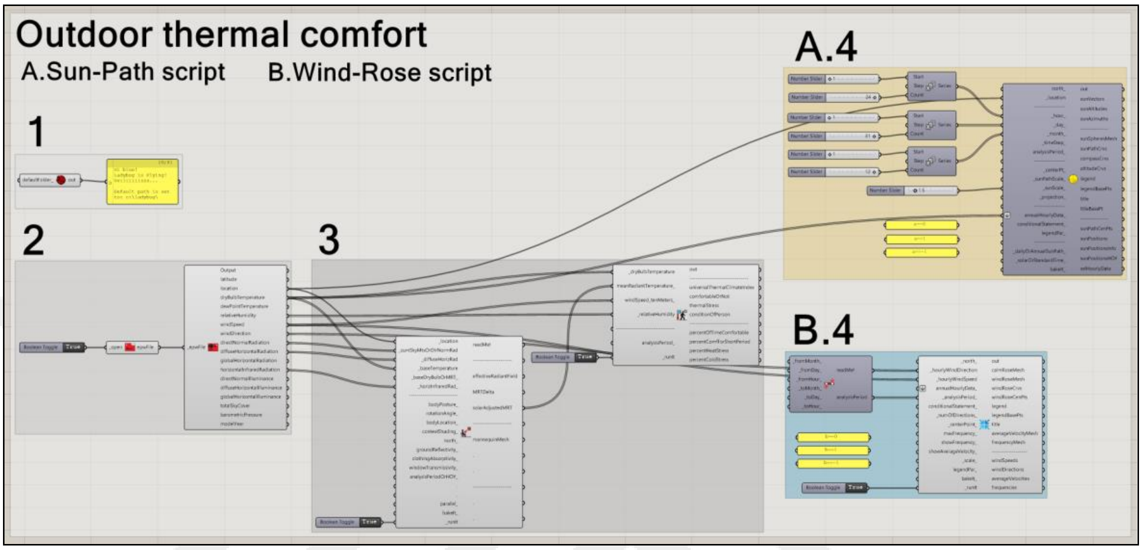
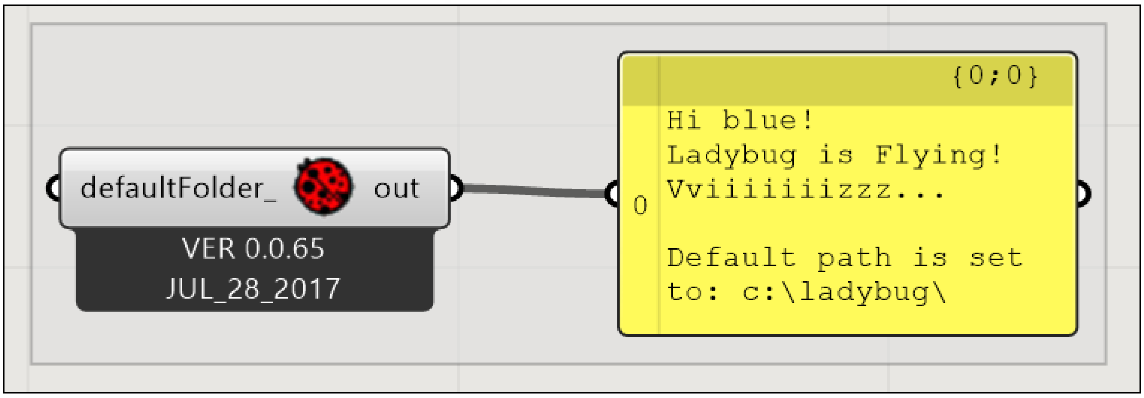
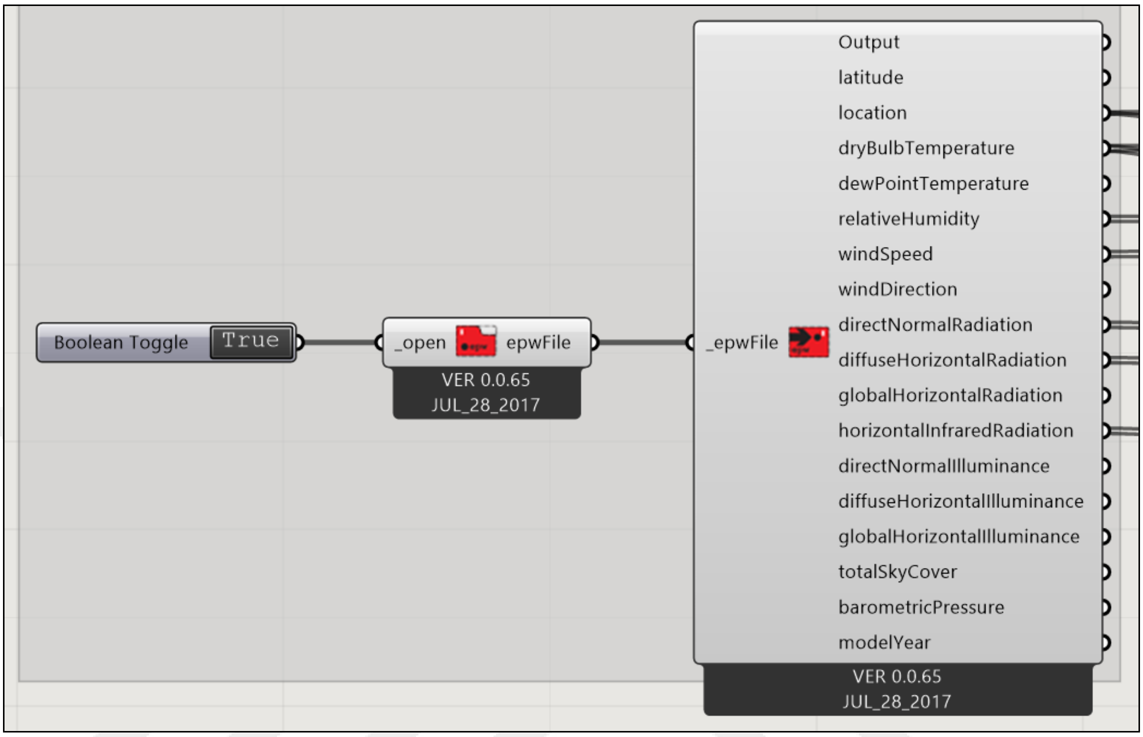


Figure 4.13: Initiating Ladybug



For importing weather data into grasshopper, Grasshopper needs three components to bring the weather data into grasshopper. First is <open EPW weather> component, it requires <Boolean toggle> with true or false value to switch on/off the component. The true initiates and links outsource EPW file (downloaded from epwmap) to the <open EPW weather> component. Then its output connected to <Import EPW weather file> component. It takes EPW data in form of (CSV-files), segregates this data and then streams them to different output channels. Epw file contains annual hourly weather data including coordinate of recorded spot on earth, latitude, dry bulb temperature, relative humidity, wind speed, wind direction, direct normal radiation, etc. (Figure 4.14).

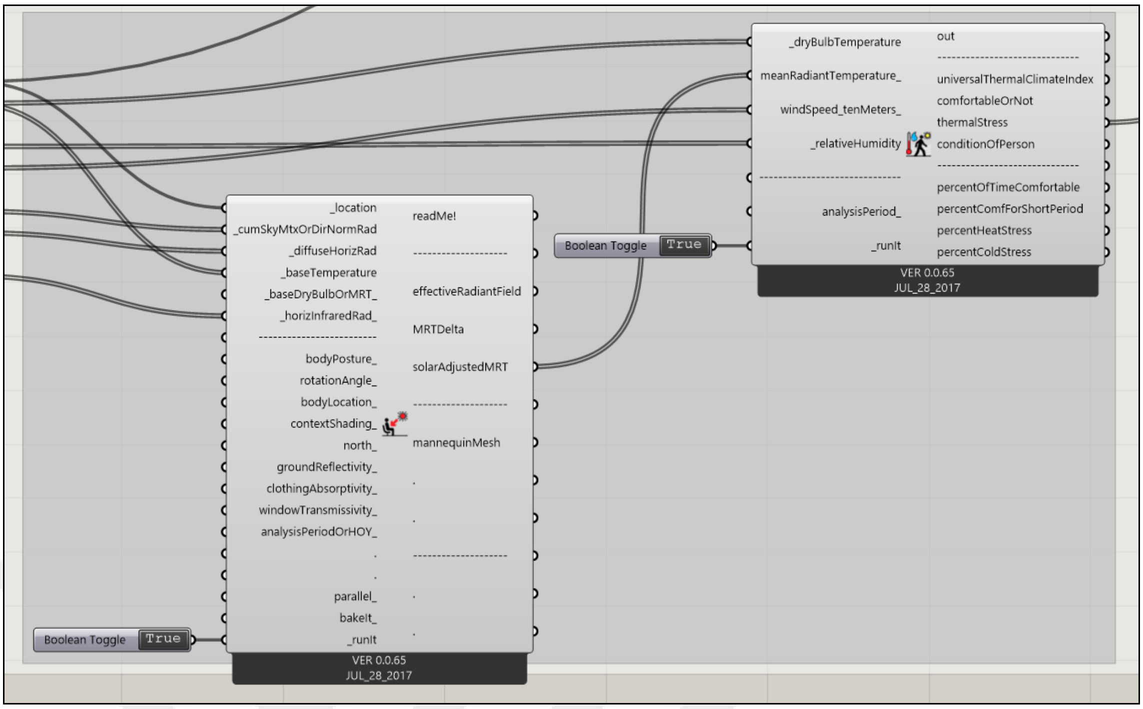
Figure 4.14: Imputing weather data into Grasshopper



The small dash line before input, indicates the obligatory state of presenting input data for running calculation. Currently, the EPW file is not available for all countries especially developing countries. The Epw file used in case study belongs to Mardin citiy, as it the nearest city to the Erbil, which has the EPW file. Mardin city coordinates are 37N, 40E and Erbil city coordinates are 36N, 44E (epwmap.com, 2018).

For detecting hourly outdoor comfort conditions, the comfort model suitable for outdoor condition is <outdoor thermal comfort> which is located in analysis weather data panel. It takes dry bulb temperature, relative humidity, wind speed and mean radiant temperature (MRT). For obtaining MRT, <Ladybug solar adjustment> component is useful, it is located in visualise weather data panel. The solar adjusted MRT output will be fed to outdoor thermal comfort models MRT input. The main objective is to get the hourly thermal stress state, which will be used in next phases (Figure 4.15).

Figure 4.15: Finding outdoor comfort state



For visualising sun path, the <sun-path> component is located in visualize weather data panel. It creates a virtual path of the sun's movement across the sky and displays the hourly sun position on that path as a sphere (Figure 4.16). The Ladybug's sun path graph (the spheres) could be colour coded using hourly temperature or hourly thermal stress (Figure 4.17). Temperature alone is not reliable indicator for users comfort at outdoor environment. On the contrary thermal comfort model is more reliable as it takes mean radiant temperature, wind speed, humidity and dry bulb temperature for calculating thermal stress (Figure 4.15). The thermal stress colour coding is very advantages as it uses just three distinctive colour for denoting comfort states (Figure 4.18). This simple graph helps identifying the problematic area on the graph and enables the designer to target that specific area of graph. Before making any analysis or conclusion the <sun-path> or <Wind-rose> north direction has to be matched to the real sites north direction by using <2point vector> component.

Figure 4.16: Ladybug Sun-path generator

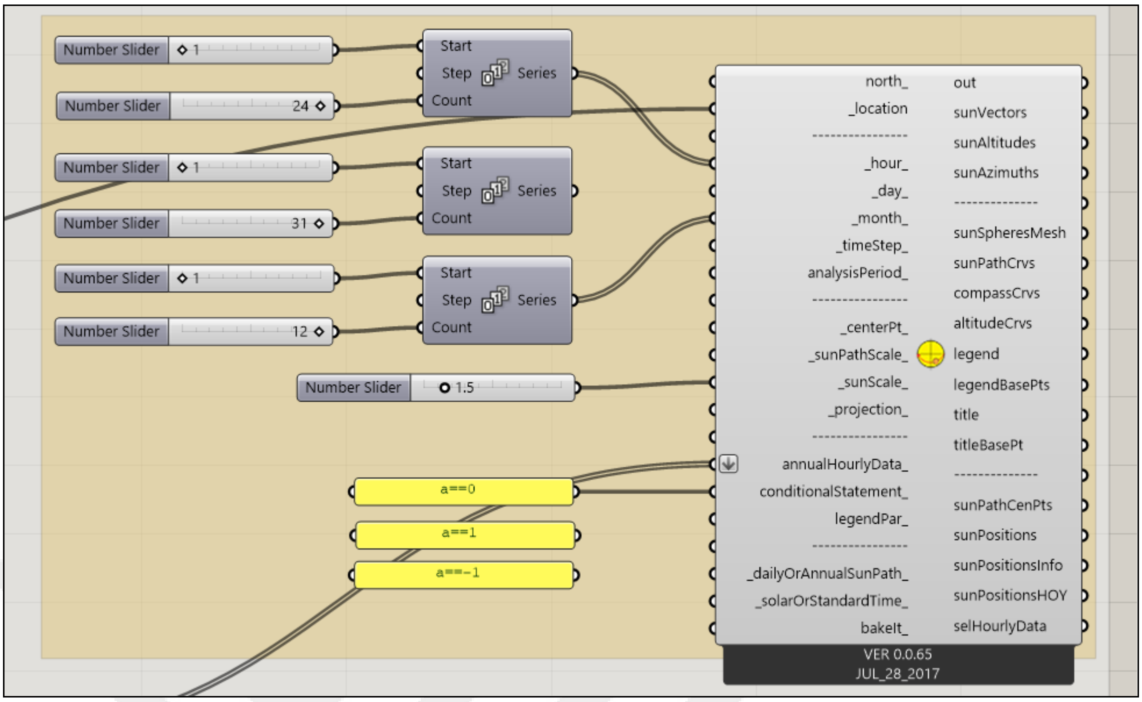


Figure 4.17: Sun-path colour coded by Left-hourly temperature, Right- hourly comfort state

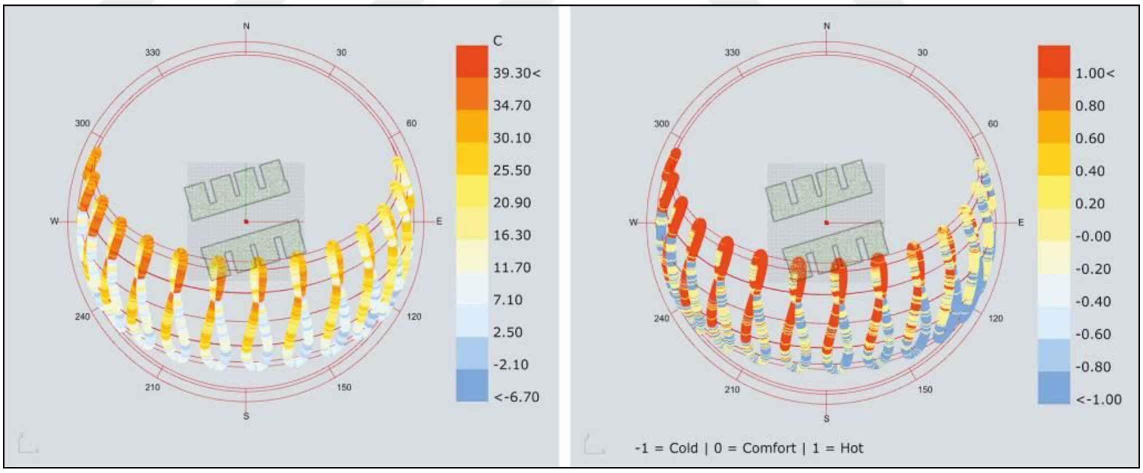
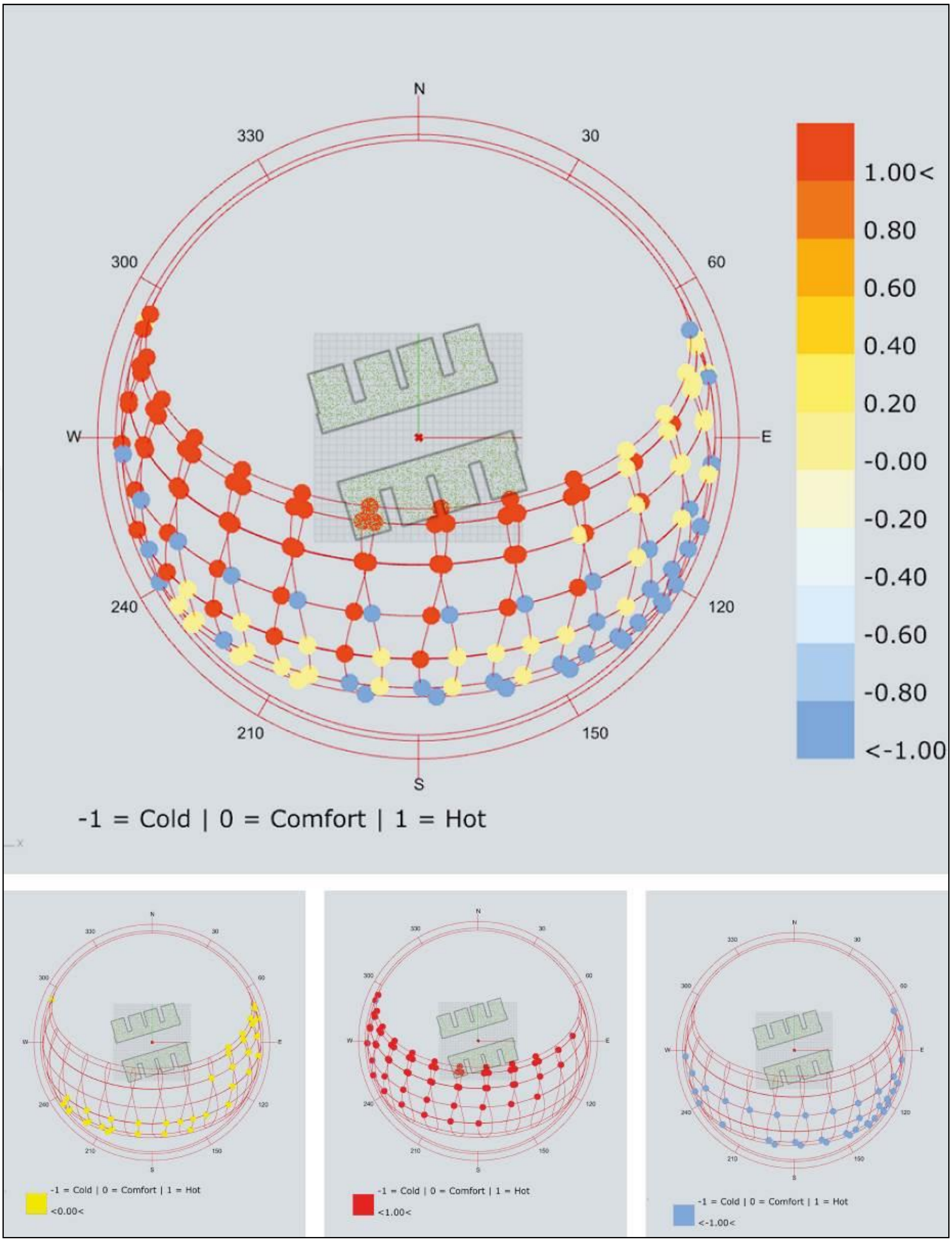


Figure 4.18: Sun-path colour coded by hourly comfort state separating states



After setting the sun-path for the project site, it is then coloured accoring to thermal stress (cold, hot and comfort). It has become obvious undesired sun radiation is dominating the SW direction (180-280 from the north) figure (4.18). As a counter action,the membranes first anchor point should be lowered in SW direction. On the other hand, the radiation during cold period comes from SE direction (90-180). To let in the law angled sun radiation during winter, the first anchor point should be lifted up.

Preparing wind rose graph

For generating wind rose graph, the first, second and third step is similar to sun-path weather data analysis (Figure 4.12). For generating wind rose, the <wind rose> component is used. The component is located in 3-visualize weather data panel, It takes in wind direction wind speed and <Boolean toggle> component to run the graph. The graph is adjustable to project site, then annual hourly data input is fed with thermal stress and conditional statement to separate thermal states as displayed in the graph.

Figure 4.19: Ladybug generate Wind rose component

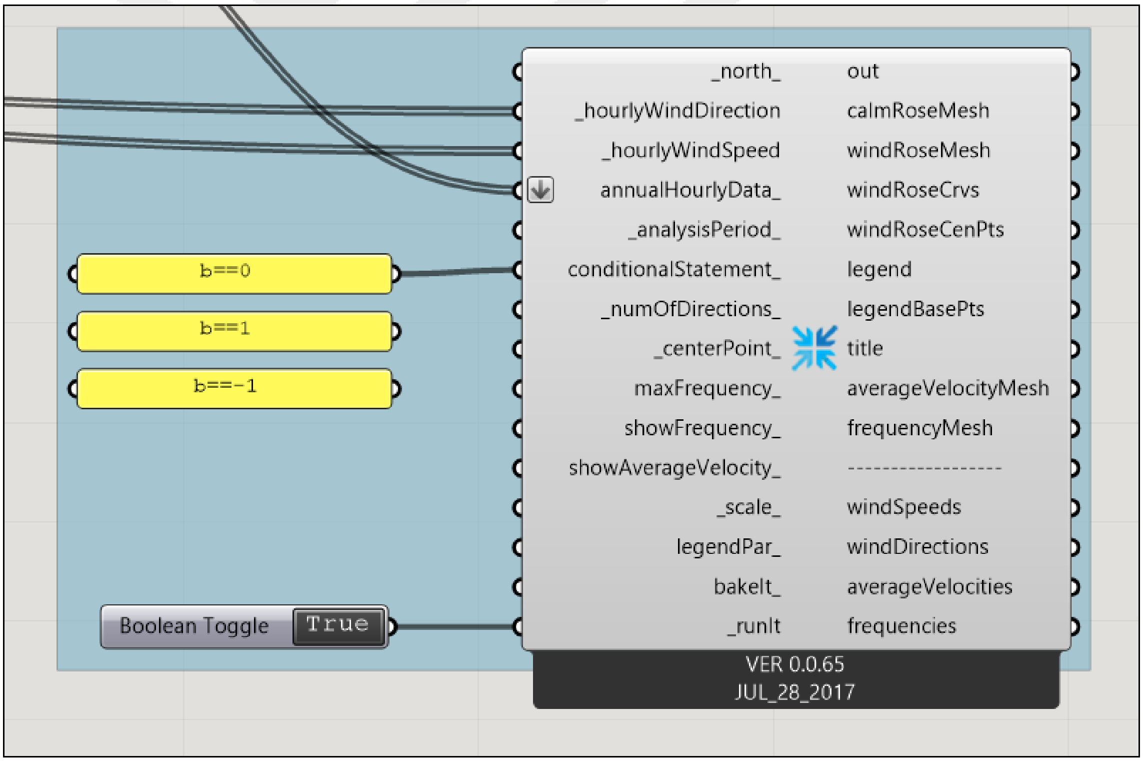
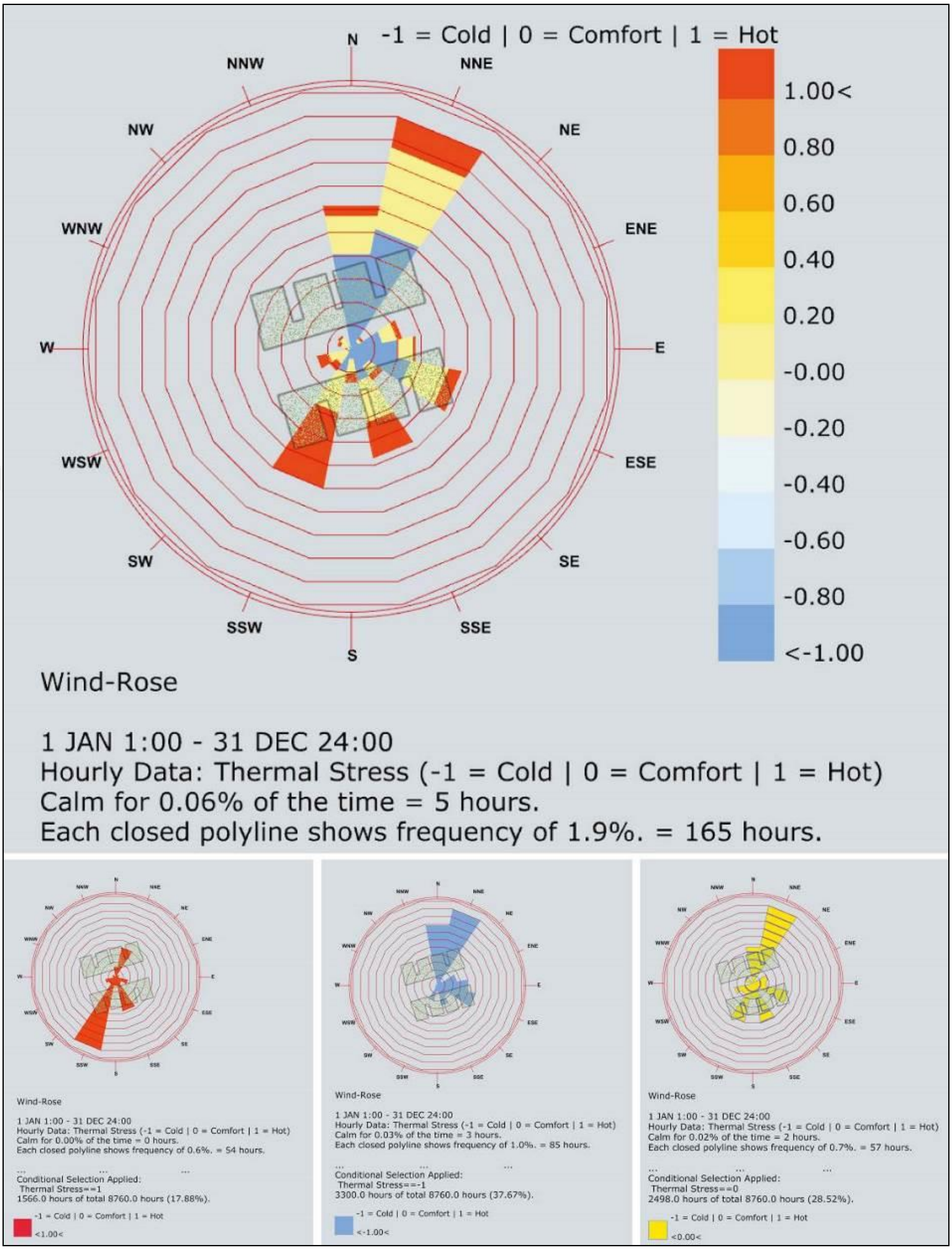


Figure 4.20: Wind rose colour coded using comfort state



The generated wind rose is for the whole year including 8760 hours. The graphics show that the wind is dominantly cold hence the city has cold nights and hot days (Figure 4.20). From the graph, it is obvious the hot wind comes from SSW (190-215). In rder to prevent undesired wind, the first anchor points from SSW should be lowered. The comfort wind is coming from NNE (12.5 -32 in respect to north) hence first anchors in NNE direction hall be lifted up.

Depending upon the results of pre-design weather data analysis, anchor points are set (Figure 4.21)

According to sun path analysis results: First anchor-points from South-west orientation should be low hence their values have been set between (4.5 - 6.5) meters. First anchor from SE orientation, the Z values are set between (6.5 - 9.5) meters. The middle points are set between 4.5 – 9.5 and back middle points facing North are between (6.5-11) m.

According to wind rose analysis results: First anchor from SSW (190-215) degree should be low hence their z values have been set between (4.5 - 6.5) meters. This point contradicts with the outputs from sun path hence it set to to (5.5 - 7.5) meter. For the first anchor from NNE, the value is (6.5- 9.5) m.

