School of Technology and Architecture
Department of Architecture and Urbanism

Towards a Bio-Shading System Concept Design Methodology

Maria João Marques de Oliveira

Thesis specially presented for the fulfillment of the degree of
Doctor in Architecture and Urbanism
Specialization in Digital Architecture

Supervisor:
Doctor Vasco Moreira Rato, Associate Professor,
ISTAR-IUL, ISCTE-Instituto Universitário de Lisboa
Co-supervisor:
Architect Carla Leitão, Adjunct Professor/Lecturer,
School of Architecture Rensselaer Polytechnic Institute

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Jury
Doctor Mónica Ribeiro Moreira Pacheco Navarro, Assistant Professor,
ISCTE – Instituto Universitário de Lisboa (President by delegation of the Rector)
Doctor Alberto-Tomás Estévez,
Full Professor, ESARQ Universitat Internacional de Catalunya
Doctor Ricardo Jorge Soares Massena Gago
Researcher, Lisbon School of Architecture, Universidade de Lisboa
Doctor Alexandra Cláudia Rebelo Paio
Assistant Professor, ISCTE-Instituto Universitário de Lisboa
Doctor Vasco Nunes da Ponte Moreira Rato
Associate Professor, ISCTE-Instituto Universitário de Lisboa

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ABSTRACT

Cities and buildings play a critical role in setting the conditions for human well-being while contributing to more just and environmentally conscious societies and economies. The design of environmentally and socially meaningful buildings has benefitted, in the past two decades, from scientific progress in the fields of computation and materials, as well as from a new way of looking into Nature as an inspirational example. This research focuses on the design of shading systems for building façades, assuming that biomimetics and computational design are a valid and proved combination. The main research question is how to develop architectural shading systems mimicking the adaptation strategies of Nature. The challenge is addressed by developing a design methodology for the creation and optimization of solar control systems based on the biological adaptive systems of terrestrial plants; creating a transfer and interpretation process of biological concepts to an architectural lexicon; and creating a universal methodology applicable to a diverse set of climatic, functional and local contexts.

The research proposes a bioshading system design methodology, developed on a problem-based approach. Starting with the architectural challenge of design, solutions are sought in Nature to solve specific performance requirements of shading systems. The development of the methodology rests upon an informed process that integrates and interrelates three domains: architecture, Nature, and artifact. The ‘architecture’ domain is based on the conceptual process, the computational and parametric environmental analysis, and a diagnosis that informs the understanding of the performance requirements that need to be fulfilled. The ‘Nature’ domain is defined through an abstraction process: sustained by a mapping of plants’ features and adaptation strategies, the creation of a meme semantics triggers a performance-based design process. The ‘artifact’ domain is the physical materialization of the design concept, enabling its evaluation and emulation.

The Nature-inspired design methodology developed in this research makes it possible for architects to solve the challenges of shading building façades, integrating local climate-related performance requirements with formal architectural criteria, using biomimicry as a mediator. In a step-by-step path, the user identifies specific project-related requirements, discovers and explores natural processes that guide inspiration, and conceptualizes a design proposal that is further simulated and prototyped.

Keywords: Bio-Shading; Shading Systems; Plants; Architecture; Biomimetics; Computational Design; Methodology.

RESUMO

As cidades e os edifícios desempenham um papel crítico na definição das condições para o bem-estar humano, contribuindo para sociedades e economias mais justas e ambientalmente conscientes. O projeto de edifícios com significado ambiental e social beneficiou, nas últimas duas décadas, do progresso científico nos campos da computação e dos materiais, bem como de uma nova forma de encarar a natureza enquanto modelo inspirador. Esta investigação centra-se no design de sistemas de sombreamento para fachadas de edifícios, assumindo que a biomimética e o design computacional são uma combinação válida e comprovada. A principal questão de investigação é como desenvolver sistemas de sombreamento arquitetónicos mimetizando as estratégias de adaptação da natureza. O desafio é abordado através do desenvolvimento de uma metodologia de projeto para a criação e otimização de sistemas de controlo solar tendo por base os sistemas de adaptação biológicos das plantas vasculares terrestres; criação de um processo de transferência e interpretação de conceitos biológicos para um léxico arquitetónico; e criação uma metodologia universal aplicável a um conjunto diversificado de contextos climáticos, funcionais e locais.

A presente investigação propõe uma metodologia de projeto de sistema *bioshading*, desenvolvida através de uma abordagem *problem-based*. Partindo do desafio arquitetónico de projeto, são procuradas soluções na natureza para resolver requisitos de desempenho específicos de sistemas de sombreamento. O desenvolvimento da metodologia tem por base um processo informado que integra e interrelaciona três domínios: arquitetura, Natureza e artefacto. O domínio 'arquitetura' tem por base o processo conceptual, na análise ambiental computacional e paramétrica e num diagnóstico que informa o entendimento dos requisitos de desempenho a serem cumpridos. O domínio 'Natureza' é definido por meio de um processo de abstração: sustentado por um mapeamento de recursos e estratégias de adaptação das plantas, a criação de uma semântica de *memes* desencadeia um processo de design com base no desempenho. O domínio "artefacto" é a materialização física do conceito de design, permitindo a sua avaliação e emulação.

A metodologia de design inspirada na natureza desenvolvida neste trabalho de investigação possibilita aos arquitetos resolverem os desafios de sombreamento de fachadas de edifícios, integrando os requisitos locais de desempenho relacionados com o clima com critérios formais de arquitetura, usando a biomimética como mediadora. Num percurso progressivo evolutivo, o utilizador identifica requisitos específicos do projeto, descobre e explora processos naturais que orientam a inspiração e conceptualiza uma proposta de projeto que é simulada e prototipada.

Palavras-chave: Bio-Shading; Sistemas de Sombreamento; Plantas; Arquitectura; Biomimética; Design Computacional; Metodologia.

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ABBREVIATIONS AND ACRONYMS

φ	Latitude
λ	Longitude
δ	Declination
H	Hour Angle
h	Altitude
A	Azimuth
L_{so}	Longitude of the solar obstacle
AGS	Advanced Glazing Systems
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
BIM	Building Information Model
Biomeme	Biomimetic Meme
BMS	Building Management System
BSDM	Bioshading System Design Methodology
$C0_2$	Carbon Dioxide
CAD	Computer-aided Design
Cam	Crassulacean Acid metabolism
CAM	Computer-aided Manufacture
CC	Climate Consultant
CH2	Council House 2
CHPS	Collaborative for High Performance Schools
EDP	Energias de Portugal
EEA+DTO	Education Executive Agency & Tax Offices
EPW	EnergyPlus Weather Data File

ETFE	Ethylene Tetrafluoroethylene
GC	Global Challenges
GC	Generative Components
H_{sa}	Horizontal Shadow Angle
IC	International Conference
ICD	Institute for Computational Design, University of Stuttgart
IDF	Intermediate Data Format
IMA	Institut du Monde Arabe
IR	Infrared
ISS	International Summer School
ITKE	Institute of Building Structures and Structural Design, University of Stuttgart
LEED	Leadership in Energy and Environmental Design
MCG	Max Creation Graph
MDF	Medium-Density Fiberboard,
MET	Metabolic Equivalent Task
MIT	Massachusetts Institute of Technology
MoMA	Museum of Modern Art
NASA	National Aeronautics and Space Administration
NURBS	Non-Uniform Rational B-Spline Based System
PoC	Proof of Concept
PV	Solar Photovoltaic
RH	Relative Humidity
RMIT	Royal Melbourne Institute of Technology
TIM	Transparent Insulation Materials
TSV	Turn- und Sportverein München von 1860

UCLA	University of California, Los Angeles
UIC	Universitat Internacional de Catalunya
UN	United Nations
USA	United States of America
UV	Ultraviolet
VL	Visible Light
V_{sa}	Vertical Shadow Angle
WWII	Second World War
ZNE	Zero Net Energy

SECTION I
INTRODUCTION

1.0

[META] MOTIVATION

1.0 [META] MOTIVATION

1.1 Global Challenges

In 1996, The Millennium Project was established as an international think tank under the American Council for the United Nations University, becoming independent in 2009. The think tank has defined 15 global challenges (GC) related to climate change, access to water, energy and technology, democracy and inequalities, health, and science and education. Since the very beginning, the organization has implemented 55 projects worldwide addressing these challenges (The Millenium Project, 1996).

The same kind of approach towards global sustainability challenges has been developed since 2000 by the United Nations with the eight Millennium Development Goals, a framework that has reached its end of life in 2015 (UN, 2000). Then, The United Nations (UN) approved the 2030 Agenda for Sustainable Development Goal and its 17 Sustainable Development Goals (UN, 2015).

An essential part of all of those challenges and goals may be related to architecture in the sense that urban and built environments play a critical role in setting the conditions for the well-being of people. Therefore, as part of the contributions to the achievement of those challenges and goals, it is necessary to have strategies for the design of environmentally-responsible and socially meaningful buildings in the context of scarce material, as well as financial resources (COM(2015), 2015). One of the crucial aspects to be addressed is, among others, the design and construction of architectural systems that promote comfort, reducing the need for energy consumption (Rivas, Cuniberti, & Bertoldi, 2016). This may be accomplished through optimized usage of an infinite natural thermal resource like solar radiation (Sengupta, Habte, Gueymard, Wilbert, & Renné, 2017). Indeed, the history of architecture is rich in examples of design traditions and practices arising from local resources and climate conditions (Kultur, 2012). However, contemporary social and economic patterns, like intensive urbanization, require ever-evolving approaches so that architecture keeps answering to inhabitants' needs and, at the same time, cope with climate change, scarce resources, and the paradigm of energy transition (World Energy Council, 2016) (Basiago, 1999).

In the past two decades, scientific progress in the fields of computation and materials, as well as a new way of looking into Nature, have opened exciting paths that architecture has embraced (Tokuç, Özkaban, & Çakır, 2018). Mimicking Nature in developing new architectural design proposals through the use of powerful computational models is now a reality (Deniz & Keskin-Gundogdu, 2018).

This research assumes that biomimetics and computational design are a valid and proved combination to address the design challenges that buildings must comply with now and in the future.

Biomimetics may be considered as the programmatic link between science and technology. Biomimetics is a transdisciplinary language that connects architects to biologists. It is usually discussed as a method and characterized by the transfer of strategic information (Gebeshuber, Gruber, & Drack, 2008).

In 2008 Gebeshuber, Gruber, and Drack drew up 'A Gaze into the Crystal ball: Biomimetics in the year of 2059', pointing potential biomimetics contributions in addressing six of the fifteen Global Challenges (CG) of 'The State of the Future' report[1]. Biomimetic contributions comprised current and future (year 2059) biomimetic approaches, following GC: (1) Sustainable Development and Climate Change – by increasing exploitation of solar energy through the use of microbial fuel cells generated from electron donors in wastewater, and chemical heat production based on thermogenic plants; (2) Clean Water – Desalination with aquaporins or via transpiration and filtering through membranes, water collection based desert plants systems and even self-cleaning materials based on the lotus-effect; (6) Global convergence of Information Technology (IT) – by using virtual models for decision and optimization, replacing the slow trial and error methods; (8) Health – understanding organisms and ecosystems strategies to detect and fight diseases, developing new pharmaceuticals that use bioinspired devices; (13) Energy – Exploiting concepts for primary energy conversion such photosynthesis, radiosynthesis, oxidation of molecular hydrogen and sulfur oxygenation; and (14) Science and Technology – interdisciplinarity working groups. Coordinating the specialists are the authors' proposals to fill the gaps between inventors, innovators, and investors (Gebeshuber, Gruber, & Drack, 2008).

The term 'biomimetics' was coined in the 1950s by Otto Schmitt. At the time, it was used to define the transfer of ideas and analogs from biology to technology (Vincent, Bogatyreva, R Bogatyrev, Bowyer, & Pahl, 2006). Biology can inform technology at

[1]. Formed in 1996 by the Futures Group International, the American Council for the United Nations University and the Smithsonian Institutions, the Millennium Project (MP) - a global participatory think tank- has now 96 active Nodes (a Node can be both an entity or an individual) – government, universities, NGO's, business planners, international organizations, among others – that cooperate with the MP and with each other to provide an international perspective over our future. The MP publishes the annual 'Future Report' and "The State of the Future" (now at its 19th edition, by Jerome C. Glenn, Elizabeth Florescu, and The Millennium Project Team), summarizing the ongoing researches and studies under the MP (Glenn, Florescu, & Team, 2017). "The State of the Future" deals in detail with the 15 global challenges (annually updated) for the Humanity: (1) Sustainable Development and Climate Change; (2) Clean Water; (3) Population and Resources; (4) Democratization; (5) Global foresight and Decision-Making; (6) Global convergence of IT; (7) Rich-Poor Gap; (8) Health; (9) Education and Learning; (10) Peace and Conflict; (11) Status of Women; (12) Transnational crime; (13) Energy; (14) Science and Technology; (15) Global Ethics.

different levels such, material, structure, and mechanisms (Vincent, 2009). What Gebeshuber, Gruber, and Drack clearly propose is the usage of biomimetics as a bridge, not only between different fields of knowledge but also between technology and society. Society bases its knowledge survey on models for validation and proof.

In 1969, Alain Badiou published *The Concept of Model* where he stated that a model does not provide any type of proof; it figures scientific context as an assignable element with consistency – a concept. However, a theory is consistent if, and only if, it has a model (Badiou, 2007). Regarding the construction of the formal theory system, Badiou describes it as a game of epigraphs whose rules are explicit, foretelling every case without ambiguity. Beginning with a series of statements and axioms, generating theorems using rules of deduction concerning how epigraphs can be formed and deduced, defining syntax. The construction of a formal system aims to draw the deductive structure, the mechanizable aspects of an existent scientific domain – that is a theoretical practice whose effects are inscribed in history. However, to speak of the meaning of a system is to speak of its various interpretations (Badiou, 2007). During the 1980s, evolutionary theories and technology have gained prominence. These theories use concepts and analogies from evolutionary biology to explain technological change and innovation. One of the fundamental theories that support all these different theories is *Universal Darwinism*. The first claim of *Universal Darwinism* is that the Darwinian principles of evolution by natural selection do not focus exclusively on biological processes but also underlie creativity and the key to functional order. The second consideration claims that technological artifacts consist of evolutionary processes of variation and selection (Brey, 2008). In 1976, Richard Dawkins developed the *'Memetic Theory'*. In *'Memetic Theory'*, human culture is realized and transmitted through cultural units – *memes*. *Memes* are units of meaning that can express any idea, behavior, or design. Like genes, *memes* can replicate and be transmitted and even compete with other *memes* for survival – Darwinian principles. In his book *Darwinizing Culture: The Status of Memetics as a Science*, Robert Auger developed the theory of memetics based on Richard Dawkins' theory. Aunger states that *meme* is a basic meaningful unit of culture, and the basic unit of culture inheritance (Aunger, 2000). For Auger, *memes* appear in two formats: as ideas in the mind - which are phenotype representations giving rise to artifacts and behavior - and in brain structures as a genotype. While a *meme* gives rise to artifacts (provide the possibility of new artifacts – Phenotype/reproduction), artifacts provide memes feedback (reproducing new memes – Genotype): this is coevolution (Aunger, 2000).

The three basic concepts and principles of the theory of evolution itself, formulated by Darwin in his "Origin of Species" (1859) are: *Phenotypic Variation* - All individuals of a particular species show variation in their behavioral morphological and/or physiological traits – their phenotype; *Heritability* - Part of the variation between individuals in a species is heritability, meaning that some of that variation will be passed on from one generation to the next; and *Differential Fitness* - Some individuals of a species are better adapted to their environment than others and, therefore, have higher chances of survival and reproduction. Individuals in a species differ in their fitness, or in their propensity to reproduce. Three additional principles specify underlying mechanisms for the processes described in these three principles: *Genetic reproduction* - Inheritance of traits takes place through the reproduction of genes; *Mutation and recombination* - accidental changes in genomes, and redefinition, the crossing between alleles; *Blindness* - Variations and selection are blind processes (Darwin, 1859).

"The evolution of technology is not a biological process since technical artifacts are not biological species. An evolutionary theory of technology cannot be part of evolutionary biology. Instead, a theory of technology can only be evolutionary in an analogous sense: assuming that technological change and innovation depend on principles that are strongly analogous to the principles underlying biological evolution." (Brey, 2008, p. 65).

Is technology an outcome of intelligent design? Alternatively, could it be that technology is an outcome of evolutionary processes, rather than intelligent design? Evolutionary theories of technology make more systematic use of concepts and principles of evolutionary theory for the analysis and explanations of processes of technological change and innovation (Basalla[2], Mokyr[3] and Anger[4] theories). Thus, if designers are the initiators of new variants that then undergo selection in society, they are also agents of mutation and recombination in the production of new variants. The success of the variants they produce in the subsequent selection process can only be predicted or controlled by designers to a very limited extent (Brey, 2008). They have partial control over the production process. In this sense, it may be considered that technology is a purposive activity of designers driven by a blind evolutionary process.

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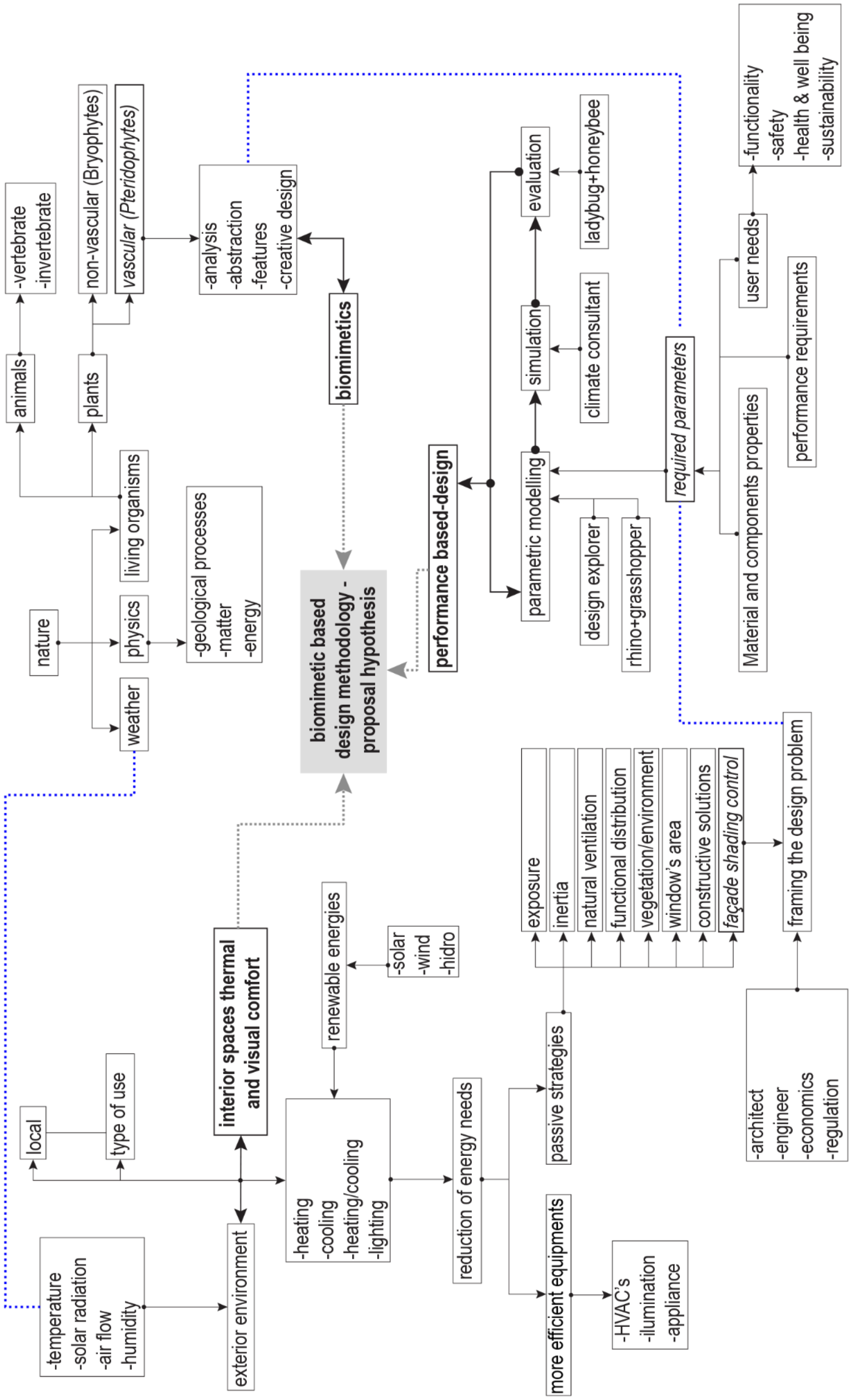
[2] George Basalla's theory of technological artifacts exploits several similarities between biological and technological evolution, while also admitting to several dissimilarities. Basallas's theory claims analogous versions of the principles of Variation, Inheritance, and Differential Fitness. Variation and selection are not blind but evolve conscious human agents making purposeful choices: Regarding the creation of novelty and the selection of artifacts.

[3] Joel Mokyr's theory-based knowledge in the 'What' and 'How': What - Ω (omega) Useful knowledge Scientific knowledge + engineering knowledge + quantitative empirical relations between properties and variables – Genotype; and How - λ (Lambda) Techniques
The techniques. Techniques are sets of instructions or recipes that tell the user how to manipulate aspects of the environment to attain a desirable outcome – Phenotype. In Mokyr's theory, the object is techniques, which are a type of knowledge. In both cases, the trajectory of these objects may be described in evolutionary terms but is nevertheless, the immediate result of human deliberation and purposive action. Mokyr's believes in the primacy of 'useful knowledge' over techniques - Ω (defines what society knows) over λ (what it can do).

[4] Robert Anger's theory developed an account of technological change within the context of memetics (initially proposed by evolutionary biologist Richard Dawkins (1976). A *meme* is the basic meaningful unit of culture and the basic unit of cultural inheritance. *Memes* are capable of reproduction and are subject to Darwinian processes of blind variation and selection. Memeticists believe that the basic selection mechanisms for memes is not conscious and involves forces that are beyond the control of individual agents. Aunger's theory incorporates an analog of most principles of biological evolution, and he conceives of technological change as strongly analogous to biological evolution.

Architecture is regularly referred to as our primary skin (clothes the second, and our 'ultimate' skin) (Gruber & S., 2010). However, if we think that throughout our evolution, humankind has not developed physical skills to face the weather or even its current surroundings, it will not be wrong to say that architecture is our last defense barrier. In this context, architects are the great makers of the Humans' ultimate skin – building façades. To create such an organism, the ultimate barrier between humans and the environment, architects must take into account internal and external premises (Pallasmaa, 2005). The responsibility to conceive and design such mediated organism puts us into a very high responsible action. This action has multiple repercussions and impacts on the way we live with and on our planet. Through the last centuries, architecture kept up with: industrial and material (re)evolution, climatic constraints, new technology capacity and production, mutable and fast forward societies, cultural and religious premises. Biomimetic processes, in several areas, have revealed to be successful and anticipatory to many problems, diseases, catastrophes, and even materials. All the means and the know-how to solve our present challenges are here, with us, at present. Although there are necessary bridges to build. One of the biggest challenges in transdisciplinary teams is the lexicon. Biomimetics is a field that already constructs some common lexicon with areas such as engineering and medicine. Integrating its know-how and lexicon in architecture schools and practices could improve future building responsiveness and interaction in very early stages of project development and *a posteriori* a better and greater environmental and human interactions and adaptation. The following research investigation presents a design methodology that could conduct architects through biologic concepts and processes, building a fluid and deductive system that could lead them into a physical model.

1.2 Thesis diagram



1.3 Questions

The main question addressed in this research investigation is:

How to develop architectural shading systems mimicking the adaptation strategies of terrestrial plants?

To answer this question, we must first answer the following sub-questions:

1. What are the main advantages and gaps found in the current biomimetic design methodologies?
2. What are the shading systems fundamental functions that fulfill the demands and requirements of its inhabitants?
3. What are the fundamental types of adaptations strategies and their categorization found in terrestrial vascular plants for implementation in shading systems?
4. How to translate and represent the plants identified adaptation strategies into the architect's design lexicon?

1.4 Thesis goals

1. Develop a project methodology for the development and optimization of solar control systems based on the terrestrial plant biological adaptive systems;
2. Create a transfer and interpretation process of biological concepts to an architectural lexicon;
3. Create a universal methodology applicable to several climatic, functional, and local contexts (surroundings conditions).

1.5 Outline

The thesis is divided into seven chapters and ten sections. On the whole, the thesis comprises one meta introduction chapter, one background chapter containing three sections, one chapter dedicated to preliminary experiences report, three chapters devoted to the design methodology construction, and a final contribution chapter.

1.5.1 Section I: Introduction

Section I is composed of Chapter 1.0 META[MOTIVATION]. This Chapter provides a philosophical theoretical framework of the presented thesis, sharing ideas, concerns, and clues that have sustained the methodology development. The thesis questions and goals are settled in this Chapter, and a thesis diagram is provided to its readers. Organized according to the structure of the thesis, a brief summary of each chapter of the thesis is given.

1.5.2 Section II: Background

Section II is divided into three chapters, 2.0 Solar Radiation, Comfort and Shading, 3.0 Fundamentals of Biomimetic, and 4.0 Digital Architecture. 2.0 Solar Radiation, Comfort, and Shading chapter is a disintegration of the solar radiation concept. It provides a clear definition of solar radiation and shading control, presenting an overview of solar geometry and the way it intersects our buildings. 3.0 Fundamentals of Biomimetic chapter provides a *Biomimetics and Architecture* short history, contextualizing the connections of the different fields referring to key events, projects, and figures. Biomimetic design methodologies and tools are also referred, and some main researches are presented. Finally, chapter 4.0 Digital Architecture provides a brief history of the development of digital tools into the architecture field, as well as a state-of-the-art of its contemporary application and tendencies.

1.5.3 Section III: Preliminary Experiences

Composed of chapter 5.0 Kine(SIS)tem’17 – International Conference + Summer School, this section reports the pilot experience that brought this research investigation to daylight. chapter 5.0 describes from a critical point of view Kine(SIS)tem'17 the international event divided into two moments: Conferences and Workshop. During the conferences, issues related to Time matter and matters, Human nature, Biological-inspired, and Architecture as an Inter(trans)disciplinary field were some of the discussed themes, while regarding the workshop, its organization, and preparation for a defined period of time were determinant to its success. The workshop was composed of a back-office stage one, devoted to the creation of a skeleton and a climatic analysis of a specific context, and stage two, entirely devoted to the design studio where the participants were the essential creative elements.

1.5.4 Section IV: Nature

Section IV is composed of chapter 6.0 Plants. This chapter starts by considering the Gaia Hypothesis, followed by plant evolution. Focusing on terrestrial vascular plants, the sections describe these organisms, contextualizing their adaptation strategies and strategies categorizations. This chapter holds the *Plants adaptation strategies* – Morphological, physiological, and behavioral tables, that will integrate the nature domain survey of the BSDM.

1.5.5 Section V: Adaptative Building Envelopes

Composed of chapter 7.0 Shading Systems, this chapter begins to explain the relevance of façade elements in the building life cycle. Shading systems functions, actions, and agents, as well as its integrated relationship, are a central theme in this chapter. Lastly, but not less relevant, shading systems type of structures and type of actuators are listed through several real scale examples.

1.5.6 Section VI: A Biomimetic Design Methodology

This Section is divided into two chapters. Chapter 8.0 Proof of concept (PoC 1.0) and chapter 9.0 Bioshading System Design Methodology. Chapter 8.0 Proof of Concept reports an 8-hour living experience, where the main goal was for the participants to develop a shading system for a pre-determined building and a specific context, using the Bioshading System Design Methodology. PoC 1.0 aimed to test and evaluate the developed methodology in: 1- *Methodology Clarity* (evaluated by the participants at the end of the experience); 2- *PoC 1.0 sessions* [participants were invited to evaluate i) clarity in the oral presentation and in the supplied digital material in what the methodology is concerned, ii) time of session, and iii) the available means]; and finally 3- *Method Operability and its Outputs* (researchers evaluation, over each developed project, about their method clarity and applicability, goal definitions, biomimetic *meme* path matrix generation, design solutions and its technical implementation). Chapter 9.0 Bioshading System Design Methodology describes, step-by-step the developed methodology, providing examples and instructions to its practice.