Figure 4.21: Design variable bounds (individual membrane units)

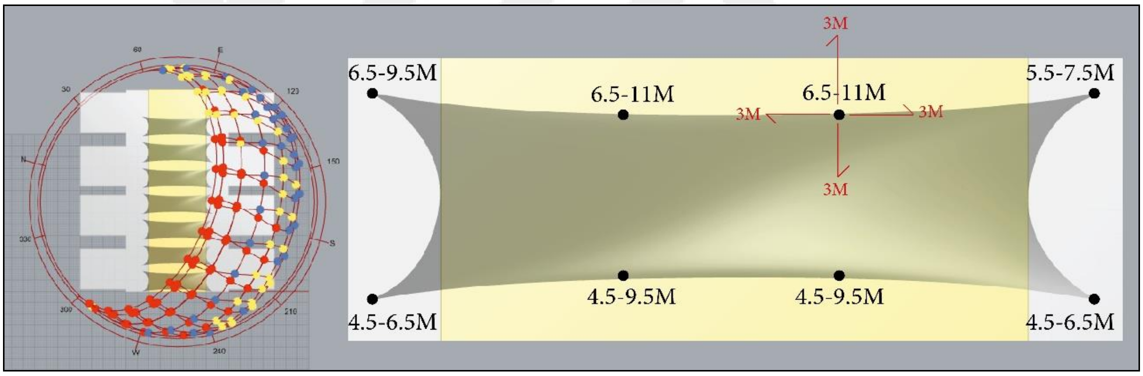
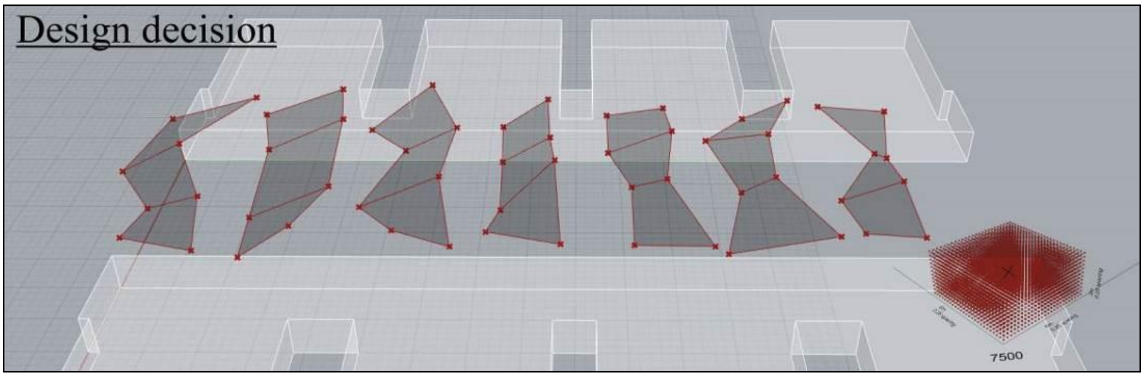


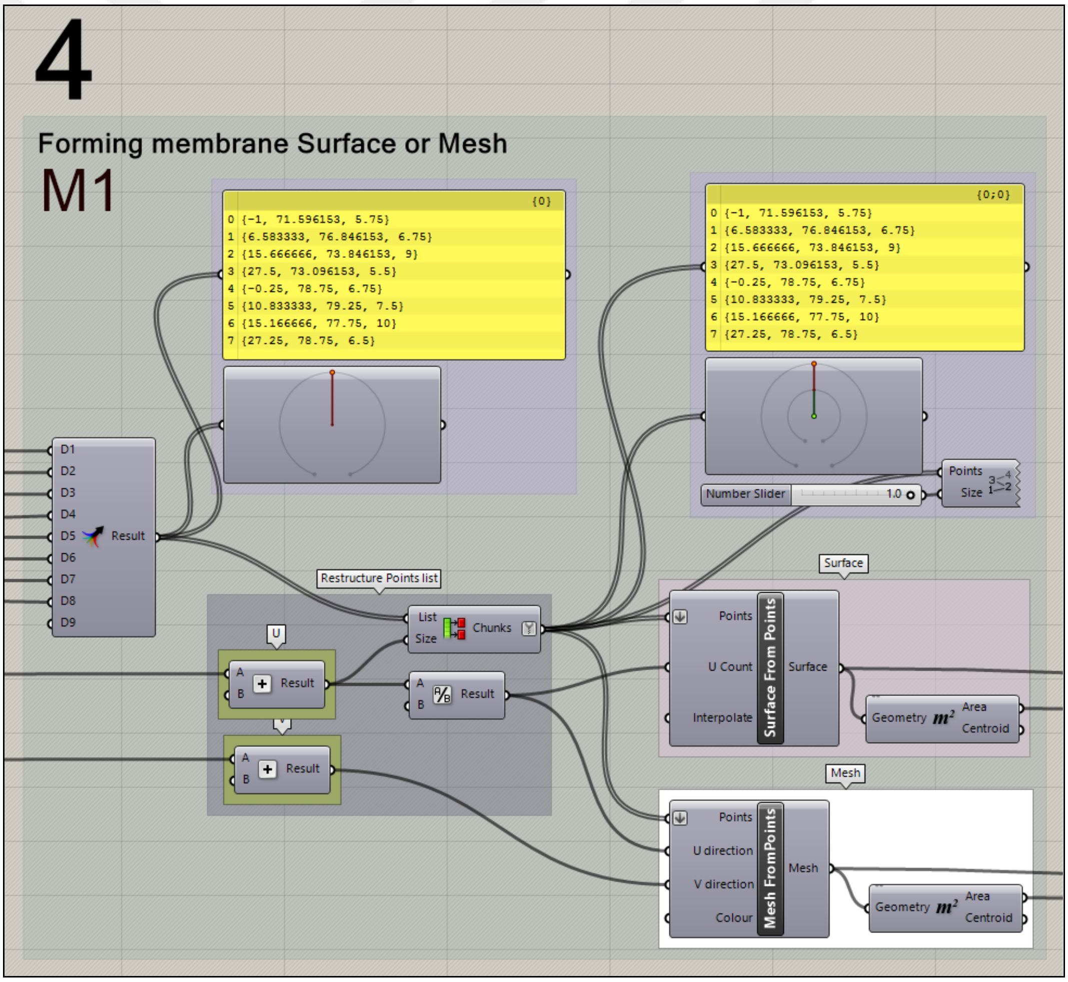
Figure 4.22: Design variable bounds



Due to the massive number of design variable (search space) and multi-objectives, the slider is customized to iterate with 0.25 increments. Each one of 56 variables have approximately 7500 possible location in the in the space (Figure 4.22). Cross combination of all possible locations for anchors, defines the proposed designs search space.

After setting the movement value. Each sequential branch is merged to create membrane surface in an alternate pattern such {0-1}, {2-3} and others. For forming individual membrane surfaces, a mesh geometry is formed from {0-1} or any other two sequential branches. As follow, all points of two selected branches are merged in a sequential order using <Merge> component. The merged data is then fed to points input of <surface from points> component. The component takes in the points in flatten mode and for U count input as there are two points within the width of membrane surface (Figure 4.23).

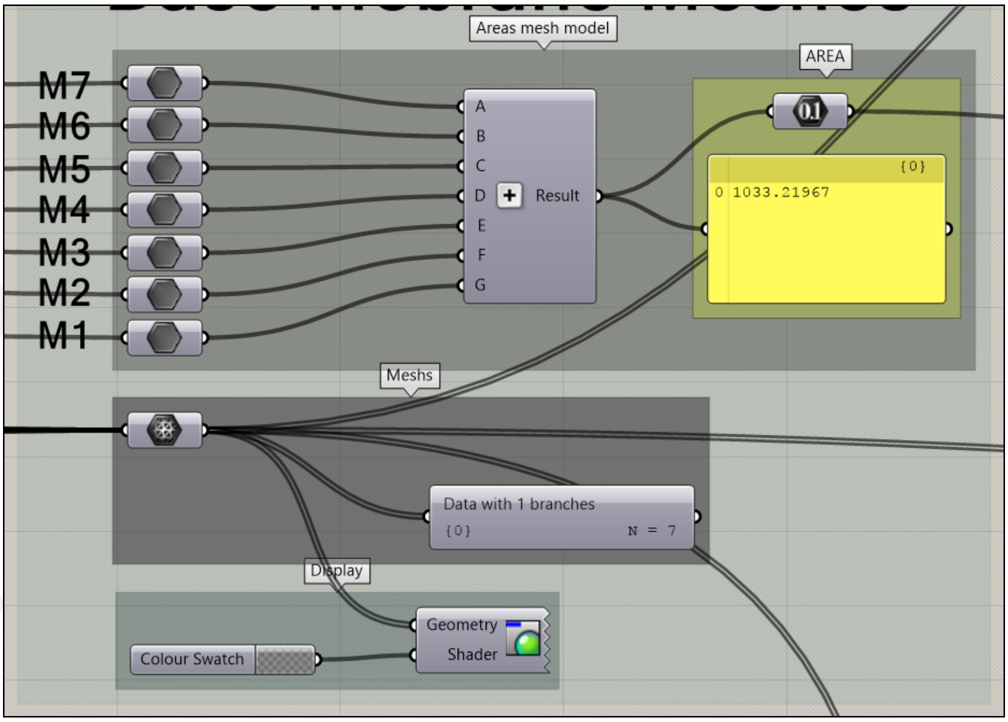
Figure 4.23: creating membrane surface from points



For conducting radiation analysis we need membrane geometry. The constructed membranes are in separated nodes as individual pieces. For combining all mesh geometries in one node, all units are streamed into <Mesh>container, also all individual NURBS surfaces are streamed into <Surface> container. The surface container that contain all membrane pieces streamed into the context input of <sunlight hourly analysis> component (Figure 4.24).

For measuring total surface geometries area, we use <area> component. Then the area of all surfaces are combined using <addition> component. By using <mass addition> component, the total area of membrane could be obtained.

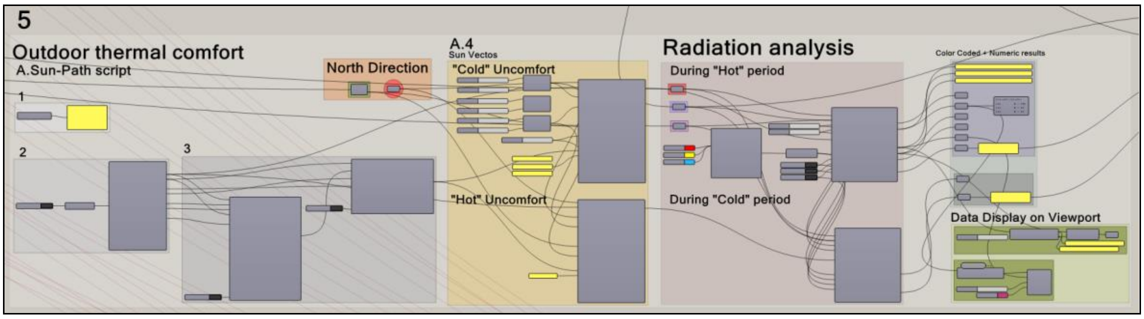
Figure 4.24: Membrane geometry and area



4.2.3 Radiation analysis

In this phase, the performance of the membrane geometry for blocking the sun radiation from the play yard is simulated. The main inputs for any radiation analysis are discomfortingsun vectors figure (4.25). In analysis, the vectors are divided to discomfort hot period and discomfort cold period. The metrics is radiation-hours.

Figure 4.25: Radiation analysis’ whole script

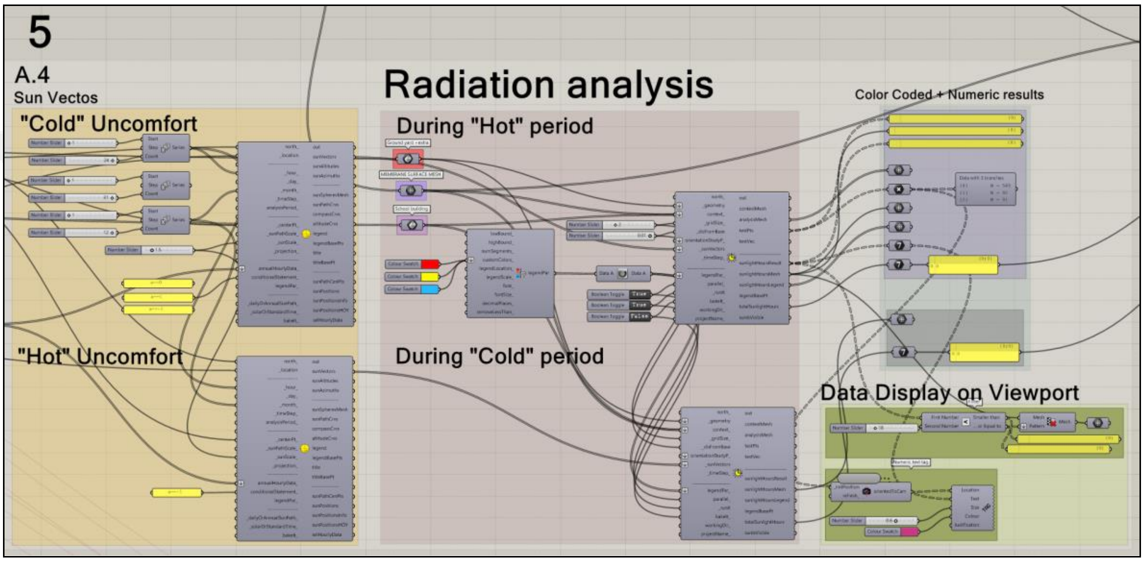


During radiation analysis, the first, second and third steps are similar to weather data analysis steps. For finding discomfort period’s sun-vectors for radiation analysis. The <Sun path> component provides the hourly sun vectors for 4364 daytime hours. It is located inside visualise weather data panel. The output data from <outdoor thermal comfort> model (stress state) is fed to annual weather data analysis through input of the <sun path> component. The <Sun path> will display the sun-hour position and colour codes it depending on stress state (0=comfort displayed in yellow; -1=cold displayed in blue and 1=hot displayed in red). Sun path accepts conditional statement for the input data and the thermal state can be separated using conditional statement (a==0 for comfort, a==1 for overheat and b==-1 for cold) in order to eliminate the comfort and cold hour. (a==1) is used as the conditional statement. According the calculation, there are 1588 overheat hours in one year, which approximately means %38 of daytime period. For picking the cold hours, (a==-1) is applied as a conditional statement. There are 1393 cold hours during a year ,which is approximately %31 of all day time (Figure 4.26).

The analysis is performed using <sunlight hour analysis> component within environmental analysis panel. It requires north direction, geometry, context, sun vectors and <Boolean toggle> to run. In the analysis, geometries are the playground and its surrounding walls. They are the main spots to be blocked from the radiation reaching the surfaces and inhabitants during hot period and vice versa in cold periods. Context is the elements that have potential to shade and effect the sun radiation analysis. In the analysis, the tensile membrane shading and the surrounding walls of playground are assigned as the context.

The measure (meter) is the duration (hours) that target area is exposed to sun radiation. If the radiation is customised for unwanted sun during over heat hours, the lesser radiation hours is better. Moreover, if the target is maximizing total sun-radiation hours during cold period more radiation hours is better. The output of analysis is colour coded mesh in addition to the numeric values. The analysing engine divides the geometry into grid of sample with adjustable size. Each sample calculates the indecent radiation duration in hours for samples are. In addition, it provides the total radiation hours for the whole geometry. The numeric value can be mapped on the coloured meshes. We can cull the meshes with specific value for easer comparison.

Figure 4.26: Radiation analysis inputs



4.2.4 Multi-Objective Optimization

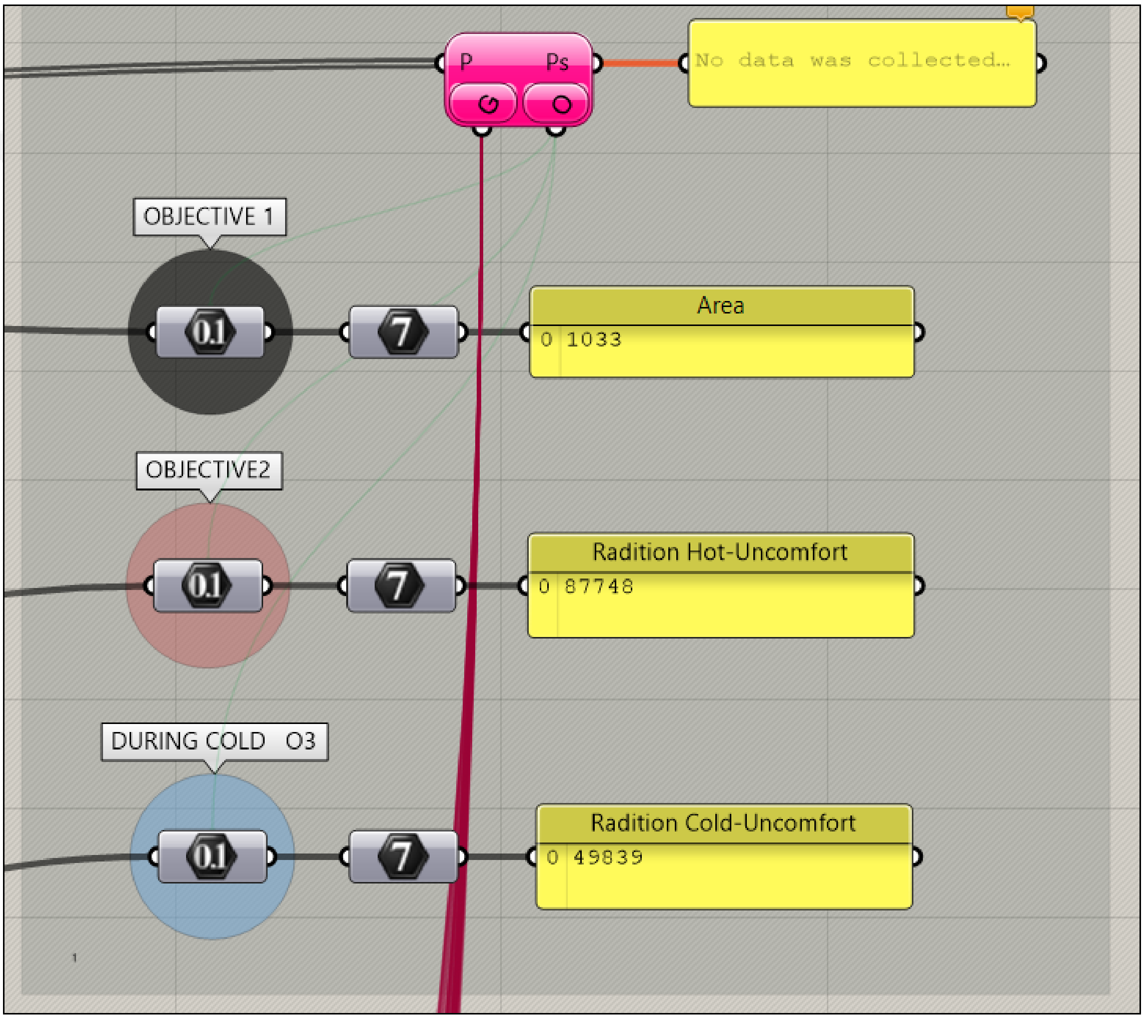
Optimisation engine uses an algorithm to control the parametric variables and change them to fulfil design goals. The algorithm follows the evolutionary process (natural selection), that exist in nature. The searching algorithms are easily customisable through plugins user friendly interface.

Octopus is used for conducting optimization process. Octopus's phenotype input is fed by membrane surface genomes (genetic data's) (Figure 4.27). The genes are total 648 eight bounds in X,Y and Z direction, forming design search space. Objectives are membrane surfaces' total area, total sunlight hours on schools playground surface and surrounding walls during hot and cold discomfort period.

The objectives are streamed through <Number> component in order to be identifiable by optimization plug-in. The optimization algorithm (selection and reduction) is guided by the results of radiation analysis. The algorithm links the outcome of analysis to inform the sequential generation process. Octopus projects the semi-optimal design option on Pareto Graph figure (4.28). Then the architect's task is to choose among them based on his judgements.

Form finding is an interactive process; during simulation process, form is unstable. Ladybug can make environmental analysis for unstable forms, however it needs a high computational power. A stable geometry should be used for optimization.

Figure 4.27: Octopus optimization component



Running optimization for entire year will take forever; moreover, it requires high performance computers. In order to reduce the amount of calculation the analysis period is limited to seventh, fourteenth and twenty-first of each month for entire year. After running the optimization algorithm for fifty generations, each generation contains a pool of two hundred options. the result search space is as shown in the Pareto graph (Figure 4.28).

Figure 4.28: Pareto 3D graph showing the results of optimization for selection purpose

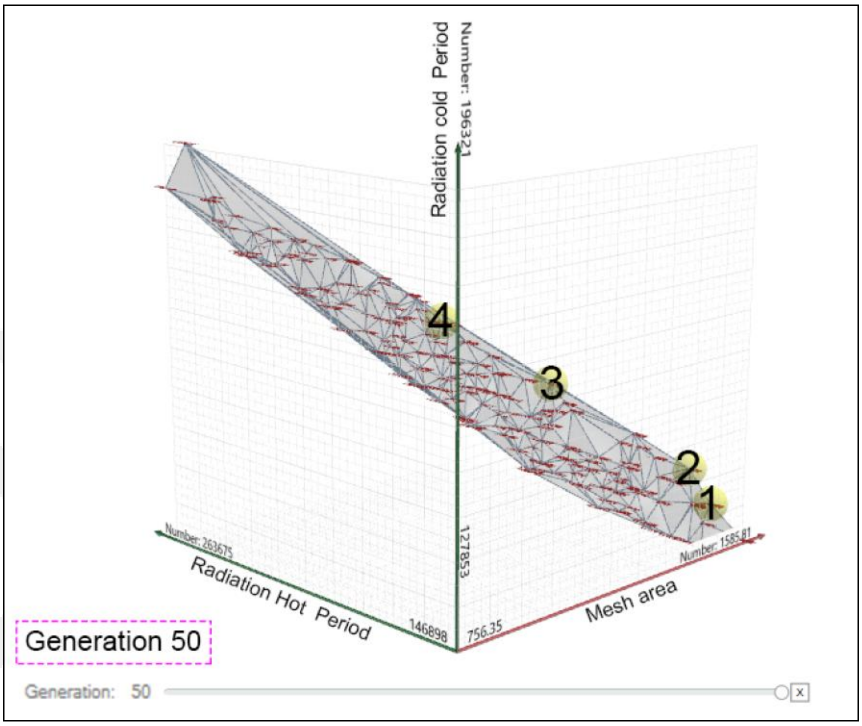


Figure 4.29: Pareto graph

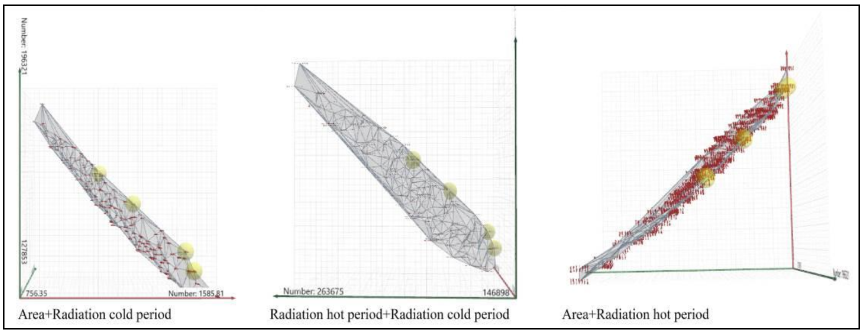
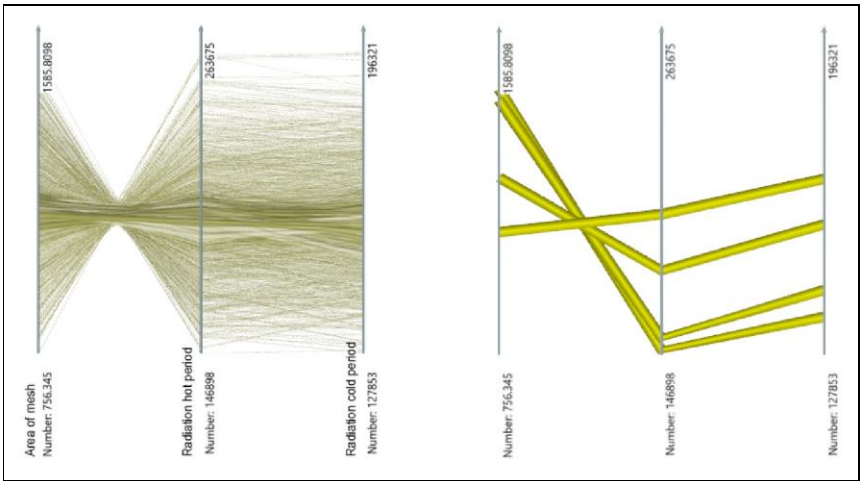


Figure 4.30: Optimal options displayed on multi-axis view



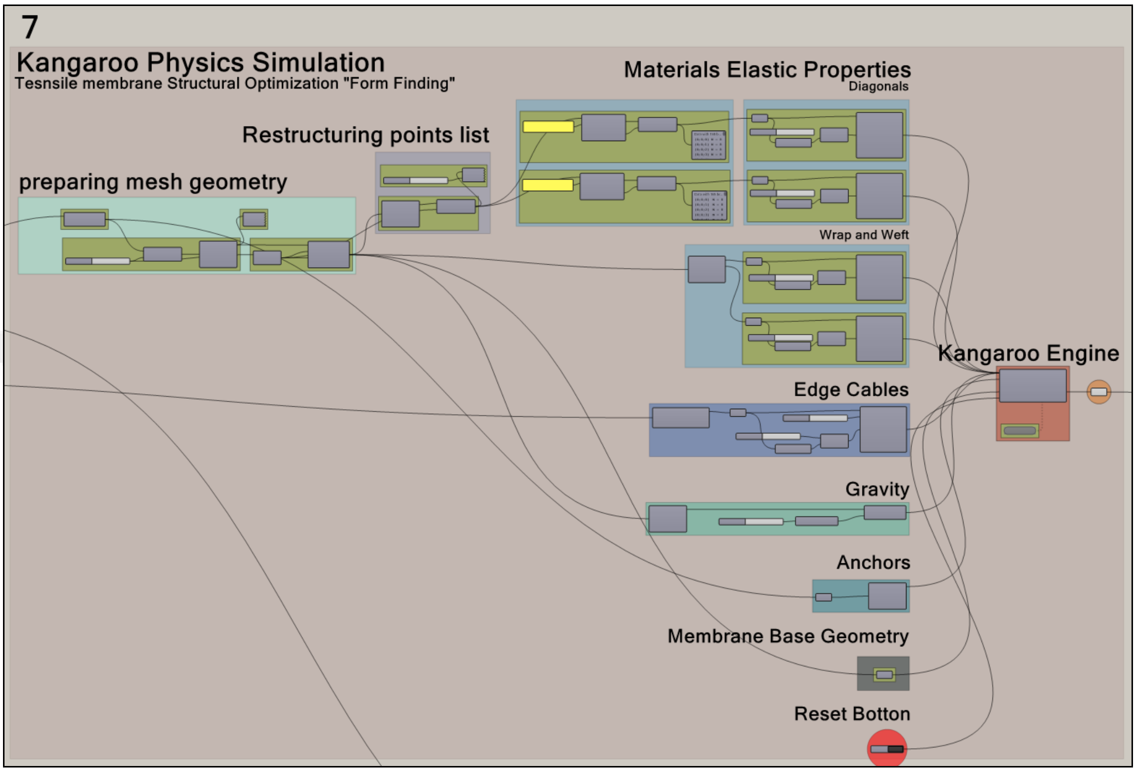
Octopus generates a range of semi-optimal options. The solutions are ranging between extreme of each determined goals. After picking four individuals from Pareto optimal options (Figure 4.28), they are converted into tensile membranes. Criteria for picking solutions are low radiation during hot period and high radiation during the cold period.
The grasshopper file at this stage contains the optimization results . However during case study, rhino grasshopper failed to open and a new GH file had to be created. Initiating Ladybug plugin then opening the GH file that contains saved octopus optimization results helped to authorize.

4.2.5 Digital form finding (Kangaroo)

There are several digital form finding techniques such as dynamic relaxation, particle spring system and NURBS form finding. The tool used in workflow is based on particle spring system. The system turns the geometry into particles (for assigning weight) and springs (for simulating elasticity of material). The inputs of devised script are base geometry, anchors (fixed boundary), spring forces, unary force (gravity), and timer and restart button (Figure 4.31). The boundary edge acts as an anchor, and it’s curvature level is controlled by the designer. For form finding, the rest length is zero. However for analysing, membrane’s elastic properties should be added for the second time. According to the material properties of PTFE, coated membrane has no strain, hence the only obligation is form finding.

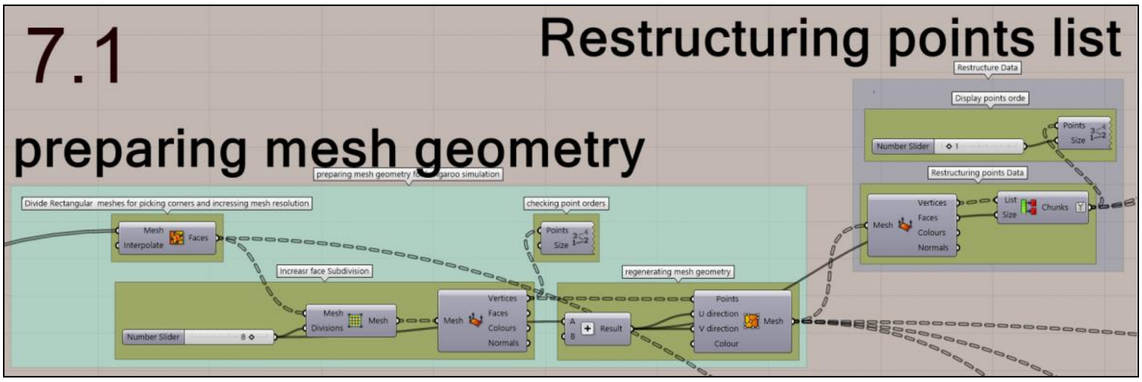
The digital form-finding tool used for the project is Kangaroo v0.099. The engine's requirements for the simulation are forces, anchor points, base geometry simulation reset button and timer.

Figure 4.31: Kangaroo membrane form finding script



For conducting form finding, The <Kangaroo engine> component can take only meshes as a geometry for calculation, by using <Mesh surface> component. NURBS surfaces can be transformed to to mesh (Figure 4.32). In the script from the early steps, the base geometry can be created both as mesh and NURBS. Each membrane mesh consists of three polygon faces. Low resolution meshes are insufficient for membrane simulation. The <mesh explode> component will divide polygon into independent faces. By streaming the mesh into <Quad Divide> component from Kangaroo plugin, subdivision is increased to form the base for particles and springs.

Figure 4.32: Preparing mesh geometry for kangaroo form-finding



For simulation forces, Kangaroo physics contains various components that could be utilized to generate digital equivalent of real-world forces. The plugin is devised to simulate the interaction between real-world forces and their effects on objects (particles in the simulation). Kangaroo uses particle-spring systems in simulations of membrane formation. From the base geometry (meshes), it extracts the edges and vertices that will become the springs and particles in the from-finding.

For simulating material elasticity: <spring force> component is used (Figure 4.33). Elasticity is identified according to materials' micro structural resistance. Kangaroo simulates elasticity as a directional force (vectored force) that exists between virtual particles of simulated object. It can simulate many existing materials including membrane, paper and others. In doing that, it follows Hooke's spring law and Newton's Laws of motion.

From the mesh, the edges are extracted by using <Wrap/Weft> component, then connected to spring force simulator for generating the elastic property of material. For the rest length, the edge lengths are measured by using <curve length> component then connected to <multiplier> which multiplies them by a <slider> between (0.00-1.00). The outcome of multiplier is the relation between the edge lengths to the rest length (the rest length is the lenghth that edges tries to reach or be) in percentage. A grid of particals (points) with zero rest length of springs will behave similar to a soap film, it tries to minimize area and shrink down to nothing. If rest length is equal to start length, it will act as origami further it can take advantage to get unrolled surface for fabrication purpose. Between 0-1 it can be used for displaying the deformation of form under changing loads.

The edges of meshes determine the directional forces that exist between particles. the edges of squire grid act like a cable net (figure 4.34). Spring force acts directionally and there's nothing to prevent the particles from moving towards each other in diagonal directions hence its behaviour is not correctly. For a more realistic model of membrane behaviour shear springs shall be added. Diagonals, which prevent each square from deforming into a diamond shape (Figure 4.34). Different stiffness values can be used for the main square grid springs and the diagonal shear springs for different cloth properties in regard to elasticity in warp and weft directions.

Forming the diagonals: after obtaining a point grid from <deconstruct mesh> component, the points list has to be restructured by using the <relative item> component and offset input. Data path can be changed between different levels to data structure. This will enable the construction diagonal lines and then convert them to springs.

Figure 4.33: Material physical properties scripting

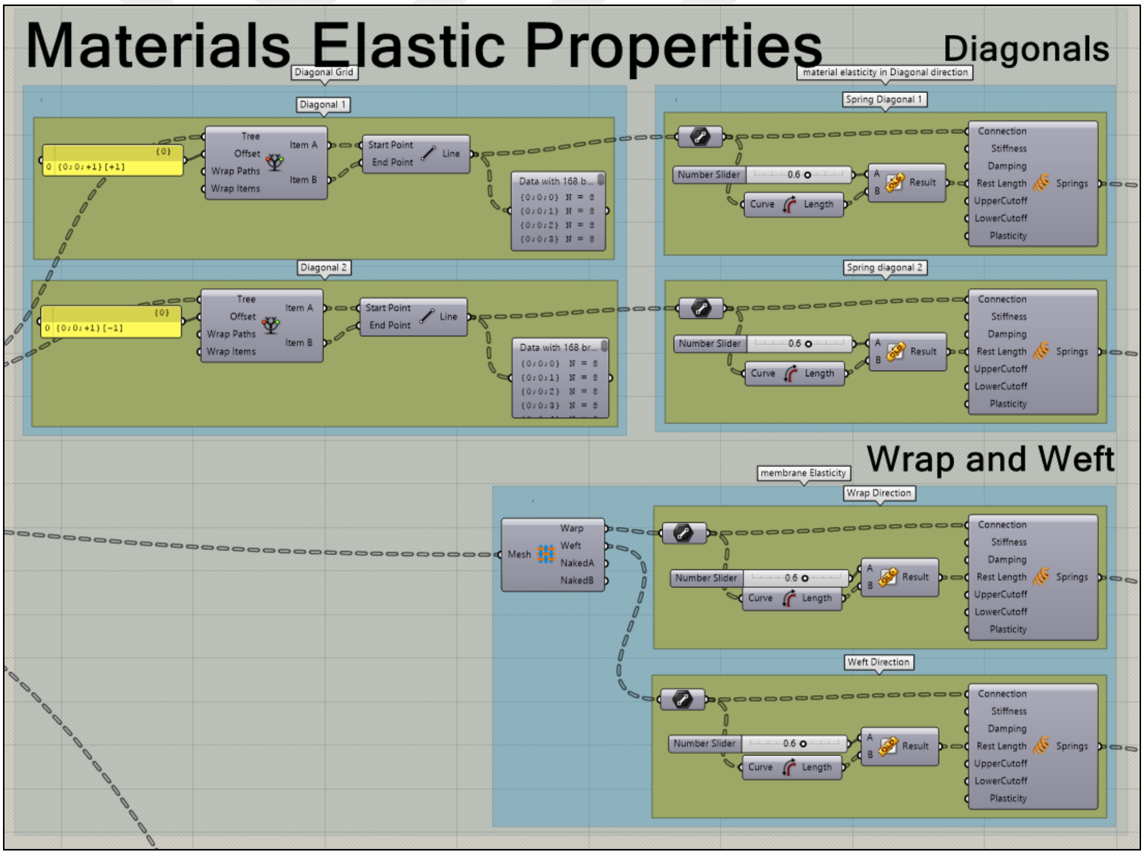
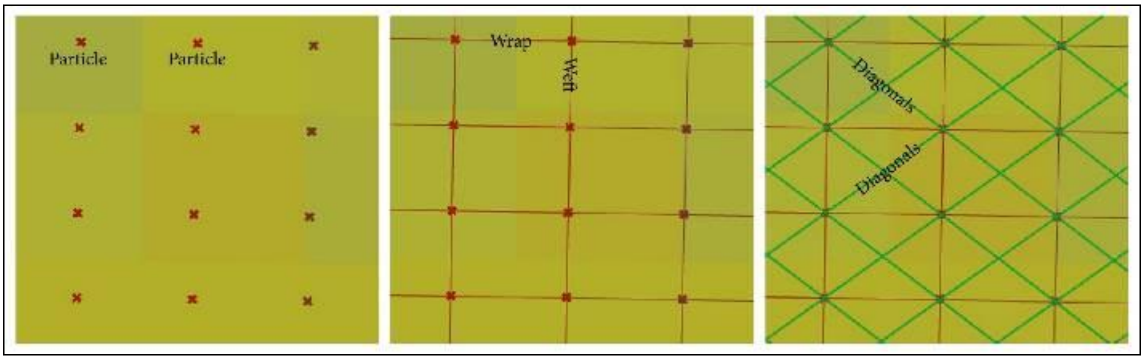


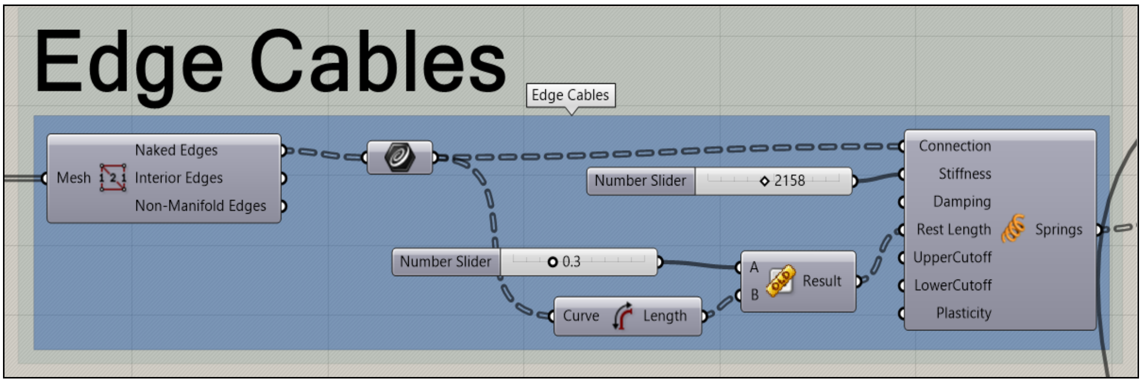
Figure 4.34: Assigning material property



Edge cables are modeled as forces and Kangaroo intelligently converts edges to anchors. That stabilizes membrane by applying tension to membrane boundaries. From the mesh, the outer edge can be extracted by <mesh edge> component, and then the edges are fed to connection input of the <spring force> generator component. The stiffness of springs is adjusted until desired form is obtained. For the rest length, curve length is multiplied by a <slider> with the value changing between (0.00-1.00). Detailed material properties is provided at Appendix-A.

Setting rest length value to absolute zero occasionally resulted in problems, output from the Kangaroo engine is deformed then it disappears.

Figure 4. 35: Edge cable Properties



The <Unary force> component is able to simulate earth's gravitational force. The engine's algorithm reproduces a gravity that acts upon objects by assigning weight to particles (vertices of mesh geometry). In real world, an object's weight is relative to its mass. According to Kangaroo's manual: "Kangaroo engine in order to compute the effects of gravity on object and assign true weight, it applies the initial mass of one".

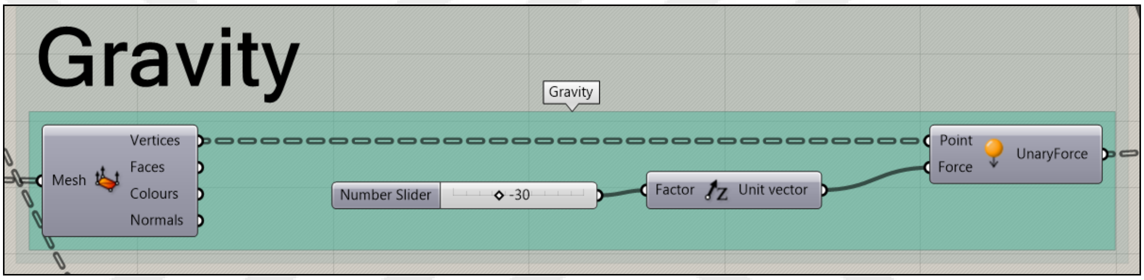
This value can be changed to following mathematical equation (G=W/N). For the soap bubble formation, self-weight is neglected however, for analysis weight adapting the equation shall be applied as:

$$G=W/N \qquad \textbf{(1.1)}$$

G: unary force vectors value W: real weight N: number of particle

The mesh output is connected to <deconstruction mesh> component and vertices from deconstruct mesh is fed to unairy force to generate the gravity (Figure 4.36). The gravity is neglected for soap form finding, but for analysis of actual membrane, the weight divided by particles and the result connected to unit z are then streamed to force input of unary force component. All forces are fed into the 'Force Objects' input in flatten mode.

Figure 4.36: Gravity force



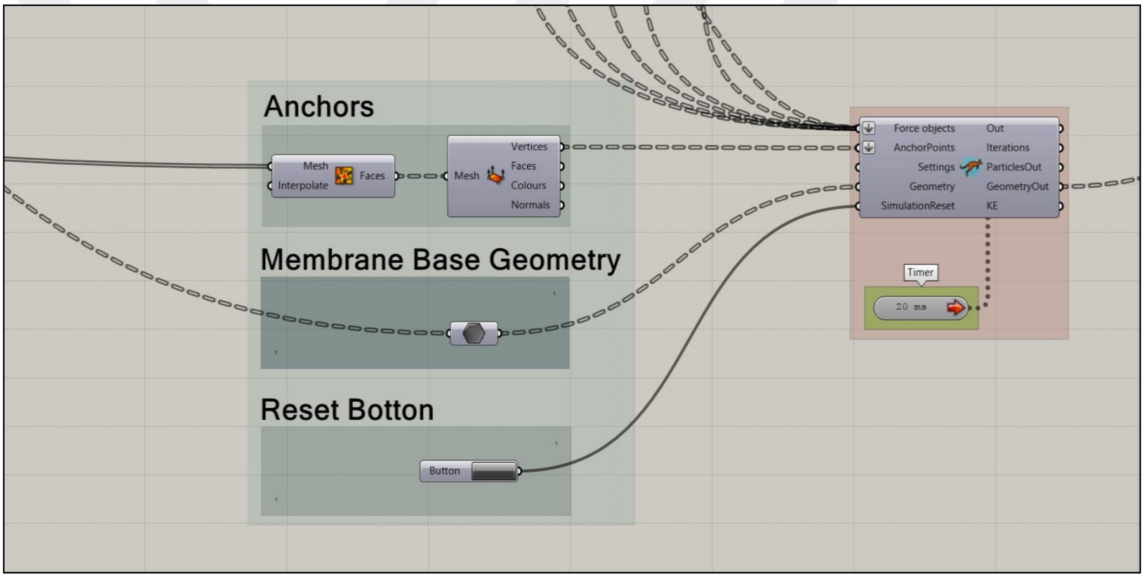
Anchor points are fixed points, and no matter what forces are applied to them they stick firm to their restrained position. Anchor points shall always positioned at particles' location. If their positions coincide or they are within tolerance limit, the engine will smartly convert those particles to anchors. Any miss match before running simulation will cause loosing the link between anchor and moved points.

Corner points are usually used as anchors. Four corner-points are extracted by using the <Mesh Corners> component from base geometry.

Running the simulation

For the engine to start its computation, it requires a <Boolean toggle> component that reruns the simulation each time if turned on and off. When the toggle is set to true (on) the engine, it initiates the calculation and converts all the inputs to the algorithm's identifiable inputs. The simulation is live; all inputs can be manipulated interactively.
The <Timer> component systematically updates the simulation results on the screen. The timer has an interval setting which controls how long (in milliseconds) it waits between regeneration of solutions. The update intervals are customisable by right clicking on timer, it shows possible pre-set options in addition to custom input options.

Figure 4.37: Kangaroo engine



For optimization, a simplified mesh geometry wasused, however when the meshes were converted to the membrane, curvature was introduced to the form. The edge curvature was adversely effecting the performance. In the first attempt figure (4.38 to 4.41), curvature level of optimized forms had to be used to control the performance and balance between the performance and area of membrane. However, in this method for higher performance the curvature characteristic of form is lost. In case of straight form, extra stress shall be applied for gaining stability for built structures.

Tensile membrane options from Pareto graph

Figure 4.38: Option one from Simulation one, comparing efficiency before and after conversion to membrane

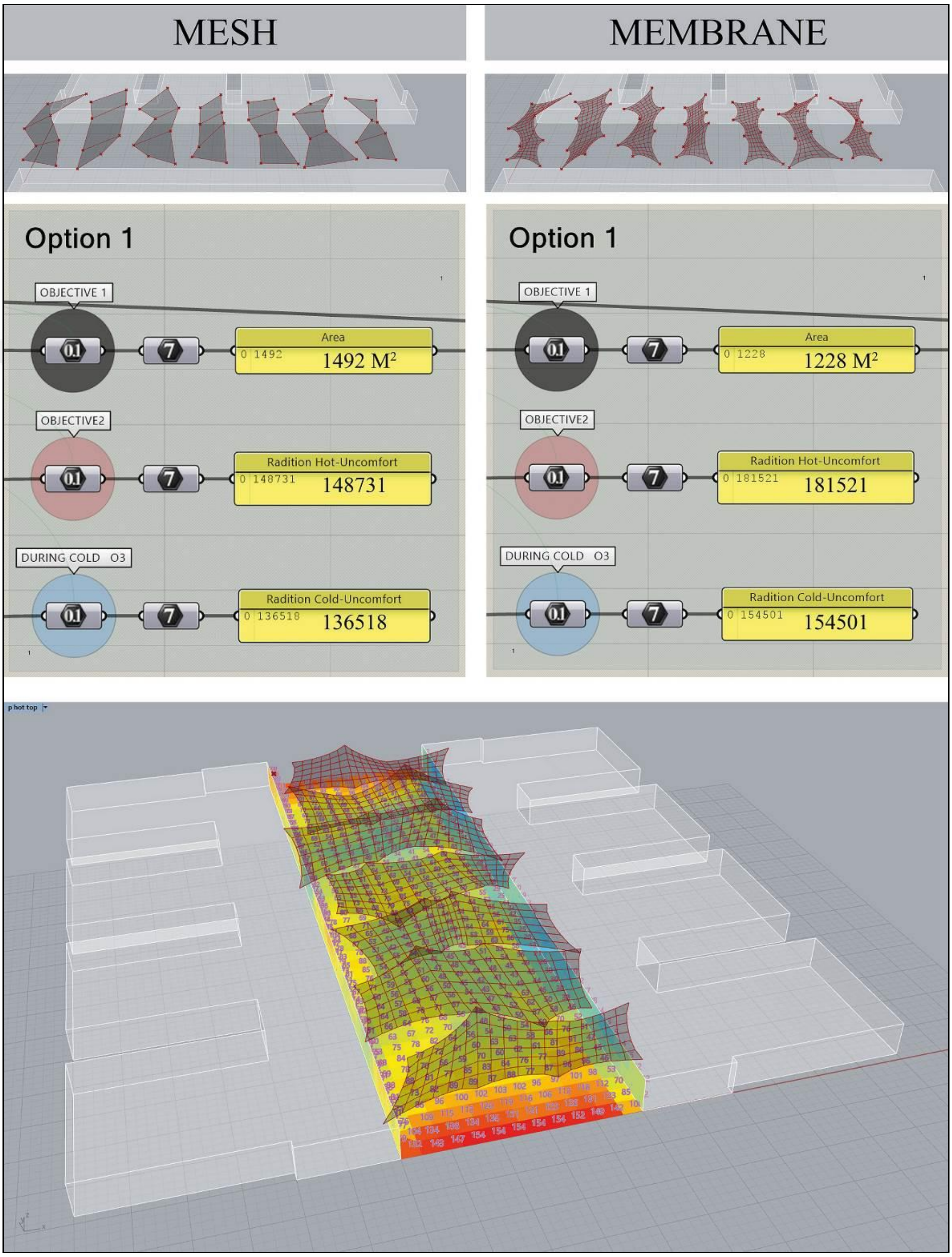


Figure 4.39: Option two from Simulation one, comparing efficiency before and after conversion to membrane

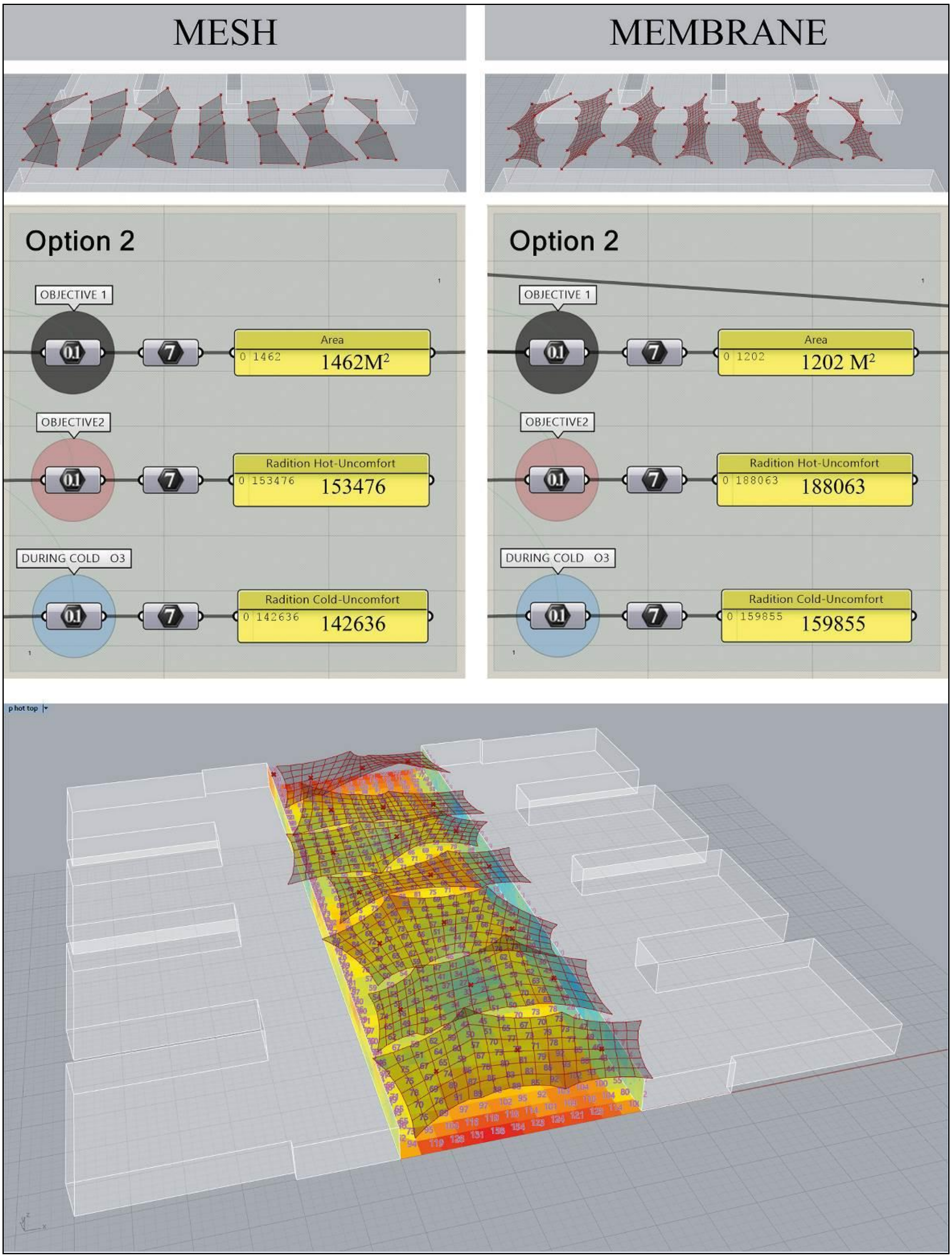


Figure 4.40: Option tree from Simulation one, comparing efficiency before and after conversion to membrane

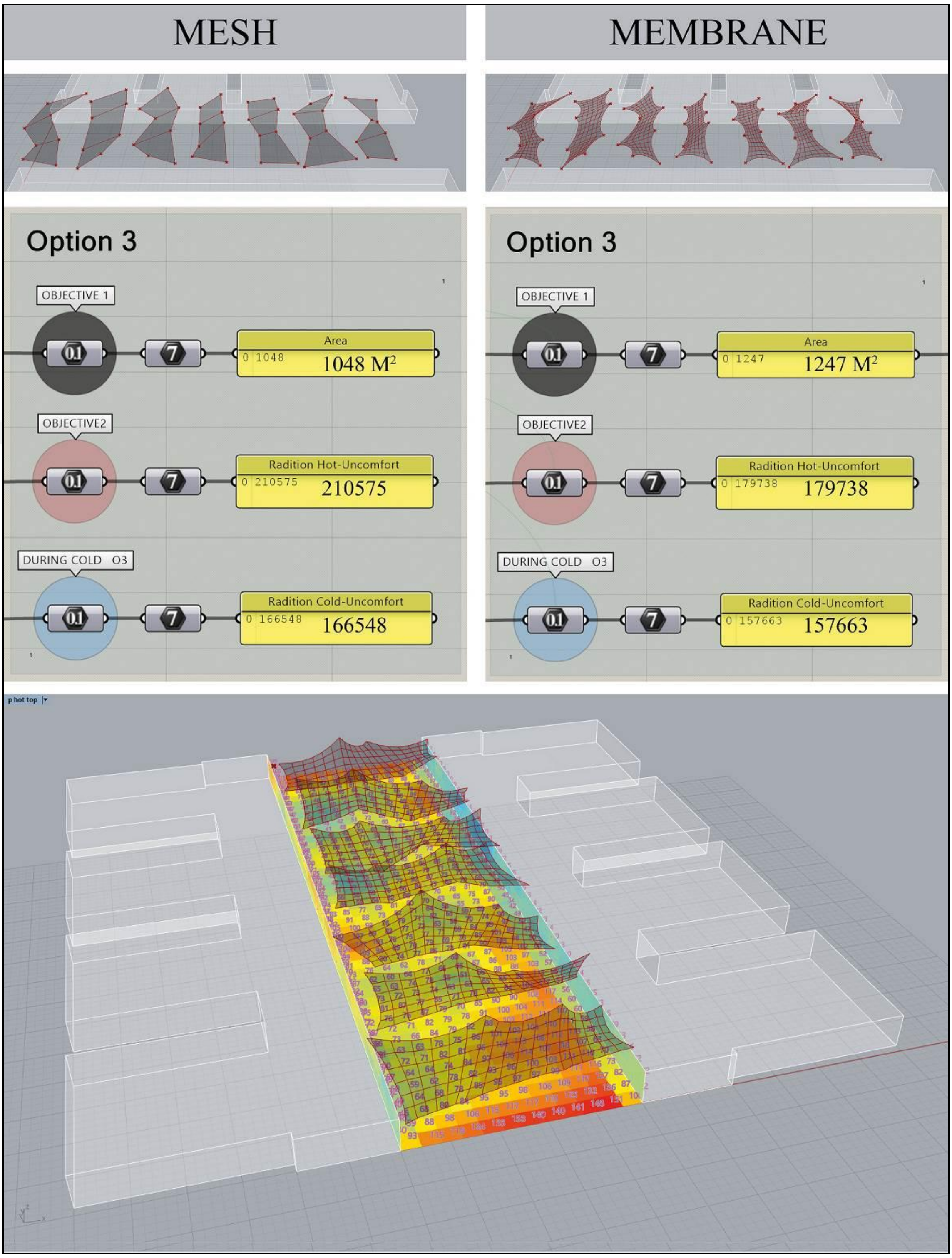
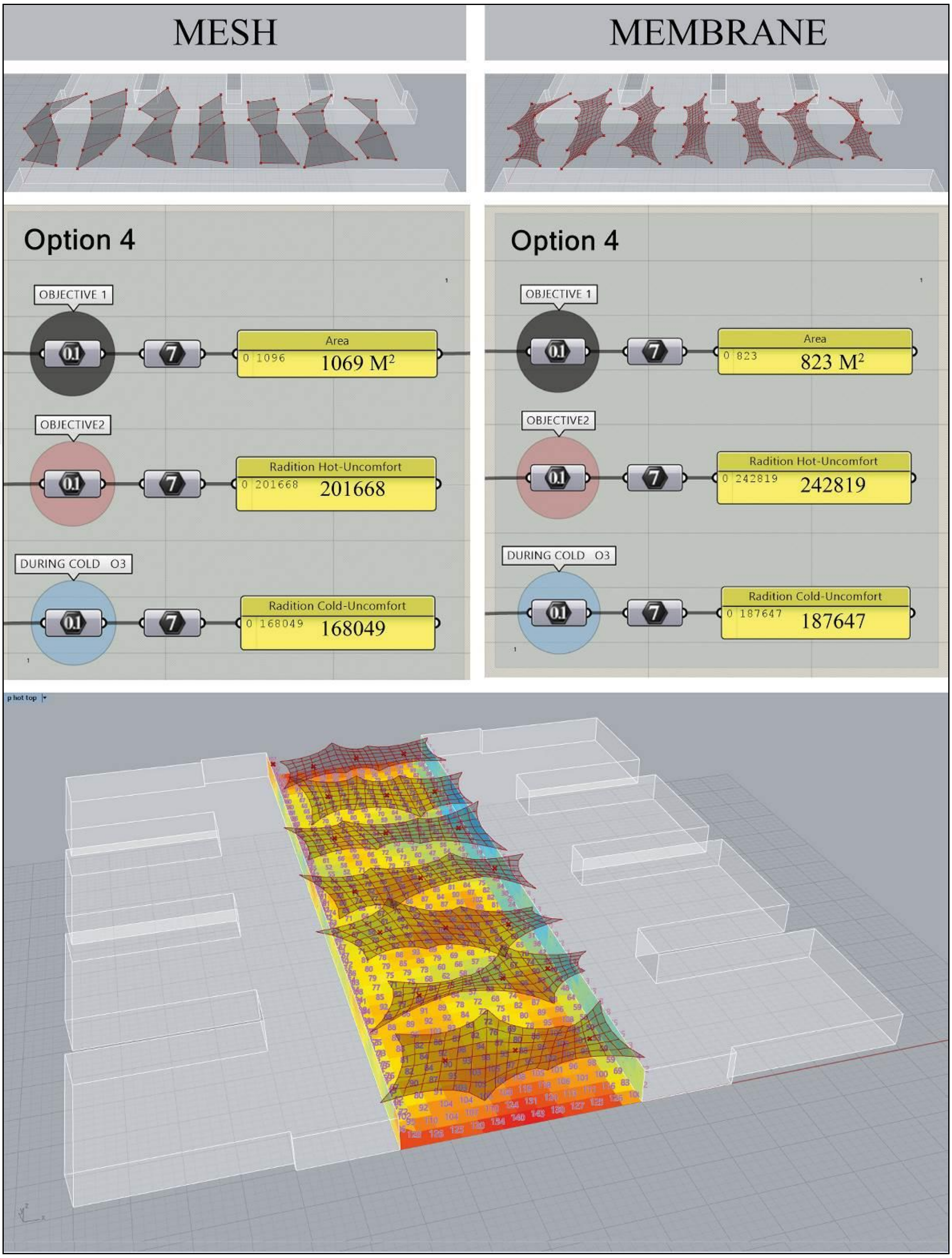


Figure 4.41: Option four from Simulation one, comparing efficiency before and after conversion to membrane



Comparing option one to the existing tensile membrane structure

Radiation analysis done for three specific days of each month. The results of analysis for those days with no shading structure is shown in the Figure 4.42. Thus means the scale or metrics for hot period is (0-388259H) and for cold period is (0-258198H). The number comes from the sample areas (points) of ladybug geometry.