1.5.7 Section VII: Contributions

Section VII, chapter 10.0 considers the theoretical and methodological contributions of the thesis. The section revisits the thesis' initial questions, as well as it identifies its relevant advantages and limitations.

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SECTION II
BACKGROUND

2.0 Solar Radiation, Comfort and Shading

2.0 SOLAR RADIATION, COMFORT AND SHADING

The Sun is a star. A 1,391,016 km diameter fire sphere of glowing gases at the heart of our solar system (Nasa, 2017). It holds 99.8 percent of the solar system's mass and is roughly 109 times the diameter of the Earth — about one million Earths could fit inside the Sun. The temperature of the visible part of the Sun is about 5,500 °C, while temperatures in the core reach more than 15 million °C, driven by nuclear reactions. The Sun is one of more than 100 billion stars in the Milky Way galaxy. It orbits some 25,000 light-years from the galactic core, completing a revolution once every 250 million years. Sun’s chemical composition, like other stars, is predominantly made of hydrogen and helium, the remaining matter being carbon, iron, oxygen, neon, magnesium, nitrogen, and silicon (Choi, 1999). Of the total energy released by the Sun, only a small fraction reaches the upper layers of the Earth’s atmosphere, and only about half of this energy reaches the surface of the Earth.

Solar radiation is vital for life on the planet and is the most important factor in the formation of climatic conditions. Climate is a complex system integrating the atmosphere's different layers (troposphere, stratosphere, mesosphere, thermosphere, and exosphere), the hydrosphere, and the pedosphere, and all the physical and chemical processes that occur in the boundaries between these elements. The energy provided by solar radiation induces temperature differences within the atmosphere, as well as the oceans, which give rise to air movements through the corresponding differences in air pressure. Water evaporation is also a consequence of the energy provided by solar radiation transmitted by solar radiation to the surfaces of water masses.

Besides the above-mentioned direct relationship between solar radiation and climate, solar energy is also a crucial factor for hygrothermal comfort conditions inside buildings. Whenever external conditions are too cold, solar energy provides heating that may be directly used to warm internal air, or that may be stored for later use. On the other hand, hot external climate conditions demand for strict control of solar radiation to avoid internal overheating due to excessive heat gains.

2.1 Solar Radiation and Shading Control

2.1.1 What is solar radiation?

Solar radiation is the energy emitted by the Sun in the form of electromagnetic radiation. Radiation is emitted or transmitted in the form of rays, electromagnetic waves, and particles (Dunbar, 2018) (Rask, Vercoutere, Navarro, & Krause, 2018). Electromagnetic radiation crosses a range of wavelengths called the electromagnetic spectrum (Figure 2.0:1). Electromagnetic radiation includes radio waves, microwaves, infrared (IR), visible light (VL), ultraviolet (UV), X-rays, Gamma-rays, and cosmic rays

(Stark, Light, 2018). Solar radiation ranges from infrared to ultraviolet, and includes visible light, which is the one that is captured and processed by the human eye and the human optic system. Radiation with longer and shorter wavelengths is not visible to the human eye, but it can be sensed to some extent, enabling humans to visualize patterns that are not visible just through visible radiation (Phillips & Fritzsche, 2017).

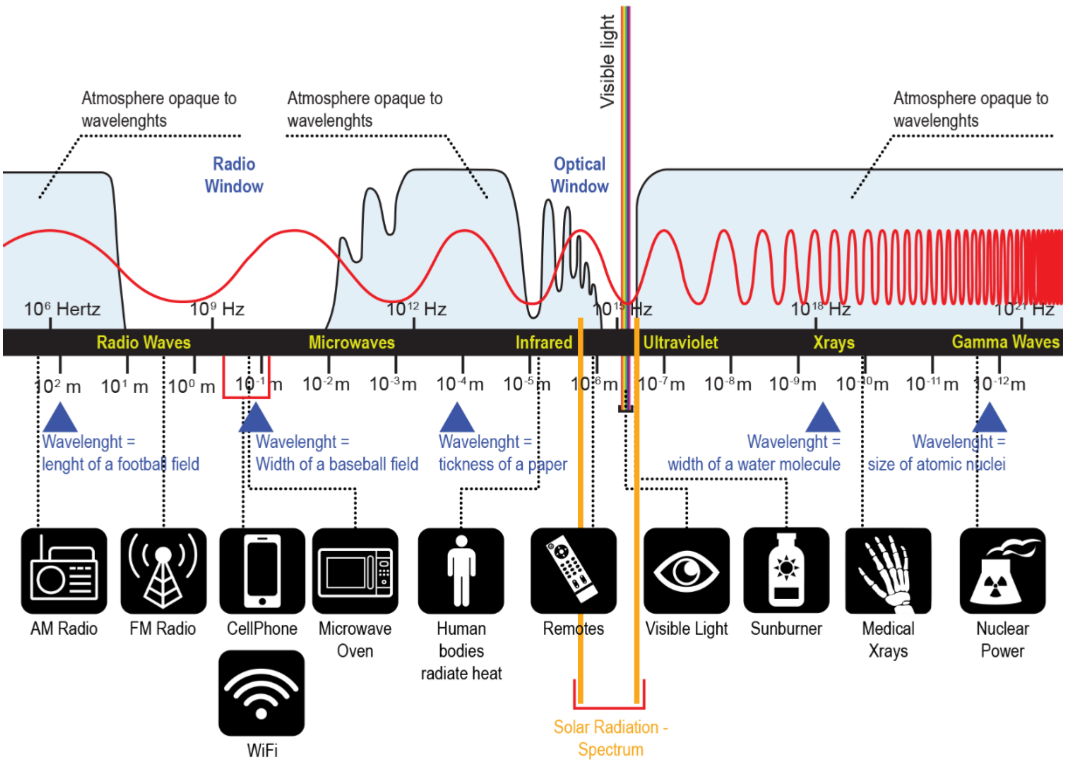

Figure 2.0:1. The Electromagnetic Spectrum[1].

Infrared radiation is not visible to the human eye; however, it can be sensed under the effect of heat. Discovered in 1800 by astronomer Sir William Herschel, infrared wavelengths extend from the red of the visible spectrum to approximately 10^{-9} m. Infrared applications range from surveillance, night vision, and tracking to thermal analysis, temperature sensing, environmental monitoring, among others (Hackforth, 2012).

Starting from the violet, at the other end of the visible light, ultraviolet wavelength extends until the X-ray wavelength, approximately between 10^{-7} to 10^{-10} m. In its natural state, UV is undetectable to the human eye; however, depending on the material surface of contact, it may cause fluorescence emitting lower energy in the form of visible light. Due to its low power of penetration, UV effects in the human body are limited to the surface

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[1] *The Electromagnetic Spectrum*, NASA, viewed May 7th, 2018 <https://www.nasa.gov/sites/default/files/thumbnails/image/ems-introduction.jpeg >

skin. However, its direct effects could be serious, ranging from redness to severe damage like blisters and sloughing of the outer skin (Younis, 2012).

Visible light corresponds to the fraction of the complete electromagnetic radiation spectrum that is visible to the human eye (Stark, 2019). The spectrum of visible light does not contain all the colors that the human eye and brain can identify (Surhone, 2010). For instance, magenta variations are not present, because only a wave by a wavelength overlapping can produce them. Colors that only contain one wavelength are called spectral colors (Figure 2.0:2).

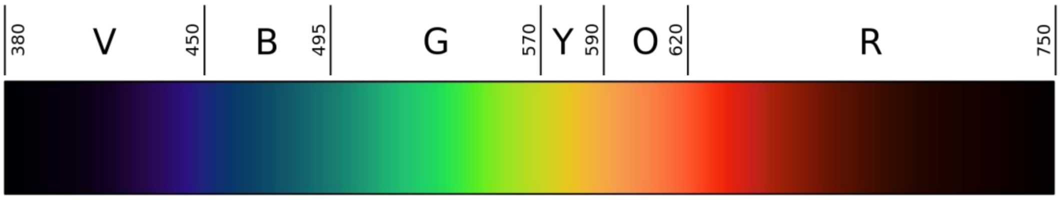

Figure 2.0:2. Spectral colors[2].

2.1.2 How does solar radiation reach the Earth?

At the top of the atmosphere, solar irradiance is 1367 W/m^2 through the complete solar spectral wavelength; this irradiance value is known as the Solar Constant (World Meteorological Organization, 2017). In the atmosphere, a small part of that radiation is reflected to space, and another small part is absorbed. A portion of the remaining radiation hits the surface of the planet (direct radiation) directly, while the other portion scatters through multiple reflections in the atmosphere's particles (such as air molecules, water vapor, clouds, dust) until it is reflected back to space or down to the planet (diffuse radiation).

Besides the effect of climate conditions and the atmosphere's composition in the amount of solar energy reaching the planet, location also plays an important role. Due to the curvature of the planet's surface, sun rays hit the Earth from different angles, ranging from 0º to 90º, in relation to the plane of the horizon. This angle, designated as *solar altitude*, varies from place to place and, within the same place, varies along the day and the year. Finally, due to orography, the local landscape may also influence the solar energy received on the surface.

Solar geometry is the tool used to understand how solar radiation reaches the surface of the planet as well as the surface of buildings and cities. With 12,742 kilometers in its greater diameter, the Earth revolves around the Sun in an elliptical orbit, named

[2] Gringer, *sRGB rendering of the spectrum of visible light, image*, viewed May 7th, 2018 <https://en.wikipedia.org/wiki/Visible_spectrum>

Ecliptic, at a distance between 152×10^6 km (the point in the orbit where the distance to the Sun is greater is called Aphelion, occurring around July 1st) and 147×10^6 km (the point in the orbit where the distance to the Sun is smaller is called Perihelion, occurring around January 1st). The full revolution takes 365 days, 5 hours, 48 minutes, and 46 seconds (Figure 2.0:3).

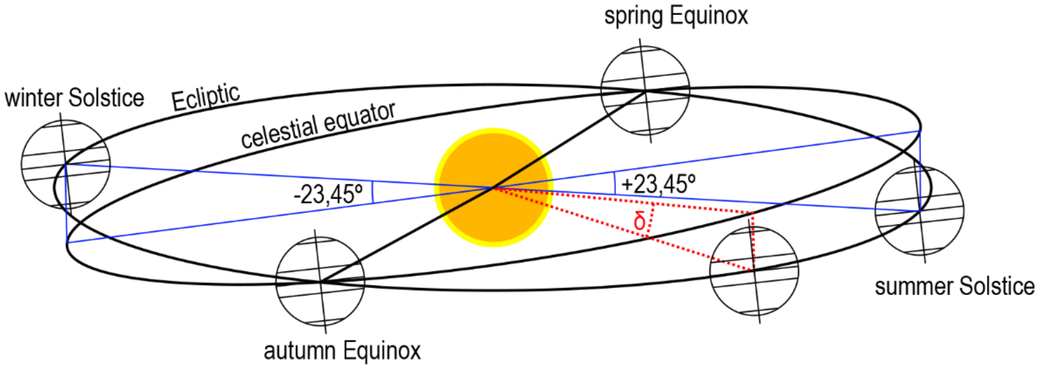

Figure 2.0:3. Earth's trajectory around the Sun adapted (González, 2004, p. 132).

The incidence of solar radiation on the planet's surface varies along the year and the time of the day. In the first case, variations are due to the fact that the Earth's rotation axis is tilted 23,45° in relation to the plane containing solar radiation; variations along one single day are due to the 24 hour-period rotation of the planet. These variations may be better understood if we consider the Earth to be in the center of the celestial vault, and the Sun to revolve around the planet, in what is called the apparent movement of the Sun. In this convention, the apparent position of the Sun is defined according to four coordinates, grouped in two reference systems: the plane of the celestial equator (equatorial coordinates) and the plane of the horizon (horizontal coordinates). However, as it was mentioned above, the geographic location of a given place is determinant in calculating the sunray incidence due to the curvature of the Earth's surface, considering that solar beams are parallel to each other. Therefore, the coordinates used to define a specific location on Earth using the reference ellipsoid – latitude and longitude – are also needed to calculate solar coordinates.

Latitude (φ) is the angle between the plane of the equator and the normal to the surface of the reference location and describes the north-south position of a given place. Latitude is measured in relation to the equator (0°) and ranges from -90º (or 90° South), at the South Pole, and +90º (or 90° North), at the North Pole. Lines with constant latitude are called parallels. Longitude (λ) is the angle between two planes, both containing the North and South Poles: a reference plane crossing the planet's surface at Greenwich (England),

and the plane crossing the planet's surface at a given location. Longitude describes the East-West position of a given place. Lines with constant longitude are called meridians.

Equatorial coordinates

The equatorial coordinates are Declination (δ) and Hour Angle (H) (Szokolay, 1996) (González, 2004) and are angular measures in reference to the plane of the celestial equator.

Declination is the angle between the plane of the Earth's equator and the solar beams. This angular measure varies throughout the year because the planet's rotation axis is tilted 23.45° in relation to the ecliptic (Figure 2.0:4).

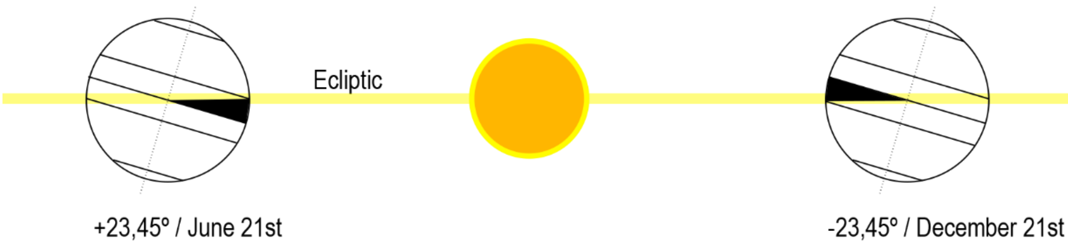

Figure 2.0:4. Declination of the Earth (adapted from Szokolay, 1996).

Declination varies between -23.45° (December Solstice) and +23.45º (June Solstice). At the time of the equinox (proximally March 21st and September 21st), declination is zero (Szokolay, 1996). Declination (δ) may be calculated according to equation 1 (González, 2004):

$$\delta = 23.45 \cdot \sin\left(360 \cdot \frac{284+N}{365}\right) \qquad \text{(eq. 1)}$$

where, N: day number.

The Hour Angle expresses the relative position of the Sun, for a given time of the day with respect to the solar noon. It is the angle between the plane containing solar radiation and the plane of the local meridian. For a given time of the day, the Hour Angle is independent of the day of the year, latitude, and longitude. Hour Angle (H) may be calculated according to equation 2 (González, 2004):

$$H = 15 \cdot (12 - t) \qquad \text{(eq. 2)}$$

where, t: time of the day.

Horizontal coordinates

The horizontal coordinates are Solar Altitude (h) and Solar Azimuth (A) (Szokolay, 1996) (González, 2004) and are angular measures in reference to a given location's horizon plane (the plane that is tangent to the Earth's surface at that location).

Solar Altitude (h) is the angle, measured on a vertical plane, between solar radiation and the horizontal plane; it may be calculated according to equation 3 (González, 2004):

$$h = \sin^{-1}(\sin\varphi \cdot \sin\delta + \cos\varphi \cdot \cos\delta \cdot \cos H) \qquad \text{(eq. 3)}$$

where, φ: latitude; δ: declination; H: hour angle.

The maximum solar altitude for a given location on a given day, corresponding to the time at solar noon, is calculated through equation 4 (González, 2004):

$$h_{max} = (90 - \varphi) + \delta \qquad \text{(eq. 4)}$$

Solar Azimuth (A) is the displacement of the vertical plane containing solar radiation relative to its position at solar noon, measured in the plane of the horizon. There are two types of conventions to measure Solar Azimuth. The first is referenced to the geographic North, which corresponds to 0°, and evolves through East (90°), to South (180°) and West (270°) up to 359°; for instance, this is also how navigation systems refer to the direction of movement. The other type of procedure is more related with the study of how the Earth's surface garners solar radiation and how it affects human activities; in this case, the reference (0°) is the direction of solar radiation at solar noon: North in the Southern hemisphere, or South in the Northern hemisphere. Solar Azimuth may assume positive values when the solar radiation's direction is to the East of the reference or negative values when it comes from the West of the reference. This last convention is widely used in Architecture because it is directly related to the analysis of how solar radiation affects buildings and their use. In this research, the reference to calculate Solar Azimuth is South.

Solar Azimuth (A) may be calculated according to equation 5 or equation 6 (González, 2004):

$$A = \sin^{-1}\left(\frac{\cos\delta \cdot \sin H}{\cos h}\right) \qquad \text{(eq. 5)}$$

$$A = \cos^{-1}\left(\frac{\sin\varphi \cdot \sin h - \sin\delta}{\cos\varphi \cdot \cos h}\right) \qquad \text{(eq. 6)}$$

where, δ: declination; H: Hour Angle; h: solar altitude; φ: latitude.

Equation 5 is more accurate concerning negative values of the Solar Azimuth and in locations at low latitudes. Equation 6 is only accurate for the Northern Hemisphere at latitudes higher than 10° (González, 2004).

2.1.3 Solar incidence on buildings surfaces

Solar radiation may reach the surface of a building either directly – direct radiation –, or indirectly – diffuse radiation from the atmosphere and reflected radiation from the surroundings (which is dependent on the type of constructions and materials surrounding the building). How incident solar radiation translates into energy gains inside a building depends upon the available solar energy, the angle of incidence, and the shading control strategies in place. Therefore, solar altitude (h), the surrounding obstacles, and the building's solar orientation play an essential role (Hausladen, Saldanha, & Liedl, 2008).

The incidence of solar radiation in buildings plays a decisive part in its occupant's visual and hygrothermal comfort. In the heating season, the goal is generally to let direct solar energy inside the building to increase and/or maintain comfortable temperatures. Storing heat, for instance, taking advantage of the material's thermal properties, is also an opportunity to keep a steady balance throughout the day. In the cooling season, the strategy is the opposite, avoiding as much as possible direct solar radiation in the building to prevent, or reduce, overheating in the internal environment. In this case, heat storage, through the same effect of thermal inertia, may also be beneficial to delay the internal peak temperature. However, it should be noticed that if there is no effective night cooling, heat storage in Summer will not be adequate. These general goals must, nevertheless, be adjusted according to the building's use, solar orientation, building materials, and the particular features of the local climate. Depending on the relationship between climate and the use of the building, different strategies may be adopted to control solar radiation. The type of use is an important factor because what happens inside the building conditions the amount of heat that is produced as a result of that activity – the internal heat gains. This combination of climate and building use has been the basis for a recent proposal regarding climate classification in which buildings may be considered as *heating dominated*, *cooling dominated*, or *heating and cooling dominated* (Cory, Lenoir, Donn, & Garde, 2011). In this context, solar control plays a very significant role in obtaining internal comfort conditions. The main aspect to consider is the difference between residential and service occupancies. The latter implies much more internal heat gains, due to the higher occupancy rate. Therefore, it may be the case, depending on the local climate, that even in Winter, solar gains shall be avoided. Table 2.0:1 includes the major strategies to consider for the Portuguese climate.

Table 2.0:1. Solar gains, according to the orientation of the façade and the season, adapted to Portuguese geographic coordinates (Gonçalves, et al.,2014)

Façade Orientation	***Winter Season***	***Summer Season***
North	Does not receive direct solar radiation	Receives a small fraction of direct solar radiation – early morning and late afternoon.
South	During the day, the solar route is made by azimuths very close to the geographical south. This orientation favors the highest solar gains.	The solar path throughout the day is close to that of the zenith. If there is shading, solar gains can be easily attenuated.
East	Receives direct solar radiation for a few hours in the morning, with a small angle of incidence.	Receives enough solar radiation from sunrise until noon. Rays strike perpendicular to the façade, maximizing gains (undesirable at this season).
West	Receive few solar radiations during the day (only during some hours in the afternoon). The incidence angles are high, reducing the incidence effect.	Slight solar radiation during the day (only during some hours in the afternoon). The incidence angles are high, reducing the incidence effect.

In Portugal, according to its geographical situation, the South quadrant is the one that receives the highest solar radiation during the day. This is, therefore, the privileged orientation in making the most out of the solar gains (Figure 2.0:5).

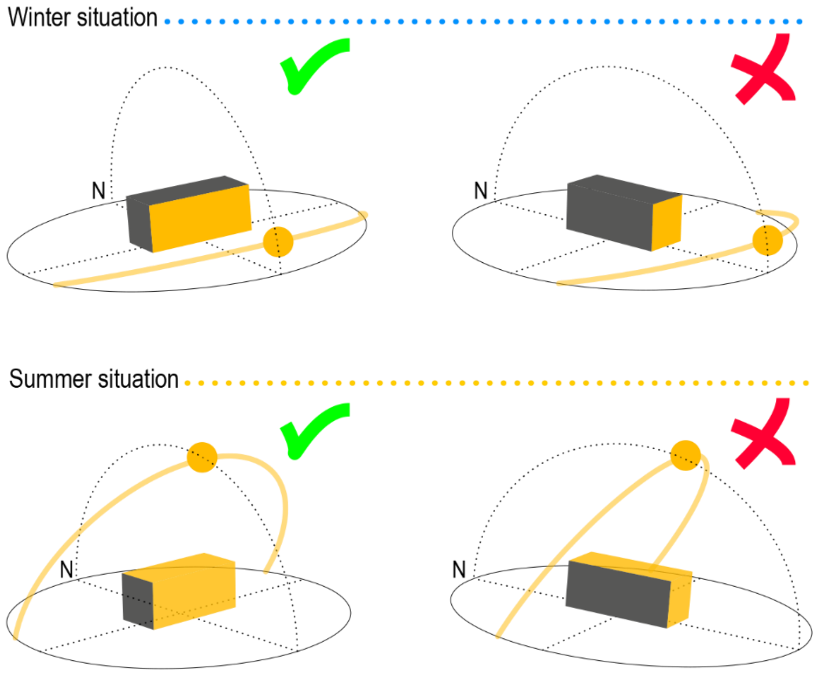

Figure 2.0:5. Evaluating the building orientation according to with Portugal's geographic coordinates.

Buildings' solar gains depend on several aspects related to local, as well as architectural properties: i) climate; ii) window area; iii) type of glass; iv) solar screening; and v) internal thermal storage. Window and glass properties also have an important influence on heat loss through the building envelope. Therefore, window design has to consider an adequate balance between the heating and the cooling seasons, evaluated according to the climate and the functional requirements for the building. Solar screening is a fundamental factor in controlling how solar radiation enters the building. In the heating season, solar gains are a benefit in most cases, while in the cooling season, they almost always represent a significant disadvantage. Ideally, based on the exterior environment temperature, solar screening should adapt (open/close) according to the room's temperature (Hausladen, Saldanha, & Liedl, 2008).

2.1.4 Shading calculation

Shading devices are an effective way to control solar radiation, creating a better balance between the admission and blockage of radiation as a function of the outside climate and the use of the building. Shading devices are used either internally, externally, or in between a layered façade. They can be mechanical equipment, projections, cantilevers, louvers, fins, or even textiles. Shading devices can be fixed, manually and automatically moveable, but their primary goal is always to create and improve a more comfortable internal environment.

External shading devices can eliminate the direct radiation component and also reduce the diffuse component. Depending on the type of climate and the latitude, it may be possible to design shading devices that let in the heating season's solar radiation and block it during the cooling season. The design of these shading devices employs two shadow angles, the Horizontal shadow angle (H_{sa}) and the Vertical shadow angle (V_{sa}) (Szokolay, 1996).

The horizontal shadow angle is the result of the difference between the solar azimuth and the building surface azimuth (Figure 2.0:6).

$$H_{sa} = A - A_w \qquad \text{(eq. 7)}$$

where, A: solar azimuth; A_w: building surface azimuth.

The vertical shadow angle is a function of solar altitude and H_{sa} (Equation 8):

$$V_{sa} = arctan\,[\tan h \cdot (\cos H_{sa})^{-1}] \qquad \text{(eq. 8)}$$

where, h: solar altitude.

Considering the shadow angles and the longitude of the shadowing obstacle (L_{so}), horizontal and vertical shadow dimensions (H_{sl} and V_{sl}) can be calculated using equations 9 and 10.

$$H_{sl} = L_{so} \cdot \tan H_{sa} \qquad \text{(eq. 9)}$$

$$V_{sl} = L_{so} \cdot \tan V_{sa} \qquad \text{(eq. 10)}$$

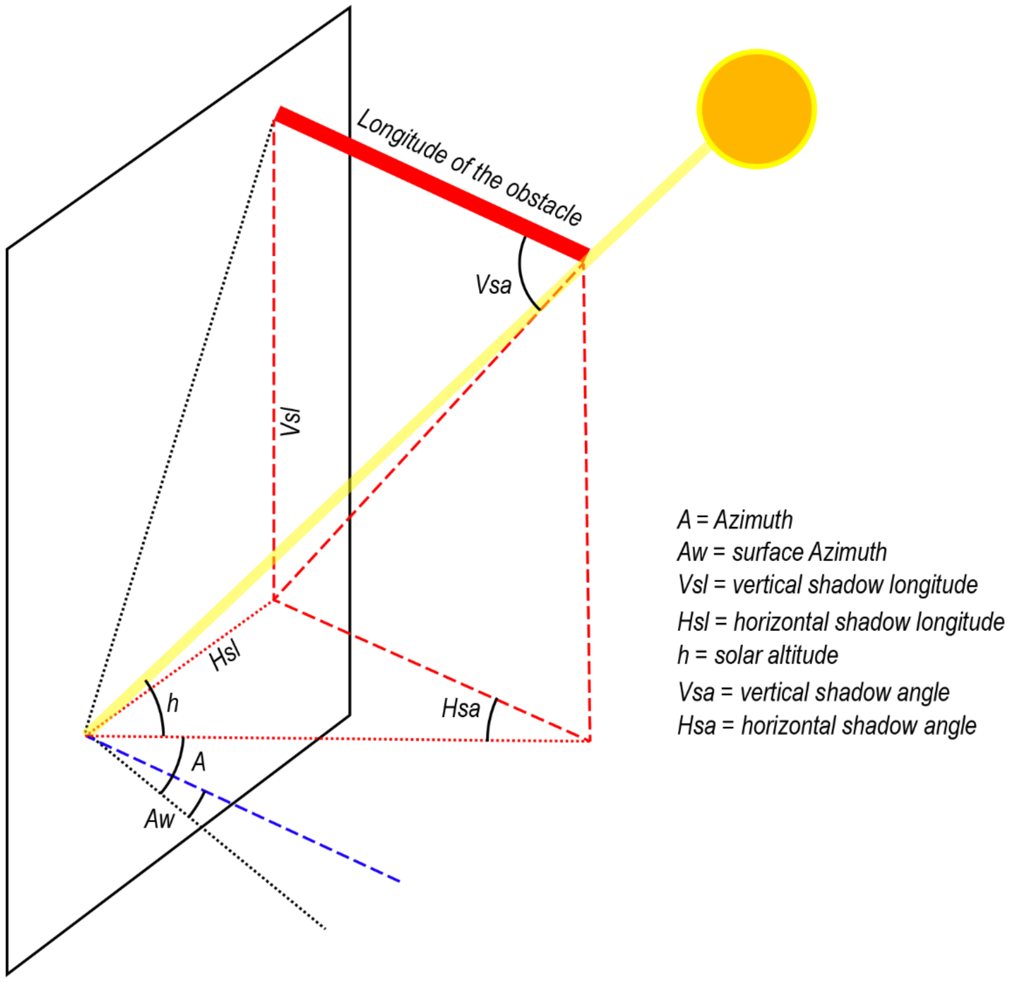

Figure 2.0:6. Angles and shadow longitude on a vertical surface, adapted from González, 2004, p.165.

2.2 Solar radiation in the context of hygrothermal comfort

Two factors determine human thermal comfort: 1- environmental factors, conditioned by the human surrounding environment, being affected by climate, space and its inhabitants, establishing a psychological and physical equilibrium state; and 2- personal factors, when the body reaches the level of homeostasis, or as Olgyay defined a "*point to which the individual spends the least quantity of energy to adapt to its environment*" (Olgyay, 2015, pp. 14-15). Human homeostasis is intimately connected with temperature and relative humidity of the surrounding environment leading to the definition of hygrothermal comfort.