Figure 4.42: Radiation analysis without tensile membrane shading

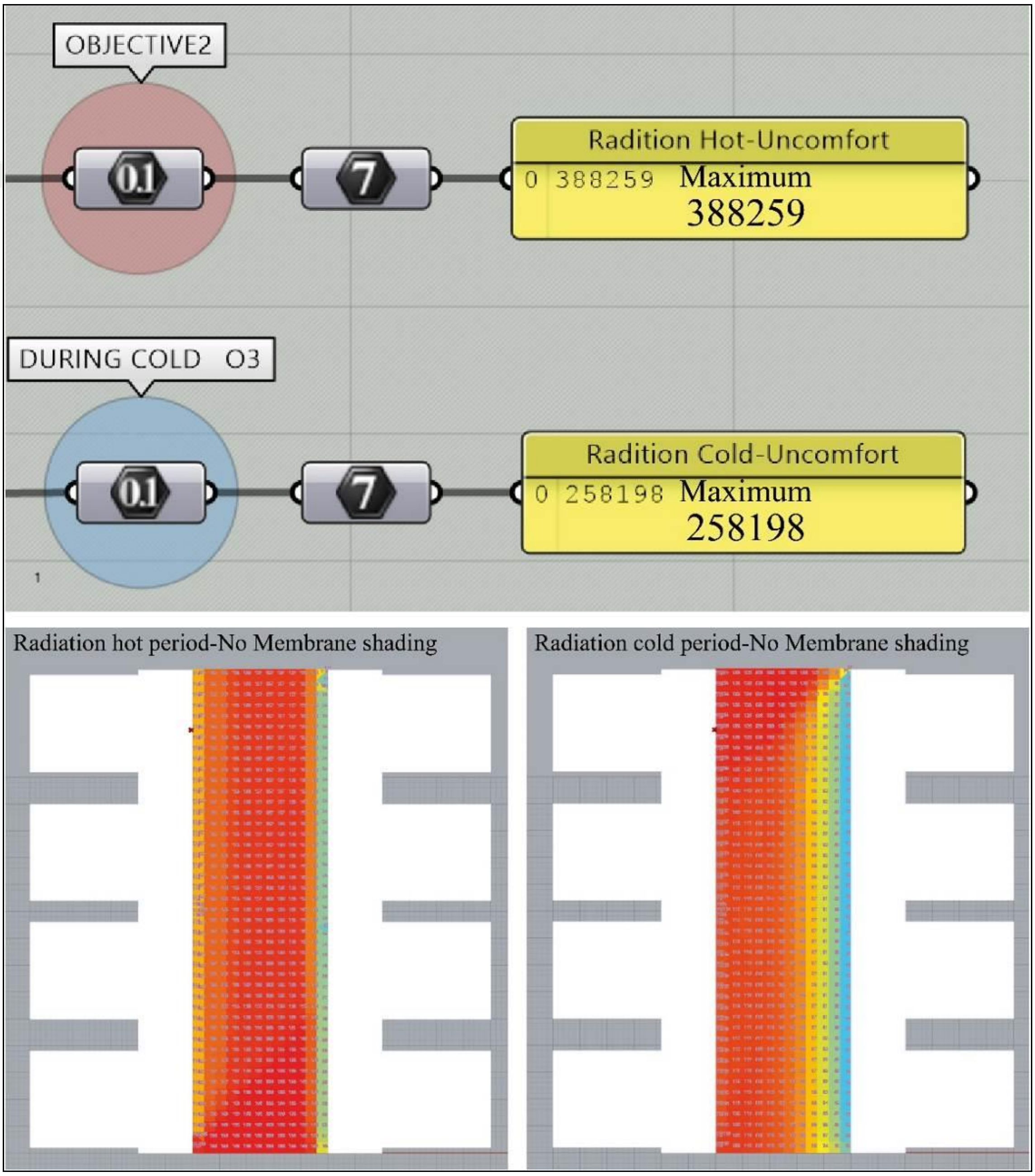


Figure 4.43: Comparison of radiation between existing membrane and option one from simulation one

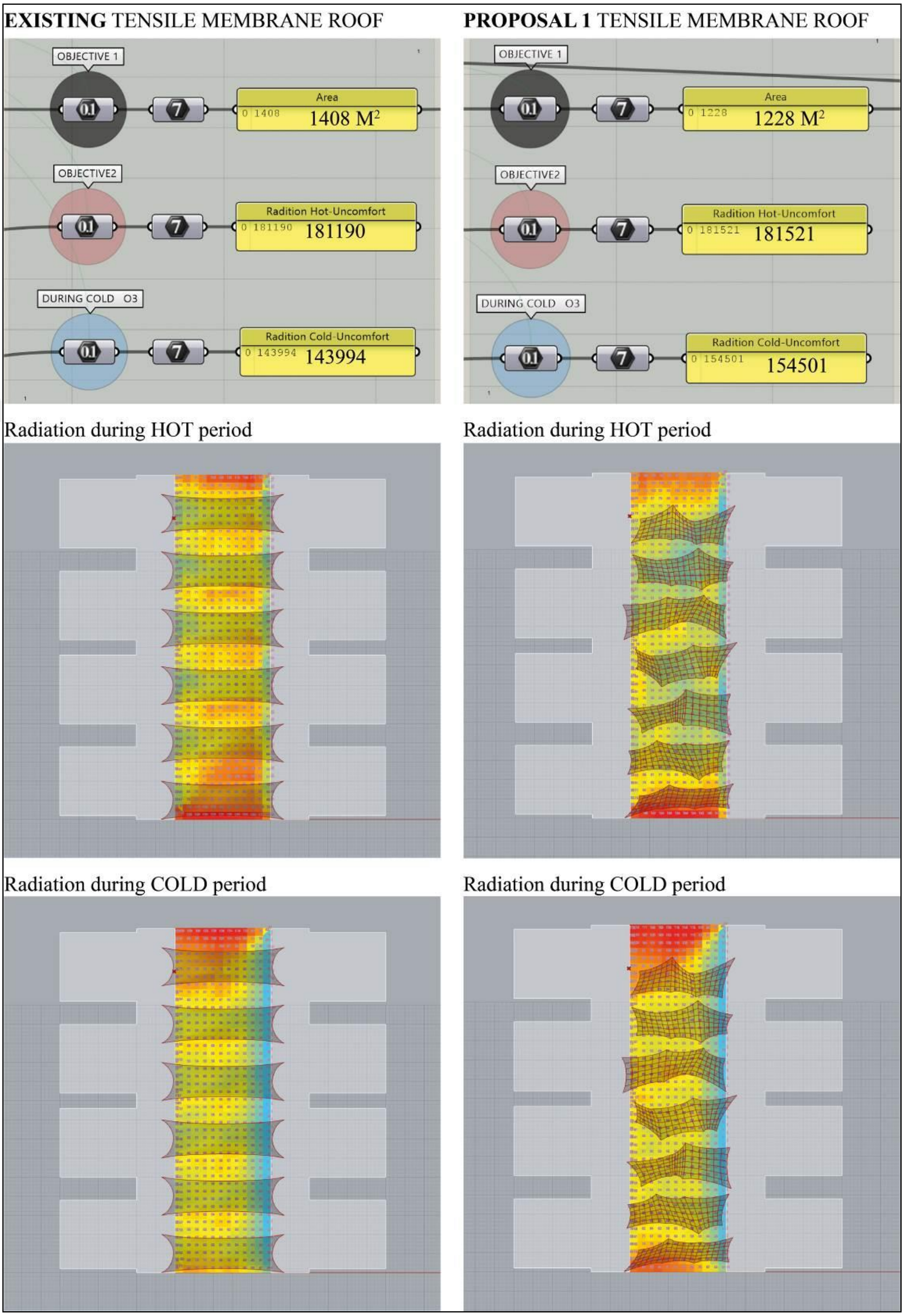


Figure 4.44: Comparison of radiatin between existing membrane and option one from simulation one in perspective view

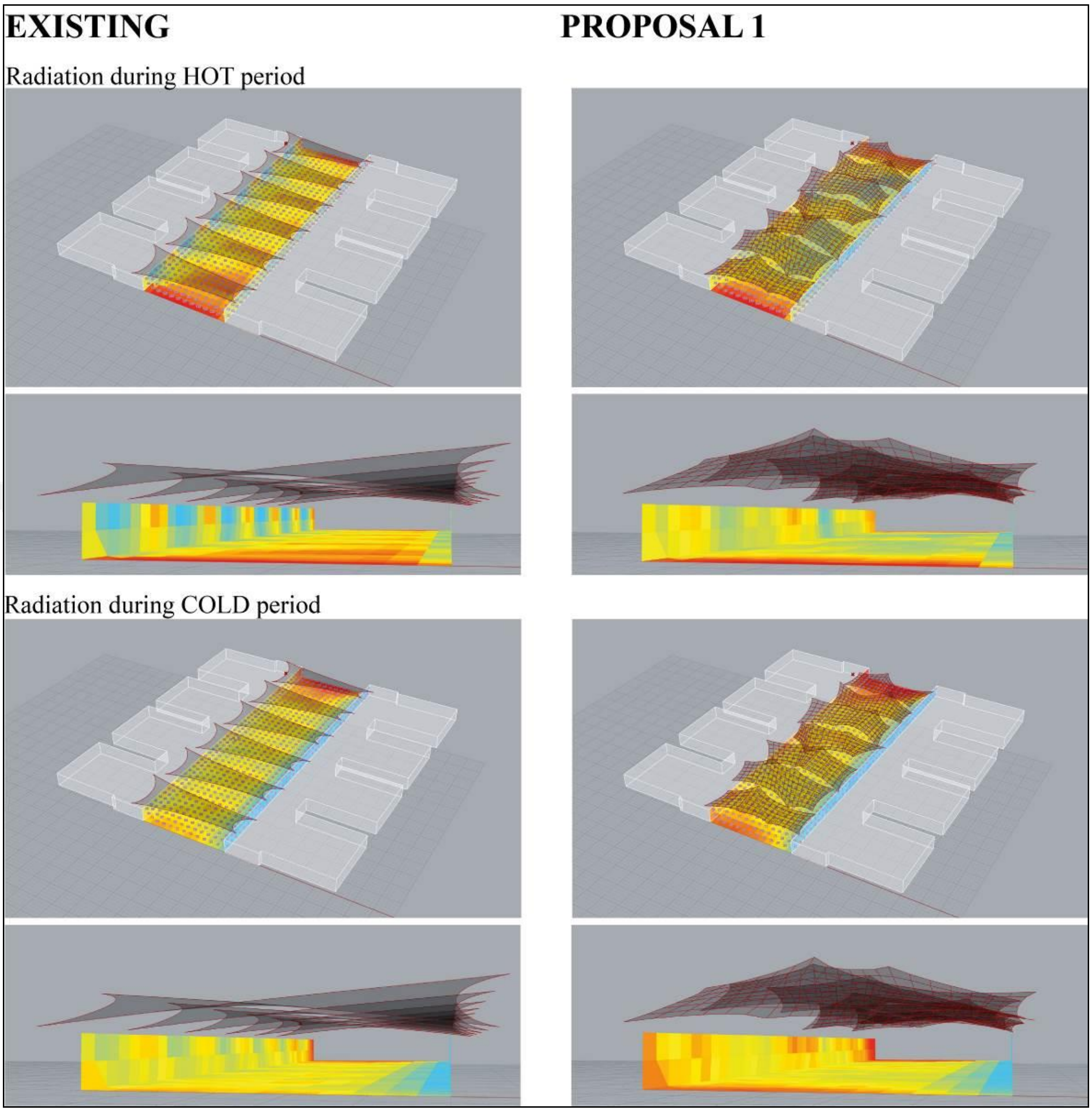
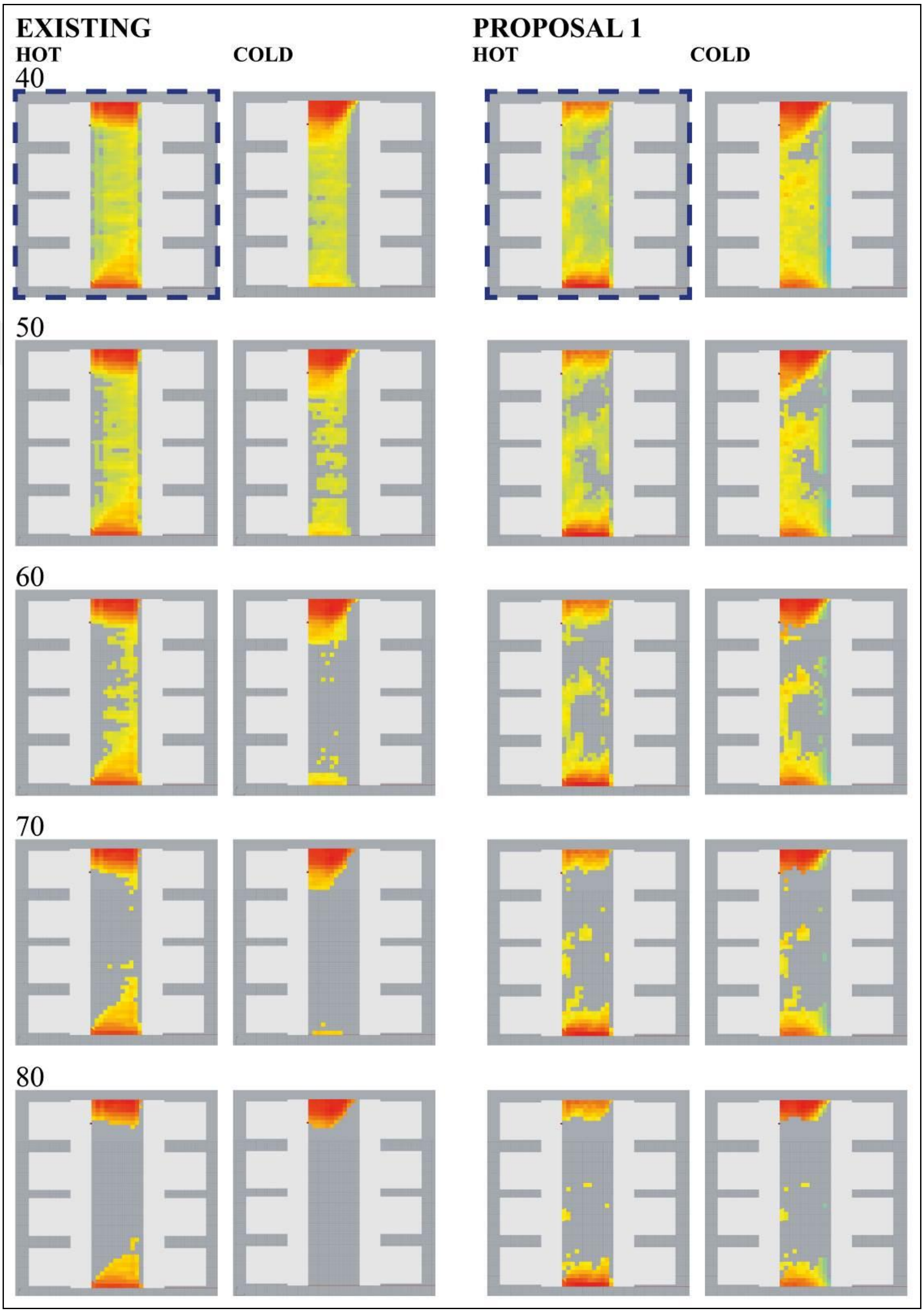


Figure 4.45: Graphical comparison for duration and distbution of the radiation hours by eliminating the samples (spots) that receive less than (40-50-60-70-80) hours of radiation during detrmined simulation period (between existing membrane shading and the option one from simulation one)

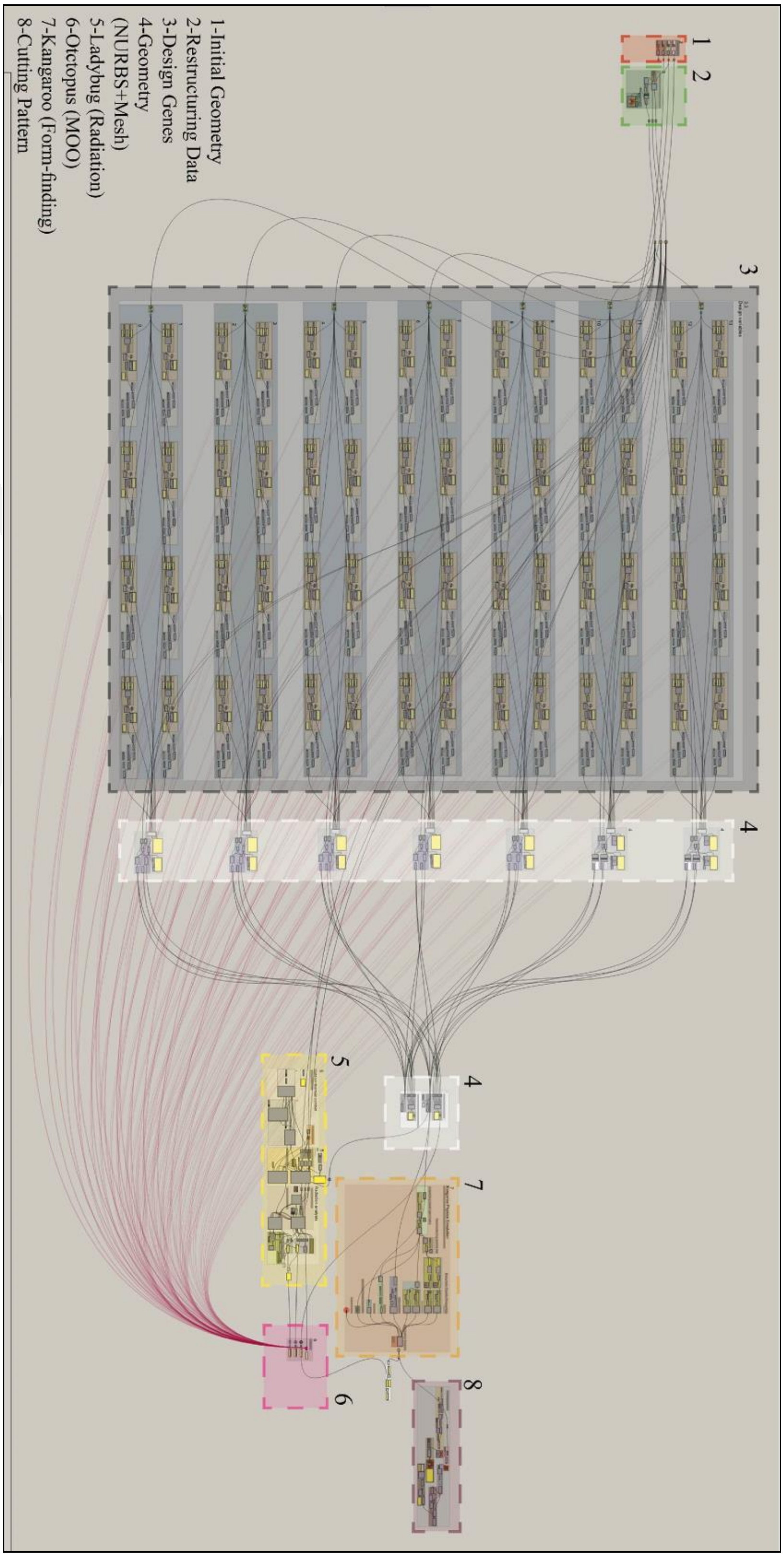


Outcomes

From the examined options (Figure (4.38 to 4.45), it is apparent that the workflow can successfully reduce the total membrane area; also it can reduce radiation during the hottest period of the day; and increase it during the coldest periods. According to option one, despite the reduction of the membrane area by $180m^2$, the total radiation during the hottest period is the same and for the coldest period, it is increased. According to option four, the membrane area is divided almost by half; the defect is approximately 25% of the radiation during the hottest period.

Structural form-finding or converting mesh to membrane reduces the membrane's surface area. This reduction adversely affects the total number of sunlight hours. Therefore, during the option selection among semi-optimal design options on the Pareto chart, the total sunlight hours had to be prioritized rather than the area of the membrane surface. During the modeling process, the relationship between the mesh geometry and the membrane geometry was found to depend on the membrane's rest length parameter for material or rest length (stress level) of the edge cable. By stressing the edge cable, reduction in shading performance can be controled. Another option for dealing with the problem is to convert the geometry of the mesh to a membrane-like shape (with inward curves between anchors) or conduct form-finding before optimization. Running Kangaroo (structural optimization) before Octopus optimization will result in a more reliable outcome. If it is not possible, the computer may crash. Ladybug interactively performs environmental analysis; however, too much change in the formal configuration will cause the computer to crash. The form shall be frozen before conducting Ladybug analysis. Kangaroo enables interactive form-finding during the process as the form changes continuously, so the timer shall be stopped before analysis. An Octopus optimization search for multiple options systematically creates and analyses multiple alternatives. These three actions (Kangaroo, Ladybug, and Octopus) together require massive computational power. The solution can be writing script to automatically stop Kangaroo simulation after each alternative generated, and then feed the results of the Ladybug analysis to Octopus. The resultant form is moving toward rectangular roof more than free form membrane with decent curved level. Conceptually optimal forms are configured but still they are mostly effected by the edge curvatures. Another solution could be establishing membrane like stable forms for optimization and the process could be repeated again.

Figure 4.46: Simulation 1 visual script (the whole Grasshopper visual script)



Second simulation

In the first simulation attempt, the design alternatives from Pareto were subjected to great deficiencies in performance when converted to membrane. To get an accurate prediction of membranes performance on Pareto graph and preserve the curvature quality of membrane while seeking for optimization in performance, the following script is introduced to the workflow (Figure 4.49). The extra code creates a membrane like form, which is not result from kangaroo’s from form finding process but it is approximation of the membrane form. The script is resulting in a NURBS surface, which is smoothly curved in comparison to mesh and it has a static state. In second attempt, the NURBS is used as an input for optimization and mesh geometry as input for form finding process. Both (input of optimization and input of form finding) share the same 56 anchor points.

Creating NURBS membrane surface for optimization

First, a surface is created between each four-anchor points as shown in Figure 4.47. The lines connecting anchors are fed to <Surface from edge> component (Figure 4.49). Those surfaces are created to find centre point of each four anchors. The output from <Surface from edge> is fed to <Area> component. Area finds the centre point of input surface. Then, midpoints of each segments are found by using <Evaluate curve> component. The parameter input of <Evaluate curve> component is 0.5 and it’s curve input is re-parameterized. Then a new line is formed between mid point D and Centre C using <2point line> component as shown in the Figure 4.49. After that a point is calculated on each C, D line by using <evaluate curve> component (Figure 4.48). The input of parameter is a slider that is bound between 0-1. The curve input is re-parameterized to cope with curve input of the component. The slider determines the location of E point and controls the curvature of each edge cable representation within NURBS surface. The main goal of previous steps were to replace AB line with an interpolate curve that is formed between A, E and B points. Then using the surface from edge component a new surface with curved border is created. Finally, the NURBS surfaces are combined (collected) using <Surface> container component and fed to context input of radiation analysis for optimization purpose.