According to the ANSI/ASHRAE Standard 55, thermal comfort is the condition of the mind that expresses satisfaction with the thermal environment and is a subjective evaluation (ASHRAE, 2017). Satisfaction with thermal environment is maintained when the heat generated by human metabolism can dissipate, enabling the organism to maintain its thermal equilibrium with the surrounding environment. Six aspects affect thermal comfort, which are grouped into two factors:

1- Environmental aspects: i) air temperature, ii) mean radiant temperature, iii) relative humidity, and iv) air speed;

2- Personal aspects: v) metabolic rate and vi) clothing.

The air temperature is the average temperature of the air surrounding the occupant, for a specific location and time. Air temperature influences body heat transfer (gain and loss) via conduction and convection. Mean radiant temperature is related to the amount of radiation heat transferred from a surface. This depends on the material´s ability to absorb or emit heat – its emissivity. The mean radiant temperature depends on the temperatures and emissivity of the surrounding surfaces as well as the solar screen, or the amount of the surface that is exposed by the object. Relative humidity (RH) is the ratio of the amount of water vapor in the air to the amount of vapor that the air could hold at the specific temperature and pressure. At high RH, the air has close to the maximum water vapor that it can hold, so evaporation and heat losses are decreased. On the other hand, very dry environments where RH range between 20-30%, are also uncomfortable. This happens because of their effect on mucous membranes. ASHRAE Standard 55 establishes the recommended level of indoor humidity in the range of 30-60%; however, new standards on adaptive thermal comfort allow lower and higher humidity, depending on other factors involved in thermal comfort (Velleia, Herrera, Fosas, & Natarajan, 2017). Based on the ASHRAE Standard 55, air speed is the average speed of the air to which the body is exposed, for specific location and time.

Depending on their environment and activity level, people have different metabolic rates. ANSI/ASHRAE Standard 55 defines metabolic rate as the level of transformation of chemical energy into heat and mechanical work by metabolic activities within organisms (Figure 2.0:7), usually expressed in terms of unit area of the total body surface. The metabolic rate is expressed in Metabolic Equivalent of Task (MET) units.

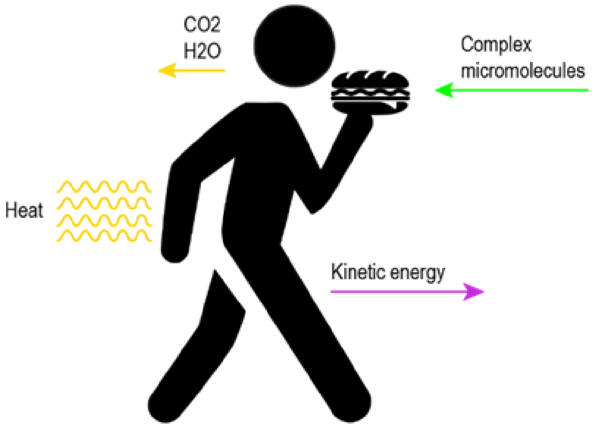

Figure 2.0:7. Metabolism.

The amount of *clothing* worn by a person has a substantial impact on thermal comfort because it influences the heat loss and, consequently, the thermal balance. ASHRAE Standard 55 recommends internal air temperatures of 20-23 ºC in winter and 22-27 ºC in summer considering for normal clothing. There is, therefore, a close relationship between solar radiation and hygrothermal comfort. Controlling how this radiation enters the building is an important task of the design team. Depending on the use of the building, local climate, and architectural properties, the interface between solar radiation and the internal environment must be carefully considered so that the best possible balance between assuring and avoiding solar gains is obtained. Controlling solar radiation is also a part of passive solar systems deployed in architecture as a way of achieving hygrothermal comfort with the least possible energy consumption. The set of the main passive solar systems for thermal comfort includes strategies for direct, indirect or isolated heat gains, and Trombe walls. Shading is a part of these strategies in the cooling season. On the other hand, solar control systems need to ensure adequate levels of daylight inside the building. Together with the need for ensuring direct views to the external environment, the design of shading systems has to consider the need for transparency. In the cooling season, visual comfort is, therefore, obtained through diffuse radiation. In turn, in the heating season, the objective of letting in solar radiation is generally the means to obtain daylight. However, an important aspect is the need to avoid glare in a time of the year when solar altitude is lower, increasing the risk of visual discomfort by direct solar radiation.

2.3 Solar façades – case studies

The design strategies above described are valuable reviews, both from an environmental and an architectural point of view. A short list of case studies is now presented, based on different urban contexts, in generic business spaces, providing a clear range of examples of how different approaches embedded environmental thinking within a variety of design positions.

Located in downtown Los Angeles, the Caltrans District 7 Headquarters (Figure 2.0:8A.), designed by Morphosis Architects (2004-2011), was the first building to be commissioned under the Design Excellence Program. The building is noticeable for its mechanical skin, that reacts to its surrounding environment by a close-coupled fixed, planar, open-jointed, integrated photovoltaics (PV) shade screen, depending on temperature and sunlight conditions. This creates a constantly shifting façade that is closed and private during the daytime and becomes open and transparent during the night. Neo Solar Power Energy Corp., also known as NSP (Figure 2.0:8B.), is a Taiwan-based solar cell and module manufacturer designed by J. J. Pan & Partners (2009-2012). The new building has a 'foldable' unit composed of a glass and aluminum curtain façade that converts sunlight into electric energy, through the use of photovoltaic cells. The perimeter of each floor varies with the advancing and recessing surface walls, and the trimming steel beam curving with the floor slab serves as the fixed end of the curtain walls. In order to present a clear-cut and transparent look, the large glass exterior walls of the office building are complemented with movable vertical blinds to shield off light from the north (Pan & Partners, 2011).

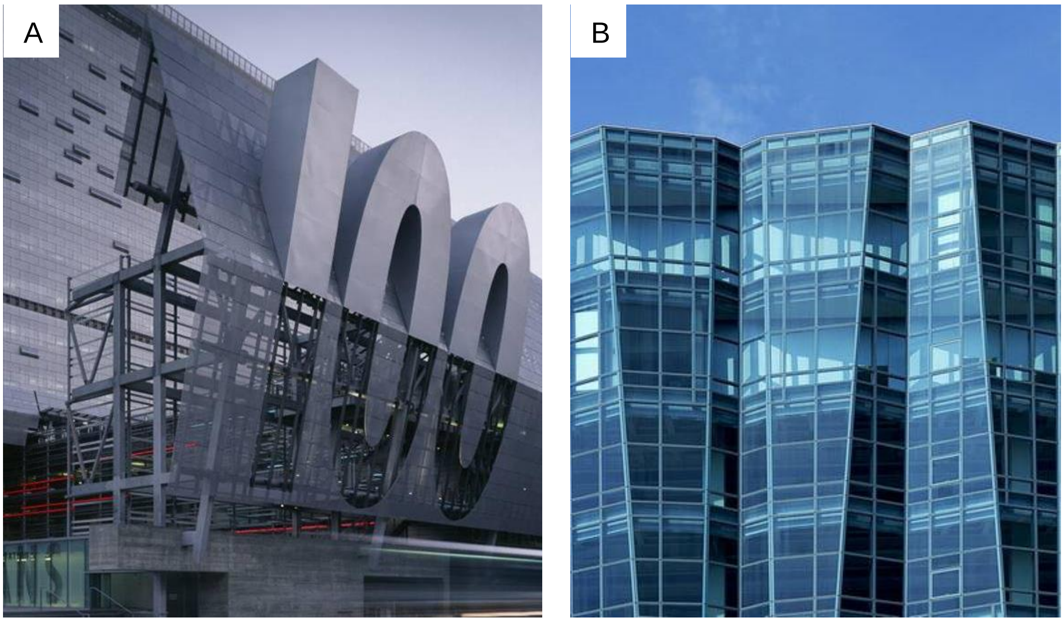

Figure 2.0:8: A. Caltrans District 7 Headquarters[3](2004); B. Neo Solar Power Corporation[4] (2005).

Designed and material developed by Decker Yeadon, New York, USA, 2013, the Homeostatic façade (Figure 2.0:9A.), is a prototype system that comprises an engineered ribbon, inside a double glass façade. The system consists of a ribbon that flexes and bends as an artificial muscle reacting to solar heat gain by changing shape on its own. The ribbon

[3] *Caltrans District 7 Headquarters*, n.d. photograph, viewed 30 May 2018, <https://www.morphosis.com/architecture/13/>
[4] *Neo Solar Power Corporation*, 2011, n.d., photograph, viewed 30 May 2018, < https://inhabitat.com/neo-solar-power-headquarters-has-a-striking-blue-folded-facade/neo-solar03>

is made of dielectric elastomers, coated with silver electrodes, that reflect light and also distribute electrical charge through the material. The increased charge causes the elastomer to expand, making the core of the muscle to bend by pulling it to one side, creating a closing-up effect that blocks the sunlight (Yeadon, 2014). This system regulates the building temperature by responding to environmental conditions (Minner, 2011). Located in Groningen, Netherlands, the EEA+DTO (Figure 2.0:9B.), designed by UNSTUDIO office (2006-2014) is an aerodynamic high-rise building, characterized by its organic and asymmetric design. It accommodates two institutions, the Education Executive Agency and the Dutch Tax Office. Sustainability steered the design of the façade into fin-shaped elements wrapping the building, integrating sun shading, wind and daylight control. The system manages daylight and blocks excess heat, thus reducing the requirement for cooling, an essential feature in office buildings. Fresh air, adjustable heating, and ventilation were also important factors contributing to the comfort of the individual workspaces throughout the building. A high-pressure ventilation system, with intake and extraction of fresh air via the central main shaft and façade valves, provides an underfloor supply of air, which is then extracted via ceilings (UnStudio, 2014).

Figure 2.0:9: A. Homeostatic Façade System[5] (2013); B. Education Executive Agency Tax Offices[6] (2014).

During the social and urban experience of Sociopólis in Valencia, Spain, Ábalos+Sentkiewicz Arquitectos designed the Torre Solar (2012). Torre Solar (Figure 2.0:10A) below, explores the possibilities of a tower that is fragmented at its crown, multiplying the indoor and outdoor spaces with identities of their own. Its passive strategy

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[5] *Homeostatic Façade System,* n.d., photograph, viewed 30 May 2018, <https://materia.nl/article/homeostatic-facade-system/homeostatic-facade-system-10/>

[6] *Education Executive Agency Tax Offices*, n.d., photograph, viewed 30 May 2018, <https://www.dezeen.com/2011/04/19/duo%C2%B2-by-unstudio/>

takes advantage of its height, guaranteeing sunlight exposure and promoting cross-ventilation. Being a social housing project, environmental strategies were conditioned, leading to a more operative and economical solution that combines the reduction of heat gain, using ventilated reflecting façades with cross-ventilation, designing dwellings oriented in two directions, and fully opening windows with high-performance glass. With a minimal impact, Torre Solar explores the physical and landscape characteristics of high-rise constructions, obtaining an average of almost 300 days of passive comfort (Abalos & Ortega, 2015). Introducing the EDP Headquarters project, the architects stated that the pattern of the façade 'resolves' the whole building. Designed by the Aires Mateus office, the EDP Headquarters (2015) (Figure 2.0:10B) is located in the Portuguese capital, Lisbon. Rising perpendicularly to the river, the building is marked by its sharp vertical lines on the façade. The glass façade is supported by steel columns, which also serve as the supporting structure for white glass-fiber reinforced concrete vertical blades. These iconic and monotonous building images came from the research of a system of lights and shadows. These vertical elements, although static, also perform the function of sun-shading and shape the signature appearance of the building. They are placed at an angle to counter the strong East/West solar exposure (Nyawara, 2017).

Figure 2.0:10: A. Torre Solar[7] (2012); B. EDP Headquarters[8] (2015).

The previous case studies exemplify passive and active systems, present through both dynamic and/or static systems, materialized by distinct strategies. While Caltrans

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[7] *Torre Solar,* José Hevia, Photograph, viewed 5 March 2019 < https://www.archdaily.com.br/br/01-118223/torre-solar-slash-abalos-plus-sentkiewicz-arquitectos/518cf3d2b3fc4bd5cd000043-solar-tower-abalos-sentkiewicz-arquitectos-photo>

[8] *EDP Headquarters*, n.d., photograph, viewed 30 May 2018, <https://www.archute.com/wp-content/uploads/2017/11/featured_image.jpg>

District allies PVs to an open-close exterior single skin mechanical system, creating a dynamic façade, the Neo Solar Power Corporation and the Education Executive buildings use material combination on a single skin static strategy façade to convert sunlight into electric energy. Inspired by the behavior of the muscles, the Homeostatic façade is composed of open-close elements, creating a passive dynamic system, exploring material properties and characteristics. More than a material-based prototype, homeostatic façade is also a double-skinned façade with direct ventilation (during the hot season, these openings allow the intake of air supply without increasing the temperature in the façade cavity). In the EEA+DTO, the architectural office UN Studio explored, through the study of environmental fauna and flora, aerodynamics and material characteristics, how sustainability can steer the façade design. In the last two cases, the Torre Solar and the EDP Headquarters, both Mediterranean examples, controlled direct sunlight using two different strategies. The Torre Solar, in addition to curvilinear geometry coated by reflection material, works in a double layer plan, creating a situation where the windows are back in relation to the exterior façade, whilst the EDP Headquarters protects its excessive glass façade using a secondary structure of vertical fiber-glass reinforced concrete static blades that block East and West direct sunlight. Environmental issues and sustainability are on the order of the day, and reducing buildings' operational energy costs is an important task today. One of the main strategies to reduce buildings' energy demands and providing comfortable interior environments is an efficient building façade system. The study of façades becomes (again!) a central theme in Architecture, after all, it is the buildings' façades that separate and mediate the relationship between external elements and variables from the internal uses and inhabitants, providing them more sustainable and comfortable living conditions.

2.4 Insights

In the European Union, construction is the largest industrial sector, being the one which consumes most natural resources, space, materials, energy, and water - while also producing the most significant adverse environmental impact. For a more sustainable construction, it is necessary to reflect on the constructions of yesterday and the constructions of tomorrow. It is crucial to rethink the process of project development, the constructive process of considering aspects such as climate, culture, landscape, and industry resources. Sustainable architecture cannot be limited to the application of general principles or absolute recommendations because it must be a response to specific habitability requirements in a given territory. The integration of principles of environmental sustainability in architecture is reflected in the use of energy and materials, so to achieve appropriate levels of user light, comfort, and a lower environmental impact obtained from the interaction with the climate itself. The different approaches adopted can be: "ecological architecture" integrating the totality of natural and human resources; "bioclimatic architecture" focusing primarily on issues related to energy and comfort; "passive solar architecture" which privileges solar energy as a source of comfort and low environmental impact.

The ecological design of a building should minimize consumption in the construction phase and enhance the optimization and generation in the usage phase. In this phase, energy efficiency depends on real decisions related not only with constructive systems but also with the incorporation of elements generating energy. In relation to building construction systems, the energy performance of buildings is conditioned by their inertia, insulation, heating and cooling, ventilation, and space lighting. Optimization and the generation of renewable energy systems can partially replace fossil fuels and reduce $C0_2$ emissions associated with the use of buildings. The systems are divided into two: (1) Passive systems for conservation and direct utilization of energy that does not add other components or technologies to the base system; (2) Active systems, associated with conversion systems, characterized by the addition of elements to the construction system. The energy-related energy functions of a building, which are the key aspects of a sustainable project, include climate control (heating and cooling), ventilation, lighting, and integrated control of environmental conditions.

The solar heating of the buildings is obtained from direct and indirect gains. The direct gains are captured by glazed surfaces exposed to the South, opening directly into habitable compartments in order to allow the storage of heat. The indirect gains are obtained by elements of high thermal mass orientated to the South, that store the heat and indirectly warm the habitable compartments. The shape, orientation, and layout of a building's space conditions the use of solar gains and, therefore, the heating efficiency of buildings. However, to take advantage of solar radiation, it is also necessary to ensure the storage of heat in buildings' construction elements. These should gradually restore the heat while also considering the existence of devices that prevent overheating. Solar heating is based on: *Collection* - the collected solar energy is converted to heat; *Storage* - heat collected during the day is stored for future use; *Distribution* - the heat collected is stored and redirected to other rooms that require heating; and *Conversion* - the energy is converted into thermal or electrical energy.

The interaction between interior spaces, building elements, and the outside environment causes natural heat transfer, which under certain conditions, may have the effect of ventilation. When two air masses meet at different temperatures, the movement of the air moves from the cooler zone to the warmer zone. This flow can be harnessed and conducted to ventilate and cool the interior of buildings. Before dissipating excessive heat from ventilation and cooling, the minimization of heat from solar radiation generated by occupants and equipment must be provided, using preventive heating actions such as reducing the penetration of solar radiation into spaces; provision of a shade compatible with passive heating and natural lighting; coloration of exterior surfaces with light colors for partial reflection of the incident radiation; use of vegetation and water elements for shading and evaporative cooling; use of the thermal mass of the earth for cooling the air; minimization of external and internal heat gains through insulation, reduction of opening of gaps, thermal inertia, application of reflective materials, more efficient use of natural lighting and ventilation (Mourão & Pedro, 2012).

In a direct passive system, conventional building components are used as devices to capture direct gains from solar energy, wind, or water. In order to design a bioclimatic space, the main strategies are the orientation of the building, direct evaporative cooling from water, natural cross or rising ventilation, direct use of daylight, and the introduction of insulation and thermal mass. Indirect passive strategies require specific building components for capturing, storing, and releasing energy gains. The Trombe wall (for conservation); ventilated façade and double skin (cooling and ventilation); vertical ventilation and lighting elements, and indirect lighting devices are some of the components that perform different 'energy functions'.

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SECTION II
BACKGROUND

3.0

Fundamentals of Biomimetics

3.0 FUNDAMENTALS OF BIOMIMETICS

Biomimetics is a research field that observes natural models to improve human-made systems. Biomimetics is also often described as the study of the formation, structure, or function, of biologically-produced substances and materials (e.g., enzymes or silk) and biological mechanisms and processes (protein synthesis or photosynthesis) for synthesizing similar products by artificial mechanisms which mimic natural ones (Merriam-Webster, 2013). In other words, in biomimetics, humans seek to use natural examples and natural systems to inform the process of creating materials, components, products, and processes. Therefore, biomimetics is a creative form of technology that uses or imitates nature to improve human lives (Hwang, et al., 2015).

When exploring the term *biomimetics*, several semantic derivations arise. *Bionics*, *biomimetics*, and *biomimicry* are the central terms of this discussion. Although for many people these terms are unclear and hard to distinguish, time and mean separate, nonetheless, these three terminologies.

The first to emerge as an accepted term was bionics. During the early '60s of the 20th century, Jack Steele, a USA Air Force Aerospace Medical Division engineer, coined the term bionics to describe technological advancements. The term combines biology with technics, and it was described as a copy, an imitation, which learned from a biologic process. In 1960, the first Bionics Symposium: *Living prototypes - the Key to New Technology* takes place at the Wright-Patterson US Air Force Base in Ohio. Later in 1998, in his book "Cats, Paws and Catapults", Steven Vogel defined *bionics* as a design system.

[bionics] "(…) is based on living systems. The word 'systems' came naturally to those, mostly engineers, initially involved; neural systems and physiological controls formed biological parallels to human technology's cybernetics and systems theory (…)" (Vogel S. , 2000, p. 250).

In 1969, Otto H. Schmitt, a biomedical engineer that devoted the early stages of his career producing a device that mimicked the electrical action of the nerve, coined the term biomimetics. Biomimetic found its roots from the Greek words bios and mimesis. *Biomimetics* mainly focuses on the technical aspects of the translation of functional strategies used by biological organisms or systems, recognized as an emerging field and a promising approach for a more resilient environment (Al-Obaidi, Ismail, Hussein, & Abdul, 2017). *Biomimetics* aims to create new forms of technologies that can supplant existing ones or become iconic artifacts, always being monetarily rewarded.

Biomimicry was coined in 1997 by Janine Benyus, a natural sciences writer, with a degree in natural resource management and economic sustainability (Louguina, 2012). *Biomimicry* is an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies (Benyus & Schwan, 2006). It means Nature as a model, measure, and mentor. *Biomimicry* is often described as a research field that studies Nature's models and then imitates or takes inspiration from these designs and processes to solve human problems. It uses ecological standards to judge the rightness of human innovations. It offers a new way of viewing and valuing nature, based not on what we can extract, but on what we can learn from it (Benyus J. , 1997). Relating *biomimicry* with a mimicking practice, Benyus describes her methodology in three stages: Form, by copying the attributes of an organism, as its appearance, visual shape, components and morphological features; Process, by looking deeper and reproducing a biological entity, its physiological development and procedures; Ecosystem, applying mimicking to a large platform where the design goes beyond entities to identify its explicit and implicit effects in the environment (Benyus J. , 1997).

In 2014, Denise DeLuca, Director of the Biomimicry for Creative Innovation Network, states that both fields, *biomimetics* and *biomimicry* “(…) *face the same challenge of forwarding a different thinking, approaches and innovations in an otherwise conventional world* (…)” (DeLuca, 2014). However, while biomimetics is concentrated on a scientific translation, technological innovation, and its consequent commercialization, biomimicry is concentrated on a reconnection with Nature, by means of inspiration, ideation, and education, using biomimetics technical skills to enable their innovations.

3.1 Biomimetics’ and Architecture Short History

The use of analogies and the direct application of various principles and strategies of Nature in the search for new conceptual and innovative solutions in various areas such as architecture, engineering, and design, among others, is unquestionable. Moreover, although this seems to be transversal in several areas of research along time, it is still difficult to establish an exact chronology of all turning events related to the contemporary state of the art of the biomimetics field. However, there are several key moments documented in History that could help in establishing a *biomimetic timeline*. The following 'short history' aims at being a sample of facts.

A classical starting point for biomimetics experiences and field is usually attributed to Leonardo DaVinci Codex on the Flight of the Birds (Figure 3.0:1A). The revealed texts and plans speculate over the potential and ability of humans to fly. In the Codex, Da Vinci detailed a mechanical engine, inspired on the flight of the birds, where he designed some possible strategies and mechanical solutions similar to the ones present in today's airplanes. It is necessary to go back to the 19th century to find a second history mark about *biomimetics*. In 1859, Joseph Paxton built the Crystal Palace (Figure 3.0:1B) pavilion for the first Great Exhibition of the Works of Industry of All Nations, held in London. The Crystal Palace, inspired by water lily leaves, was a 92.000 m^2 open space, covered by crisscrossed iron girders that supported 300.000 glass surfaces. In order to ensure the free open space, Paxton conceived a structural solution based on the rib's interconnectedness of the water lily. This ribs system enables the possibility of free space through the distribution of weight.

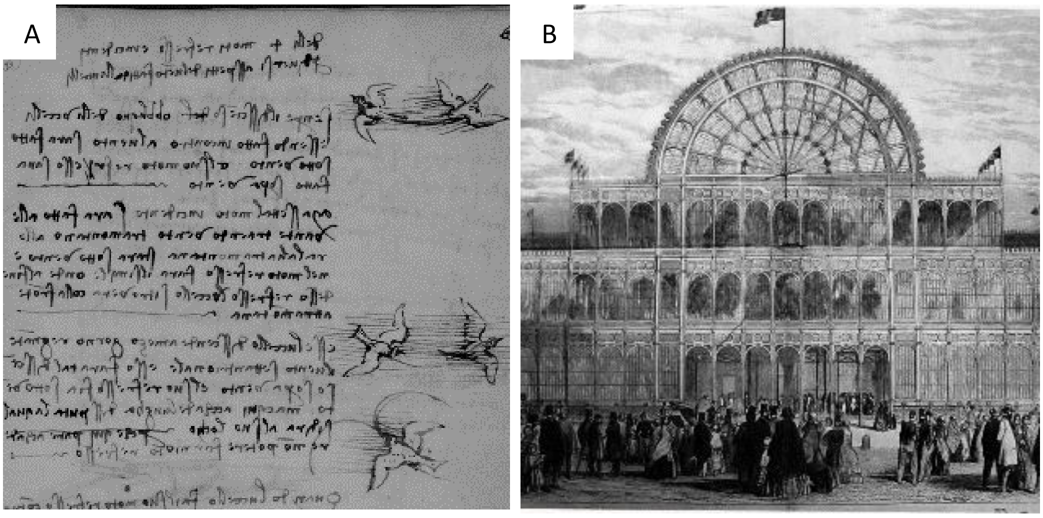

Figure 3.0:1: A (left). Codex on the Flight of Birds[1] *(1505); B (right). The Crystal Palace, South Side*[2] *(1851).*

It took 400 years, since Da Vinci Codex, for the first-ever successful airplane flight to happen (Figure 3.0:2A). It was in 1903 that two brothers, Orville and Wilbur Wright, flew over Kitty Hawk, in North Carolina, for just over a minute. Like Da Vinci, the Wright brothers' craft model, especially the wing control mechanism, was inspired by the way birds use air currents to gain lift and change direction. The first half of the 20th century brought both world wars, but also remarkable technological advancements. Nature was a powerful source of inspiration, and several nature-based products were developed. Later, in 1955, the Swiss electronic engineer, George de Mestral (Figure 3.0:2B), patented Velcro. The product was based on the sticky, prickly cocklebur plant: two pieces of fabric, one with hooks and the other with loops.

[1] *Codex on the Flight of Birds*, n.d. photograph, viewed 11 May 2018, <https://www.wdl.org/en/item/19477/view/1/15/>
[2] *The Great Exhibition Building, South Side*, n.d. photograph, viewed 11 May 2018, <http://www.iln.org.uk/iln_years/year/1851.htm>

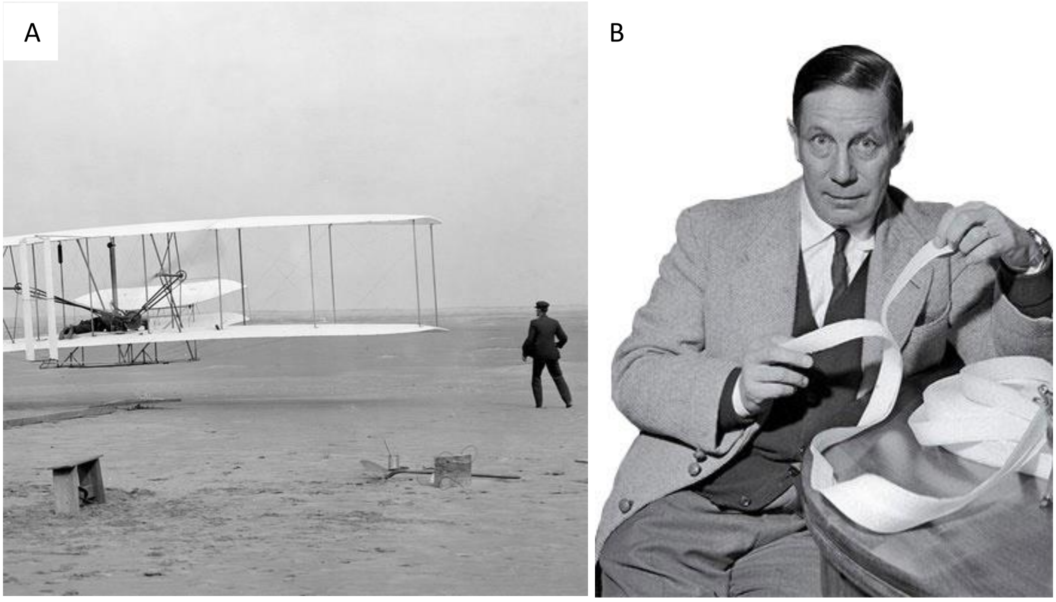

Figure 3.0:2: A (left). Wright brothers flight invention[3] (1903); B (right). George de Mestral[4] (1955).

Three major events marked the 1960s for biomimetics. In 1960, the Wright-Patterson USA Air Force Base in Ohio hosted the first Bionics Symposium: Living prototypes - the Key to New Technology, putting side to side Nature and Technical Biology. In 1962, the British novelist James Ballard described a 'psychotropic house' (Figure 3.0:3A) as a mood sensitive house that could respond and learn from its occupants. The house was conceived to be built from a new material creation called plastex, a combination of plaster and latex, that enables it to change its configuration and form. Equipped with sensor cells, the Psychotropic House was capable of interpreting its occupants' mood and position, in a way that could change its configuration and environment, fulfilling the needs of its users (Oliveira, Rato, & Leitão, 2017). The Psychotropic House presents the possibility of human-made productions, like objects, buildings, and forms, which grow and evolve just like any other living organism. In the late 1960s, the American biophysicist Otto Schmitt (Figure 3.0:3B) uses for the first time in the academic context, the term biomimetics in a scientific article that he presented at the *International Biophysics Congress* in Boston.

[3] *Wright brothers flight invention,* n.d. photograph, viewed 11 May 2018, < https://newsela.com/read/lib-nasa-wright-brothers-invention/id/25690/>
[4] *George de Mestral*, n.d. photograph, viewed 11 May 2018, <http://www.sobrefavoritos.com.br/o-que-e-tecnologia/>

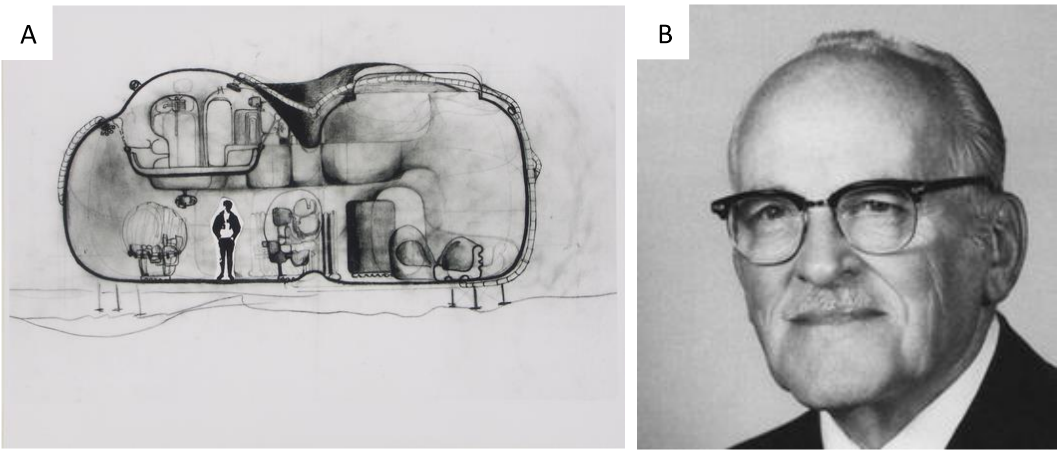

Figure 3.0:3: A (left). Living Pod[5] *(1962); B (right). Francis O. Schmitt*[6] *(1969).*

In 1978, Peter Pearce published the book 'Nature is a strategy for Design' (Figure 3.0:4A). In general terms, he presented the concept of 'minimum inventory – maximum diversity' applied to several mechanical systems. In his book, this concept was applied to a kit of modular parts and rules of assembly. While not being a new concept (during the 19th century, Charles Darwin documented and talked about it in several essays and lectures), its physical application to human-made materials had never been documented. Today at the MIT (Massachusetts Institute of Technology), Neri Oxman applies this concept invariably in work developed by the Media-Lab Research Group. In biomimetics, animals are a valuable source of inspiration. Their capacity in adapting to change through environmental strategies are fundamental sources in the understanding of how they can improve defense and offensive strategies, as well as fine-tune their integration, with minimal resources and maximum diversity. Sharks are one of the most aerodynamic organisms living on the planet. This feature is based on their shape and skin (Figure 3.0:4B), since they allow high-speed by reducing the water/skin friction effect. In 1986, based on shark's skin pattern and chemical composition, NASA (National Aeronautics and Space Administration) and the 3M Company developed a 'skin' that improves jet planes' aerodynamics. The created 'skin' was composed of small indentations, coined riblets, attached to the outer shell of the aircraft with adhesive, in order to reduce drag.

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[5] Greene, D, 1966, *Living Pod*, photograph, viewed 11 May 2018, <https://thefunambulist.net/literature/literature-psychotropic-houses-by-james-graham-ballard>
[6] Bloom, Floyd E, *Francis O. Schmitt,* photograph, viewed 11 May 2018, <https://en.wikipedia.org/wiki/Francis_O._Schmitt>

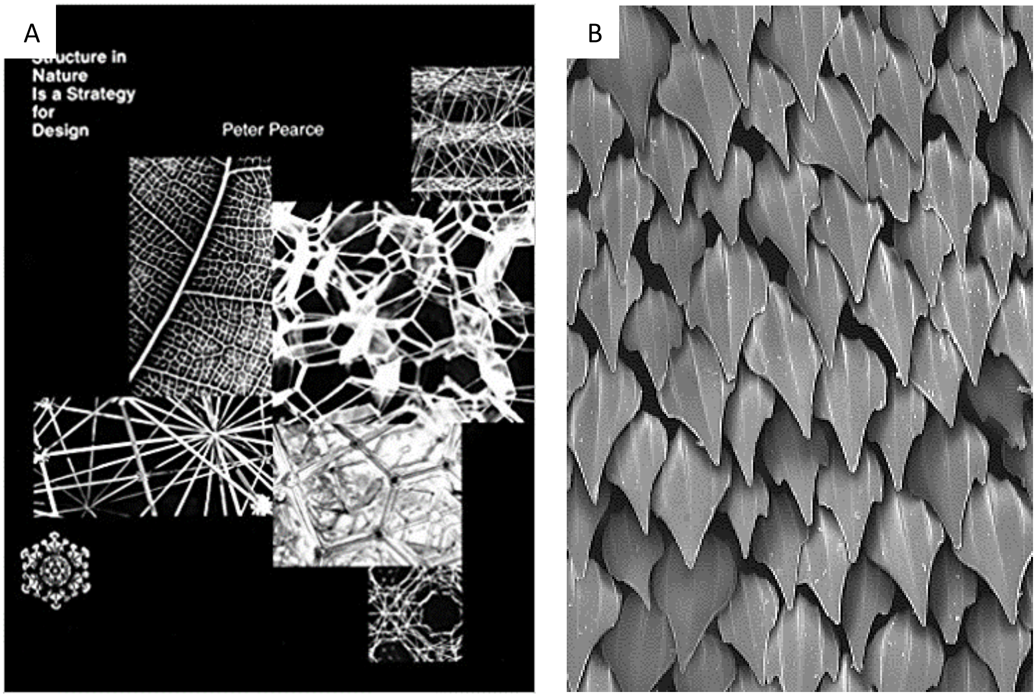

Figure 3.0:4: A (left). Structure in Nature is a Strategy for Design[7] (1978); B (right). Microstructure of a shark's skin [8] (1986).

During the 20th century, biomimetics was present in several extraordinary breakthroughs in a wide range of areas of study such as aeronautics, automotive, material engineering, biomedicine, physics, and chemistry. Architecture had to wait until 1987 to see the first large scale building integrating environmentally adaptive principles. Designed by Jean Nouvel's office, the Institut du Monde Arabe (IMA) (Figure 5A), in Paris, was the first large scale building with an adaptive façade. Known by his attention to façade detailing, Nouvel developed a new interpretation of an archetypal element, the mashrabiya, based on solar studies and heliotropic motion. An advanced responsive metallic brise-soleil on the south façade, composed of hundreds of light-sensitive diaphragms that regulate the amount of light allowed inside the building. Almost ten years later, in 1996, inspired by the self-cooling mounds of African termites, Mick Pearce designed the Eastgate Centre in Harare, Zimbabwe (Figure 3.0:5B). The large office and retail space do not have a conventional heating and cooling system; rather, it uses ventilation chimneys that naturally promote airflow to maintain a temperate environment.

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[7] *Structure in Nature is a Strategy for Design*, n. d., photograph, viewed 11 May 2018, <https://www.amazon.com/Structure-Nature-Strategy-Design-Pearce/dp/0262660458>
[8] *Microstructure of a shark's skin*, n. d., photograph, viewed 11 May 2018, <http://www.biomimicrybe.org/portfolio/shark-skin-inspired-surfaces/>

Figure 3.0:5: A (left). Institute du Monde Arabe, architect Jean Nouvel[9] (1987); B (right). Eastgate Centre Harare[10] (1996).

In 1997, Janine Benyus, a scientist and writer, publishes the book Biomimicry: Innovation Inspired by Nature. In her book, Benyus frames the concepts of biomimicry and biomimetics, developing a type of manifesto around the urgent goal of ending environmental destruction. Today, Benyus' book is considered an essential resource for everyone who wants to work or contribute to these fields of research. During the 1990s, the biomimetics field had already caught the attention of a restricted group of architects – Alberto Estévez, Karl Chu, Dennis Dollens, Mike Weinstock, and Michael Hensel, among other pioneers. Several lectures and essays have been produced, but it was only in 2000 that Alberto Estévez launched the master's degree in Biodigital Architecture at the Universitat Internacional de Catalunya (UIC), in Barcelona, Spain. The pioneer program combines architecture, biology, digital tools, and other trends into a 2-year program, where students are invited to study, explore, and develop new logics and processes of conceptual design, products, and innovative ideas.

3.1.1 Biomimetic Architecture experiences in the XXI century

Every natural system is built upon a minimum inventory/maximum diversity concept (Pearce, 1980). In a successful system, the rules of assemblage and physical components work as natural organisms where rules grow from modules, and modules grow

[9] ©Viennaslide*, Institute du Monde Arabe,* Photograph, viewed 6 March 2019, < http://www.constructionphotography.com/Details.aspx?ID=34794&TypeID=1>
[10] *Eastgate Centre Harare Image #7*, n.d., photograph, viewed 6 March 2019, < http://ttnotes.com/eastgate-centre.html#gal_post_4590_eastgate-centre-harare-6.jpgZ

from rules, creating a relationship of interdependency and consequence (Oxman N. , 2010).

The first decade of the 21st century witnessed a boom in the architectural world. New ways of thinking, but also new resources and materials, new digital tools, and new exploratory links to the industrial design and vocabulary emerged. Resulting from a partnership between architects, horticulturists, and materials manufacturing industry, the Eden Project emerges in 2001 (Figure 3.0:6). Located in Cornwall, United Kingdom, the Eden Project is a horticultural building structure, designed by a multidisciplinary team led by the Grimshaw Architects Office. The project found its basis in clusters of bubbles for its general form and dragonflies' wings to solve a 23.000 m^2 open space structural challenge. The result is one of the lightest structures ever created and a building that is mainly self-heated, making use of passive solar design principles.

Figure 3.0:6: Eden Project [11]

In 2006, Richard Bonser published 'Patented Biologically-inspired Technological Innovations: A Twenty-Year View' in the Journal of Bionic Engineering. The article assesses the growth in the industry of biomimetic innovation. In the following year, Robert Kronenburg published 'Flexible: Architecture that responds to change'. In this book Kronengurg argues that for a building to be flexible, it must be capable of (i) adaptation, to

[11] *Eden Project*, n. d., photograph, viewed 11 May 2018, <https://theredlist.com/wiki-2-19-879-606-226649-view-grimshaw-nicholas-1-profile-grimshaw-nicholas-eden-project.html>

respond to multiple functions, uses and spatial requirements; (ii) transformation, being able to reconfigure its shape, volume, form, and appearance; (iii) movability and (iv) interaction, encompassing the interior and exterior of the house, using intelligent systems. In 2007, Philip Beesley presented at the Musée Des Beaux-Arts, in Montreal, Québec, Canada, the Hylozoic Soil installation (Figure 3.0:7). The installation explores the narrow frontiers between architecture, design, art, and engineering, through the materialization of the relationship between the biological and the artificial.

Figure 3.0:7: Hylozoic Ground [12]

In 2008, Harvard University received from Hansjörg Wyss a donation of $125 million to create the Wyss Institute for Biological Inspired Engineering. Based on biological principles, the goal of the institute is to develop innovative engineering materials and products for the medicine field of study. Thirteen years after having coined the term

[12] Charron, P., *Hylozoic Ground*, photograph, viewed 11 May 2018, <https://www.dezeen.com/2010/08/27/hylozoic-ground-by-philip-beesley/>

biomimicry, Janine Benyus co-founds the Biomimicry 3.8 platform. The name of the consulting company is a direct reference to 3.8 billion years of natural life, and it actuates by training and educating other institutions on how to incorporate bio-inspired innovation into their every-day practices.

In the second decade of the 21st century, many professional and academic experiences have been reported and documented over possible biomimetic applications, means, and concepts. In 2012, at the University of California, Doris Sung led her work team to design and build a sun-tracking installation indexed by time and temperature, called 'BLOOM' (Figure 3.0:8A). The installation combined material experimentation, structural innovation, and computational form/pattern, making it an environmentally-responsive installation. At a different scale, SOMA designed the 'One Ocean' pavilion for the 2012 South Korea World Exhibition (Figure 3.0:8B). The main façade of the pavilion is made of 108 reinforced glass-fiber kinetic polymer gills. Each gill can be individually controlled, reflecting an overall choreography.

Figure 3.0:8: A (left). Bloom Installation13 (2012); B (right). One Ocean, Thematic Pavilion14 (2012).

Taking biomimetics into an all-new level, the MIT Media Lab, led by Neri Oxman, presented in 2013 the Silk Pavilion (Figure 3.0:9A). Inspired by the way silkworms weave

[13] DO|SU Studio Architecture, *Bloom Installation*, photograph, viewed 6 March 2019, < https://www.arch2o.com/bloom-installation-do-su-studio-architecture/#jig[2]/2/>

[14] SOMA, *One Ocean, Thematic Pavilion/soma*, photography, viewed 6 March 2019 < https://www.archdaily.com/236979/one-ocean-thematic-pavilion-expo-2012-soma/5001233f28ba0d2c9f000af2-one-ocean-thematic-pavilion-expo-2012-soma-photo>

a delicate cocoon from a single yarn, the pavilion was created based on a pattern of yarns, robotically assembled around a steel frame, and by 6,500 living silkworms that were released on the structure. This was a remarkable performance documented in real-time that fostered human and animal collaborations. Later in the same year, the Institute for Computational Design at the University of Stuttgart, Germany, presented the HygroSkin: Meteorosensitive Pavilion (Figure 3.0:9B). Designed by Achim Menges in collaboration with Oliver Krieg and Steffen Reichert, the Hygroskin is a climate-responsive pavilion, based on the concept of programmable matter. Lacking high-tech equipment and resources, the responsive capacity of the pavilion is intrinsic to the material properties. These were probably the two turning-point projects that clearly stated the importance of matter in architecture.

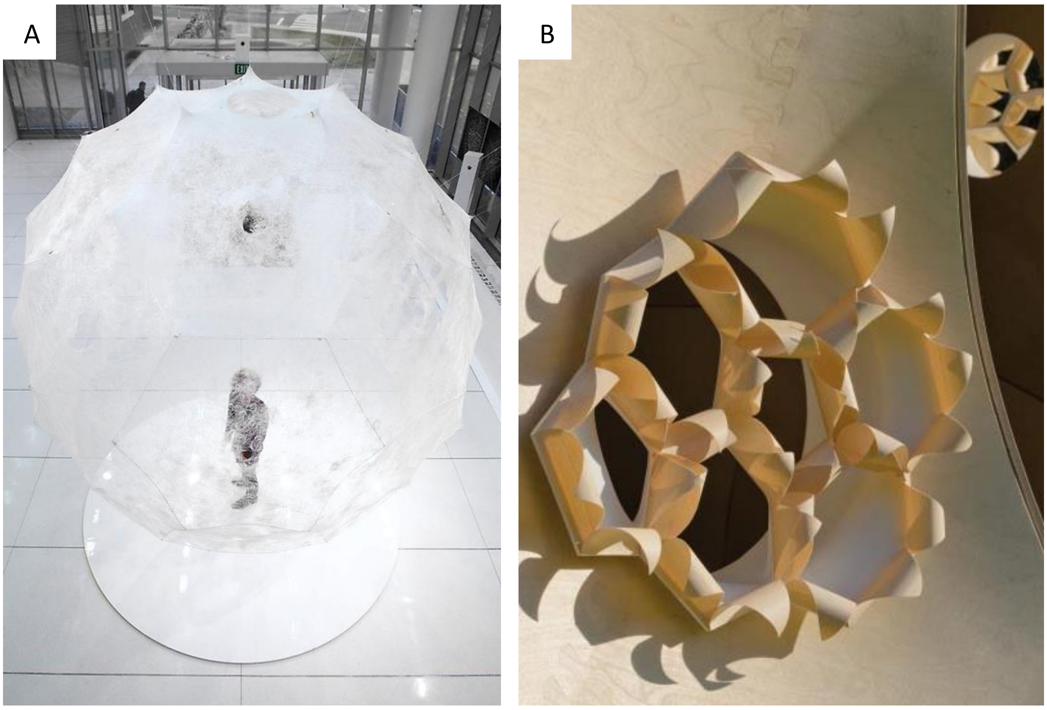


Figure 3.0:9: A. Silk Pavilion[15] (2013); B. HygroSkin – Meteorosensitive Pavilion[16] (2013).

At this point, the focus was all about programmable matter; but how could matter be optimized and controlled, just like nature does, to build our environment sustainably? Many scientists, architects, and engineers have looked to this question as a premise to develop possible concepts and solutions. In the same year of 2013, the Exploration Architecture office, in collaboration with the biologist Julian Vincent, designed the Reef Biomimetic Office Building (Figure 3.0:10). The team also included materials, structural, environmental, fire, workplace, and financial consultants. To encourage limitless ideas and

[15] The Mediated Matter Group, *Silk Pavilion*, photography, viewed 6 March 2019 < http://cooperhewitt.photoshelter.com/image/I0000_ZYX9cFHoYs>

[16] *HygroSkin – Meteorosensitive Pavilion,* n. d., photograph, viewed 11 May 2018, <http://www.achimmenges.net/?p=5612>

working approaches, this conceptual project was carried with minimum constraints: no site specification or budget restrictions. Considering the usage of daylight as one of the primary principles, the Reef Biomimetic Office Building was rooted in several animal and plant adaptation strategies. The astonishing bioluminescence effect produced by the mirror eye structure of the spookfish, the extremely thin walls of the cuttlefish's bone, the incredible passive cooling system of termite's habitat, and the arrangements of the mimosa pudica leaves that provide the perfect shading system enabling just the right amount of light to pass through, were just some of the biological inspirations sources (Exploration, n.d.). At the end of the project, the environmental consultant team predicted that this office building, when built, would be one of the lowest energy-consumption office buildings in the world (Campos, 2015). As another relevant outcome, the Reef Biomimetic Office Building team produced a film about the process development of the project, introducing biomimicry as a discipline, describing how biology could be used as a knowledge source to rethink building design. This film was presented at the Architecture Foundation in 2014.

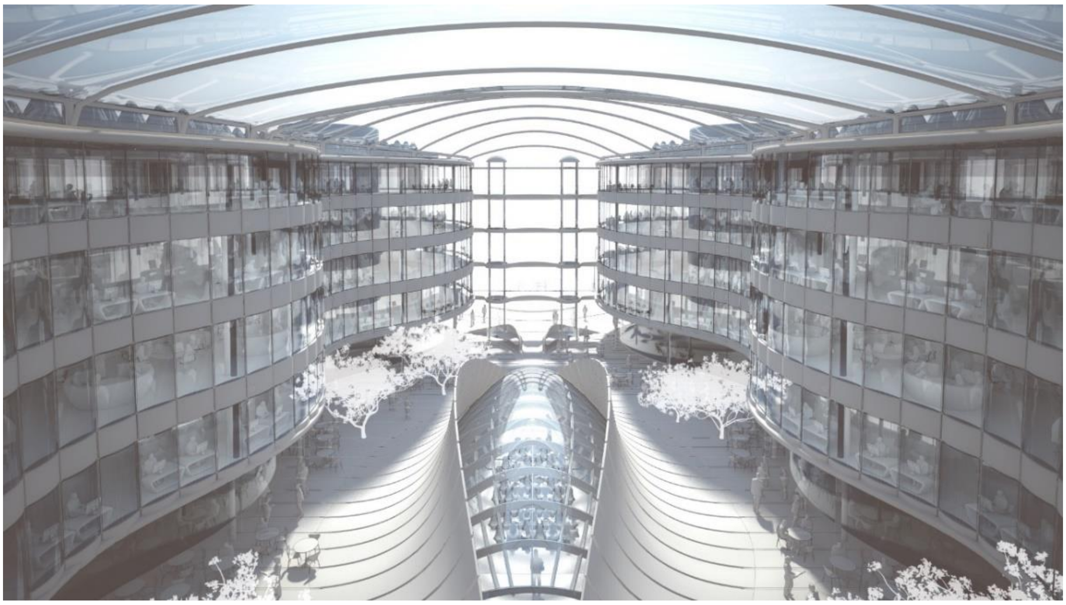


Figure 3.0:10: The Reef Biomimetic Office Building17 (2013).

The 'Chameleon' building (Figure 3.0:11) designed in 2015 by WWF Architects, is another project based on biomimetic principals. Its façade design, the most prominent element, is rooted in the chameleon skin characteristics. The building façade is composed of an external macro cellular structure composed of a hexagonal grid that can mechanically adapt to the Sun's trajectory. When solar radiation is too intense, the façade cells close, blocking the sunlight. When the building's internal body is too cold or too dark, the cells open to let in the sunlight. In order to collect the maximum sunlight during the day, the

[17] Exploration Architecture, *The Reef Biomimetic Office Building,* image render, viewed 8 March 2019 < https://archadeldn.wordpress.com/2015/06/25/exploration/>

façade contains hundreds of PV nano cells located on the exterior wall, transforming it into energy. The excess energy is stored and used to power the building's nighttime LED façade system.

Figure 3.0:11: 'Chameleon' and front plaza[18] (2015).

In October 2016, together with Instituto Gulbenkian Ciência, VitruviusFabLab-IUL presented an interactive and itinerant installation called 'Musical Morphogenesis' (Figure 3.0:12). The interactive installation translated into sound and movement the dynamics of the development process of a small white flower called Arabidopsis Thaliana. The development of an organism, or even a tissue or an organ, is controlled by several genes that, although having an individual action, end up functioning in a network controlling patterns which lead to the formation of the organism. In this installation, one can visualize and interfere with the dynamics of the process of genetic regulation by turning on or off genes and proteins. In doing so, there is a likelihood of diverting a normal organism (in the wild) to a mutant, and perhaps bringing it back into the wild. 'Musical Morphogenesis' was a robotic structure composed of four parts of the flower's organs: petals, sepals, stamens,

[18] WWF, *'Chameleon' and front plaza*, mage render, viewed 8 March 2019 <
https://www.designboom.com/architecture/wwf-architects-chameleon-mixed-use-office-building-12-30-2015/>

and the central carpel. The process of genetic regulation is controlled by touching a musical instrument, where each key on the keyboard is a gene or protein. When playing this instrument, the audience activates or inactivates one or more genes, triggering a song. The musical cadence is modified when members of the audience activate a gene that produces a significant effect on the dynamics of the whole network and, consequently, on the structure of the flower. However, the public will find that the same gene, after some time, can no longer control the genetic network, and will have to find out which genes have become essential (Oliveira, Sousa, Costa, Oliveira, & Mena, 2017).

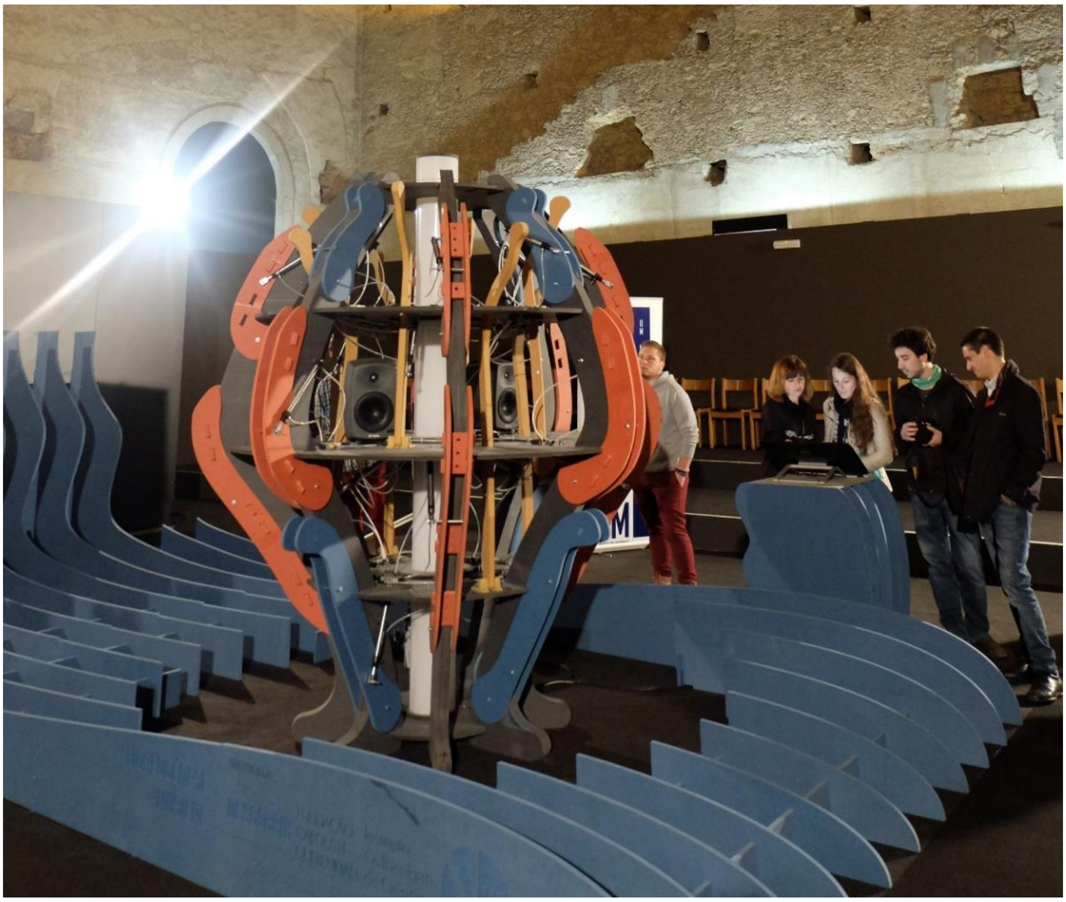


Figure 3.0:12: Musical Morphogenesis on Tour[19] (2016).

Elytra Filament Pavilion (Figure 3.0:13) was projected between 2015-2016 by Achim Mengues, Moritz Dörstelmann (ICD – Institute for Computational Design, University of Stuttgart) and Jan Knippers (ITKE – Institute of Building Structures and Structural Design, University of Stuttgart) team, for the Victoria & Albert's Engineering Season. The pavilion is the result of a four-year research project, based on a biomimetic process empowered by the most recent advancements in contemporary computational design, simulation, and fabrication. The main goal of this project explores how biological fiber

[19] Gaspar, M., Musical Morphogenesis on Tour, Belém Art Festival, Lisbon, 2016.

systems could be translated and integrated into architectural processes. Inspired by Nature's lightweight structures, as the fibrous structures of beetles' forewing shells (elytra), the 200 m^2 canopy was formed from a hexagonal cell grid structure and vertical columns. Biological load-bearing structures are often fibrous systems, in which strength and flexibility are directly related to its morphological organization, direction, and density. Elytra was built using two 6-axis industrial robots, which respectively wind carbon and glass fibers (both resin-impregnated) onto the hexagonal frames. The resin cure occurred when the fibers were wound over/crossing each other, unifying it into a solid state. Robotic fabrication enables an almost infinite range of possible morphological solutions since it is based on a continuous feedback loop.

Figure 3.0:13: Elytra Filament Pavilion, Victoria and Albert Museum[20] (2016).