Figure 4.47: NURBS geometry

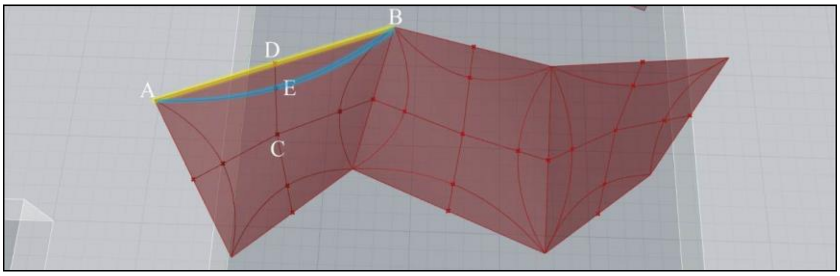


Figure 4.48: preparing NURBS for radiation optimisation

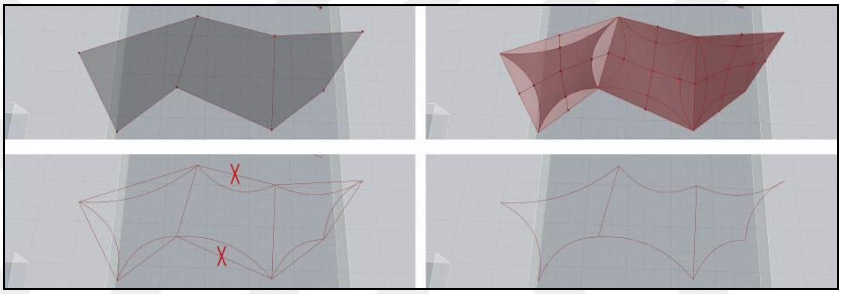


Figure 4.49: NURBS geometry GH script

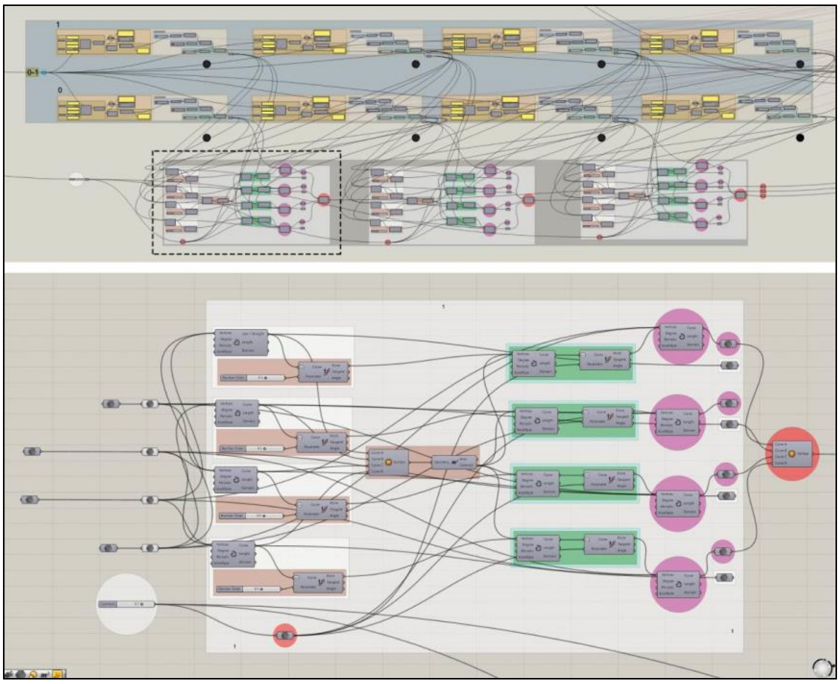
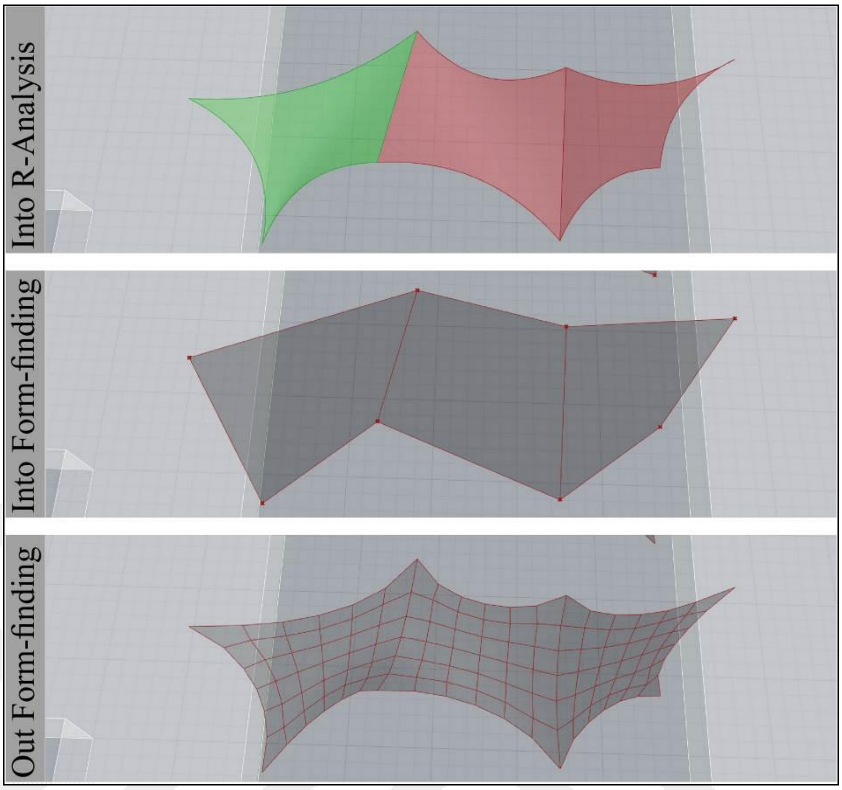


Figure 4.50: Geometry (curvature) used for optimisation and the final membrane output



In the second attempt, the computer to made more computation until it reached 248th generation. During the optimization, the calculation was pused and some individuals from blue area of Pareto graph were marked to preferred objects (Figure 4.51). The algorithm started to concentrate on the genes of preferred object and improved the performance of those selected objects to reach Pareto optimum solution. They were located in area that had low radiation during hot period as first priority and high radiation during cold as second priority and small as third priority.

Figure 4.51: Pareto graph second attempt

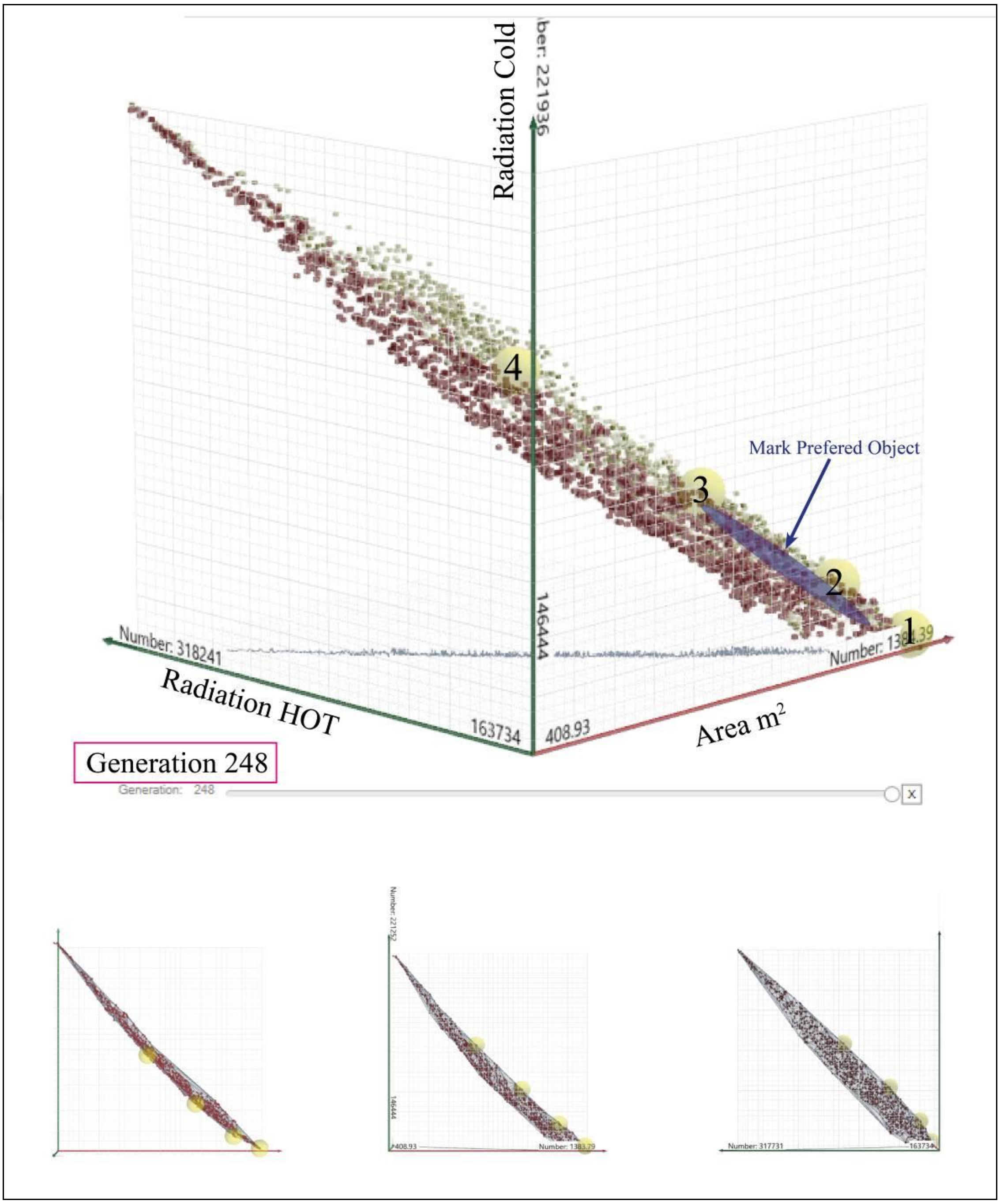


Figure 4.52: Option one from simulation two, comparing functional efficiency of NURBS, mesh and membrane geometries

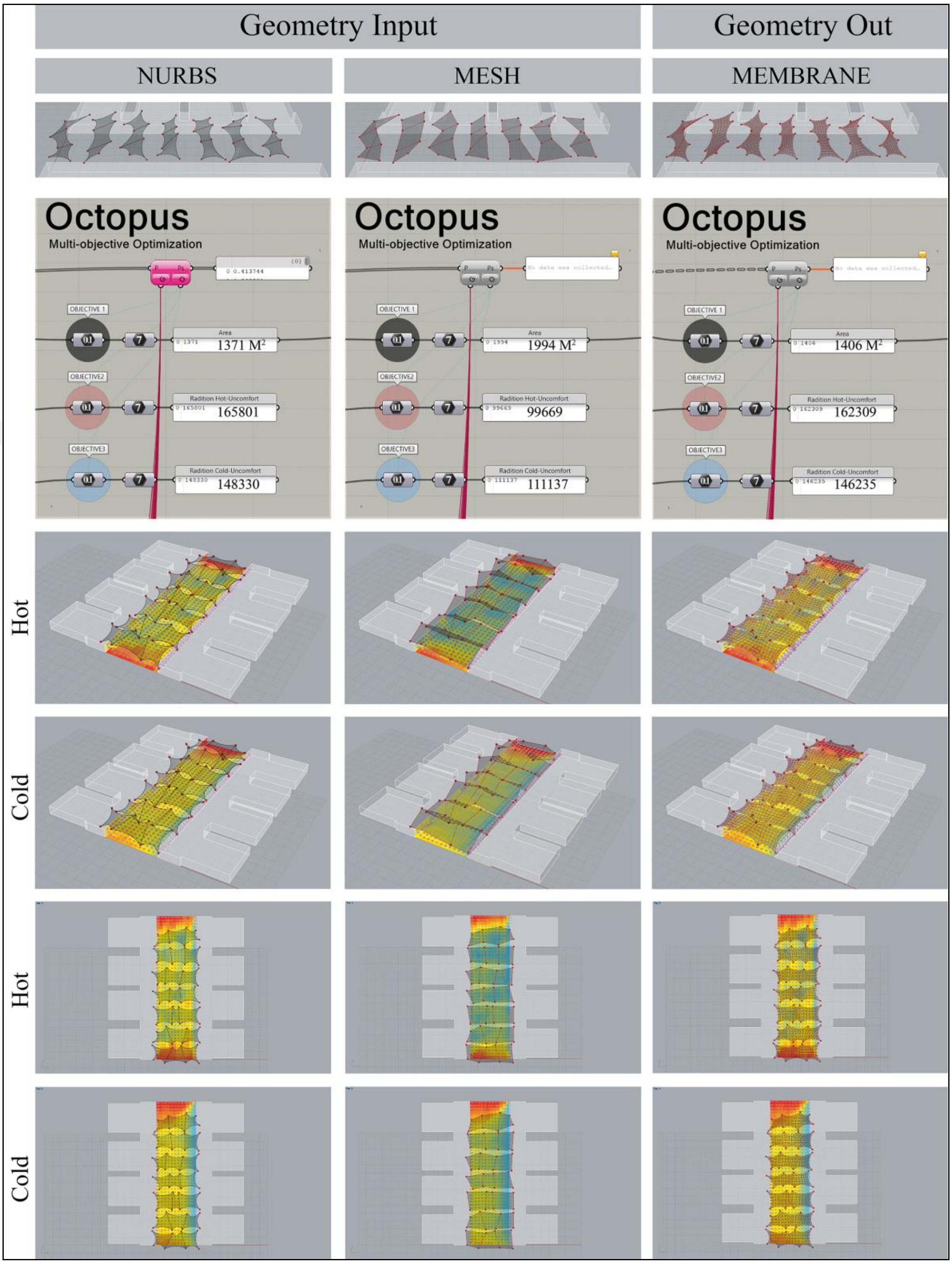


Figure 4.53: Option two from simulation two, comparing functional efficiency of NURBS, mesh and membrane geometries

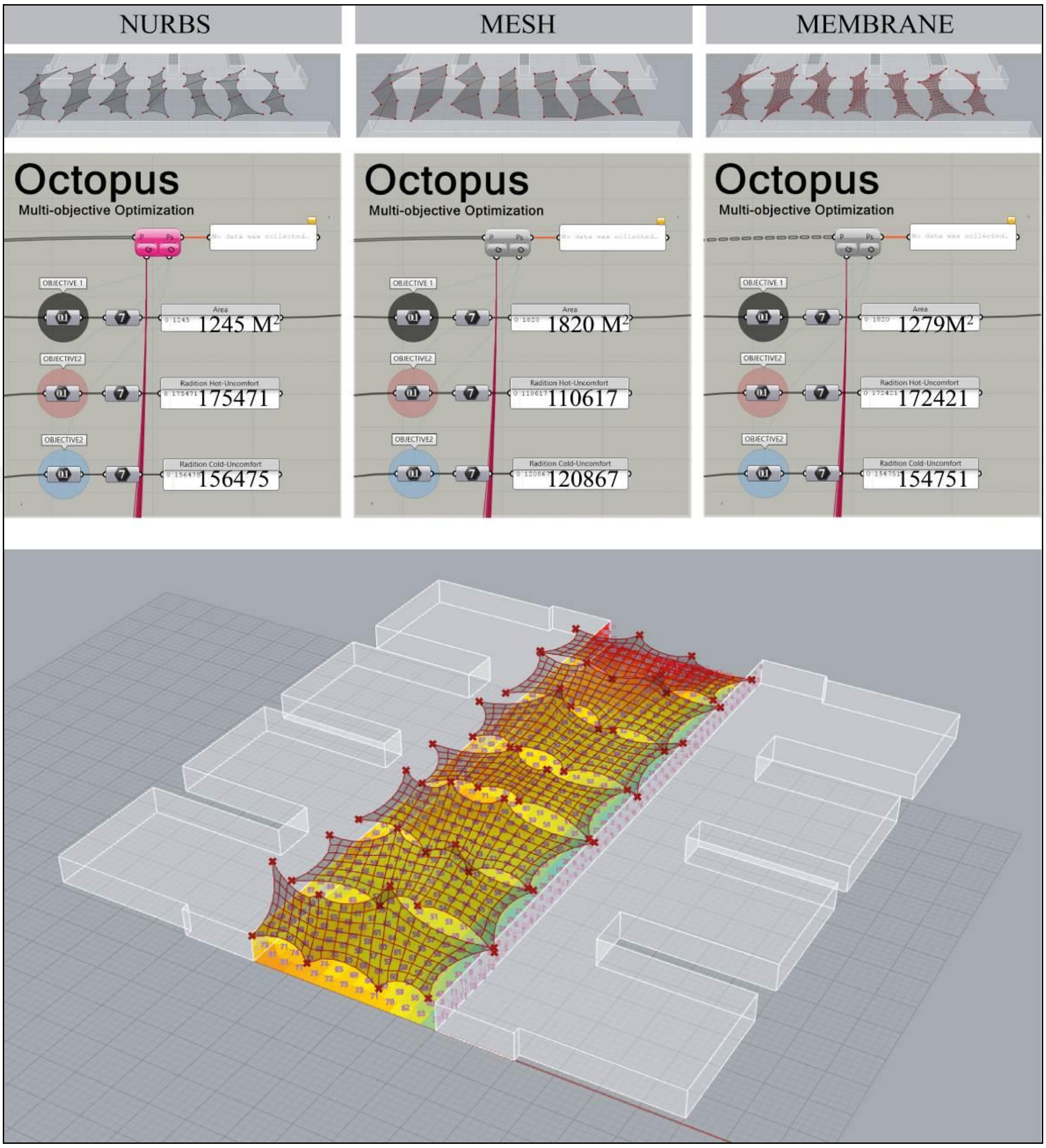


Figure 4.54: Option tree from simulation two, comparing functional efficiency of NURBS, mesh and membrane geometries

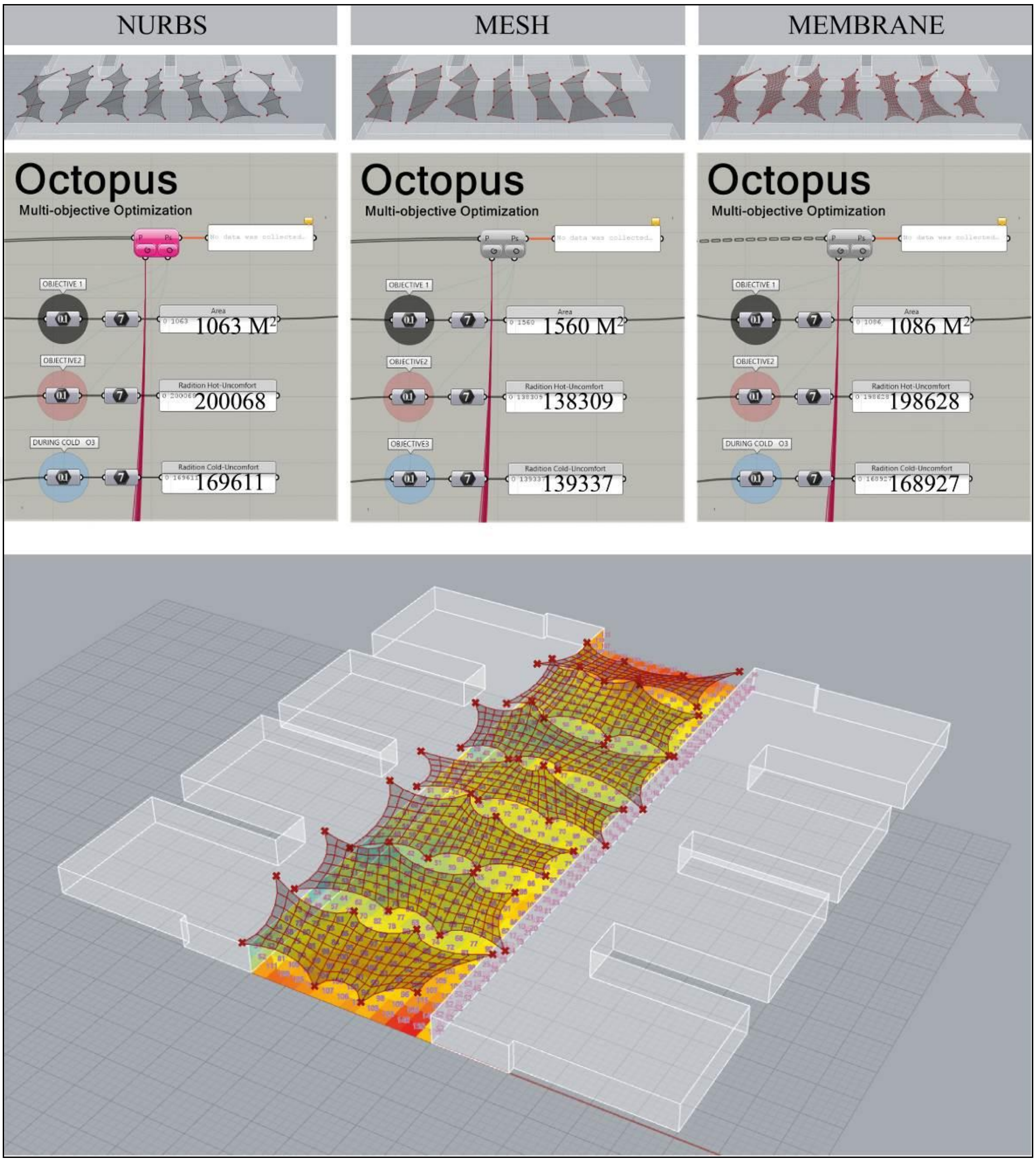
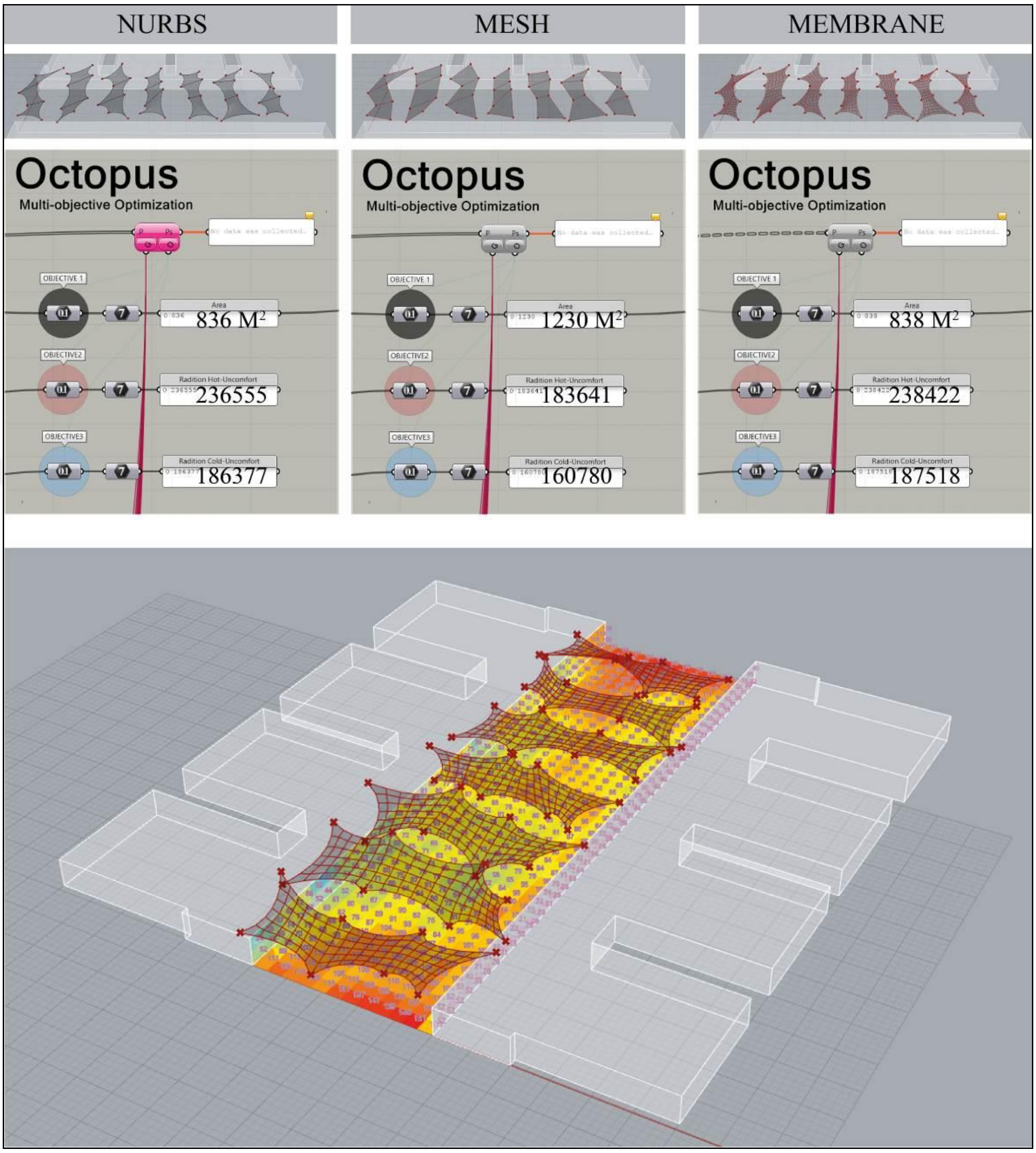


Figure 4.55: Option four from simulation two, Comparing functional efficiency of NURBS, mesh and membrane geometries



A good approximation of the membranes performance could be obtained even before form finding but still there were some minor defects on performance level when the mesh to was converted to membrane. There still was an option for manipulation of edge cable to increase/decrease the performance and curvature levels.

Table 4.1: Area and functional efficiency of all options created by simulation one and two

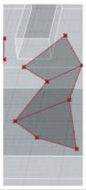
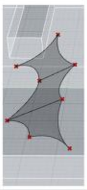
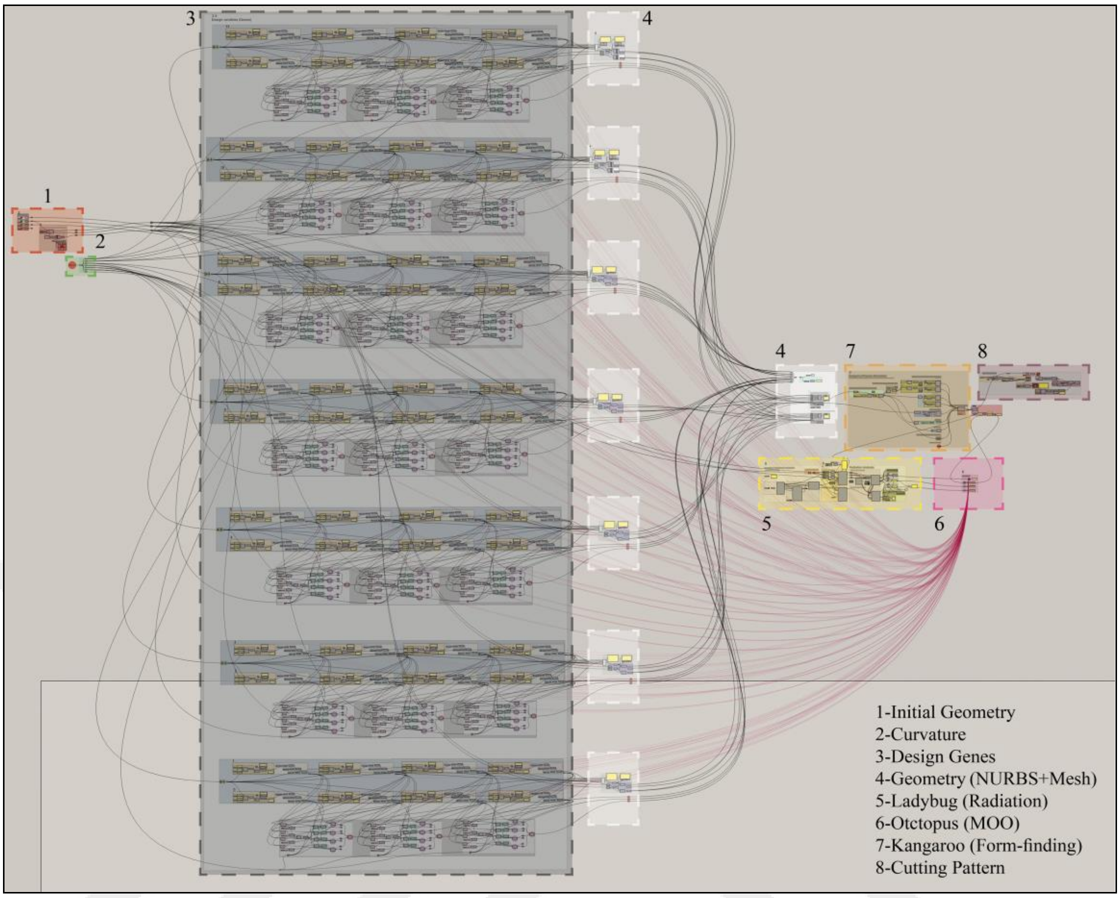
	Options	**Area**	**Radiation During hot Uncomfort period** (Minimise)	**Radiation During cold Uncomfort period** (Maximize)
Simulation 1 by controlling edge cable curvature Mesh surface 	Option 1	1228 M^2	181521	154501
	Option 2	1202 M^2	188063	159855
	Option 3	1247 M^2	179738	157663
	Option 4	823 M^2	242819	187647
Simulation 2 by using Inward curved NURBS Surface 	Option 1	1406 M^2	162309	146235
	Option 2	1279M^2	172421	154751
	Option 3	1086 M^2	198628	168927
	Option 4	838 M^2	238422	187518
	Existing	1408 M^2	181190	143994

Figure 4.56: Simulation two visual script (the whole Grasshopper visual script)



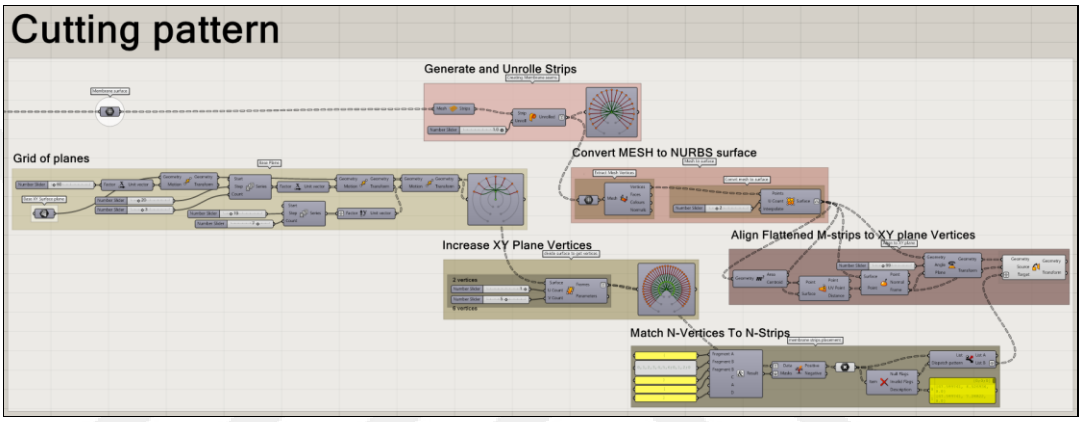
Outcome

The script efficiently predicts and enhances the optimized membrane tensile membrane structure. With increase in the number of options, a workstation computer had to be employed. While opening the GH file, it took 5 minutes for the file to be loaded completely.