As a conclusion from the above-mentioned professional and academic projects, based on biomimetic and biomimicry principles and processes, much remains to be done. Most of the current biomimetic experiences remain closed inside the academic environment, some are translated to the installation scales, and others are waiting for funding and openness by industries to develop their projects. Some of the difficulties rely on adequate comprehension, translation, and implementation of ideas and functions from the natural systems into human-made creations. This transition, from Nature to human-made creations, has to perform in different areas, industries, and scales, requiring comprehensive knowledge in different fields of research. While biology works in one

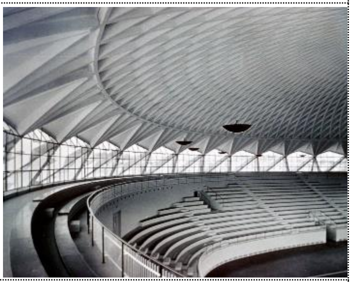
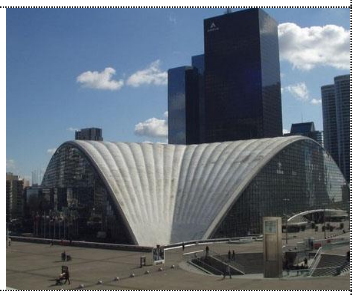
[20] Naaro, Elytra Filament Pavilion, Victoria and Albert Museum, photography, viewed 8 March 2019 < https://icd.uni-stuttgart.de/?p=16443>

context, technology operates at a different one. As it will be later described (see Section VI), this doctorate research aims at developing and exploring a design methodology that could empower architects to link both contexts.

3.2 Biomimetic structures in Architecture

One of the most common approaches in biomimetics is the transfer of functions, stemming from the hypothesis that in Nature, all materials, structures, and constructions have a functional role. Over time, architecture becomes more than a simple living space supplier. Biomimetics pointed to new and innovative solutions, by providing architects an extensive range of possible solutions based on natural organisms and systems. In Nature, there is no differentiation between material, surface, and structure, revealing a significant energy efficiency. While Nature presents almost an infinite set of examples of forms and structures based on their material and environmental context, biomimetics has the potential to offer the same database more autonomously through different mechanical principles. In the field of engineering, these principles can be categorized into several types. Cable-structures could be easily associated with spider cobwebs that are strong and resilient. Frei Otto's Olympia stadion in München, Germany, used a tent-like shape for the Summer Olympic Games as a roof; this solution, covering a total area of 74,800 m2, is similar to the cobweb's design, using minimal material consumption. Thin-shell structures are often linked to a thin-walled structure made up of two curved surfaces. The thickness of the shell is based on the distance between the two surfaces. In Nature, some of these structures may be found in eggs, snails, seashells, and nutshells. A representative example of a thin-shell structure is the Paris National and Technology Center, built in 1958, by Jean Prouvé, Robert Edouard Camelot, Jean de Mailly, and Bernard Zehrfuss. The iconic roof of the building adopts a segmented prefabricated double hyperbolic reinforced concrete shell structure. Membrane structures are based on natural phenomena through which the shape of objects is maintained by internal air pressure, such as cellular structures or soap bubbles. Over the last decades, several projects have been developed using this principle. The Beijing National Aquatics Center used ethylene tetrafluoroethylene grid cell structures and foaming, the working principle of which is similar to cell swelling. Cavity structure refers to the application of wind, solar, and rain natural energy to the biological cavity that can regulate micro-climate (Yuan, et al., 2017).). In the New German Parliament, Norman Foster created a dome on the building's rooftop, ensuring its vertical ventilation through the chimney effect, using the same principle of the termite mounds ventilation system. By creating an inverted cone, with mirrored glass closure for its interior, the dome allows the unleashing of a natural ventilation system inside the building. The cold air enters inside the building and descends, pressing hot air to rise, being released through the dome. Colombia's EDU Headquarters building in Medellín is another emblematic example of this type of ventilation system. Coated with prefabricated elements with thermal properties, the building is organized in a logic of empty/fill, around a solar chimney, that allows the heating of the cold air and its distribution through different workspaces. Other architectural examples, principles, and types of biomimetic explorations, leading to diverse structures and forms, are presented in Table 3.0:1.

Table 3.0:1. Biomimetic examples applied to building structures (adapted from Yuan, et al., 2017).

Type of Structure	Nature example	Architectural example
Multi-ribbed slab This type of slab could sustain ten times more than its own weight, being much more material-efficient than conventional solid slabs. These are very lightweight structures that use several elegant central elements of weight discharge.		
	Lotus leaf vein[21]	Rome Gatt Wool Factory[22] (Carlo Cestelli Guidi, 1951)
Reinforced concrete grid structure This type of structure is similar to the multi-ribbed structures, but instead of having the discharge point at the center of the pattern, these curved structures discharge in several points located at its perimeter.		
	Sunflower[23]	Palazzeto Dellospori of Rome[24] (Annibale Vitellozzi, 1957)
Thin-shell structure These structures are based on the relationship between the degree of curvature and material thickness.		
Continue…		

[21] Inian, S., *Lotus Leaf*, photograph, viewed 18 May 2018, <http://www.treknature.com/gallery/Asia/India/photo85969.htm>
[22] *Gatti Wool Mill,* n. d., photograph, viewed 18 May 2018, <http://www.ce.jhu.edu/perspectives/protected/ids/Index.php?location=Little%20Sports%20Palace>
[23] *Sunflower Fragrance Oil*, n. d., photograph, viewed 18 May 2018, <http://www.brambleberry.com/Sunflower-fragrance-oil-p6495.aspx>
[24] *Little Sports Palace*, n. d., photograph, viewed 18 May 2018, <http://www.ce.jhu.edu/perspectives/protected/ids/Index.php?location=Little%20Sports%20Palace>

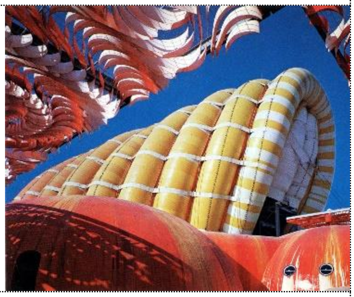
Type of Structure	Nature example	Architectural example
	Eggshell[25]	National Industries & Techniques Center in France[26] (Robert Edouard Camelot, Jean de Mailly, Bernard Zehrfuss, 1958)
Assembling type spherical grid Spherical grids relate the extension of the pattern directly to the size of the cell. As highly resistant patterns, these structures have been used for the most variable types of applications.		
	Honeycomb[27]	The US Pavilion of Montreal International Expo[28] (Buckminster Fuller, 1967)
Inflatable membrane structure These structures are commonly known for their foldable capacity, and for covering large areas or supporting other elements (roofs or shelters) with a high degree of transparency.		
	Soap bubble[29]	Fuji Pavilion of Osaka World Expo[30] (Yutaka Murata, 1970)
Suspended-cable structure These structures are easily associated with spider cobwebs that are strong and resilient. Using light-thin structural elements to stretch elastic and deformable materials, these structures are used to cover large areas, using less material.		

Table 3.0:1 (Cont.). Biomimetic examples applied to building structures (adapted from Yuan, et al., 2017).

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[25] *Eggshell*, n. d., photograph, viewed 18 May 2018, <http://undergroundhealthreporter.com/5-minute-health-tip-eggshell-toothpaste/>
[26] *CNIT Shopping Center in La Defense*, n. d., photograph, viewed 18 May 2018, <http://www.parisdigest.com/monument/la-grande-arche.htm>
[27] *Honeycomb*, n. d., photograph, viewed 18 May 2018, <http://www.mudgeehoneyhaven.com.au/shop/honeys/beepower-honeycomb-350g/>
[28] Maia, R., *Montreal Biosphere / Buckminster Fuller*, photograph, viewed 18 May 2018, <http://www.archdaily.com/572135/ad-classics-montreal-biosphere-buckminster-fuller/546a754de58ece7d25000036-rodrigo_maia-jpg>
[29] Theboypedro, *Popping Soap Bubbles*, photograph, viewed 18 May 2018, <http://www.turbosquid.com/3d-models/3d-soap-bubble/1084958>
[30] *Fuji Group pavilion,Expo '70, Osaka, 1970*, n. d., photograph, viewed 18 May 2018, <http://www.oldtokyo.com/expo-70-osaka-1970/>

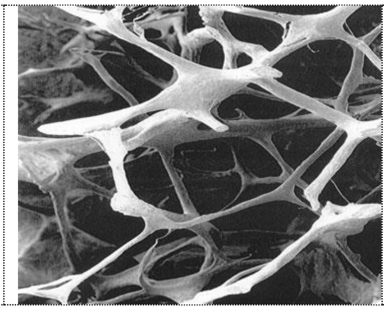
Type of Structure	Nature example	Architectural example
	Cobweb[31]	Olympia Stadion in Münich[32] (Frei Otto, 1972)
Suspension structure This type of structure works like a spine system. All the volumes are attached to a central element that concentrates in itself the whole discharge of weight and balance.		
	Ears of Wheat[33]	BMW Office Building in Munich[34] (Karl Schwanzer, 1973)
Barrel structure Results from a vertical extrusion of a shape outline. This type of structure is usually used to reach great heights, reducing floor area towards the top.		
	Bamboo[35]	Willis Tower[36] (Skidmore, Owings and Merrill, 1974)
Folding structure Folding structures are complex skeletons, composed of tubular light elements. The tubular system combines the structural efficiency of bending rigidity hollow tubs with optimal material efficiency.		

Table 3.0:1 (Cont.). Biomimetic examples applied to building structures (adapted from Yuan, et al., 2017).

[31] *Cobweb*, n. d., photograph, viewed 18 May 2018, <http://blogs.biomedcentral.com/bmcseriesblog/2017/03/21/cobweb-spiders-wrap-prey-diverse-silk-proteins-expanding-silk-applications/>
[32] *Frei Otto's Olympia Stadion in München*, n.d., photograph, viewed 6 March 2019, < https://www.welt.de/kultur/kunst-und-architektur/article138306234/Sein-schoenstes-Luftschloss-ist-das-Olympiastadion.html >
[33] *Ears of Wheat*, n. d., photograph, viewed 18 May 2018, <http://dogsfirst.ie/health-issues/what-are-dogs-allergic-to/wheat/>
[34] Dalbéra, JP., *La Tour BMW (Munich)*, photograph, viewed 18 May 2018, <http://www.flickr.com/photos/dalbera/31007913905>
[35] *Panneau Bamboo,* n. d., photograph, viewed 11 May 2018, <http://www.aufildescouleurs.com/panorama/4608-bamboo-r11821-4.html>
[36] *Willis Tower*, n. d., photograph, viewed 11 May 2018, <http://www.skyscrapercenter.com/building/willis-tower/169>

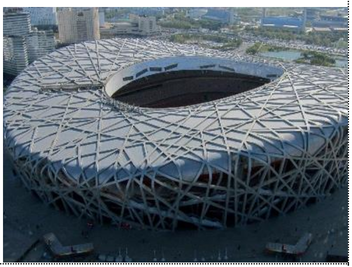
Type of Structure	Nature example	Architectural example
	Animal bone[37]	Milwaukee Art Museum - the Quadracci Pavilion[38] (Santiago Calatrava, 2001)
Cross/shaped steel trusses structure This type of structure is usually used to create maximum volume through a dense and complex intersection of thin elements.		
	Bird's nest[39]	Beijing National Stadium[40] (Herzog & de Meuron, 2007)

Table 3.0:1 (Cont.). Biomimetic examples applied to building structures (adapted from Yuan, et al., 2017).

3.3 Implementing Biomimetic design methodologies into the creation of the built environment

Badarnah and Lepora et al. stated that the major drawback in Biomimetic design is the lack of a clear systematic methodology (Badarnah & Kadri, 2015) (Lepora, Verschure, & Prescott, 2013). In architecture, three main general obstacles limit the implementation of biomimetics. The first obstacle is the identification, selection, and exploration of strategies from Nature; the second obstacle is related with scaling difficulties as some functions only work on specific scales (for example, at the nano or the micro scales); the third obstacle is to integrate parts from different contexts into a unique design concept, giving rise to conflicts (Vogel S. , 2013) (Royall, 2010). Overall, the three obstacles are interrelated and connected by one common factor – the lexicon. Biomimetic projects have a major biological component, involving very specific knowledge. Ahmar, in his article "Biomimicry as a tool for sustainable Architecture Design" (El Ahmar, 2011), named seven issues that help explain the difficulty in implementing Biomimicry processes: specific knowledge, skills, and tools; the design approach depends on computer software; the identification of the material for a system requires a large number of physical tests and geometry descriptions; find a relation between components that could lead to a minimum/maximum inventory concept; the selection of a suitable algorithmic growth process; the recurrent interfacing with appropriate analysis applications; and the control of continuous evaluation and feedback. How can then architects transport this biological lexicon into their own lexicon? Or even,

[37]The Bone Orchestra, *Bone*, photograph, viewed 18 May 2018, <http://www.spectacle.co.uk/catalogue_production.php?id=26>
[38] *Milwaukee Art Museum*, n. d., photograph, viewed 18 May 2018, <http://inhabitat.com/amazing-calatrava-shade-pavilion-for-the-milwaukee-art-museum/>
[39] *Bird's Nest,* n. d., photograph, viewed 18 May 2018, <http://www.silkfamilylaw.co.uk/The-Silk-blog/Blog/October-2016-(1)/Pros-and-Cons-of-bird%E2%80%99s-nest-parenting?feed=The-Silk-Blog-RSS>
[40] Fotoflyer, *Bird's Nest Stadium*, photograph, viewed 18 May 2018, <http://www.flickr.com/photos/fotoflyer/5190565357>

should architects absorb the biology lexicon, or should they adapt it and integrate it with their own?

3.3.1 Biomimetic approaches and possible outcomes

Practitioners and researchers in the field of architecture and design usually address Biomimetics considering three possible directions (Al-Obaidi, Ismail, Hussein, & Abdul, 2017) (Badarnah, 2012) (Bogatyrev & Bogatyreva, 2014): 1- Development of architectural specialization courses and consequent experimental design projects – often reported through workshops and summer schools; 2- Advancement of design tools, like software and plug-ins, and methods to establish systematic and organized research; 3- Development of actual design models by architectural firms and research groups.

The most common design methodologies that have been used are based both on bottom-up and top-down approaches (Gamage & Hyde, 2012) (Gruber P. , 2011) (Speck & Speck, 2008) (Figure 3.0:14). Badarnah (Badarnah & Kadri, 2015) indicated that a bottom-up approach worked as an induction or indirect approach, or as a solution-based approach, which refers biology to design. This direction relies first on the biologists to adapt biological properties into human technology to find answers and then identify human design problems. The identification has to be directed at a particular characteristic or behavior of an organism or ecosystem and then shape it as a guideline for developing architectural designs or industrial products (Sung D. K., 2008). Vincent (Vicent, 2003) and Zari (Zari M. P., 2009) state that the theories obtained from the bottom-up approach include adapting and evolving self-organization and resource optimization rather than maximization, free energy, and improving the bio-sphere using life-friendly materials and processes. The majority of these theories were mainly implemented in industrial products; however, they are still limited in concept and materialization, and some of them were unexplored in architecture (Al-Obaidi, Ismail, Hussein, & Abdul, 2017).

The top-down approach seeks an answer from Nature for a given problem-based design process, which may be done directly or through analogy (Vattam, Helms, & Goel, 2009). In this case, design problems and human needs are at the basis of the process that seeks to find answers in other organisms or ecosystems with similar problems (Baumeister, 2014). El Ahmar stated that, through this approach, reaching potential biomimetics solutions is possible without collaborating with a biologist or ecologist or without an in-depth scientific understanding. Research held at the Georgia Institute of Technology (Greene, Trent, & Bachand, 2008) identifies the steps in conducting biomimetic research.

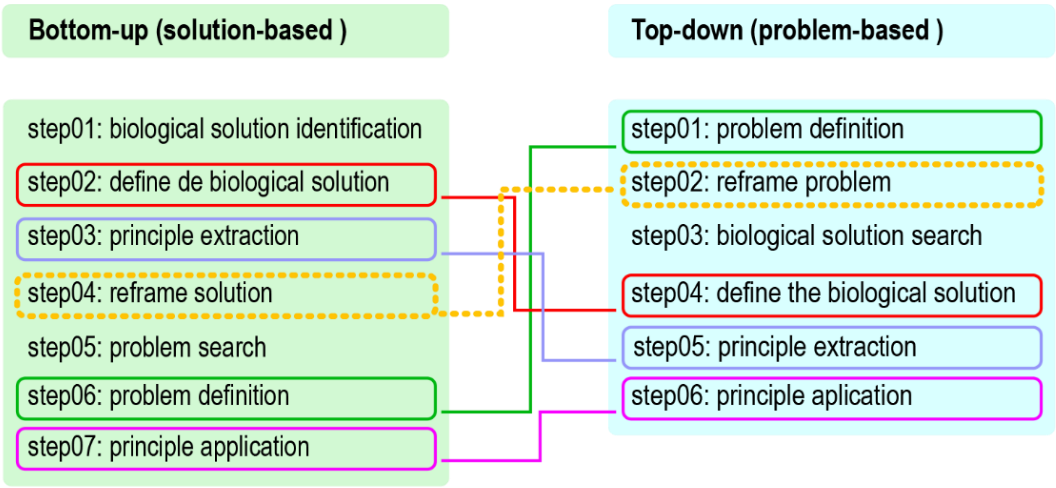


Figure 3.0:14. Design methodologies: Bottom-up and Top-down approaches.

From the existing biomimetics and biomimicry literature, the two different approaches evolved in biomimetic design, can lead to different outcomes. In architecture, Zari points out two main possible outcomes of the biomimetic design process. Following the direction of Nachtigall (Zari M. P., 2007b), operating at a macro scale, the first outcome relies on features inspired in Nature: Form (mimics the appearance of the natural system); Material; Construction (mimics the structure and/or assembly of the natural system); Process; and Function (actions and operations of the natural system). The second possible outcome operates at a micro-scale, emphasizing the features of Nature that are imitated in a sequential order: Organism, Behavior (of the organism), and Ecosystem (by mimicking the biotic and abiotic components and interaction level between its components). Zari and Storey (Zari M. P., 2010) focused, and further developed, the theory on the ecosystem level through establishing a network of interconnected processes that demonstrates the complexity in Nature's order, where they addressed six principles of how a natural ecosystem operates, and how that could be translated to any system such as building façades: 1- Dependent on sunlight, use renewable and available energy from the sun based on planar and spatial mechanism (planar mechanisms are bidimensional, meaning that all motions of the rigid body are in one or parallel planes; spatial mechanisms are three dimensional, meaning that motion occurs in different and not parallel planes); 2- Optimize the system rather than its components: energy must transfer efficiently between systems and components as form follows function. Energy and material used in the same system should be applied for multiple functions; 3- Depend on local conditions and situations, materials should be sourced locally and adapt to a specific environment; 4- Gain resilience and diversity from the relationship of the several components; 5- Create favorable conditions to sustain life: life exists in a cooperative framework as relating the web interaction that ensures resource transfers, redundancy, maintain and improve the biosphere; and 6- Adapt and evolve at different levels and at different rates: constant flow achieves a balance of non-equilibrium and self-healing systems.

Most of the outcomes are applied at organism levels, such as developing material or product (Al-Obaidi, Ismail, Hussein, & Abdul, 2017). Developing a product without considering its relation to the ecosystem produces non-sustainable systems (Reap, Baumeister, & Bras, 2005). To design within biomimicry/biomimetic, the ecosystem must be considered in order to design a completely sustainable system.

Thus, it can be argued that two main approaches exist with a varied lexicon in biomimetics: a 'bottom-up approach', 'biology to design', 'working by induction' and 'solution-based' (Badarnah & Kadri, 2015); and a 'top-down approach', 'challenge to biology', 'working by analogy', seeking for a solution from Nature to a pre-determined 'problem-based' challenge. Some research and professional groups have developed strategies for design concept generation inspired by Nature. Some of their work is often published, but in general, the biomimetic process is not reported or is completely muffled by the research's final product. Some selected groups that were chosen based on their research viability, visibility, and on their biomimetic process clarity, are presented below for comparison and evaluation (Table 3.0:2 and 3.0:3).

Table 3.0:2. Selected groups applying biomimetic strategy (adapt from L. Badarnah and U. Kadri).

Groups	**Bottom-up (Solution-based)**	**Top-Down (problem based)**
Biomimicry 3.8	●	●
BioTriz		●
Biomimetics for Innovation and Design Laboratory		●
Design & Intelligence laboratory	●	●
Plants Biomechanics Group	●	●

Table 3.0:3. Solution-based (biology to design) and Problem-based (challenge to biology). The steps adapted by the investigated biomimetic strategies (adapt from L. Badarnah and U. Kadri).

Bottom-up (solution-based)	**Biomimicry 3.8**	**BioTriz**	**Biomimetics for Innovation and Design Lab**	**Design & Intelligence laboratory**	**Plants Biomechanics Group**
Biological domain	Discover natural models	----	----	Biological solution identification and definition Principle of extraction	identify biological system and principles through biomechan-ics, morphology and anatomy
Transfer phase	Abstract biological strategies into design principles Identify function and context, brainstorm bio-inspired ideas	----	----	Reframe solution	abstract from biological model
Technological domain	Integrate, Emulate and Measure (using) life's principles	----	----	Problem search and definition Principle application	Implement technology through testing and prototyping
Top-down (problem-based)					
Problem definition	Identify function Define context Integrate life's principles	Define, analyse and reframe the problem	Problem definition	Define and reframe the problem	Formulate the technical problem
Exploration and investigation	Discover natural models; Abstract biological systems into design principles	Find functional analogy in biology and compare solutions	Search and assessing biological analogies	Biological solution search and definition Principle of extraction	Seek for analogies and identify corresponding principles in biology Abstract from the biological model
Solution development	Emulate design problem; Measure using life's principles	List principles from both technical and biological domain Develop idea	Applying biological analogies	Principle application	Implement technology through prototyping and testing

In the **solution-based process**, the several phases are categorized under biological and technological domains. In the **problem-based approach**, the five research groups referred to in Table 3 have a similar "*Problem definition*" initial sentence. At the "exploration and investigation" phase, all strategies aim to discover a biological source model through design principles abstraction. In "*Solution development*" research groups adopt different strategies: *Biomimicry 3.8* (Biomimicry3.8, 2010) incorporates Life's Principles (Figure 3.0:15)) in the validation of the design concept; *BioTriz* (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006) provides a list of biological principals but it's not involved in the solution development; *Biomimetics for Innovation and Design Laboratory* (Vakili & Shu, 2001) provides biological analogies; *Design and Intelligence Laboratory* (Goel, Rugaber, & Vattam, 2009)) applies the principles in *"Solution development";* and the *Plants Biomechanics Group* (PBG, 2011) proceeds the method to a prototype phase and consequent physical tests. Both approaches show a similar trend in the transfer from the biological to the technological domain. The major difference lies in the way the different groups approach the different phases of the biomimetic process (Badarnah & Kadri, 2015).

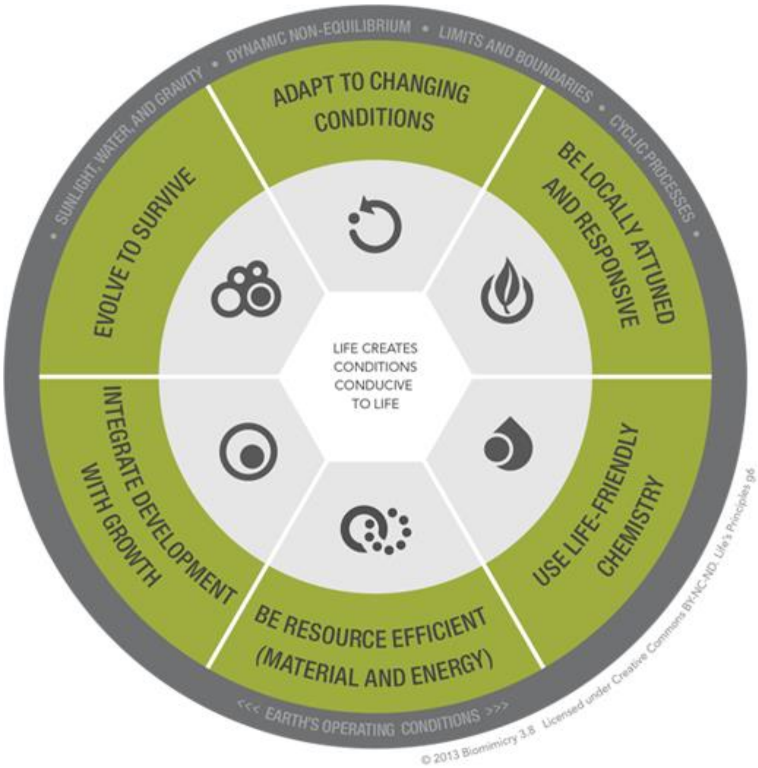


Figure 3.0:15. Life Principles (Biomimicry3.8, 2010).

Among other goals, biomimetic design seeks to address the challenges and errors that always exist in designing efficient systems and products (Royall, 2010). 'Bio-design', published by William Myers in 2012, explores biomimetic and biomimicry structures, prototypes, and concepts, highlighting some remarkable architectural and design projects, where biological processes replaced standard industrial and mechanical procedures. Mazzoleni explored ways of utilizing animal skins for performative buildings. Several academic research has been conducted in this line, such as 'Bio-Skin' (Gruber & Gosztonyi, 2010), 'Towards the LIVING envelope' (Badarnah & Fernández, 2012), and 'Architecture Follows Nature' (Mazzoleni, 2013); these are some of the most well-documented and often presented biomimetic design methodologies.

3.3.2 Biomimetic design methodologies and tools

During the last two decades, several methodologies to implement biomimetic processes have been developed (Baumeister, 2014, p. 8). However, their reliability and practical application at the architectural scale remains a challenge. Hereinafter, considering its relevance and potential impact on the architectural domain, five biomimetic design methodologies will be presented.

Biomimicry Design Spiral (2005)

In 2005, the industrial designer Carl Hastrich developed the *Biomimicry Design Spiral* (Figure 3.0:16). The design spiral is a visual representation of a Biomimicry-inspired design. This biomimetic feedback-loop method, combined with the Life's Principles filters application, should help the designer in creating new and sustainable design solutions. Starting from a standard design process, Hastrich added some steps needed for biomimicry. The spiral is composed of six essential steps: 1- identify the functions of the design; 2- translate those functions into biological terms; 3- find in nature strategies that perform those functions; 4- abstract those strategies back into technical terms; 5- apply those strategies in your design solution and; 6- evaluate the design quality and strategy (Deluca, 2016). The Biomimicry Design Spiral is rooted in a problem-based approach since it initiates its journey establishing the goal functions of the design product.

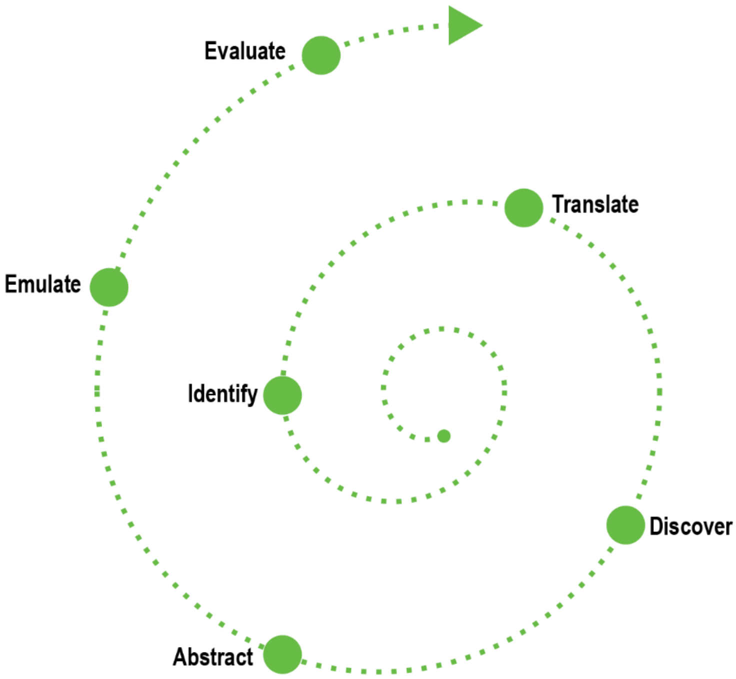


Figure 3.0:16. Biomimicry Design Spiral (adapted from Deluca, 2016).