4.3 FABRICATION (GENERATING CUTTING PATTERN)

The fabrication script (Figure 4.57) cuts membrane geometry to strips, following mesh topology of geometry. Then it unfolds the strips and places them on the ground plane, which is created as a placement for the strips. Finally to get read of jugged (segmented) seams, the mesh is replaced by a NURBS which has continuous smooth curve edges. The new cutting NURBS strips use the same vertexes of the mesh geometry.

Figure 4.57: Cutting pattern visual script



For creating cutting seams, the <stripper> component from Kangaroo plugin is capable of creating cutting patterns (Figure 4.58). Number of strips dependS on the mesh topography hence the <Quadmesh> component, which was used before in form finding, is controlling the division of strips (Figure 4.32). The <Unroller> component takes the strips and flattens them. The flatten faces should be reoriented and placed on the WCS's XY plane for fabrication purpose.

Figure 4.58: Striping and Unrolling

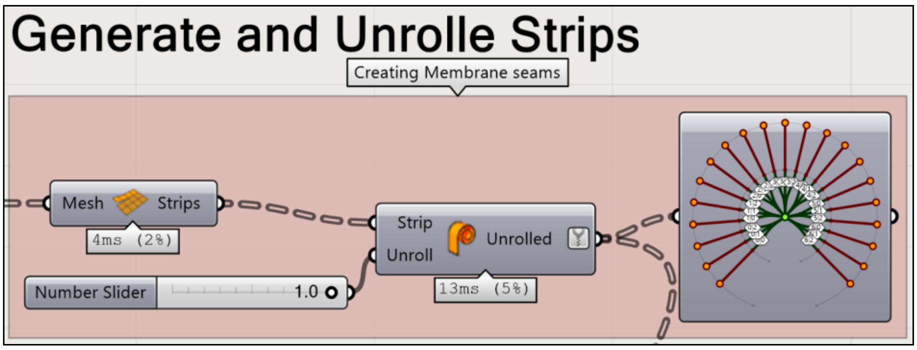
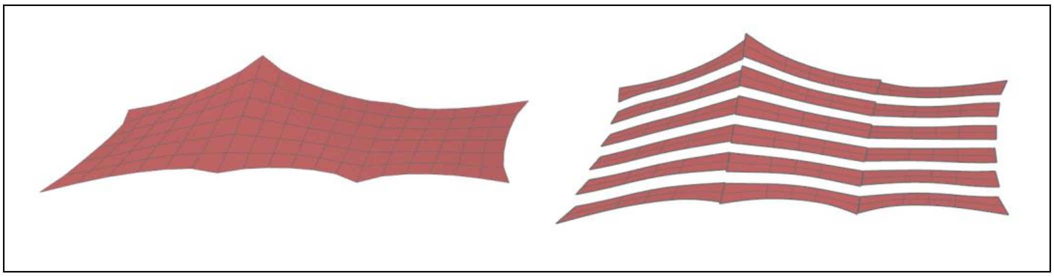
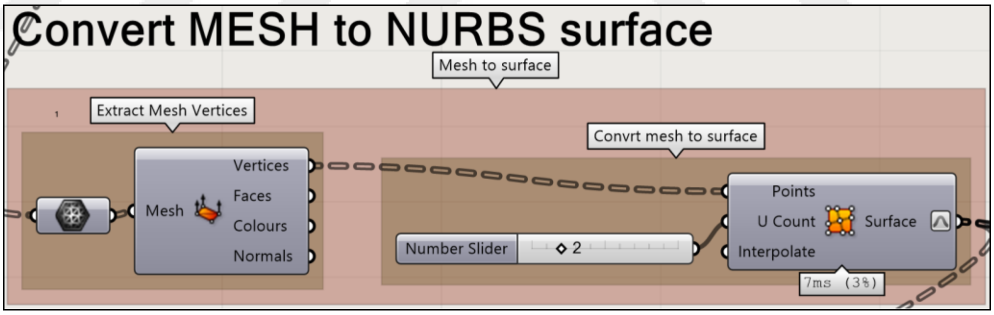


Figure 4.59: Illustration of cutting strips



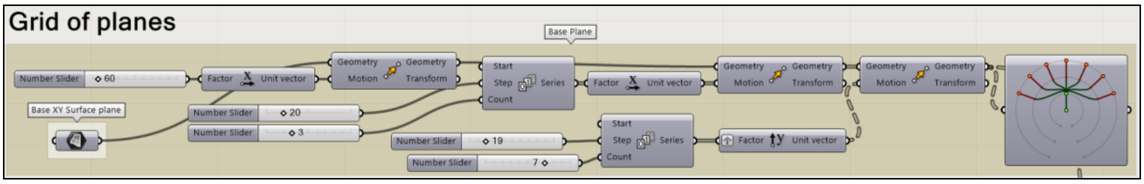
Cutting lines shall be smooth, however Kangaroo produces pixelated (jagged) mesh geometries and cutting lines from mesh geometries. Meshes create rough approximation of smooth edges (TJMcCue, 2018). Even by increasing the subdivisions, it is impossible to achieve perfect smoothness required for membrane fabrication. In order to avoid pixelated edges or mismatch in jointing strips, a NURBS surface is generated from the vertices of flattened mesh geometry (figure 4.60). The vertices from <deconstruct mesh> component is fed to the <surface from point> component's point input. The U Count is two, since each meshed strips has two columns of points.

Figure 4.60: NURBS Cutting pattern



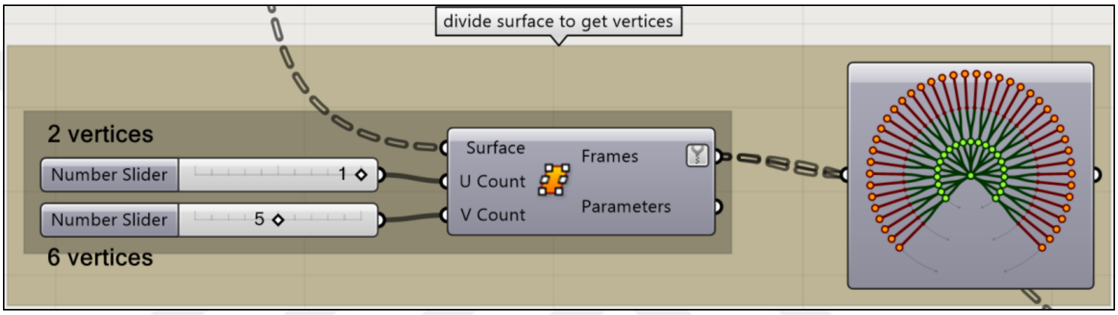
In order to align the unrolled surfaces to an orthogonal view, a set of points on that view is required as the placement for the strips. A surface is created inside Rhino3D, and then using <Surface> container component, it was imported into Grasshopper. The surface is multiplied by using <move> in X and Y directions. By streaming the <series> component into move factor a grid of surface is created (Figure 4.61). The number of surfaces in the grid corresponds to the number of membrane pieces between four anchor points.

Figure 4.61: Plane Grids



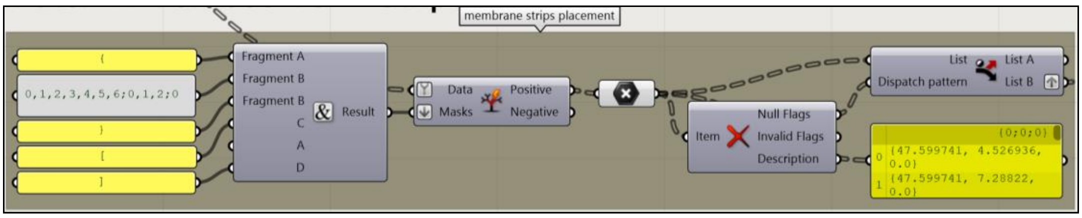
Each plane should be divided to increase the points that hold the strips of each membrane piece. The <Surface frame> component divides a surface and generates a XYZ USC that can used as a reference in placement process (figure 4.62).

Figure 4.62: Increasing base plane vertices



Each membrane is divided into seven strips, however the points of the surface corresponding to number of steps have to be limited (Figure 4.63). By using <tree branch> component,t the extra points can be eliminated, otherwise the component will repeat the last strip again and again.

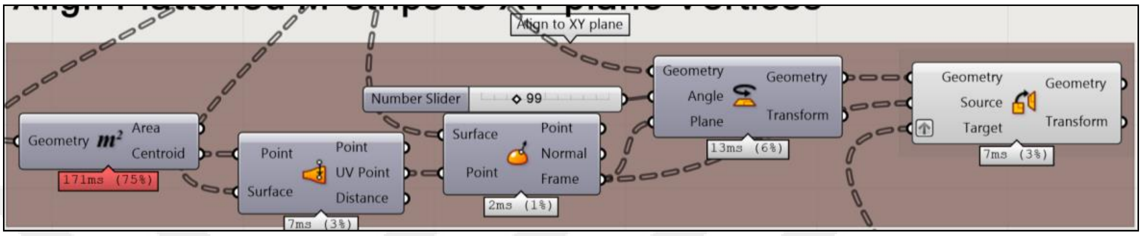
Figure 4.63: Matching number of vertices to number of strips



The final step will be alignment of strips to base planes. In the process, the normal of each unrolled surface is aligned to XYZ of each USC from base plane's vertices. Finding normal requires the <area> component for finding the center of the face. The <surface closest point> component takes in the surface and a center point then creates a point exactly on the surface. The main reson for using <surface closest point> is to find

UVpoint. The <evaluate surface> component takes the strips face and UV point and generates a normal on the surface that describes the local USC on that surface. By using the <orient> and <orbit> components, we can align the normal of the faces to USC of each point (Figure 4.64). Through the process, each component deals with a list of data with different levels, hence managing data structure is an essential part of the preparing cutting pattern process.

Figure 4.64: Alignment of strips



After alignment, the strips shall be rearranged, in this case they have to be flipped, since the normal of membrane geometries from Kangaroo were downward. The components of Kangaroo does not display a clear logic for arranging data. Occasionally, somefaces out of the Kangaroo components are flipped. The significance of the scripts is that the output is interactive, Replacing the selected option (from Pareto graph) intrigue instant response, and updates the cutting pattern. ,

Figure 4.65: Cutting pattern out of Grasshopper Script for option one from simulation one

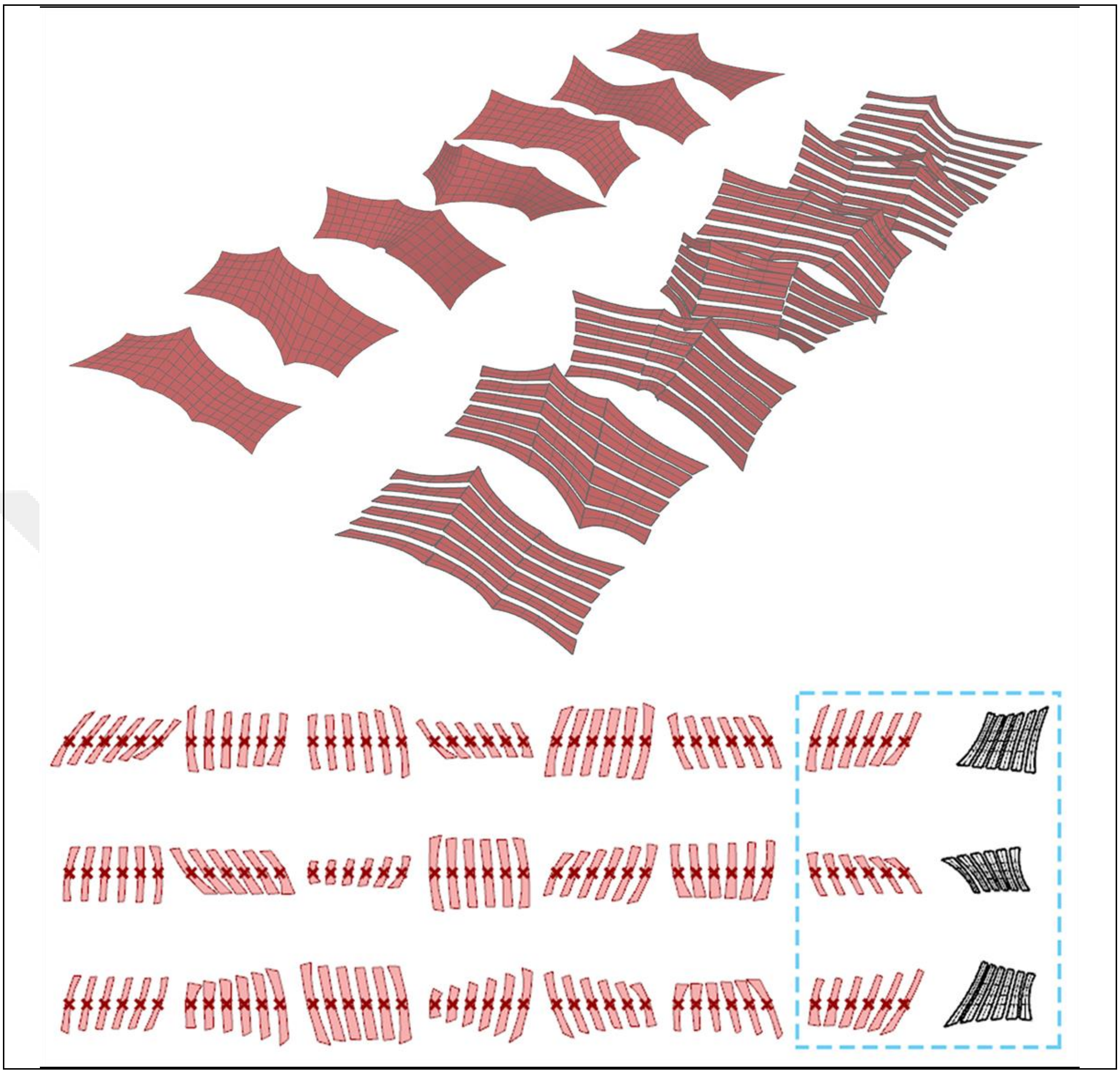
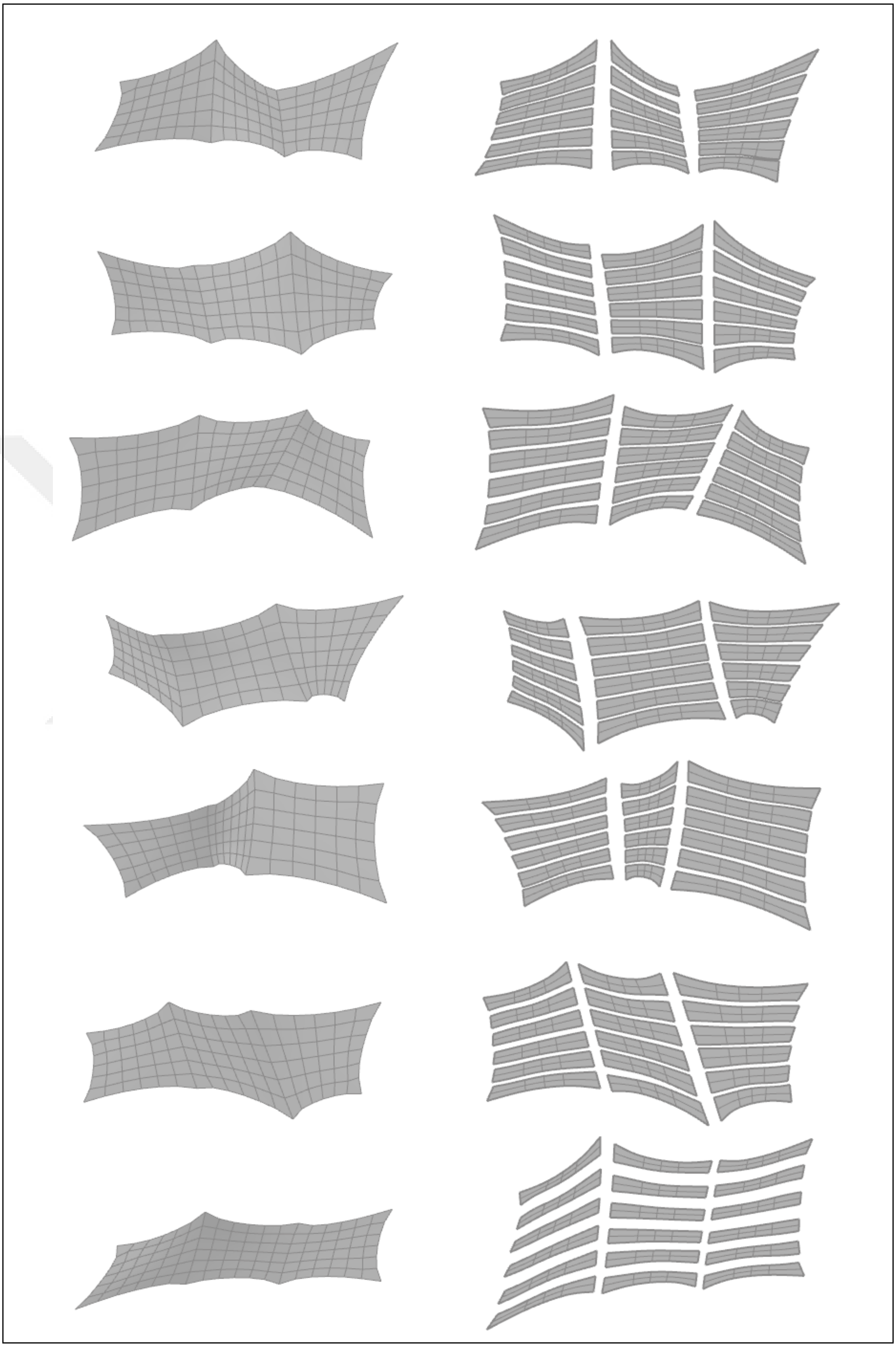


Figure 4.66: Cutting pattern for option one from simulation one



5. CONCLUSION

The main aim of the study was to propose an optimal parametric workflow for design and fabrication of tensile membrane shading structures. The proposed workflow was based on parametric modeling tools and parametric design concept. Another aim was to inspect the parameters included in the tensile-membrane design process, and then to test the functional fitness of tensile-membrane shadings employed in Erbil's climate. The process of proposing and testing a workflow required an understanding of the architecture of the tents, structural engineering, and fabrication of tensile-membrane structures. It also required comprehension of the essence of parametric design and the use of specific parametric tools in order to conduct the case study.

The literature review on the architecture of tents revealed their historical, cultural, and environmental values. It also identified the appreciation of the visual qualities and thermal comfort conditions of tents in theories and practice of architecture. Tents as an archetype and their unique features, make membrane structures widely appealing to architects. The strength, material and structural optimization in regard to material consumption are additional keys to their continuity and omnipresence in the future. According to climate and shading studies, it is apparent that the demand for shelter is urgent, and membrane construction is one of the most valuable tool at our disposable for addressing the problems related to global warming. The examination of the black tent revealed its inherent, environmentally responsive quality as a material, structural form, and orientational configuration. The pre-existence of black tents in the region conceptually justifies their use, and the study can be seen as a revival of an architectural element native to the Middle East. From the literature review, a set of parameters of design were selected.

The tensile membrane, is a uniquetype of structure with a highly distinctive design and production process. Its inevitable requirement is its structural form-finding. The first membrane form-finding was conducted by Otto in the 1950s, which has been the last major development in the membrane design process. The emergence of computer technology was the main force behind the expansion of membrane application and celebration of the membrane's formal characteristics to its full potential. Membrane design is mainly dominated by engineers as their design applications are distinct from standard CAD and CAM applications used by architects. This separation was the reason for the membrane's stagnation and alienation within the field of architecture. The thesis uses membrane tools that work within architectural applications and proposes a method that facilitates the membrane design by architects. The proposed workflow has proven to be functional and operates in accordance with the design purpose.

Digital technologies are invading the design and fabrication processes in architecture. The tools' developments are continuously reshaping the workflows used and their outcomes. The emergence of new Visual programming (VP) modeling applications and increase in computational power are enabling the introduction of new parameters into the design workflow, taking into account multiple parameters of the design process, especially those that have been neglected due to massive calculations and human limitations. The VP applications are single-platforms that enable parametric modeling, algorithmic designs, and file-to-factory production in a seamless process. Their strongest advantage is their capability of integrating design, analysis, simulation, and optimization on the same platform by using common coding languages and data-management systems.

In the proposals, initially the black tent was taken as a reference for the generation of the proposal's dynamic model. Through the design process, a tensile-membrane dynamic model evolved based on the effects of the parameters included in the design process. the climate-responsive quality of the black tent was very challenging as it required special file formats and technical skills. Kangaroo could successfully conduct form-finding for almost any shape and is limited only by the modeling capability of the designer. Octopus followed an efficient algorithm for identifying semi-optimal designs out of millions of iterative options. In fact, multi-optimization dates back to as early as the 1970s; however its lack of implementation has been related mainly to the availability of the tools and integration into standard applications used by architects. The comparison of the existing membrane roof to the semi-optimal options based on the Pareto chart demonstrated the practicality and success of the workflow in spite of several deficiencies related to computational limitations. The multi-optimization algorithm enabled the form to be optimized both functionally and formally. One of the advantages was that the nodes from the design script were reusable for other projects. Therefore, the study combined multi-optimization with tent structures. The final outcome is the design of optimized shading structures by implementing parametric tools and methods. The parametrical membrane revelaed superior advantages over membranes designed using conventional methods because it considered environmental factors and allowed tem to become a set of defined design objectives. The workflow contained several deficiencies regarding the sequence of applied tools, but those could be resolved by writing custom scripts.

In terms of the design effectiveness enhancing comfort levels, an optimization algorithm was devised to find the formal configuration that enhancds the comfort state of the user by blocking or allowing extra radiation depending on thermal stress. The optimization process was conducted as follows: The genetic algorithm started by exploring the design space with a pool of 200 random design solutions. It then narrowed the search in accordance with the fittest of the solutions from the previous generations. The primary advantage of the algorithm was its efficiency in searching for the semi-optimal solution out of a large search area. The Pareto graph compared how the solutions would perform on a single graph. The X, Y, and Z axes were replaced by the objectives and solutions were projected onto a 3D space in accordance with their performance in regard to the objectives. The comparison of analysis results between the proposal and the existing roof, as shown in Figure 6.42, displayed the improvement in the membrane's performance. Figure 6.43 shows a graphical comparison of the effectiveness of the new roof both in cold and hot periods despite material saving by $180m^2$

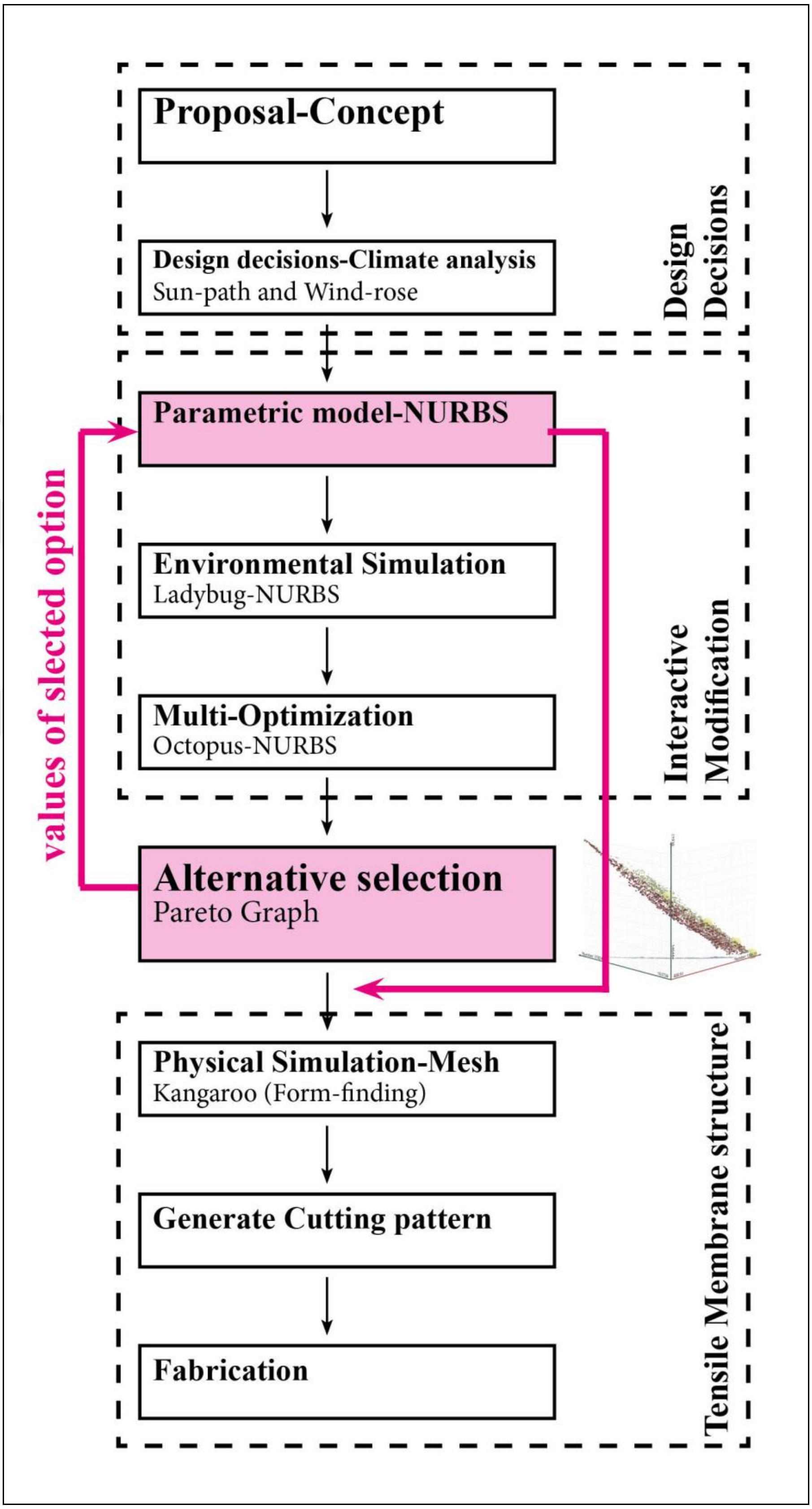
Due to the problems that were faced, the order of implementing the tools were changed. Ladybug required high computational power to analyse oscillating forms. The forms needed to be stabilised in order to record a single performance measure for any set of parametric value. Kangaroo did not hold automatic stop for the simulation, also the stop behaviour had to be controlled by optimisation engine. Before stopping simulation, the form took some time to reach the equilibrium state. Time intervals significantly increased the overall calculation time. As a solution, a mesh geometry had to be used for structural optimisation and a NURBS geometry for functional optimisation. In this case, the goal was to match the kangaroo output to the NURBS geometry used for calculation. Using such approach could get almost more than ninety percent match between the two geometries. This method offered additional control over the formed membrane with real-time performance feedback.

Geometries out of Kangaroo components had problems in regard to their internal data structure. The problem encountered during experimentation were the change in the order of points and the flip of the normal of faces without obvious reasons. Just by pressing Boolean for repeating calculations, with no change in settings such normalities took place. Mesh geometries could not be used for membrane fabrication since mesh resulted in mismatch in details (joints) and it was not smooth (it was jugged). Hence the proposed tool had to automatically generate NURBS instead of mesh geometries. Kangaroo components should be checked or components should explained in details. The tools used in workflow were new, hence tutorials and guides about them were limited.

Another problem encountered was, the increase of the file size, and failing initiation of Ladybug most often. The tool had to be initiated in new empty GH file. Longer significantly increased the size of file and required more storage (RAM) capacity. During the experimentation with tools, the impression arose that they were still under development thus still held great potential for the future use.

In the term of the impact of the study on tent design applications in Erbil, currently, there are no membrane design and production firms in Erbil. The modern membrane structures are quite new; only a few structures have been designed and fabricated in Turkey and installed by local installation firms. The study could be a valuable source for reviving membrane architecture in the region. Moreover, it could be a useful guide for coping with the exponentially growing environmental problems faced by the city now and in future. It represents a parametric tool and workflow to be used by designers of membrane structures. (Figure 5.1).

Figure 5.1: Suggested Parametric workflow for desiging and fabrication membrane structures (the outvome of the study)



6. FURTHER SUGGESTIONS

-Membrane structures need to be reintroduced to the public, to architects, and to architecture students as a method of building and an effective environmental solution.

-Optimization processes for architectural design may also be expanded to include visual comfort as it has strong connections to user's comfort conditions.

-Currently, there are several outstanding proposals that could become game-changers in membrane implementation, such as photosynthetic membranes, translucent insulated membranes, and green-roof textiles. The success of proposals could inevitably attract many architects and urban designers to embrace the structure and would increase its popularity within the field of architecture. Therefore, studies should be conducted to investigate alternative material proposals.

-Existing tent applications could be made more sensitive to climate conditions, but VP has the potential to completely replace the existing membrane applications. The membrane design using the Rhino/Grasshopper combination is a relatively new approach; it requires testing during production of actual-scale structures (real-world projects).

-Feasibility of the tools should be tested for fabrication of true scale structures.

-Kangaroo's stripper component converts mesh edges to seam lines, hence Kangaroo requires powerful components for controlling the mesh topology. After enriching Kangaroo tools with modeling components, it can be employed by architects and membrane-production firms.

-Kangaroo can perform form-finding successfully, but for analysis, it requires predefined properties of common membrane materials. It also lacks an algorithm that can estimate specific pre-stress.

-In future studies, CFD (computer fluid dynamics) could be part of the design to simulate the impacts of wind or rain.

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APPENDICES

Appendix A.1 Membrane Materials

Membrane is one of the most intriguing architectural materials; its popularity comes after stone, metal, glass and timber (Heybroek, 2014, p. 9-10). Membrane is a flexible thin material with high tensile strength, if compared to commonly used materials; it is lightweight and capable of covering huge areas with the smallest possible mass. The tensile strength is a very important characteristic of an architectural membrane because it determines the loads that the tensile structure can resist. The tensile resistance is directly linked to the strength of the base structure or fibres. Membranes are comprised of a network of natural or synthetic fibres and sometimes a coating layer. The exterior coating does not promote the overall tensile strength of the membrane material. However, the visual characteristics are greatly affected by the coating layer. Membranes' mechanical behaviour with physical properties determine the character of the entire structure.

Buildings that utilise membrane material are usually utilising the membrane's properties to their fullest extent. Membrane material can be practically employed for different projects hence it enables the realization of imaginative forms. It also has a promising quality to fulfil the architect's ambition to innovatively engage in approaching environmental problems in a sustainable way. In the near future, efficiency in resource exhaustion will be driving architectural design. In this respect, membrane materials has low resource consumption. Furthermore, it can be fabricated from different natural or artificial materials.

1. Membrane material specification

Membrane materials are optimal because of their many specifications. They have excellent tensile strength and are typically lightweight and deployable. The light weight nature of membrane materials affords them a great amount of speed and flexibility during erection and removal. Their foldable property has boosted their usage in the retractable architecture field. They possess incredible durability with a lifespan of 10 to 25 years depending on material type. Membrane has the ability to create any free form shape and come in different colours and textures. Furthermore, they can easily be fritted or printed upon. Membrane materials' fire retardancy and earthquake resistance make the structure its constructed from very safe. New developments have allowed the creation of flexible photovoltaic panels that can be integrated with a tensile structure. Also, membrane materials contain a self-cleaning technology. More recently, in the study published by Heinzelmann, Bristogianni, and Teuffel (in Fabric structure in architecture 2015, p. 159-182) several new membrane material applications are proposed. Firstly, the innovative integration of green roof into membrane structure. Secondarily, adding aerogel granules to translucent membranes can lead to highly translucent and insulated lightweight structures. Third photosynthesis membranes can produce energy and low energy illumination if algae cultures are integrated along the membrane's surface.

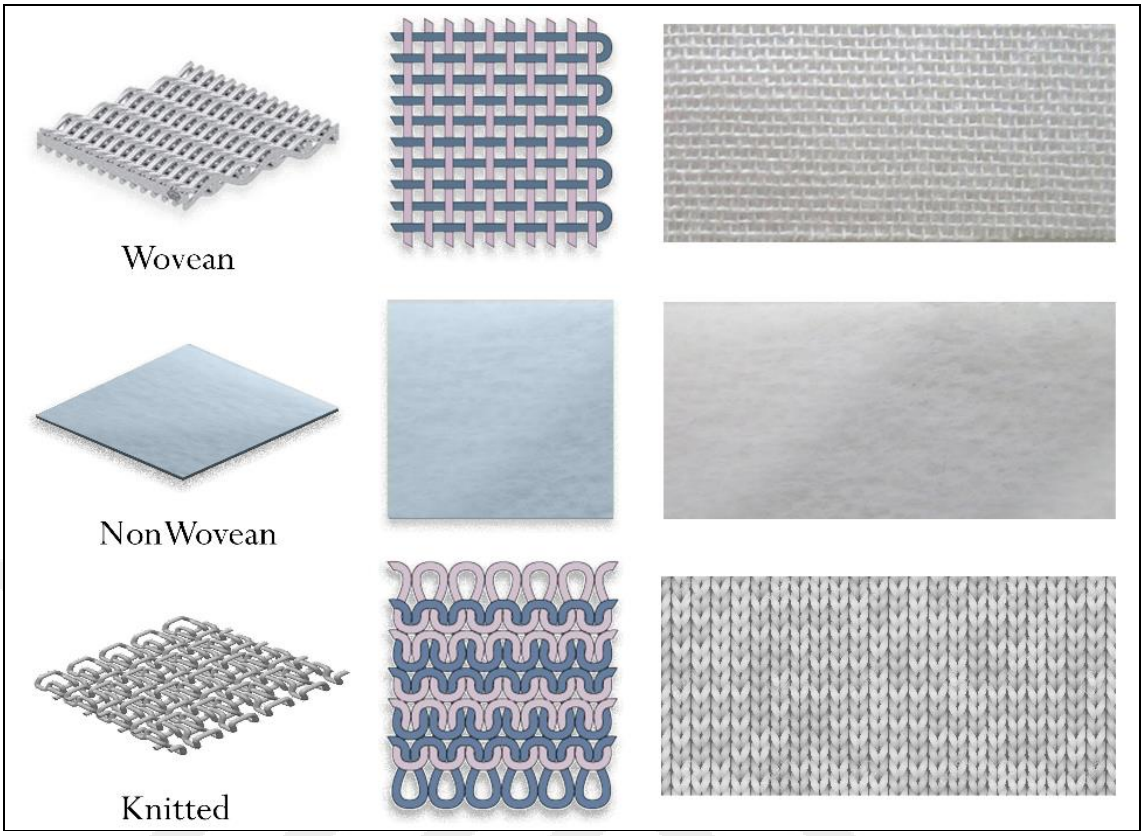
Membrane materials can be classified into three categories according to their production types: Non-woven, woven and knitted (Beccarelli, 2015, p. 10) (Figure A1.1).

Non-woven: The material has a flat structure, and it has been produced chemically or thermally. It does not require converting material to threads, nor does it require weaving or knitting to form a binding structure. Non-woven is regarded as a cheap substitute for traditional textile techniques; nylon is well known as a non-woven material.

Woven: It is formed from interlacing yarns in two main orthogonal directions: warp and weft. The interlacing provides strength, and a coating is added to enhance the quality of the membrane. The woven materials have different strengths in different directions. The warp fibres (those fibres that are originally straight—equivalent to the starting fibres on a loom) can carry a greater load than the weft or fill fibres, which are woven between the warp fibres.

Knitted: This is a special technique of making textiles, following a series of consecutive intermeshing of loops, mainly used in many types of clothing.

Figure A1.1: Woven, Non-woven and Knitted textile material



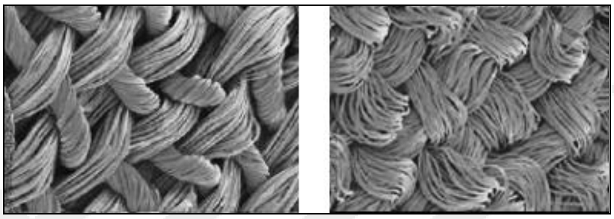
Source: http://www.bbc.co.uk/schools/gcsebitesize/design/textiles/fabricsrev1.shtml [Accessed 15 Jul. 2018]. http://jualgeotextileid.blogspot.com/2017/04/geotextile-woven-vs-non-woven-jual.html[Accessed 15 Dec. 2018].

Membrane materials are formed from natural or artificial fibres (Beccarelli, 2015, p. 10) (Figure A1.2).

Natural Threads: The traditional tents are made of textile weaves, which are mostly built from natural threads (goat's hair or cotton). Natural fibres have a restricted length, a poor tensile strength, a relatively high elasticity and small cross-sections, from 5 to 24 µm (Houtman, 2015, p. 102). Natural threads can absorb water hence they can become very heavy when wet. However, swelling tends to block any minute holes therefore wet cotton has a better waterproof quality than dry cotton (Faegre, 1979). The miniature holes allow natural ventilation in hot climates. Cotton textile is often treated with natural oil to enhance its water resistance. In contrast, goat's hair is naturally oily, and so it has a natural resistance to water.

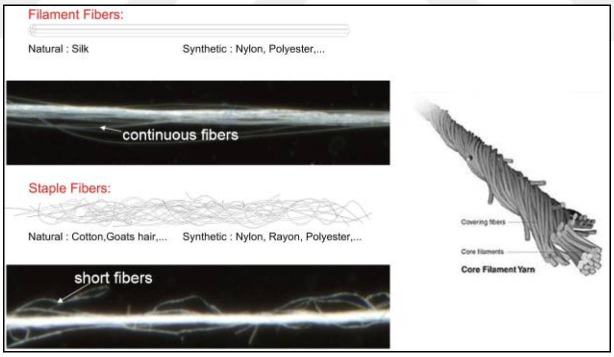
Synthetic Threads: Today, the emphasis is predominantly on new materials that exhibit enhanced properties. Synthetic membranes were indeed developed to surpass the properties of natural fibres. The Textile Institute of Manchester defines synthetic membranes as “a textile membrane that is manufactured mainly for their technical and performance superiority instead of their aesthetic or decorative characteristics” (Byrne, 2000, p. 1–23). They can be fabricated with almost infinite length. Their artificial fibres are called filaments whose cross-sections are greater than 100 µm (up to 500 µm) (Houtman, 2015, p. 102). Synthetic membranes are far lighter than cotton or goat’s hair and absorb smaller amounts of water hence, with suitable coatings, they can be waterproof (Figure A1.3).

Figure A1.2: Enlarged view of artificial and organic fibres used in weaving



Source: http://www.yarnsandfibers.com/news/news-tags/psf [Accessed 20 Oct. 2018].

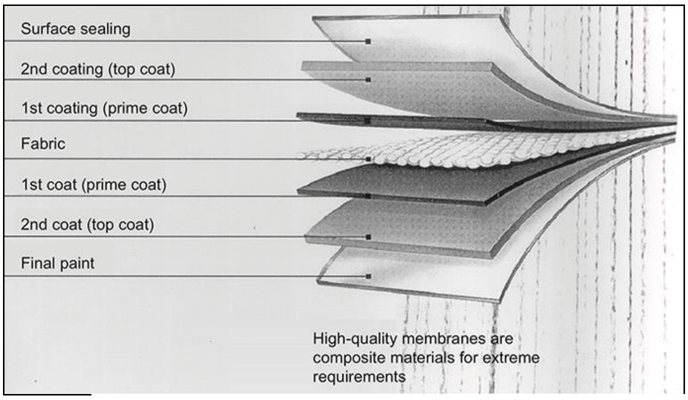
Figure A1.3: Types of threads used in artificial and organic textiles



*Source:*http://www.keywordbasket.com/Y29yZSBzcHVuIHlhcm4/ [Accessed 20 Oct. 2018].

A membrane material has a coating layer that ensures it to become waterproof and moisture-proof; protects against damages associated with UV and atmospheric exposure; stabilises the base weave; allows easier bonding between two edges at seams; and smooths the transmission of stress between bonded strips. The most common treatments to make fabric waterproof are silicone impregnation or polyurethane coating (Houtman, 2015, p. 108-109) (Figure A1.4).

Figure A1.4: Membrane coating layer

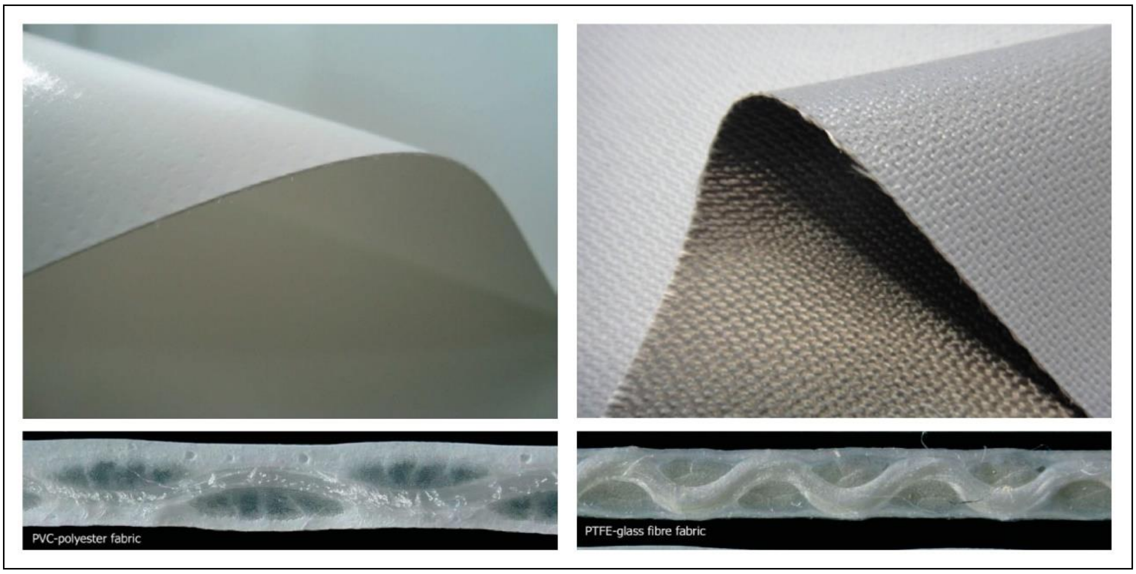


Source: European Design Guide for Tensile Surface Structures, The TensiNet Partners [Accessed 20 Oct. 2018].

2. Popular membrane materials

Development of hi-tech membrane materials have increased the potential of membrane structures to be applied more in architectural design solutions. The most commonly used materials for doubly curved membrane structures are PTFE-coated fibreglass and PVC-coated polyester, whose properties are shown in Figure A1.5 and Table A1.1

Figure A1.5: Visual and structural difference between PVC and PTFE coated fiberglass



Source: http://meiyongglassfibers.btrworlds.com/productimage/3732-130p1-ptfe-coated-fiberglass-fabrics-1162731.html [Accessed 25 Oct. 2018]. https://www.researchgate.net/figure/Architectural-fabric-cross-sections-showing-highly-crimped-woven-yarn-bundles-encased-in_fig2_265646877 [Accessed 25 Oct. 2018].

Table A1.1: The Comparison of PTFE-coated fibreglass and PVC-coated polyester

	PVC Coated Membrane	PTFE Coated Membrane
compose	Polyvinyl chloride coated polyester fabric.	polytetrafluoroethylene coating with fiberglass woven base
Use	Employed mainly for semi-permanent exterior structures.	The material is generally promoted for permanent outdoor structures.
Durability Life span	The material is fairly durability, and has approximate 10-15 years or longer, depending on location, and exposure to environmental their life span can change.	It is remarkably durable with an anticipated service life exceeding 25 years.
Strength	Polyester fibres has outstanding tensile and tear strength.	It has significantly higher tensile strengths, but lower tear strengths in comparison to PVC-coated polyester.
Weather resistance	PVC coating offer waterproof properties, it does not afford self-cleaning property so it retains dirt.	The coating made it totally Waterproof. The surface is highly slippery dirt cant stick to surface. It has the self-cleaning property, each time the surface exposed rainwater it will be washed from all dirts.
UV resistance+d irt	PVC can be treated to be stain and UV resistant by the application of several topcoats over PVC coating (R. Houtman, 2015, P.108-109).	It is perfectly immune to UV radiation in-turn it inherited longer life span to material.
Folding	It can be folded so it excellent for retractable structures and portable structures.	Fibreglass fabric is designed to be permanent applications and it cannot be relocated, retracted or folded (R. Houtman, 2015, P.111).
Cost	It is inexpensive if compared to PTFE coated fiberglass.	The material is relatively high cost, especially compared to Polyester-PVC.

Maintenance	It requires Frequent maintenance. Low durability as it tends to deteriorate from UV radiation. It also exhibits creep behaviour, losing significant levels of pre-stress by aging and sometimes requires re-stressing.	Due to fact, Fiberglass is more susceptible to brittle failure; PTFE-coated fiberglass must be handled with cautiously during transport and installation.
Fire	Fire resistance, the material will retreat from a flame, allowing the roof to be self-venting. The material is Class A in terms of flame spread, and does not produce flaming droplets.	It is Non-combustible cannot be burnt.
Reuse	PVC is classed as a recyclable fabric, and is therefore an increasingly popular choice for green building. The process does not affect the lifetime of the recycled PVC	The process is complicated and energy intensive.
Usage	It has reduced its use for temporary and low budget projects and for geometries with a high level of curvature.	It have been used for several high quality tensioned structures
Transparency	Generally, it allows 5-15% of light to pass-through. The rate of transmission is dependent on the colour of the fabric, printings and environment (R. Houtman, 2015, P.116).	It is Regarded as a good light transmittance allowing up-to 20% of light to pass-through (R. Houtman, 2015, P.116).
Weight g/m2	A-750, B-900, C-1100, D-1300, E-1450.	T1-800, T2-900, T3-1200, T4-1500
Strength Wrap/Weft N/50 mm	A-3000/3000, B-4200/4000, C-5800/5400, D-7500/6500, E-10000/9000.	T1-3500/3500, T2-5000/4500, T3-7000/6000, T4-8000,7000
Tensile strain Wrap/Weft %	A-15/20, B-15/20, C-15/25, D-15/30, E-20/30	--N--

Appendix A.2 Interview

In order to understand the design process that was followed, an interview, given below, was handled with the owner of the firm Ahmed Auni in 12th April 2017.

How do you design tensile membrane structures?

“We have not employed any designers until now, usually we simply take site photos and measurements then send them to the main company, which is called İmaj Branda, in Turkey. They design it and send back the rendered images. Then we get approval from the project owners before ordering the fabrication of pieces. The application used for design is Forten, which is specialized for designing membrane structures. The software contains several prescribed shapes; which are fitted by the user on the boundaries of the project. Inside the application, you select the shape and it will give you the slope range, stress and cutting pattern.”

Why do not you design them yourself?

“The applications are expensive and they cost around 7500 dollars. If your catting patterns are not precise, the structure will get ripples. Precise cutting needs accurate machines. The cutting machines are expensive hence we do not own them yet.”

What is the main consideration for tensile membrane formation during the design process? Do you respect environmental conditions such as sun angle, sunshine duration or location etc?

“Our main consideration is tensile stress. We do not calculate sun radiation at all. We also neglect wind load. We have been working in this field since 2010. The main issue of a tensile membrane is stress and reinforcing its foundation to withstand this massive stress.”

How do you decide the highest and lowest points of your geometry?

“We shape and decide the slopes according to rain and snow loads. The slope may range from five to eighty-five degree. In all cases, a membrane structure cannot stand accumulation of more than 15cm thick layer of snow. The steeper slopes automatically gets rid of snow on the other hand less inclined slopes require manual removal of snow.”

What is the relation between geometry and shadow cast on the ground?

“Actually, we do not know it accurately, but general assumption is that if we have 100m2 membrane in average it will give us around 50m2 shade on the ground.”

What are customers' perceptions toward membrane structures?

"They are mainly accepted as decorative elements. People prefer to remain interiors during hot summer days."

Can you give some details about BISK's membrane structure?

"The project owners were simply attracted by the stylistic look of the membrane structures and they were trying to brand the school as futuristic and high class. That is indeed it is the only school complex in the city, that uses membrane shading. It is our firm's biggest project until now. The structure has 1400m2 of membrane surface. The span is 24.5m. The lowest points are 80 cm and the highest points are 250 cm above the school's roof. We used PVC coated polyester fabric however; the membrane's colour changed and became dirty due to ageing. Now they have to clean it or replace it with PTFE coated fibre. PTFE it 2.5 times more expensive than existing PVC coated membrane."

In the light of the interview results, the need for reviving the traditional black tent concept for solar protection and developing a new design tool for membrane structures is explicit. The tool will be handling local environmental data for providing shadow while preserving some openness for the public space.

Figure A2.1: Case study Erbil British International school

Source: imaj membrane.com [Accessed 22 Aug. 2018].

Appendix A.3 Applıcatıons used for conducting the thesis

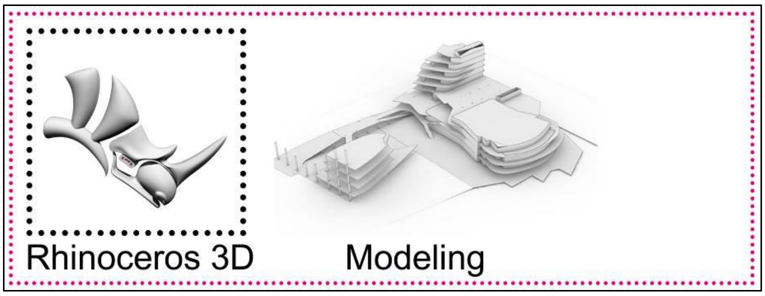
The chosen software to design tensile membranes is Rhinoceros. The reasons can be summarised as follows: Firstly, the application has endless modelling capabilities, exclusively used for complex free forms. Second, its data interoperability accepts the vast majority of file formats used in the design industry. The Rhino and Grasshopper combination enables models created in Rhino to have full interactive interoperability throughout the design process. Third, integration with third party plug-ins, such as Grasshopper, Ladybug, Octopus and Kangaroo Physics, expands its modelling ability to embrace parametric modelling. Furthermore, simulation and optimisation are allowed within the modelling platform.

3. 1. Visual programming (VP) and Rhinoceros3D

Rhinoceros, or Rhino3D, is a stand-alone commercial application developed by McNeel & Associates in 1992 (rhino3d.com [Accessed 12 Dec. 2018]). It is a highly sophisticated computer-aided design (CAD) tool capable of easily modelling complex geometries. Rhinoceros3D mainly focuses on NURBS mathematical curves and NURBS equations, which mathematically produce precise representations of curves and free-form surfaces. Hence, it offers advantages compared to polygon (triangulated faces) mesh-based modelling tools. Nevertheless, Rhino 3D still supports polygon meshes for surface representation.

The application is mostly used to model organic or free forms in architecture, product design, industrial design, marine design and automotive design. The NURBS originally developed by McNeel corporate for free form modelling, also McNeel is developer of Rhinoceroses 3D. In architectural design, Rhino 3D is commonly used for parametric design in conceptual design phases as a quick means to create and evaluate different design concepts. The mathematical base offers a high accuracy to the Rhinoceros virtual model, which makes it ideal for computer-aided manufacturing (CAM) and the rationalisation and digital fabrication processes. Hence, Rhinoceros is a key digital tool in any workflow starting from design to the manufacturing process, as it supports CAD, CAM and CAE through the same interface (rhino3d.com).

Figure A3.1: Rhinoceros3D



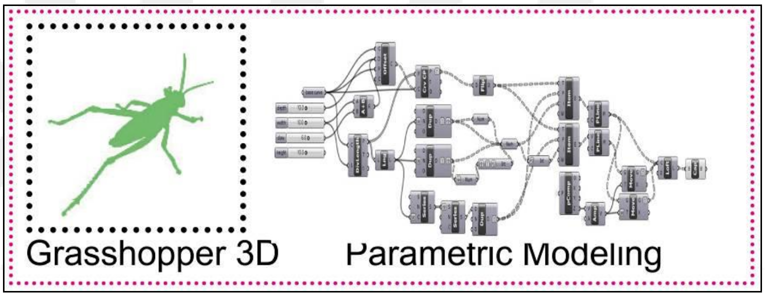
Source: https://www.rhino3d.com/6/features [Accessed 1 Apr. 2018].

The visual programming (VP) approach stems from the discipline of computer coding, unlike traditional CAD applications used in architectural design, such as direct modelling or limited dynamic modelling. Baker (2017, p. 10-11) stated: “It is programming performed through a visual interface that allows users to create and edit code indirectly by connecting pre-packaged groups of code (nodes/components) together”. Rhinoceros supports VB Script, C# scripts and Python scripts that can be used to create nodes. VP’s intuitive interfaces enable non-programmers to design using sophisticated algorithms and scripts. Reilly (2017) stated: “Algorithmic modelling is where design and programming intersect”. One major advantage of visual programming environments is the break of the limitation of standard CAD application, which is bounded by predefined shapes and tasks. Another advantage is their simplicity over lines of code; however, for advanced tasks, line-coding skills is crucial (Vierlinger, 2014, p. 611). Modelling inside the VP interface is known as scripting design thinking or generative parametric modelling, which requires writing a script or an algorithm to define a model or process. Olsson (2012) described the evolution of CAD systems as the exploration of the fourth dimension of “time” for a building’s future forecasting as “the building’s response to human activity and environmental effects over time”. Making time part of the design process provides real time feedback to inform the design process. VP reflects the current state of “digital design” that holds numerous possibilities to customise workflows to solve a wide variety of design problems. It offers the same freedom that computer programmers own. The designer can create and dynamically manipulate geometry, customise and automate the workflow and coordinate building information by integrating analytical results with 3D modelling and providing additional links between different external applications.

Parametric modelling with Grasshopper

Grasshopper is a free and open-source visual programming plug-in developed by Rutten at McNeel & Associates; it was first publicly released in September 2007. Grasshopper operates as a "graphical algorithm editor" or a "visual scripting language". It allows designers to develop algorithms and scripts for design by establishing parametric and rule-based dynamic systems (Anton and Tănase, 2016, p. 12). The plug-in is considered to be a parametric modelling extension with the aim of expanding the capabilities of Rhino3D. Due to its extensibility with different analysis, simulation and optimisation plug-ins, Grasshopper has become one of the most widely adopted parametric platforms in design practice.