BioTRIZ (2008)

In 2008, Nikolay and Olga Bogatyreva presented BioTRIZ as a methodology for eco-innovation. Based on the TRIZ method (the Russian initials for Teoriya Resheniya Izobretatelskikh Zadach, literally Theory of the Resolution of Invention-Related tasks), BioTRIZ is "*a problem-solving, analysis and forecasting tool derived from the study of patterns of invention in the global patent literature*" (Hua, Yang, Coulibaly, & Zhang, 2006). BioTRIZ methodology is fully capable of dealing with contradictions between biology and technology because its main mechanism is based on revealing conflicting requirements and a win-win resolution. Win-win is a strategy or negotiation in which all the parts benefit one way or another.[41] (Bogatyrev & Bogatyreva, 2014). Gruber (Gruber P. , 2011) stated

[41] Win-win is a strategy or negotiation in which all the parts benefit one way or another.

that buildings are complex systems. This method could not consider the necessary multiple interactions among buildings components, revealing to be ineffective in architecture (Bogatyreva, Vincent, & Pahl, 2002).

BioGen (2014)

Based on Badarnah's Ph.D. dissertation, Badarnah and Kadri presented BioGen (Badarnah & Kadri, 2015) in 2014, a methodology for biomimetic design concept generation (Figure 3.0:17). The methodology settles on the exploration of natural organisms and natural systems and on the extraction of principles and characteristics that perform specific and required functions – those are referred to as pinnacles. The methodology is a "problem-based" approach, relying on the search for possible solutions to specific problems, divided into four main phases as facilitated by the design tools: I) exploration model, II) pinnacles analysis, and an abstraction phase composed by a III) pinnacle analyzing matrix and IV) design path matrix. Each of these four phases are developed along with ten sub-phases: identifying the fundamental issue; exploring the natural systems; extracting the function (the pinnacles); elaborating; analyzing; classifying; abstract strategies and principles; combining a set number of chosen strategies seeking convergence; generating conceptual design; and evaluating and validating the solution. This methodology relies only on the conceptual design stage, creating a closed-loop in the conceptual creation of the solution. Technology and prototypes are not considered in this methodology process.

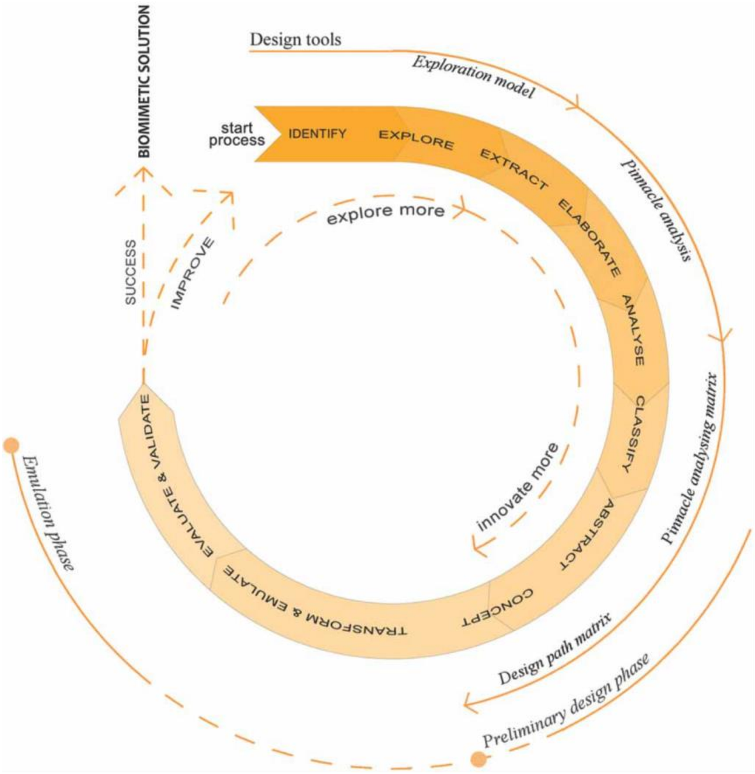


Figure 3.0:17. BioGen methodology flowchart (Badarnah & Kadri, A methodology for the generation of biomimetic design concepts, 2015).

Ecomimetic design method (2014)

The Ecomimetic design method presents a conceptual approach based on the previously presented methods, developed by Garcia-Holguera. Ecomimetic is a systematic approach to biomimetic design for architects, engineers, and designers (Garcia-Holguera, Clark, Sprecher, & Gaskin, 2014). The method uses a top-down approach, following the helix model as a spiral, expressed by two main levels: abstraction and design tools. Ecomimetic is divided into six phases: identification of one or several design objectives; search for an ecological solution using AskNature; abstraction and representation of ecological systems; correlation of architectural and ecosystem components; translation of ecosystem's principles to an architectural system; and modeling and benchmarking (Garcia-Holguera, Zisa, & Clark, 2016). The Ecomimetic method achieves the creation of a virtual model, with enough information to run a performance evaluation for design.

Biomimetic principles for the development of adaptive envelopes (2017)

This method is entirely based on understanding plants at its macro and micro scales, with emphasis on the relationship between Nature and climate and assuming that climate is the main factor that influences the principles of adaptation. The method is founded on two phases. The first phase is based on analysis and data collection of plants' strategies to adapt to their environment, categorizing and organizing a survey based on morphology, physiology, and behavior. The second phase of the methodology leads to a conceptual design map, so to facilitate the transfer between the biological information and the architectural application (Figure 3.0:18). In order to understand how plants' principles can be used to create adaptive architecture, this phase is divided into two subphases: I) works inside the Nature domain refer to the identification of adaptive strategies and mechanisms present in biological organisms; II) working inside the Architecture domain encourages the abstraction, interpretation, and transformation of the selected ideas, from the Nature domain into innovative solutions. Climate data is transversal to both phases (López, Rubio, Martín, & Corxford, 2017).

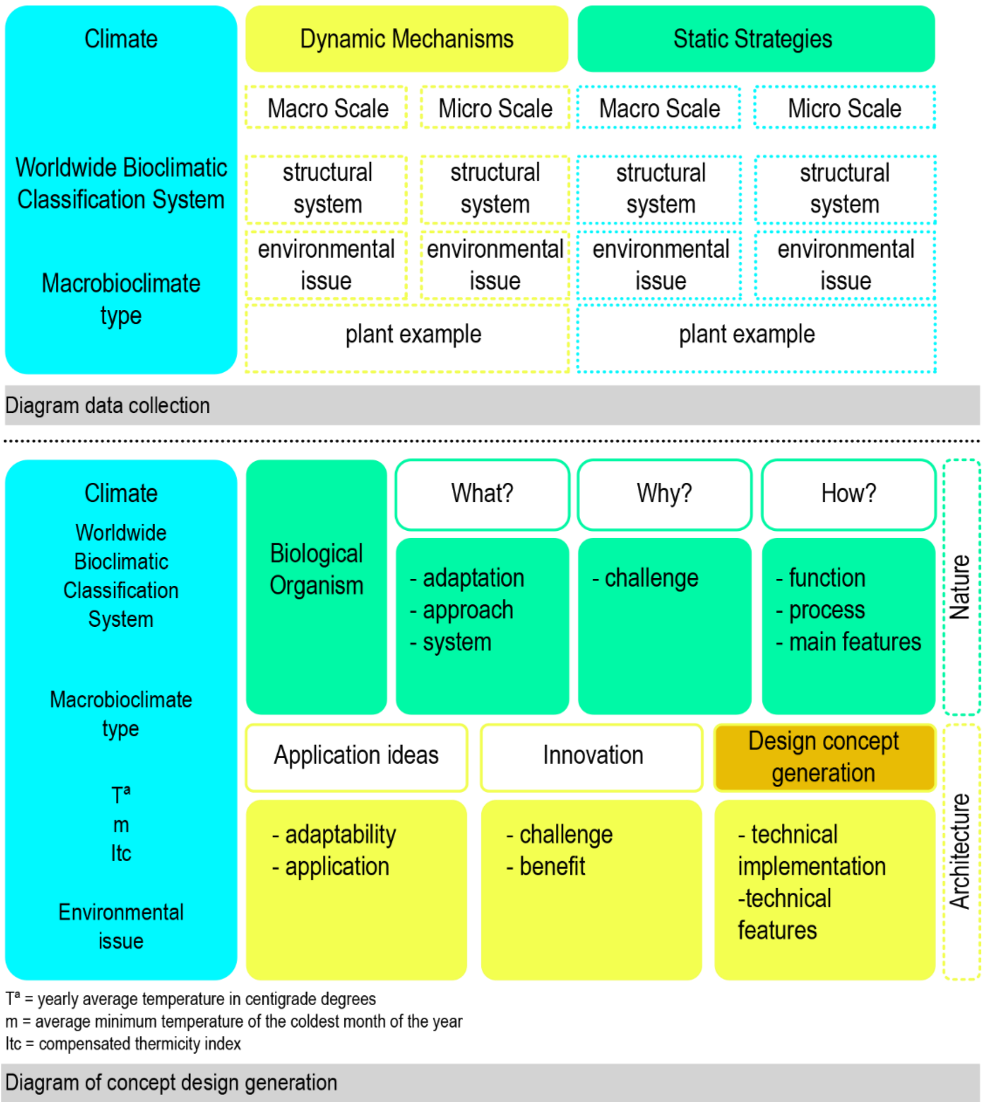


Figure 3.0:18. Diagram of data collection and design concept generation proposed by López et al, 2017[42].

[42] The diagram of Figure 3.0:18 is adapted from the original (López et al, 2017, p. 698).

López et al. (2017), presented this method based on plants' adaptation strategies, developing a design concept with environmental regulation and comfort conditions with the purpose of building façades. However, the methodology ends at the conceptual stage. This happens without the transformation of the technical solutions and before the simulation evaluation.

3.4 (Re)Thinking about Biomimetic and Architecture

The architecture lexicon has been adapted and changed over the centuries. During Classic Antiquity, architecture was classified as an 'art of necessity' taught in professional practice (Aristotle separated the 'arts of necessity' from the 'arts of pleasure'; architecture was not considered part of the Fine Arts, and thus was taught outside the philosopher's academies). In the Middle Ages, Architecture was taught by the guilds and was seen as a mechanical art. The 'arts of necessity' were then called 'mechanical arts' being taught with technical, nonscientific, instructions. During these centuries, the architectural discourse and lexicon were essentially centered around constructive yards, materials, and techniques. Then, during the Renaissance, architecture approached the liberal arts through the teaching of theory and drawing, moving away from the guilds and practice. Baptista Alberti was a fundamental key for this shift. In writing De Re Aedificatoria, he defines Architecture as a conceptual and material product, giving it an intellectual dimension. Architecture's semantics approached philosophy, also developing different geometry methods and methodologies. The architect was progressively separated from the construction lexicon and seen as a theoretical and space philosopher that communicated through drawings using the properties of materials and techniques. Between the 17th and 19th centuries, the Beaux-Arts academy introduced in the academy the studio concept, and so, theory and drawing were taught in the academy and practical knowledge in independent studios. During the 20th century, studios were largely integrated into the academy; on the other hand, science and computer laboratories started to introduce a more scientific content, based on Mathematics, Geometry, and Physics. After World War I, Bauhaus was the most successful example of the incorporation of the professional workshop in the academy, promoting the integration of art, science, and technology. During the 1960s, the architectural design process was extensively studied. Several scientific methods and processes were developed and essayed, driven by the remarkable developments in several fields such as artificial intelligence and computer technology (adding a new practical instruction to architectural education) – the science laboratory. In the 1970s, Computer-Aided Design laboratories started to be integrated in architectural schools, and in the 1990s, they became popular among Architecture studios all over the globe (Celani, 2012).

Around the same decade, digital fabrication laboratories started to be introduced in the academy. While in the 20th-century Architecture focuses on design for mass production, the introduction of digital manufacturing laboratories brought back not only the lexicon of construction on the yard, with the possibility of building prototypes to scale, but also of custom building. In this second decade of the 21st century, biomimicry and biomimetics are being considered as the third era of Architecture. Although the term 'biomimetics' was introduced in the late 1960s by the American biophysicist Otto Schmitt, architects, engineers, and designers are only now, at the entrance of the new millennium, exploring its true potential. Interdisciplinary teams involving biologists, physicists, architects, engineers, mathematicians, among others, are developing work processes, materials, and projects that integrate the benefits of different areas. However, these projects face language barriers and different methodologies, making the dialogue between the different areas an arduous task.

3.5 Insights

Biomimetic studies face several obstacles, especially when translating natural concepts into technical systems. Most biomimetic approaches only focus on individual parts rather than on the whole system. Moreover, the set of research presented above has established that applying biomimetic concepts in Architecture, in its early stage, contributes to a better and more cohesive connection between Architecture and Nature, as evidenced by the several levels and scales of ideas. Understanding the several forms of adaptation and the connection between Architecture and Nature's internal and external factors is an essential component to achieve successful functional systems.

The design of adaptive human-made systems and natural biological systems is similar, although dealing with very different factors and conditions. Most research attempts to understand the structural, procedural, and informational aspects of biomimetics. However, there are still some difficulties in relation to the classification of biomimicry concepts. This happens due to the inevitable overlapping of many categories, as well as to the complexity in having to describe biological systems. Nevertheless, Architecture is being already described, designed, and conceived based on several Nature concepts. Architects' lexicon is richer (Table 3.0:4).

Table 3.0:4: Common terms in contemporary architecture (adapted from Al-Obaidi, Ismail, Hussein, & Abdul, 2017).

Adaptive	The term responsive refers to a system moving and responding from the outside based on specific factors, thus allowing interaction with a passive environment (Hasselaar, 2006) Apud (Al-Obaidi, Ismail, Hussein, & Abdul, 2017)
Convertible	The term is mostly associated with building mobility, similar to building envelopes, that suggest change form in the short-term depending on needs and functions (Otto, 1971) Apud (Al-Obaidi, Ismail, Hussein, & Abdul, 2017)
Dynamics	*The study of movement, which occurs due to forces applied to an object. The term is commonly associated with moving building envelopes (Meriam & Kraige, 2012) Apud (Al-Obaidi, Ismail, Hussein, & Abdul, 2017)*
Interact	The term refers to either intuitive or automatic responses to meet user requirements. Interactive building architectures use sensors to operate kinetic systems and enable intelligent materials in order to initiate change in appearance and the environment (Sung D. , 2012) Apud (Al-Obaidi, Ismail, Hussein, & Abdul, 2017)
Kinetic	Kinetics is the study of movement laws, including forces and masses, and emphasizes on the relationship between motion and its causes (Lienhard, Bending-Active Structures, 2014) Apud (Al-Obaidi, Ismail, Hussein, & Abdul, 2017)
Performative	The term refers to systems that can mediate the surrounding environment for user comfort, such as building skins. Building skin systems can control external factors in relation to predefined architectural performances (Turrin, Buelow, Kilian, & Stouffs, 2012) Apud (Al-Obaidi, Ismail, Hussein, & Abdul, 2017)
Retractable	In Architecture, the term is commonly used for textile membrane roofs, either bunched or folded; a term or expression similar to movable (Barozzi, Lienhard, & Zanelli, 2016) Apud (Al-Obaidi, Ismail, Hussein, & Abdul, 2017)
Responsive	In contrast to 'manipulate', the term 'responsive' refers to a system moving and responding from the outside, based on specific factors, thus allowing interaction with a passive environment (Hasselaar, 2006) Apud (Al-Obaidi, Ismail, Hussein, & Abdul, 2017)
Smart	A process-related concept that conveys automatic control or operation of building envelopes, including heat loss or gain, daylighting, air ventilation, and other systems. Smart systems use information technology to connect several subsystems that typically operate independently (Brooks, 2011) Apud (Al-Obaidi, Ismail, Hussein, & Abdul, 2017)
Transformable	The term describes units or systems with the intrinsic property of controlled change, such as the ability to be foldable, retractable or shape-shifting (Hoberman, 2006) Apud (Al-Obaidi, Ismail, Hussein, & Abdul, 2017)

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SECTION II
BACKGROUND

4.0
Digital Architecture

4.0 DIGITAL ARCHITECTURE

The implementation of digital design tools in the field of Architecture is the result of a long development process. During the '20s of the 20th century, arose the idea that machines could be able to perform tedious tasks through computing and information management (Grisaleña, 2017). Developed during the fervent Second World War (WWII) period, the “Turing Machine” (1936) and the “Von Neumann machine” (1945) are considered pioneer contributions in the development of this field of research, primarily driven, at the time, by military intelligence departments. In the same period of WWII, Artificial Intelligence (AI) is explored by scientists like John McCarthy, Marvin Minsky, and others, pointing to its possible growing impact in different areas of study. However, it is only during the '60s that Architecture will start developing dedicated computational concepts and the integration of these types of tools in its research and practice.

In 1960, Licklider published the article "Man-Computer Symbiosis" that led the path for new ways of conceiving the relationship between man and machine, establishing the idea of a possible collaborative interaction (Licklider, 1960). The idea behind this new research area achieves its major expression in 1968 with the "Cybernetic Serendipity" exhibition, at the Institute for Contemporary Arts (ICA) in London. The exhibition gathers together authors from different fields of arts, like Gordon Pask, John Cage, Norbert Wiener, among others. In 1967, based on the idea of a cooperative dialogue between designer and computer, Nicholas Negroponte and Leon Groisser founded, at the Massachusetts Institute of Technology (MIT), "The Architecture Machine Group". The multidisciplinary group that gathered architects, engineers, and computer scientists had, as a fundamental goal, the creation and development of architectural applications and of artificially intelligent interfaces that questioned, not only the design process, but also the role of its inhabitants. In 1969, Gordon Pask published the article "The Architectural Relevance of Cybernetics", where he announced the significant relevance of the implementation of cybernetic in the future of architectural practice. In his article, Pask anticipates significant advancements with the implementation of cybernetics in Architecture, establishing the possibility of a more adaptable, dialoguing, mutable, and evolutive Architecture (Pask, 1969). Despite these visionary and influential experiences, during the '60s and '70s, most of the architects did not have the means or the technical knowledge available to put these concepts into practice.

However, driven by cybernetics, the utopian spirit of the time encouraged several futuristic projects: The adaptable and changing construction of the "Fun Palace", developed by Cedric Price and Gordon Pask between 1958 and 1964 (Figure 4.0:1); The computer software "Flatwriter" for the creation of the "Spatial City" developed by Yona Friedman in 1960 (Figure 4.0:2); The computer system sensors "Computer City" created by Dennis

Compton in 1965 (Figure 4.0:3); The Buckminster Füller "World Game" simulation project that tested the possible optimization of the planet's resources, presented in 1967 at the World Design Science Conference (Figure 4.0:4). These were the fundamental revolutionary projects that root today's computational architecture.

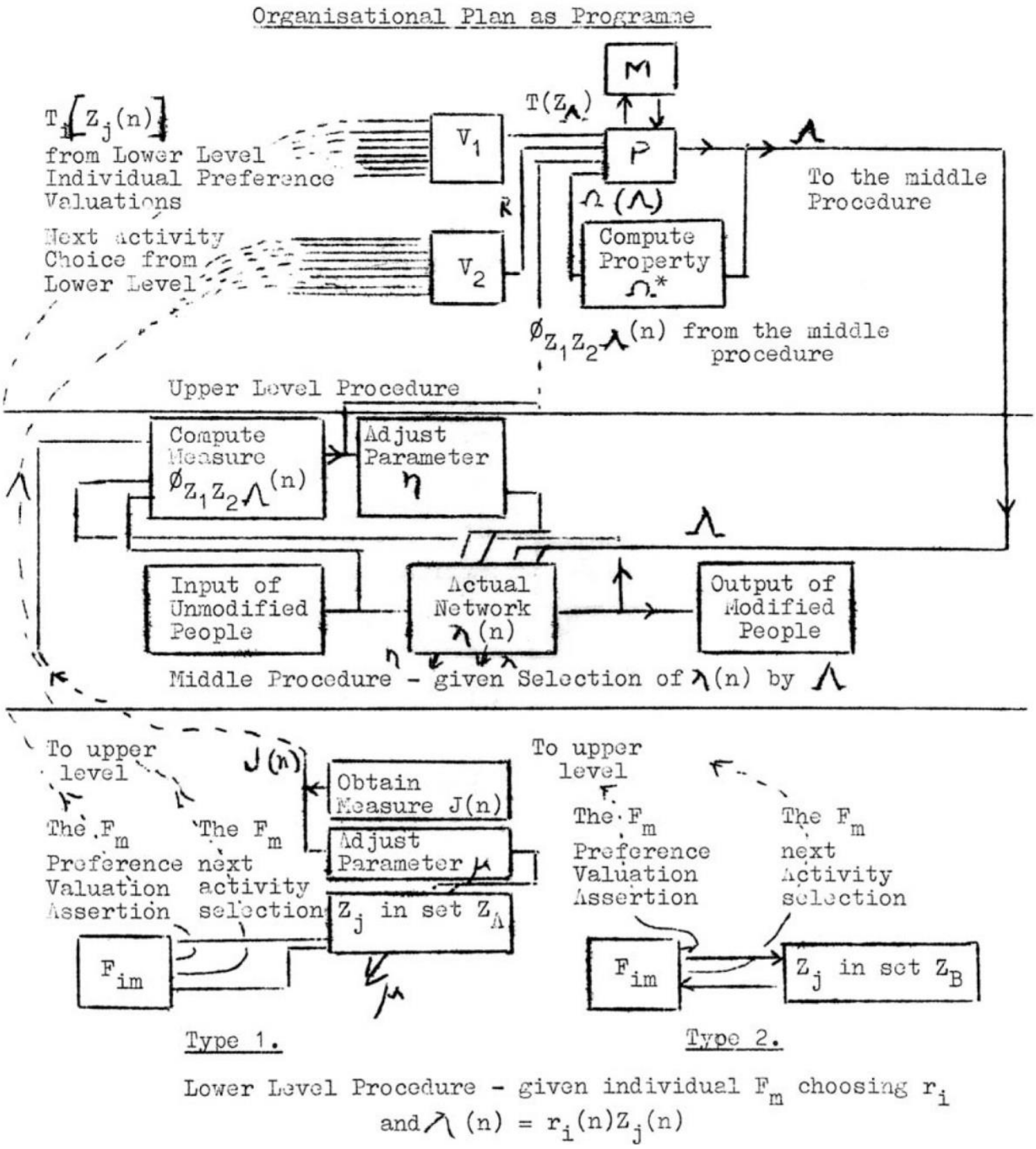

Figure 4.0:1. Cybernetic diagram of the Fun Palace program by Gordon Pask. Cedric Price Archives, Canadian Centre for Architecture, Montreal.[1].

[1] Cybernetic diagram of the Fun Palace program by Gordon Pask Cedric Price Archives, Canadian Centre for Architecture, Montreal. Cybernetic diagram of the Fun Palace program by Gordon Pask, n.d., photography, viewed April 26, 2019 <http://arch365bilgi.blogspot.com/2016/03/what-is-fun-palace.html>

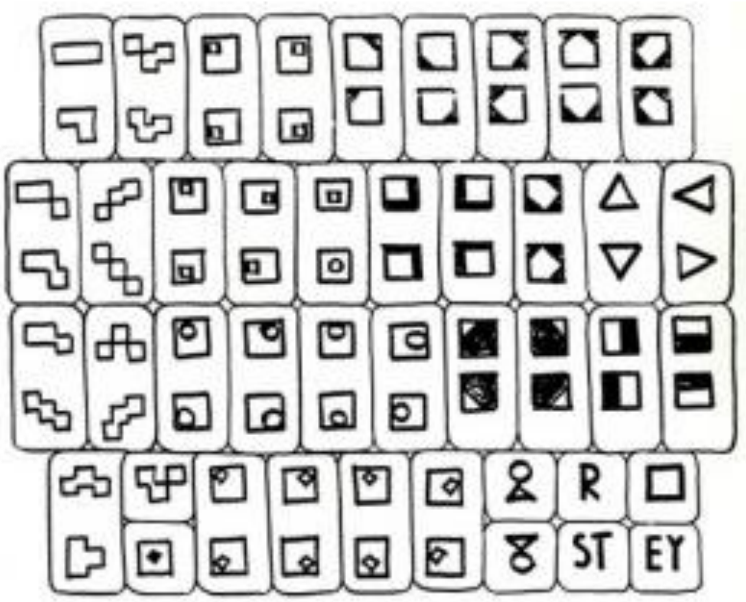

Figure 4.0:2. Flatwriter scheme of codes and operations[2].

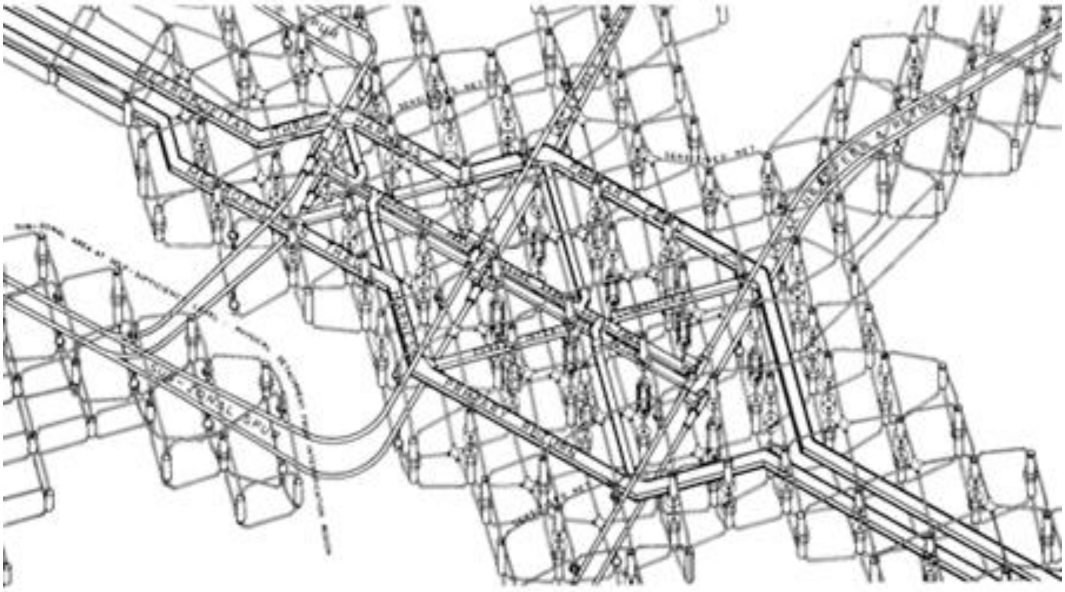

Figure 4.0:3. Computer City diagram[3].

[2] *Flatwriter scheme of codes and operations Flatwriter* n.d., photography, viewed in April 26, 2019 <http://www.yonafriedman.nl/?page_id=238>

[3] *Computer City diagram Computer City*, n.d., photography, viewed in April 26, 2019 <https://proyectos4etsa.wordpress.com/2015/02/17/computer-city-1964-ensayo-dennis-crompton-archigram/>

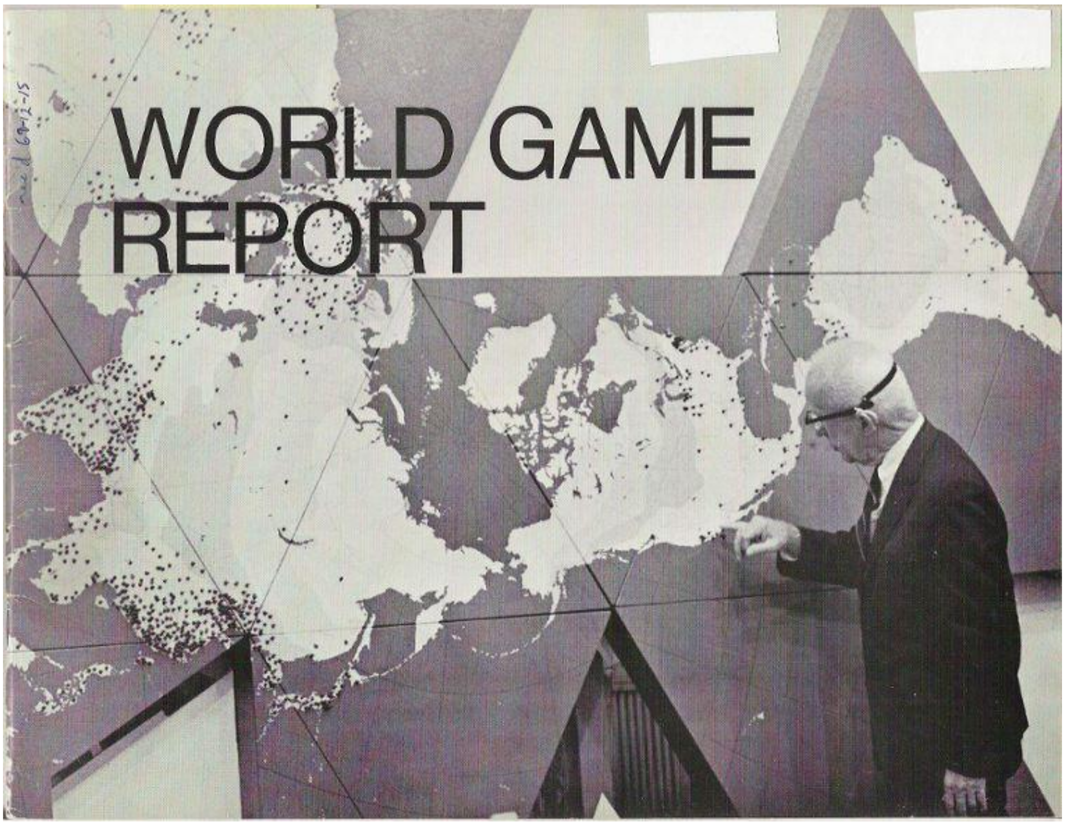

Figure 4.0:4. World Game[4].

During the '70s and the '80, the oil crisis (1973), the gap between technology's fast evolution and the slowness of socio-economic systems as well as the emergence of a "CyberPunk"[5] cultural movement were determinant events that led to the creation of the science fiction genre. One of the main works of this genre was the novel "Neuromancer" by William Gibson, published in 1984, where he coined the term "Cyberspace". In cinema, "Blade Runner" was one of the most significant movies and representative of the CyberPunk movement (Grisaleña, 2017). Despite all the technological advances and experiences, media, and cultural impact during these two decades, Architecture did not reflect the new knowledge of its architectural production. As John Frazer stated, after the pioneers, an age of "developers" - focused on the development of new tools - emerged (Frazer, 2005). Known as the decade of the "digital revolution", the '90s were marked by the arrival of computers to the masses. With the development of microprocessors and the reduction of production costs, computers became affordable and accessible to everyone. This enabled architecture offices to change their tools and to develop new design methodologies.

[4] *World Game Report*, n.d., photography, viewed in April 26, 2019 < https://www.ourworldthegame.com/single-post/2018/01/21/Our-World-Is-The-Buckminster-Fuller-World-Peace-Game>
[5] "CyberPunk" is cultural movement that relates the future with technology, combining them in a dystopian context.

4.1 Digital Tools

The definition of 'Parametric Architecture' finds its roots in 1939 through Italian architect Luigi Moretti. Moretti, together with the mathematician Bruno De Finneti, developed research where dimensions depended upon several parameters. Moretti's design parameters were linked to view angles and economic feasibility, which culminated in 1960 with the 12th Milan Triennial exhibition. According to Moretti, "*The parameters and their relationships become […] the code of the new architectural language, the "structure" in the original sense of the word […]. The setting of parameters and their relation must be supported by the techniques and tools offered by the most current sciences, in particular by logics, mathematics […] and computers. Computers give the possibility to express parameters and their relations through a set of (self-correcting) routines"* (Bucci & Mulazzani, 2006) apud (Tedeschi, 2014, p.20). From this quote, it is evident that Moretti saw and understood the potential of computers applied to Architecture.

Figure 4.0:5: Ivan Sutherland's Sketchpad on MIT TX-2[6] (1962).

In 1963, the first application for design was launched by the hands of the computer scientist Ivan Sutherland: Sketchpad (Figure 4.0:5). Sketchpad was the first interactive computer-aided design (CAD) program. The program featured operations such as block managing, zoom and snap functions, based on an associative logic. It took three more

[6] *Ivan Sutherland's Sketchpad on MIT TX-2*, n.d., photography, viewed in March 10, 2019 < https://jeromeabel.net/wiki/informatique/>

decades until commercial software embraced CAD programs. In 1982, Jonh Walker founded Autodesk Inc.® and in December of the same year, launched AutoCAD® V. 1.0 at the COMDEX trade show in Las Vegas. Later in 1987, Samuel Geisberg developed and launched PTC Creo, officially known as Pro/Engineer®, for mechanical design systems. The program enables users to associate tridimensional component geometries. This update not only reduced the cost of making changes, as well as overcame the tridimensional modeling constraints. Bigger and more profound achievements were made since the late 1980s to the present day. Practitioners and academics explored new and more advanced ways to manipulate software from its internal structure, aiming to find new forms and unexplored solutions through programming. More sophisticated software emerged, with the capacity to create more elaborated and complex geometries through structuring routines and procedures, relying on programming languages which express instructions in a form that could be executed by the computer, through a finite list of basic and well-defined instructions – the algorithm. Algorithms can define any type of geometry. The method relies on writing a draft of actions and translating it into a programming language. The development of different programming languages gave rise to parametric design processes and applications. Based on algorithmic thinking, parametric design enables the creation of form through the expression of parameters and rules, defining the relationship between design intention and possible responses. Today, several parametric applications are available to the general public. Firstly introduced in 2003, the Generative Components (GC) is a parametric CAD software developed by Bentley Systems. In the design of buildings, GC's main users are architects and engineers, but there is a growing community that uses it to model natural and biological structures as well as mathematical systems. Initially developed to run in Bentley's MicroStation software, GC is now available as a free and independent download. Rooted in CATIA V5 (CATIA - Computer-Aided three-dimensional Interactive Application), the Gehry Technologies created the Digital Project. Officially released in January 2013, the Digital Project is a parametric software application known as the software used to design, fabricate, and assemble the Guggenheim Museum Bilbao. In 2014, Trimble Company acquired the Digital Project. Developed for Trimble Sketchup since 2009, the Modelur is a parametric urban design software developed by Agilicity d.o.o. (LLC). This software stands out for its type of used parameters. Unlike other software of its type that use measurable parameters, Modelur uses key urban parameters, such as the number of floors or levels in relation to the implantation surface area ratio. Currently, Autodesk owns two visual programming languages software, Dynamo for Revit, released in 2012, and Max Creation Graph (MCG), released in the 3DS Max 2016. Both, Dynamo and MCG, are programming environment software that enable designers to create visual logic in order to explore parametric conceptual designs and automate tasks, using the concept of modifiable wired parameters to control geometries, providing users with the ability to program its functionality. Another relevant and emergent software is Marionette.

Released for the first time in Vectorworks 2016, Marionette is an open-source visual programming language that enables users to create custom application algorithms that build interactive parametric objects, automated 2D drawing, and 3D modeling. Similarly, to Grasshopper®, Marionette is built in Python programming language. Launched for the first time in 2007, under the title Explicit History, Grasshopper® is primarily used to build generative algorithms. Grasshopper® is a visual programming language (VPL) free software, developed by David Rutten, at Robert McNeel & Associates, in 2007, for Rhinoceros® (a non-uniform rational B-spline based system - NURBS). Over the last decade, Grasshopper® became one of the most popular and advanced algorithmic modeling tools, counting on with a large community of users and developers. This exponentially growing community (which includes dynamic and active works produced by its members) questions and discusses challenging problems, enabling constant updating and improvements, bug fixing and the appearance of new features, while also creating an ecosystem that extends the software's potential. Plugins developed for Grasshopper® are available for dynamic simulations, physics, structural, and environmental analysis, among others (Tedeschi, 2014, pp. 20-34). In February 2018, Grasshopper® became part of the standard Rhino toolset in the Rhino 6.0 and later.

“Process is more important than outcome. When the outcome drives the process, we will only ever go to where we've already been. If process drives outcome we may not know where we’re going, but we will know we want to be there.” (Mau, 1998, p. 1)

In the last decades, environmental analysis simulation has been wildly used to inform design decisions. The challenge has been to optimize the process of integration of quantitative data, derived from the simulation and analysis process within the design modeling process, thus establishing a seamless workflow that is both easy to apply and more efficient.

4.2 Design and analysis platforms

Currently, there is a vast selection of tools for designers to utilize. From traditional digital design tools that only provide a linear process (manual modeling), and consequently limited possibilities, to interactive modeling (parametric design), enabling the user to explore almost infinite possibilities. The designer is able to generate several different 'versions' of a design proposal and subsequently test each one against a set of performance criteria to determine the one with the optimal performance. The use of parametric design to integrate analytical results with 3D modeling reflects the current status of 'digital design' and its inclination to be more integrative, linking processes through software and hardware.

Design and analysis platforms may be classified into three different types: static, cross, and dynamic platforms. With the static platform, designers develop their model, which is then exported into an analysis software. While the design evolves, one has to go back to the modeling software and reprogram it, repeating the process. In the cross-platform type, the base geometry is conceived in a static 3D modeling software and then exported to a secondary interactive modeling software that has the ability to dialog, interpret, and translate its geometry to the analysis software. Although this secondary type of modeling software does not have the ability to conceive 3D geometry, it can, however, redraw it. Finally, the dynamic platform type enables the creation of any type of geometry, linking it to the analysis software, enabling the geometry (re)definition, adjustment, and analysis in real-time (Marroquin, Thitisawat, & Vermisso, 2013). There are several context and environmental analysis software. In the following section, some of the most relevant and accessible will be introduced. It is also important to note that the selection of a particular software is often subjected to change because of its type of access (whether it is open source or not), its ability to import and export various types of files, and also the number of intermediaries that the model has to go through until it reaches the environmental software.

EnergyPlus® (under development since 1997)

EnergyPlus® is an energy analysis and thermal load simulation program developed by the US Department of Energy. Based on the description of a building from the perspective of its physical composition, its mechanical systems, coatings, among other components, EnergyPlus calculates the heating and cooling loads required to maintain the thermal control points. It is the intent of EnergyPlus to handle as many building and HVAC design options, either directly or indirectly through links to other programs in order to calculate thermal loads and/or energy consumption for a design day or an extended period of time. EnergyPlus is not a user interface. It is intended to be the simulation engine around which a third-party interface can be integrated. Inputs and outputs are simple ASCII (American Standard Code for Information Interchange) text that is decipherable but best left to a GUI (a Graphical User Interface).

Ecotect Analysis® (discontinued since 2015) - Autodesk® Vasari® (introduced in November 2010)

Autodesk Ecotect Analysis® was an environmental analysis tool that allowed designers to simulate environmental building performance (energy, daylighting, and acoustics). The software was initially developed and commercialized by the Australian Square One Research, being acquired by Autodesk in 2008. Ecotect Analysis® combined analysis functions with an interactive display that presented analytical results directly within the context of the building model. Ecotect Analysis® was different from other analysis tools because it targeted the early stages of the concept design, a stage where the design is still uncertain and flexible. In 2015, Autodesk announced the end of new licenses to Ecotect Analysis® software. After mourning the discontinuation of Ecotect® by Autodesk®, many users are looking into Vasari. Major Ecotect® features were incorporated in Revit®, Revit® Plugins, and Autodesk® Vasari® (Figure 4.0:6). Vasari is a design tool for creating building concepts, integrating analysis of energy and carbon, providing design insights over possible decisions. One of the main features is the total compatibility with the Autodesk® Revit® platform for BIM (Building Information Model), ensuring clear fulfillment of design intents.

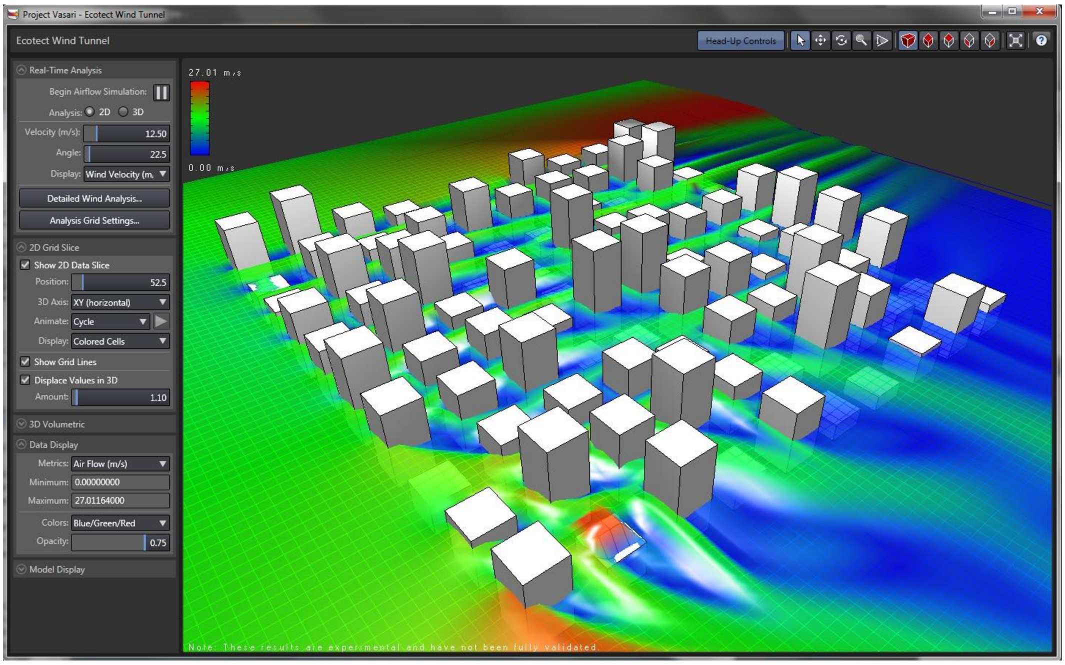

Figure 4.0:6: Vasari wind tunnel simulation[7].

DIVA® (first version available in 1996)

Initially developed at the Graduate School of Design at Harvard University, DIVA (for Rhinoceros and Grasshopper) is a plugin that runs thermal, daylight, solar radiation, and glare simulations, currently expanded and distributed by Solemma LLC. The plugin enables the user to carry out a series of environmental performance evaluations of buildings and urban landscapes. These performance evaluations are materialized in radiation maps, photorealistic renderings, climate-based daylighting, annual glare analysis, LEED and CHPS daylighting compliance as well as, multizone energy and thermal comfort calculations. DIVA simulations are based on Energy Plus, Radiance, and Daysim.

[7] *Vasari wind tunnel simulation*, n.d., print screen, viewed in March 10, 2019 <http://wiki.theprovingground.org/revit-api-py-random>

Climate Consultant 6.0 (released on July 5, 2018)

Developed by the Department of Architecture and Urban Design at the University of California (UCLA) in Los Angeles, Climate Consultant (CC) is a free and simple to use program that takes EnergyPlus® climate data (annual 8760 hour EPW format climate data) and organizes it into graphic representations (Figure 4.0:7). CC is not a simple data plotter; it organizes and represents this information showing that small meaningful attributes of climate could have a significant impact on architecture building form. Furthermore, CC also provides some user control over those representations and even provides design guidelines based on the analyzed climate. The goal is to improve the user's capacity to create more energy-efficient and sustainable buildings based on its unique spot on this planet (Milne, n.d.).

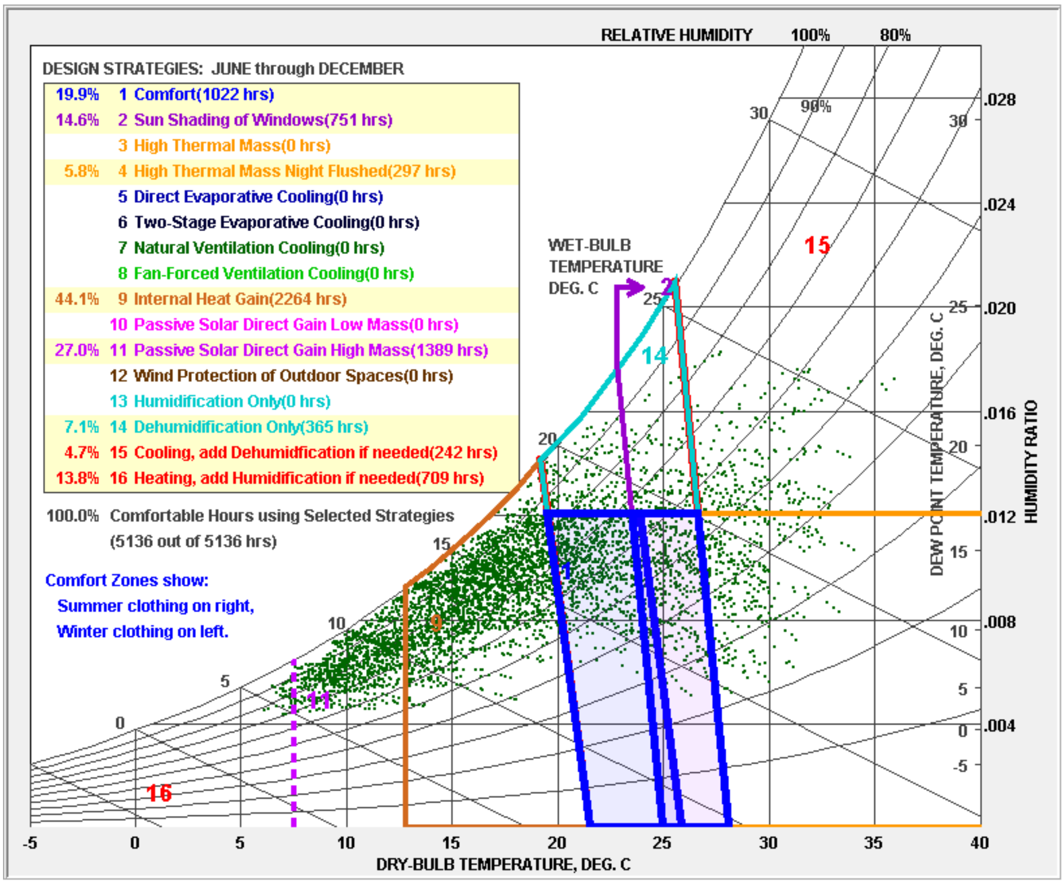

Figure 4.0:7: CS Psychrometric Chart.

Euclid® (developed since 1970)

Build on the legacy OpenStudio®, Euclid is a free and open-source extension for Sketchup (Big Ladder Softwares, 2018). Euclid is a collection of software tools to support whole building energy modeling using EnergyPlus® simulation engine and advanced daylight analysis using Radiance©. The extension is a fully featured graphical interface, including envelope, loads, schedules, and HVAC. ResultsViewer enables browsing, plotting, and comparing simulation output data, especially time series. The extension supports the reading and writing of EnergyPlus® outputs in its native Intermediate Data Format (IDF) format, adding some new features and capabilities to read and write other energy formats.

Ladybug® (released on January 2013)

Ladybug® is a free and open-source environmental plugin for Grasshopper® that supports designers during early and mid-stages of an environmental architectural design (Figure 4.0:8). Ladybug-based design processes initially start with weather data analysis, leading to high-performance design decisions. Using EnergyPlus® Weather files (.EPW) in Grasshopper®, Ladybug® provides a wide range of 2D and 3D interactive graphics to support design decisions. The plugin also supports designers to test design options for implications from radiation, sun path, and sunlight hours analysis. Integrated with Grasshopper®, Ladybug® enables a constant feedback loop between the design and the analysis (Roudsari, Ladybug Primer, 2018).

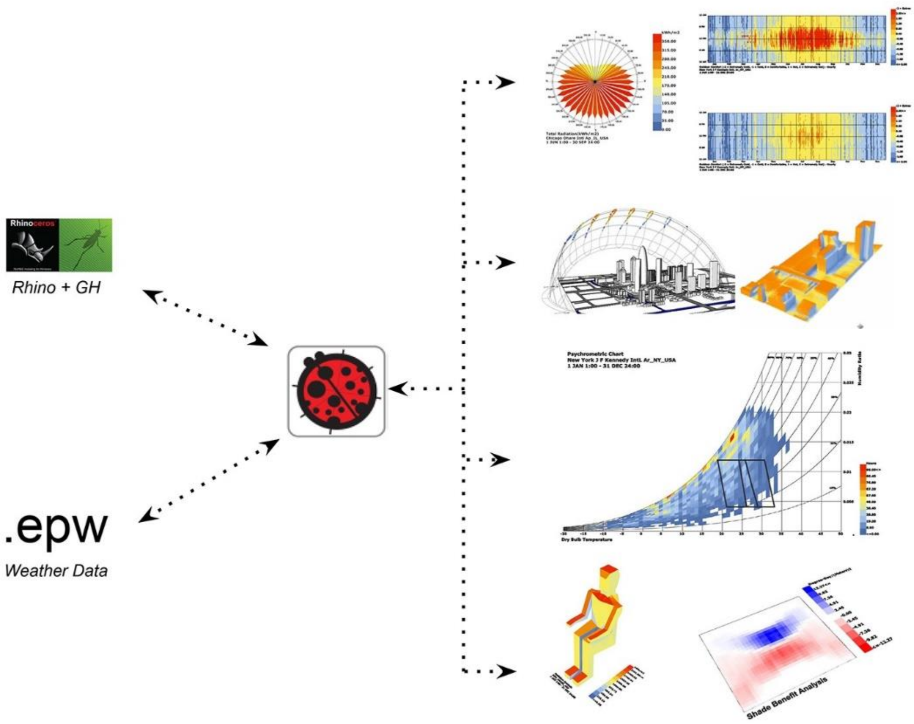

Figure 4.0:8: Ladybug workflow[8].

[8] Ladybug workflow, n.d., diagram, viewed in March 10, 2019 <https://parametricmonkey.com/2016/03/13/ladybug-honeybee/>

Honeybee© (released on January 2013)

Honeybee© is a free and open-source environmental plugin for Grasshopper® that supports detailed daylighting and thermodynamic modeling during the mid and later stages of the design process. The plugin creates, runs and visualizes daylight simulations results through Radiance® (a light simulation tool) (Fuller & Mneil, n.d.), energy models using EnergyPlus®/OpenStudio® and heat flow using Therm® (a two-dimensional conduction heat-transfer analysis) (Berkeley Lab, n.d.). Honeybee© is one of the most comprehensive plugins presently available for environmental design, due to its capacity of linking its simulations engines to computer-aided design and visual scripting interfaces such as Grasshopper®/Rhino® and Dynamo®/Revit® plugins.

Nowadays, there is a wide range of environmental analysis and daylighting software available. However, most of the designers would agree that a workflow that combines modeling and analysis tools is more comprehensive, less chaotic, and more economical in time and financial resources. Although most architects agree with this statement, their practice does not reflect it.

Currently, there is still a higher offer of static analysis software compared to the cross and dynamic ones. If we look at the Portuguese context, this may be related to the reality still present in our architecture offices. The vast majority of Portuguese architecture offices still use archaic 3D modeling platforms, reflecting strong resistance to the implementation of visual programming language software. Although the visual programming language is a very accessible form of programming for architects, designers, and engineers, many still see it as something very complex, that escapes the field of creation and enters the field of exact sciences, just like Mathematics. Though the inherent costs, most architecture offices still prefer to use static software, separating it from its modeling-based software. In this case, static software is independent of the modeling software, acting as project consultants. The user entirely filters the intersection between the results of the analysis and the pre-existing modeling. Energy Plus, Ecotect, and Climate Consultant are static software, Diva for Rhino and Euclid can be considered cross platforms, while Vasari, Diva for Grasshopper, Ladybug, and Honeybee are dynamic.

A particular case is related with Ecotect Analysis® and Revit®Vasari. Ecotect Analysis® was a very successful and well-known software for daylighting and thermal analysis that, after its acquisition by the Autodesk family, was transformed and progressively substituted by the Revit®Vasari. With this substitution and adaptation, Autodesk picked one of the most popular static analysis software and transformed it into a dynamic software that can dialogue and interact with Revit, a Building Information Modelling software, creating Revit®Vasari. This case may shed some light on the future development of static analysis software.

4.3 A brief reflection on parametric design

Parametric design has emerged as a powerful design tool. Research and praxis groups are developing parametric design theories, undergoing an epistemological shift. The development of current tools and practices for parametric design is beginning to impact forms of parametric design thinking. Architects are witnessing and contributing to a changing context, under the impact of a rising generation of scripting languages and techniques (Burry, 2011), relational topological schema, associative geometries, re-editing processes (Woodbury, 2010) and computational process models of digital design (Oxman, 2006) apud (Oxman, 2017). Parametric design thinking is driven by the need to explore and conceive the novelty and uniqueness of the design methodologies, techniques, and tools. Parametric design offers a new approach to Architecture based on advanced computational techniques. While the number of users increases, some state that architects are facing the creation of an architectural style. In his Parametricist Manifesto, Patrick Schumacher stated, "As a style, parametricism is marked by its aims, ambitions, methodological principles, and evaluative criteria, as well as by its characteristic formal repertoire" (Schumacher, 2008).

Sketching by code is not only a possibility, yet it is a norm of skill and knowledge. Visual image in paper-based design is replaced by visual form and visual code in parametric design. Leading concepts of topological design thinking offer unique design methodological approaches in parametric design thinking. Mediated by recent parametric design tools, parametric design is a new operative model of design thinking. While the traditional typological mode of thinking may limit creative processes of exploration, differentiation strategies in a topological approach of thinking support new types of creative thinking in innovated design. Understanding how to manipulate and explore associative relationships in topological parametric schema is emerging as a model and a style. Parametricism as a style may, in fact, be considered as both a new style and model of design. It represents a new body of knowledge as well as a new set of methodologies in the design disciplines. The tools and practices of parametric design are impacting new forms of development in the institutions of education and practice of design culture. Scripting and tool-making are becoming required forms of knowledge in research, education, and practice (Oxman, 2017).

However, in research, there is still a lack of established and accepted scientific methods, mechanisms, and theoretical basis for the digital age. Media often provide images without any type of explanation, theoretical foundation, or methodological process. These are the same images that are the inspirational source of architectural students, that see this without any contextualization. Universities lack 'digital design' disciplines, setting digital resources aside from the project development ideas. Architectural practice, generally, still sees 'digital design' as a substitute for the pen and pencil, an auxiliary tool that increases precision or a media resource, instead of a reflection design tool generator (Grisaleña, 2017). To generate a genuine bidirectional bound between Architecture and digital, it is necessary to build theories and methods that enable the creation of concepts, research, and experiences (Kotnik, 2010) (Oxman, 2017) (Terzidis, 2006).

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SECTION III
PRELIMINARY EXPERIENCES

5.0

Kine[SIS]tem'17 International Conference + Summer School

5.0 KINE[SIS]TEM'17 – INTERNATIONAL CONFERENCE + SUMMER SCHOOL

Figure 5.0:1. Kine[SIS]tem'17 poster.

Nature is the most reliable, sustainable, and efficient architect that ever existed. For centuries Nature's maximum inventory and minimal resources have inspired human creations, leading humans to exceed all physical boundaries, since formal, structural, material, to the invention of new materials, tools, mechanisms, systems, and methods (Oxman, 2010). During the summer of 2017, ISCTE-Instituto Universitário de Lisboa hosted Kine[SIS]tem'17 International Conference + Summer School[1]. Kine[SIS]tem'17 ([SIS]'17) was the first International Conference (IC) and Summer School (ISS) held in Portugal aiming at sharing, debating and creating research and design work related to the integration of natural concepts, systems, adaptations and geometries into architecture scale function and aesthetics (Figure 5.0:1).

This was a very significant milestone in this research with which it was possible to develop and explore a preestablished biomimetic methodology applied to Architecture, in a defined short period of time.

5.1 Introduction

Held during eleven days, between July 19th and 30th, [SIS]'17 accommodated two distinct moments. The first moment of [SIS]'17, From Nature to Architectural Matter IC, relates with the first two days of the international event, highlighted by the presence of four prominent keynote speakers in the field: Manuel Kretzer (Professor for Material and Technology at the Fachbereich Design Dessau - Department of Design); Alex Haw (Architect and CEO at the AtmosStudio); Bob Sheil (Director of The Bartlett School of Architecture, Professor in Architecture and Design through Production, and the School's Director of Technology); and Alberto T. Estévez (Founder and Director of the ESARQ – School of Architecture of the Universitat Internacional de Catalunya, UIC Barcelona; Founder of the Biodigital Architecture Master & PhD program and the Genetic Architectures Research Group and Office). The two conference days gathered academics, students, and professionals of different fields such as biology, architecture, computer science, and sociology. In these IC two days, a significant and relevant set of researches and works were presented and debated between representatives of the different fields. The Shading Systems ISS was the second moment of [SIS]'17. Developed in nine days, the design studio started with four essential masterclasses – I) Sustainability and solar radiation; II) Nature-based parametric patterns design; III) Experimentation and simulation by Ladybug; and IV) Digital fabrication, mechanics and electronics, followed by studio work assisted with regular desk reviews, prototypes construction, and by a final public presentation.