Figure A3.2: Grasshopper



Source: https://www.grasshopper3d.com/ [Accessed 1 Apr. 2018].

To grasp the parametric modelling concept, direct modelling, in which the designer directly models inside the application shall be understood. The modification on objects is done one-by-one manually without playing with mathematical logic or relations. In the direct modelling approach, design decisions have a static aspect. The geometries are explicit objects, and further changes require the creation process to be repeated rather than revised, since the models were built without a preserving data structure. However, the parametric system preserves the data structure of created objects. When the first version of Grasshopper was released in September 2007, its plug-in name was "Explicit History" (Petersen, 2008).

Parametric modelling requires variable settings, logical relations and data management flow within the entire design script. According to Kolarevic (2003), modelling parametrically occurs when "the parameters of a particular design are declared, not its shape". Various parametrical definitions can exist for a single object (Maher, 2011, p.

10). There are often multiple routes (algorithmic structures) to describe or create an object based on data: connections and expressions. The script is independently formulated inside the Grasshopper (VP) interface and linked to host software Rhino to translate the script into graphical representation. Changes and updates are in real time, hence any modification to the base script provokes an instantaneous data update on different levels as well as a re-expression of representation in accordance with the new definition. The parametric models are flexible, as they offer the ability to subsequently access an object’s database and manipulate parametric values and logic; this is in comparison to static models, which cannot be re-edited. Variables can be manipulated to explore different options whilst remaining within the bounds of the intended design. The dynamic control over the geometry and components offered by parametric models allows designers to search for suitable solutions to complex problems by assessing multiple variants at the same time (Touloupak & Theodosio, 2017, p. 509-514). This flexible trait of parametric modelling is extremely powerful when testing design variations for optimisation purposes and automating the algorithm search inside VP.

Interoperability and Integration with Grasshopper

Contemporary manifestos of architecture concentrate on efficiently addressing many design aspects at the same time. However, the current workflow adopted by designers for membrane design exclusively concentrates on structural aspects. The membrane applications are exclusively designed to generate structural form findings, load analysis and cutting patterns. Data exchange between different applications is the main problem facing the expansion of membrane design workflow in undertaking wider disciplines. Although a clear mode of data exchange between applications has always been important, it is not smoothly achievable.

The use of mono-disciplinary applications cause interoperability issues, including the use of multiple 3D models and interfaces. Complications such as unfamiliar software working methods, modelling complexities (readable by analysis applications) and demanding input data for running simulations also limit the currently employed workflow (Roudasri, 2013, p. 3130).

Computer-aided design applications employ mathematical formulas to generate geometries. When 3D models are exchanged between applications, each system interprets data differently, which may result in misreading data and a misrepresentation of geometry. Thus, unifying and supporting different file formats are necessary to eliminate interoperability problems. Interoperability is the ability to share 3D models between different interfaces and applications through seamless importation and exportation of data. The aim is to synthesise the whole design process (from conception to production) within a single model to achieve a smoother and more integrative and efficient workflow.

Analysis and Optimisation: A Single Platform with Cross- Software Plug-Ins

Traditionally, performance analysis was done by engineers utilising an independent analysis software. Such an approach was repetitive, time consuming and expensive. It suffered from the availability of reliable climatic data. The deficiency of workflow resulted in many assumptions being made on behalf of the designers and led to inaccurate answers, especially in cases requiring custom data input. Moradi (2014 p. 103-19) stated: "A traditionally followed design workflow is linear and makes an analysis after the formal development of the architecture of a building". The architect designs a small number of alternative solutions, which are then delivered to an engineering team that attempts to analyse the performance of the project under various scenarios and select one of the best scenarios. In this situation, the project will be very rigid and can implement only small changes in the formal arrangement of the project. Each notable change in the project requires a reconstruction of the analysis model and the creation of a new series of analyses. As a result, the process is laborious and limits the possibilities of design iteration and exploration. Unsatisfactory situations can also cause problems, in that the analysis rarely changes the form of the architectural artefact. This process is only intended for the analysis of an already designed building, rather than the synthesis of an optimal one or a new form generation via morphogenetic agents.

Therefore, developments in digital tools have always aimed at devising a workflow in well-interconnected phases of architectural design (from conception to production), which facilitates moving back and forth seamlessly. Developments in digital tools bridges the pre-existing gap between modelling, analysis or simulation and fabrication tools, opening up the possibility to coordinate the whole design process through an intermediary platform. It also provides the opportunity to undertake previously neglected design aspects due to the absence of integration. Roudasri (2013, p. 3130) stated that, “Designers and architects agreed to expand their design workflow to contain performance aspects only when analysis tools were integrated with design tools”. Single platforms have combined and ensured the streaming (interoperability across platforms) of information amongst various plug-ins and software (Marroquin, Thitisawat, and Vermisso, 2013). VP has successfully blended cross-software plug-ins, which are implemented in various design phases. According to Grabner and Frick (2013,pp. 142-143):

> *VP allows parametric modelling with dynamic capabilities, writing custom scripts (Python), if needed, with organized data trees (sets of data which become essential in behavioural modelling) and feedback loops, assisting in eliminating the missing gap between simulations and modelling.*

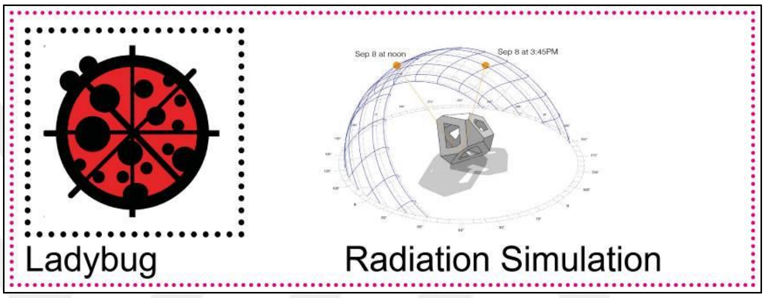
thus increasing the possibility of informed design and the bottom-up design approach. According to Roudasri (2013), “The simulation data from non-integrated software cannot be used to generate the next iterations of design, as the dynamic data exchange during simulation is not possible”. VP steps in as the problem solver by establishing an interactive loop between design, simulation and assessment tools.

3.2 Environmental Analysis with Ladybug

Ladybug is an open-source environmental plug-in developed by Mostapha Sadeghipour Roudasri that was first publicly released in January 2013. Roudasri (2013) stated: “It was developed with passive and mechanical strategies for environmental optimization in mind”, in addition to helping designers environmentally contextualise architectural design. It is a highly advanced plug-in capable of providing designers with a graphical representation of annual climate data and performing advanced environmental analysis, such as radiation, daylight, thermal comfort and energy.

Ladybug runs within the visual programming (parametric modelling) environment, hence eliminating the gap between design and analysis tools. In such an environment, the transition between 3D modelling and analysis is seamless, and feedback is in real time. Design modification was done primarily with optimisation intentions. Ladybug was originally meant to be compatible with Grasshopper/Rhino. In 2016, as an attempt to expand and share a common language with Dynamo's visual programming interface, Ladybug components were rewritten using Python scripting language, the conversion of which represented Ladybug as a "cross-platform Python library component". Braasch (2016) stated: "Being entirely Python scripts helps to ensure reliability of calculations". The designers can check and explore the underling codes of components, thereby providing full transparency. The scripting language affords users the possibility to customise the existing components, invent their own components and contribute to the source code.

Figure A3.3: Ladybug



Source: https://www.ladybug.tools/ladybug.html [Accessed 1 Apr. 2018].

Ladybug and Environmental Analysis

The environment has countless variables and scenarios for each climatic condition, material type, building form and energy nature. Neither the digital equivalence of environmental traits nor the application used to generate the environmental scenarios can be simple. Currently, although there are numerous environmental applications and plug-ins in use by designers, Ladybug is less technical compared to other tools. Ladybug developers have simplified the analytical process, automated and accelerated the calculations and provided easy-to-understand graphical representations to analyse results (Roudsari, Pak, and Smith, 2013). From an environmental specialist view, the plug-in is fairly simple; however, it is still difficult for architects, as it has too many inputs and sophisticated calculations. It requires a certain level of environmental expertise and VP skills to understand the workflow and successfully set the analytical process (Mackey, 2016, p. 49-51).

In a joint work by Roudsari, Pak and Smith. (2013, p. 26-28) comparing Ladybug with Diva, Geco, Gerilla and Heliotrope worked on the Grasshopper parametric platform and concluded the superiority of Ladybug to others. “None of the tools provide the full spectrum of the environmental studies, and there is almost no support for weather data analysis. Ladybug is an effort to support the full range of environmental analysis in a single parametric platform”. The flexibility offered by Ladybug is quite developed. Mackey (2016, p. 49) stated that, “As soon that the user tries something atypical or outside of the norm, then the tool must be ‘forced’ into solving such problems but in a sort of improvised way. Regarding that, we realized we did not need a new tool but a tool kit”. Ladybug contains multiple components to flexibly customise the workflow, making it adaptable to any project. Furthermore, it allows geometries that are more complex to be a part of the analysis, as they were previously avoided. However, some setbacks of having too many components include the need to understand the tool kit component by component and to know how and when the components can be effectively used.

Ladybug EPW and Real-Time Environmental Analysis

Ladybug supports the design process by utilising local information pertinent to each project site’s climatic conditions. Imported climatic data into Ladybug are in statistic file (Stat) or standard EnergyPlus Weather file (EPW) formats. The EPW file format, developed by the US Department of Energy, is most commonly used for environmental calculations. The file contains annual weather data, recorded on an hourly basis. It consists of roughly 123,000 recorded values for all measurable environmental factors. Regarding the immense number of data to be managed, Erlendsson (2014, p. 16) stated that, “Energy plus weather is arranged in the form of comma separated values (csv-files19) in the CSV file, each header is shown and then the data”. EPW files can be freely downloaded at the Energy Plus webpage.

Stages of usage

Supporting designers with environmental analysis tools promotes both environmental building performances and the climatic contextualisation of architectural buildings. The Ladybug bio-climatic tool helps in finding and integrating suitable environmental solutions into buildings. It is an effective tool within designers reach to head towards high performance and sustainable architecture. It is capable of facilitating real-time environmental analysis during different phases of the design process by integrating climatic data analysis and advanced simulation in Grasshopper's parametric modelling environment (Roudsari, Pak and Smith, 2013).

Pre-design analysis (Data analysis)

Awareness about the site's climatic condition helps architects in the pre-design decision-making phase and increases the possibility of making environmentally informed designs, even before a building form exists and a design is evaluated. The initial step of the workflow should analyse climatic data to identify critical environmental factors that should guide building forms. Ladybug renders a variety of 2D and 3D user-friendly, interactive weather visualisations, like sun path, wind rose, radiation rose, sky dome, solar irradiation metrics, etc. Furthermore, the VP interface allows customisation of diagrams in ways to support the early decision-making process. Roudasri (2013, p. 3130) stated: "The ability to visualize the environmental data within the design platform allows designers to make a clear connection between the data analysis and the design". Also, not considering climate data beforehand, possibly will lead designers to jump into unnecessary analysis to answer basic questions.

Design analysis

Advances in computational power enact the use of digital tools to virtually simulate the real-world environmental behaviour of architectural buildings. Simulation demonstrates the outcomes of design decisions (Lam, Wong and Henry, 1999). The graphic representation of the building performance and the comparative evaluation of design options during the early design phase inside Grasshopper's dynamic environment create real opportunities for improvement. Such control over the workflow increases the probability of success for the project to achieve the target. Ladybug evaluates design alternatives for radiation, view analyses and sunlight hour analysis results. For more advanced analyses, the Ladybug tool kit connects Grasshopper to building performance simulation (BPS tools) EnergyPlus, Radiance, Daysim and OpenStudio.

3.3. Physical Simulation with Kangaroo

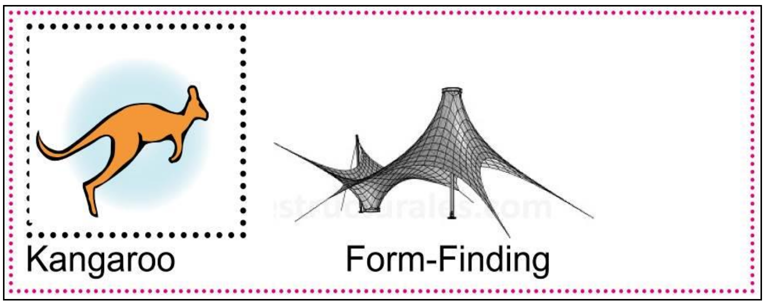
Kangaroo physics is an interactive physical simulation plug-in compatible with Grasshopper/Rhino. It was developed by Daniel Piker and first realised in March 2011.

It is utilised for optimisation (virtual form finding), structural analysis, constraint solving and animation (Foof4Rhino). The plug-in is simple and interactive, with a user-friendly and intuitive interface.

The Kangaroo engine uses algorithms and machine computational power to compute for the natural formation process. It imitates generative logic of real-world natural formation by simulating the interaction between the material’s physical behaviour, geometrical form and forces dictating the natural formation. The digital process followed by a plug-in is recognised as a dynamic relaxation of particle-spring systems (PSS) (Piker, 2013). Firstly, the forces in play follow the prevailing laws of nature that described by Newton’s law and Hook’s law. The calculated forces are the "unary force, bending force and spring force velocity and lengths of springs that are applied onto particles". (Piker, 2013). The engine iteratively computes forces to achieve an equilibrium state where the sum of the total directional forces is zero. Secondly, it feeds the actual physical properties such as bending, shear and stiffness the into engine’s main solver to generate the digital equivalence of actual material in the computational environment.

The capability of generating natural forces and replicating material behaviour has been devised to successfully simulate various scenarios for optimisation and analysing purposes. The Kangaroo engine replicates the analogue form finding process, namely the "autonomous formation processes". This leads to a minimal surface with uniform stress, which is used for finding membrane, centenary cable and shell structure forms. In addition, it can generate elements with different properties, such as rigs, cables and the membrane surface to be integrated with and related to each other. That makes an ideal platform to design the whole tensile membrane structure.

Figure A3.4: Kangaroo



Source: https://www.food4rhino.com/app/kangaroo-physics [Accessed 1 Apr. 2018].

Particle System

"Digital world is an ultimate abstraction of reality with just enough information to serve the use purpose". The Kangaroo engine converts the membrane's continuous surface into a finite number of particles (nodes), which are connected by elastic springs that are affected by real world forces and fixed at anchor points to conduct the form finding process. Piker (2013) stated: "The particles we deal with in Kangaroo are an abstraction, but one with a strong connection to our understanding of how the real world works at a fundamental level". The abstraction makes it possible for designers to assign and control the physics simulation in any formal setting in a simple way. According to Piker (2011, pp.3);Witkin and Baraff (1997):

> *Particles are objects that have mass, position, and velocity, and respond to forces, but that have no spatial extent. Despite their simplicity, particles can be made to exhibit a wide range of interesting behaviour. For example, a wide variety of no rigid structures can be built by connecting particles with simple damped springs.*

Piker (2011) stated the following in the Kangaroo manual: "Macroscopic properties of materials such as their behaviour in bending, shear and torsion can actually be seen as emergent on a molecular level from simple interaction between pairs of particles". The real material properties is assigned by engine to the geometric particles.

3.4. Optimization with Octopus

Design optimisation is the process of searching (form finding) for the option that holds the most suitable response to the design problems. The optimisation process is a system improvement by rearranging the variables to achieve user-defined objectives whilst satisfying design constraints (Salkini and Swaid, 2017, p. 8). de Leon (2016) stated: "It is the product of the relation between design parameters and design objectives". Optimisation tests different combinations of parameters to find the best results concerning the objectives in an automated fashion. According to Villamil, (2016), computational optimisation is an iterative process based on evolutionary algorithms that seeks optimal solutions from the search space without checking every individual solution for objective fitness.

There are two basic types of optimisation: Single-objective and multi-objective.

Single-objective optimisation is a process that targets just one objective. However, it is not realistic to reduce the design objectives to merely one option. Galapagos exclusively utilises single objective optimisation inside Grasshopper.

Multi-objective optimisation is a process in which several essential objectives are chosen as a focus. The process produces a pool of solutions in which none of them are a perfect optimum, but rather a balance between predefined objectives or a bias against one objective. This is due to the optimisation in some areas, which could result in an unfortunate compromise in others (adversely affecting other objectives). It is a challenge for designers to design buildings that perform on multiple fronts (Ashour, 2015), inevitably requiring the implementation of a multi-objective optimisation process. Octopus exclusively utilised multi-objective optimisation inside Grasshopper.

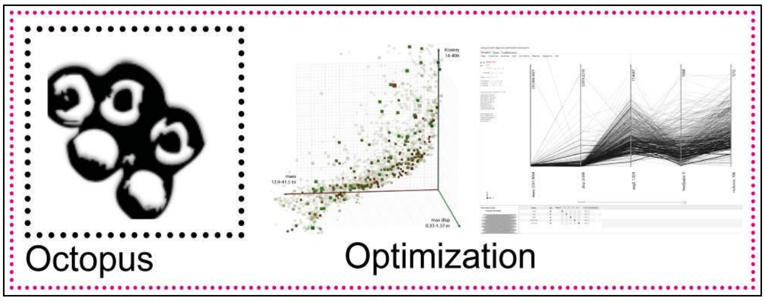
Octopus application

Octopus is an open-source evolutionary solver capable of performing a multi-objective optimisation process. The plug-in is compatible with Grasshopper/Rhino, originally developed by Vierlinger and first publicly released in December 2012. Octopus applies nature's evolutionary principles to design problem solving inside Grasshopper by fully exploiting the flexibility offered by parametric (dynamic model) frameworks (Vierlinger, 2014).

Aweida (2011) stated: "Octopus carries out an optimization search by producing a range of optimized solutions between the extremes of each goal". There is no absolute optimum solution in multi-objective optimization, but rather a population of potential 'sub-optimal' solutions. It records the search history and comprehensively arranges them by projecting results on a Pareto graph to represent the solutions in their relative optimality. The designers can thus view and explore the possibilities and select the preferred trade-off.

Octopus is an easy-to-use plug-in interface geared for flexibility during a search process regarding changing parameters, objectives, and user choices, enabling the user to customise the actual search algorithm. Due to Octopus's capacity to benefit from multiple CPUs running, it executes optimisation in an acceptable amount of time.

Figure A3.5: Octopus



Source: https://www.food4rhino.com/app/octopus [Accessed 1 Apr. 2018].

Algorithms

An algorithm is a list of step-by-step instructions for computers to execute a task; the instructions are inspired by biological mechanisms. It was first introduced in Holland's work in the 1970s as a solution generation technique for complex engineering problems (Ashour, 2015). This technique is applicable for wide range of situations and easily customisable to specific problems.

Algorithms automate the generation of design alternatives in an iterative approach (changing and updating design parameters in a repetitive manner); a cross combination of all design parameters is a possible search space. the search space is determined by design parameters and their bounds. Design spaces will grow exponentially as the parameters in the design and their bounds expand, due to the multiplication of possible variations of the design. Performance evaluations for all iterations and choosing the optimal option comprises multiple tasks.

Computers need to arrive at satisfactory solutions in an ideal runtime, which is possible when the solutions are resolved analytically. Optimisation solvers employ genetic algorithms such as Gas, a type of evolutionary algorithm (EA). Algorithms automate solution generation and the testing process to reach near-optimal solutions. Genetic algorithms provide a framework to effectively sample large search spaces.

Evolutionary algorithms are metaphors of natural evolution phenomena. Aweida (2011) stated: "Evolutionary problem solving mimics the Darwinian theory of evolution, employing the same trial-and-error methods that nature uses in order to execute natural selection to arrive at an optimized result". Computers apply a blend of the Darwinian theory of evolution and a stochastic modification of solution genes to find a better configuration of parameters. The result after several iterations and the elimination of unfit solutions is a pool of optimised design alternatives that, to a large extent, meet the objective. The Octopus algorithm has a kind of stochastic evolutionary nature despite its bio mimic approach (Vierlinger 2014, p. 1-10), using the same systems and techniques encountered in evolutionary biology, such as inheritance, mutation, natural selection and crossover. The algorithmic optimisation process is significantly affected by design space, the employed algorithm and available computational power.

Several types of EAs have been identified, such as genetic algorithms, evolutionary programming and genetic programming, covariance matrix adaptation evolutionary strategy, differential evolution, harmony search, particle swarm optimisation, ant colony optimisation and simulated annealing (Touloupaki & Theodosiou, 2017, p. 511).

Link between analysis and optimisation algorithms

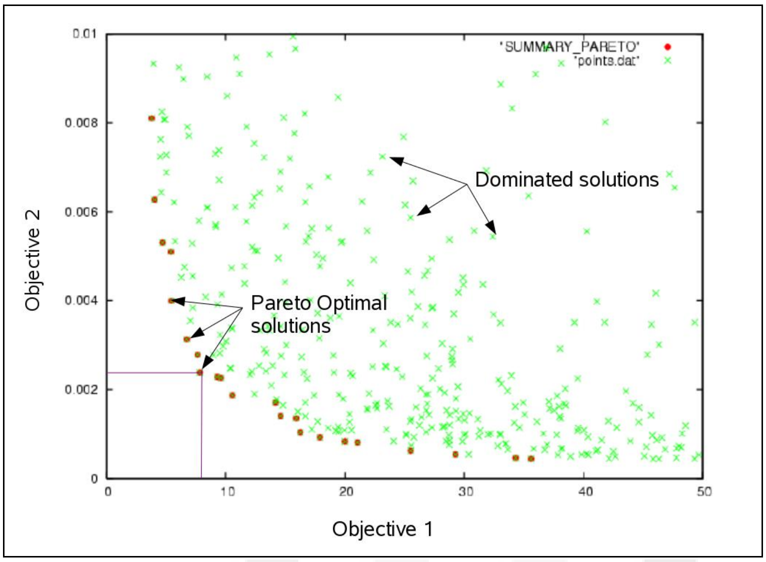
One of the major advantages of designing inside VP platforms such as Grasshopper and Dynamo is the ability to transform design from a mere visual-based formation to a more holistic formation and performance-based formation. The new workflow enable by VP emphasis performance as an “objective”, allowing workflow design to be a generative objective-based process. Objective-based workflows should contain dynamic models or systems and a broad set of analysing tools to support structural, environmental and architectural factors to produce architecture that optimally accomplishes various goals.

Dynamic models in combination with real-time analysis tools enable the process of optimisation by iterating the parameters until desired result is achieved. This iterative manipulation of geometry generates a large spectrum of alternative (search space). manual optimisation has deficiencies, as it is repetitive, time-consuming and laborious; furthermore, it is impossible to record and compare the large number of results to one another. Generative algorithms exploit dynamic control over geometry to generate and assess multiple variants in the short term. VP coding enables feedback loops by analysing the generative algorithm. Hence, analysis can actively contribute to the generative process of the architectural form by guiding the algorithm in the sample section, reduction and generation processes. These tools now enable architects to comprehensively explore the vast solution space in an efficient manner. The analysis results from each generation are devised to inform the next generation. This process is repeated until achieving an ideal combination of parameter values that exhibit the solution with the optimal performance or near-optimal population in the case of multi-objective optimisation. Salkini, Swaid and Luchente (2017, p. 307) stated, "The combination of parametric design with evolutionary solvers is a valid strategy for addressing design problems and calculating multiple performance criteria, finding the optimum solutions in a short period of time". In addition, experienced architects, like Kolarevic and Oxman, are proponents of such an approach, in which the architectural formation process is governed by the performance analysis results from different design disciplines (Anton and Tănase, 2016, p. 10).

Design Optimisation with Pareto Optimum

The concept of the Pareto optimum was invented by Vilfredo Pareto, an economist and civil engineer. Vierlinger and Bollinger (2014): The Pareto principle is defined as "an optimal distribution of limited resources, where one aspect can just be improved when degrading another". The Pareto optimum ideally spreads from one extreme goal to another, and the border is denoted by the Pareto front curve, thus translating the philosophy into a graph; the design option on the graph measures the performance rating.

Figure A3.6: Two-dimensional Pareto graph.



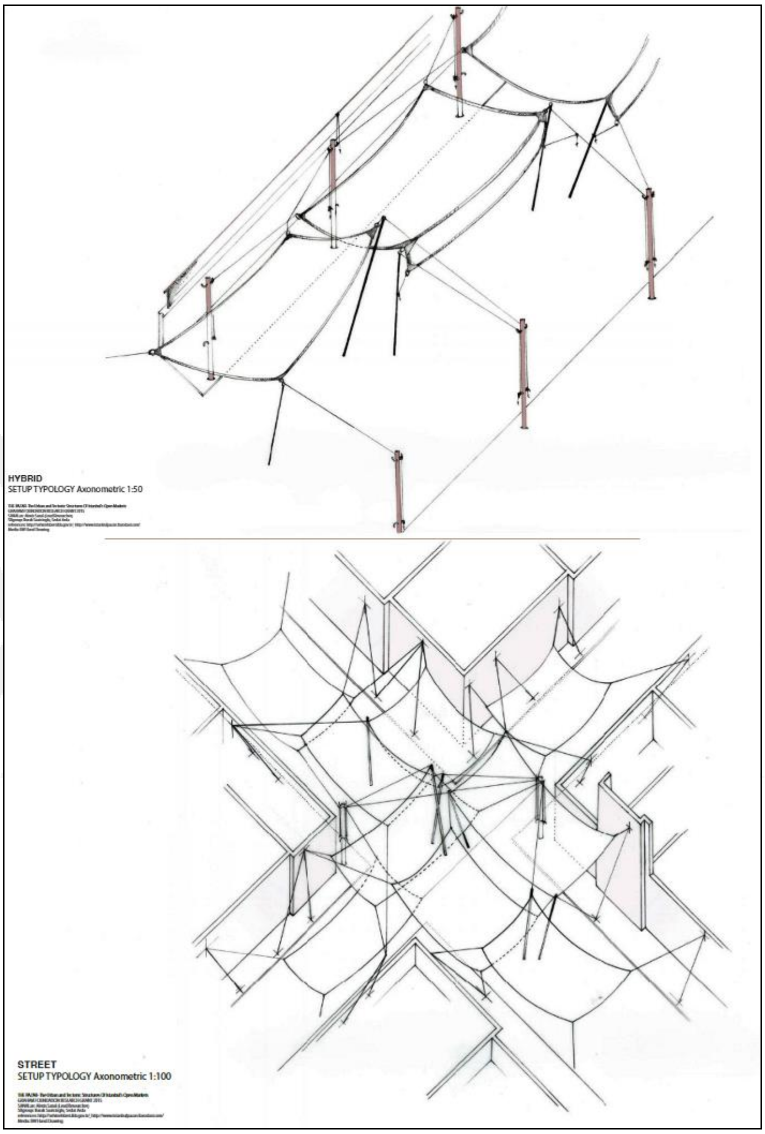
Source: http://alduomo.info/pareto-frontier-16.html [Accessed 5 Apr. 2018].

Figure 4.6 is a three-dimensional graph employed by Octopus to interactively plot optimisation results in accordance with the rating of said solution regarding pre-determined objectives. Octopus projects each solution onto the graph in real time as a cube; each cube is a mathematical representation of the performance (Vierlinger, 2014). Up to five objectives can be inspected at the same time. Each axis represents an objective; colours denote the fourth objective and cube size denotes the fifth objective. Within the Octopus interface, the designer can zoom in, explore the objective space, filter and customise the display setting and add weights to solutions based on their genotype (parameter) or phenotype (fitness) (Vierlinger and Hofmann, 2013), helping and guiding the designer in optimisation decisions.

Appendix A.4 Istanbul Pazar

SANALarc did one of the distinctive studies on membrane structures in Istanbul Pazar. The study describes the tent roof covering market places as “man-made generative structure”. The study can be expanded and the elemental relations could be computerized to morphogenesis algorithm that responds to the surrounding context including environment (sun, rain) in an optimized approach.

Figure A4.1: Pazar street coverd by tent



*Source:*https://issuu.com/alexis_sanal/docs/sanalarc_the_pazars_grahamfoundatio [Accessed 20 Feb. 2019].