5.2 [SIS]’17 From Nature to Architectural Matter

[SIS]'17 IC public presentations were divided into four sessions, each including the presentation of seven papers and a keynote closing lecture, which led to a thirty minutes reflection and debate. During the two days' of the conference, and over the four sessions, the [SIS]'17 IC was dominated by four major themes: 1- Time matter and matters; 2- Human nature; 3- Biological-inspired, and 4- Architecture = Inter(trans)disciplinary field. These themes have been addressed by several authors, through several works, and were reflected in the four main issues of the event.

Time matter and matters

During his presentation, Manuel Kretzer highlighted the importance of a process-oriented design based on the imagination and creation of disturbing dystopias and catastrophe scenarios, in order to create and develop encouraging and pleasant concepts, materials, and future design solutions (Figure 5.0:2). *''Even though the presented ideas might seem far from our reality and have various issues that at least for the time being will prevent their practical applicability, we managed to overcome the prevalent course of developing dark and disturbing dystopias, but instead created pleasant and encouraging concepts, which carry seeds of hope and joy''* (Kretzer, 2017, p. 9). This academic experience obtained remarkable clues and results regarding a possible design process that improves future design strategies for already predicted and scheduled possible scenarios. Under the title 'Digital Doubles, colliding in mid-air', Bob Sheil reported some of the current ScanLab work, always referring to the issue of time. In his work, time is the fundamental measure unit for time perception *''(…) scales of time and experience are now inextricably mingled, each performance taking place in its present physical space as well as interacting with the previously and presently recorded and soon-to-be represented space (…).''* (Sheil, 2017, pp. 161-162). Also, time became spatial when a controversial presentation led by Tsiamis and Haselman questioned the meaning of time in the creation of 'space'. Under the motto of the article "The way we'll live" published in 1999 in the United States, the authors stated *"(…) If we assume that the function of a space is defined by situations and not just a static moment, we can conclude that time is an essential factor in the creation of "place." (…)"* (Tsiamis & Haselman, 2017) At this point, Architecture could not be static. The authors followed their argument by explaining the necessity of Architecture to become transformable, enabling the creation of situations, reflecting the inhabitants' essence and the way they live. The issue of time is not new in Architecture. However, biomimetics seemed to emphasize the necessity to rethink this architectural dormant issue. If Nature is always evolving, adapting, and reconfiguring, should not space also evolve, adapt, and reconfigure according to its surrounding environment and its inhabitants' needs? Dickinson, in her paper "Design as an adaptive time-scape", reflects about the implications of change and adaptability, and its time process. *"(…)With global population growth and major sustainability problems we no longer have the luxury of endless amounts of time to correct* *our mistakes, we need to design systems and environments where we have factored these issues into the equation already, or at least try too.(…)*” (Dickinson, 2017).

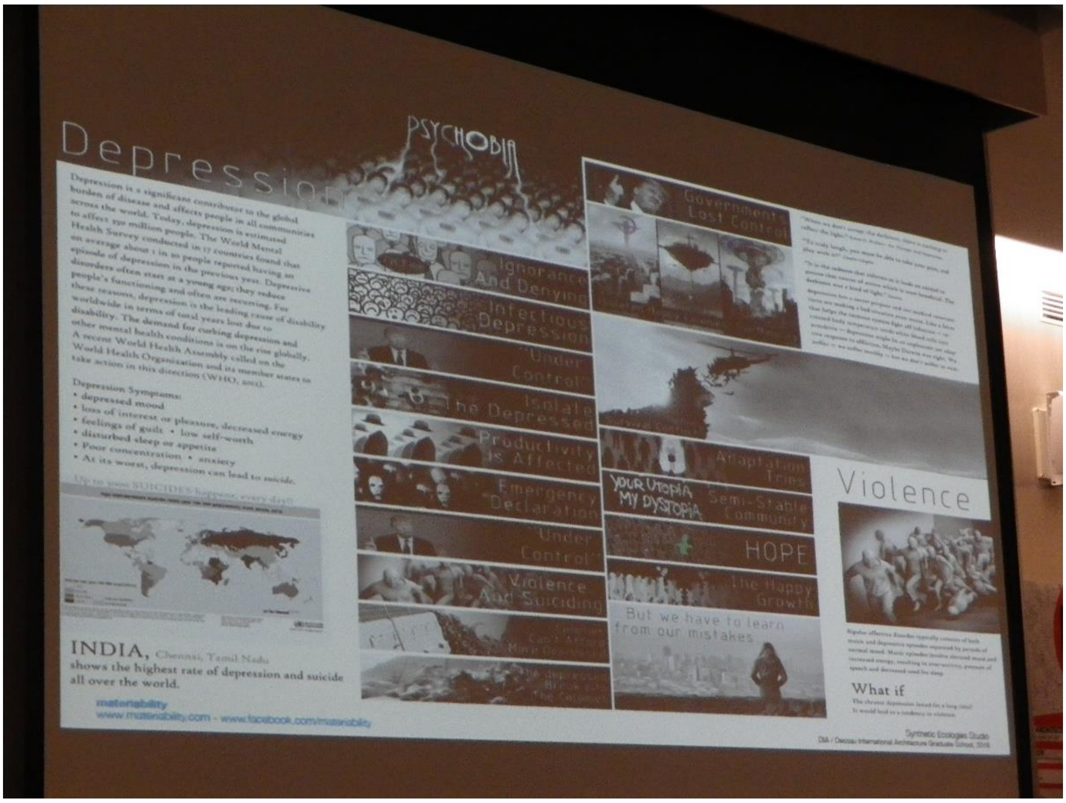

Figure 5.0:2. Manuel Kretzer presentation slide.

Human Nature

Alex Haw initiates his *“Human Nature”* article presentation with the following sentence: *“Contemporary architecture (perhaps like so many cycles of historical architecture before it) seems to love the study of nature. Yet there is one form of nature whose influence it continually suppresses: human nature. (…)”*. If considered that the above issues relate to time, and the previous statement was presented at the same event, it is hard not to imagine that there is something wrong. However, this only scratched the surface of this problem. If it is considered that time is a human mental representation for spatial change and evolution, so how could it suppress human nature? During his presentation, Alex Haw decomposed his initial issue, leading the conference audience through a journey over some few examples, produced by his studio, where they explored the core of human nature, extending the human body into the creation of a new augmented ecology (Haw, 2017) (Figure 5.0:3). Based on Ballard´s remarkable work, the emotional psychotropic house, on the second session of [SIS]'17 conference, Blanchi and Mortamais presented their article "*A psychotropic surface based on soft shape changing material - Emotional input and pneumatically driven actuator*". The article presented a developed soft changing surface, based on pneumatic systems controlled by an emotional and sensitive human perception data (Blanchi & Mortamais, 2017). Wilfredo Méndez and Esmeralda Niño presented an engineering solution aimed at (re)engineering the concept of seismic resilience rooted in generating building structures that behave like humans. Using the human skeleton as a model, they developed and autonomous structure that reproduces the human skeleton ability of equilibrium to a large-scale building construction structure (Méndez & Niño, 2017). As ever, humans are trying to learn and improve their creations looking into our planet and into themselves.

Figure 5.0:3. Alex Haw presentation slide.

Biologically inspired

[SIS]'17 IC also addressed the importance and different contemporary research and advancements in material science, electronics, and mechanical systems applied to Nature-based design, as well as programmable matter and structures. Vera Parlac presented her research based on the development of artificial materials that address natural conditions in response to early-stage design requirements (Parlac, 2017). 3D printing advancements were also pointed out by Daguin, Chaltiel, and Barney (Bravo & Chaltiel, 2017) (Daguin, Lin, & Fayiga, 2017) (Barney, Lesina-Debiasi, & Pazik, 2017). New materials are being explored and (re)created as an integrated element of the design process, part of an ecosystem of development of new forms of life. During his presentation, "*Architectural Bionics: From Living Nature to Architecture*", Kozlov guided the audience into a bionic process based on resilient structures and principles, presenting a state of the art of Eastern Europe bionic experiences as well as presenting his own human scale prototypes (Kozlov, 2017). Stepping into kinetic structures based on natural examples, Oliveira et al. presented the *Musical Morphogenesis* installation project. Designed to 'teach' the essentials of plants' biology to children, the installation interacts with its users through an electronic interface that 'grows' according to a gene combination, reflecting users' commands through pneumatic movements and sounds (Oliveira, Sousa, Costa, Oliveira, & Mena, 2017). Later at the last conference session, Gago presented the '*Morphological Generator of Biological Identity*', where he argues that human mechanical systems are composed of a set of biological geometries (Gago, 2017). Closing the conference panel, Alberto Estévez presented several of his research projects and addressed the importance of the implementation of the study of biology and genetics during architectural graduation, as a fundamental key for the future of the architectural design processes (Figure 5.0:4). *''Pedagogically, the sourcing of biological attributes through scientific equipment, genetics, and computational programming serves to technologically open pathways by which emergent intelligent architectures may inhabit nature and partner with biological life''* (Dollens & Estévez, 2017).

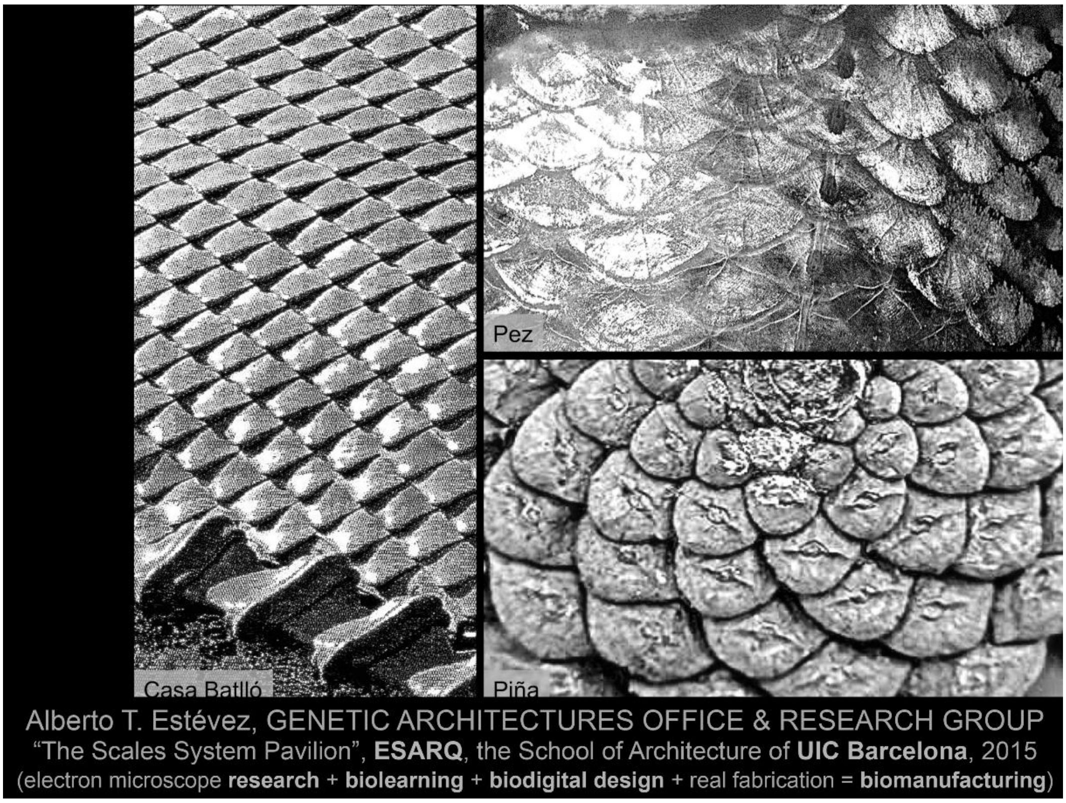

Figure 5.0:4. Alberto Estévez presentation slide.

Architecture = Inter(trans)disciplinary field

Today architecture is all about human nature. Architects are learning new field lexicons, frequently working with researchers from other fields, integrating non-architectural natural concepts into their discourse, and creating new materials. However, if, on the one hand, classic anthropocentrism seems to (re)emerge, never after the Renaissance, the definition of the 'architecture practice' has been so far from the era that created the architect's class. Today's 'architecture practice' is very similar to the condition and the daily work of a 12th century master builder, the medieval 'architect'. So yes, at the moment, architects are centered in its Human nature, but not in its lonely version of it, instead of in its condition as part of a global natural system – our planet Earth. Blonder, Osório, and Davidová presented three different research works, based respectively on bird nests, origami geometrical principles, and programmable natural matter. The fundamental hypothesis of the threefold research work was the knowledge of morphological and behavioral natural systems, applied through parametric design tools, that enable the control and integrity of their projects through the computational structural simulation and virtual material testing (Figure 5.0:5) (Blonder, 2017) (Osório & Oliveira, 2017) (Davidová, 2017). During *"Origami Textures for Adaptive Plate and Shell Structures"* presentation, Giodice presented his shell structures based on origami patterns. Working over kinematic and static behavior, validation, and final results were only possible to achieve after the tests over the physical prototypes. In his research, the use of digital fabrication was determinant to achieve reliable structural results, by the fabrication of precise models and the virtually predicted difficulties of assemblage (Giodice & Romeo, 2019). The trivialization of digital fabrication tools and methods has enabled the development and integration of other areas of study into the architectural design process. Examples are the creation of a prototype solution that explores interdisciplinary approach to agricultural design in cities, presented by Cardoso (Polites, et al., 2017); the research conducted by Zavoleas based on the concept of a biologic multi-agent - nanoscopic patterns observed on nanoparticles in structural biology (Zavoleas, 2017); or the Esbaldi research that reported the methodological process of the creation of free-form geometric shapes as a consequence of the materialization and formalization process of a material. "*(…) The realization of design is carried out through the formalization of materials (…)"* (Elbasdi & Alacam, 2017).

Figure 5.0:5. Marie Davidová presentation slide.

5.3 [SIS]'17 – Passive Shading Systems

The second moment of [SIS]'17, named [SIS]'17 Shading Systems ISS, had as a goal to develop passive, low-cost shading systems solutions for a pre-designed and assembled structure. The ISS was conducted through two main stages: previous context creation and analysis, and design studio. The creation and analysis of a context (the first stage) were developed during [SIS]'17 'backstage' period, by the [SIS]'17 tutor's team. This first stage was related to the definition of a place for the intervention, typology, morphology and occupancy data collection, site environmental analysis, and solar radiation studies. Design, fabrication, and assembly of the base structure skeleton for [SIS]'17 participants were also carried out. Design Studio was the stage when participants had the opportunity of creating, developing, analyzing, and fabricating their work: three nature-based passive, low-cost shading systems solutions.

5.3.1 Stage 1 – Creation and analysis of the context

Conducted at the ISCTE-IUL university campus, the site was chosen based on architectural criteria, as well as on the campus' solar conditions and its users' usage. Predominantly occupied only on its margins, due to the discomfort caused by the excess of heat and incident solar radiation, the selected location, was a second level 100m2 terrace, limited by two white seven-level façades cladded by lioz marble. To increase users' occupancy in the middle of the terrace, a canopy skeleton was designed as the base docking structure for the posterior shading systems produced by participants at [SIS]'17 ISS. The first step was to define the specific local implantation. Based on an environmental analysis, supported by Ladybug, an open-source Grasshopper plugin, a wind rose diagram, and solar-path analysis was conducted, in order to map the terrace conditions (Figure 5.0:6). Terrace context scenario revealed to be a determinant factor over irradiance, reflection, and refraction results. The façade cladding in white lioz marble, intensifies the reflection and refraction of the light spread effect, causing not only the heat intensification but also an elevated visual discomfort, ruling out possible types of spatial occupation. The second step was to study users' occupancy and pedestrian path patterns (Figure 5.0:7), mapping (Figure 5.0:8) and analyzing it based on the creation of analysis diagrams and graphics. The third step was to load three concepts into the canopy design: I) the canopy needed to be self-sufficient; II) canopy materials should be recycled or reusable, and III) the canopy should be designed considering minimal resources, in order to reduce production and maintenance costs. [SIS]'17 ISS was sponsored by Coretech (thermal and acoustic panels, 100% recyclable, designed by recycling automotive by-products) and limited to the existing stock, sixteen boards measuring 2200x1200x16mm.

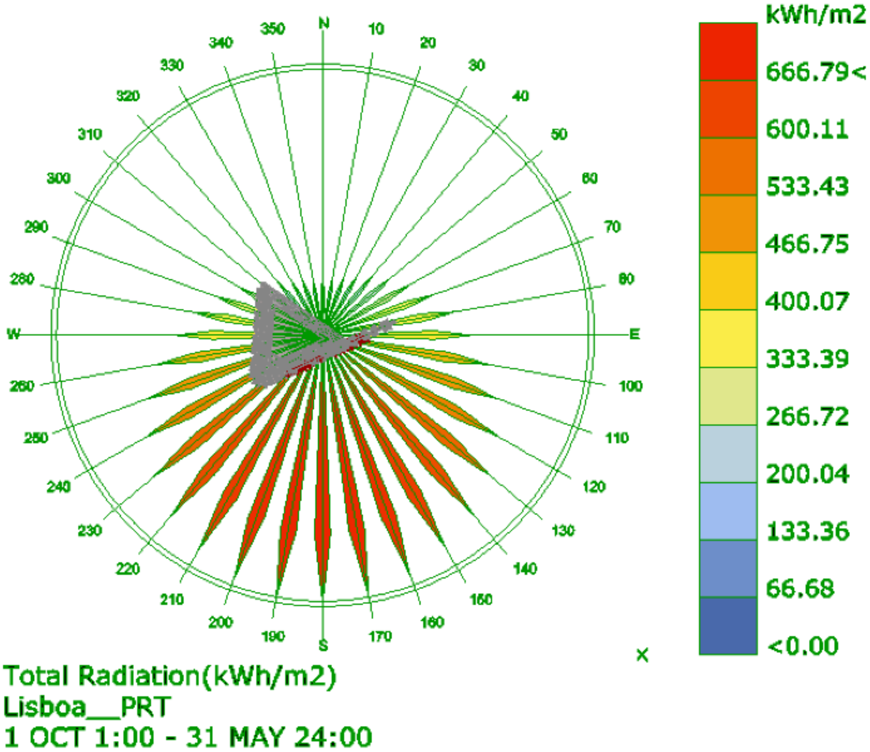

Figure 5.0:6. Radiation graphic extracted from ladybug analysis.

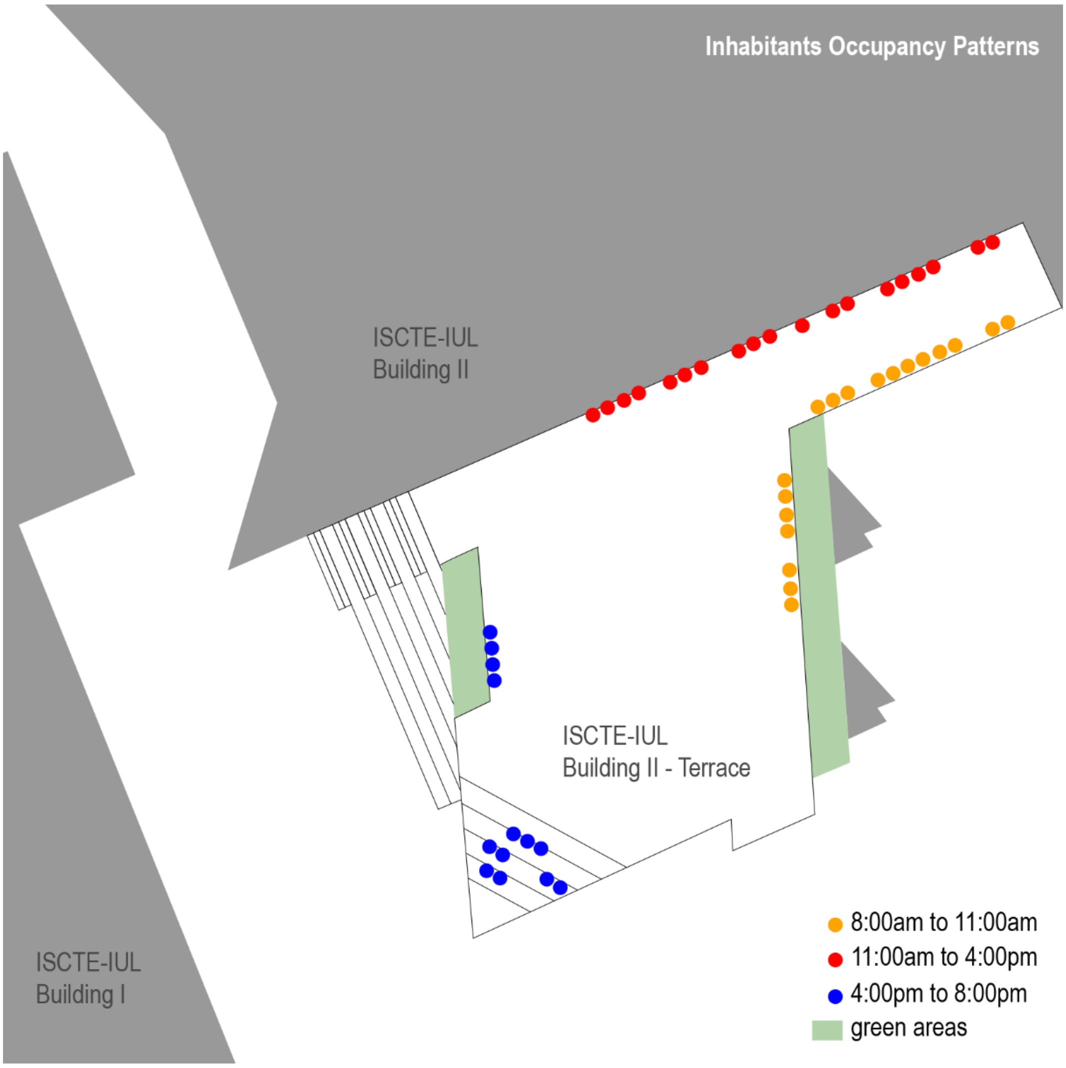

Figure 5.0:7. ISCTE-IUL terrace inhabitants occupancy patterns diagram.

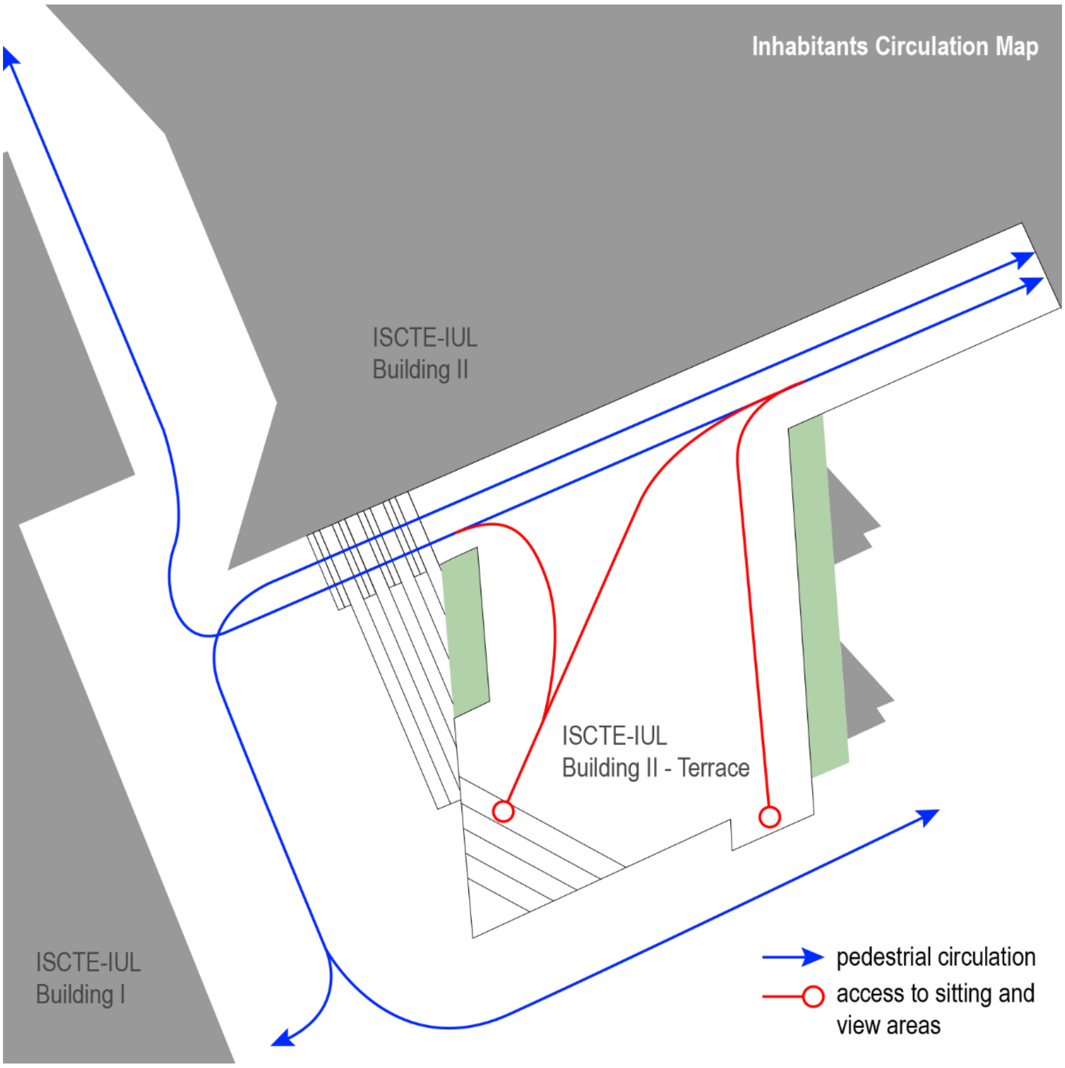

Figure 5.0:8. ISCTE-IUL terrace inhabitants circulation diagram.

Having in mind the three concepts mentioned above, the canopy was designed in order to be a completely self-assembled and supported system, without the use of any other type of materials, screws, glues, or others. Four triangular-shaped frames and a bench were the elements that defined the canopy's skeleton (Figure 5.0:9). Working as isolated modules, the four triangular frames and the bench were preassembled and then transported to the campus terrace. Once in the terrace, the elements were assembled through its locking and sealing designed system. The canopy was positioned in the campus terrace, based on the wind and solar analysis, with one frame facing West, two frames facing South/Southwest, and the fourth being the horizontal frame that linked all other frames together, performing the functions of a rooftop.

Figure 5.0:9. [SIS]'17 Shading System canopy skeleton.

5.3.2 Stage 2 - Design studio

Having as starting points, 1- Lisbon and ISCTE-IUL terrace site's specific conditions; 2- a pre-designed and assembled canopy skeleton; 3- predetermined canopy location and placement; and 4- surrounding constraints and functional data, the summer school participants were challenged to design, fabricate and assemble passive shading solutions, based on the three essential concepts, i) self-sufficiency; ii) reusable/recycled materials; and iii) low-cost, for each triangular frames of the canopy. Participants were divided into three groups. In an initial phase, they were encouraged to subdivide the presented problem into four main issues: a) structural constraints, b) material availability, c) nature inspiration, and d) its relevance and major input for the system. Thereafter, participants were invited to focus on the design and construction of the shading system and its related functional aspects: shading effects, system performance, system responsiveness to its environment and/or its users, human comfort, etc. During this process, previous environmental analysis parametric files, surrounding constraints and functional data were provided to the participants, as well as some fundamental online databases, like Biomimicry 3.8, AskNature, Diffen, among others, so they were able to find and explore possible Nature solutions, examples, and strategies. In this way, the design process was sustained by environmental analysis, enabling diagnosis and consequent improvement solutions. Having as the final goal the fabrication and assemblage of the shading systems, construction prototypes were determinant to design, plan, and solve the several phases of the projects' evolution. Questions regarding assemblage, support, mechanics, fabrication component planning, incorporation of electronic systems, among others, emerged in an early phase of the design process. For the [SIS]'17 canopy challenge, three projects emerged: *'Mechanical Leaves'* projected for the rooftop module, *'The Lotus Project'* designed for the West canopy module and *'Bioshading – a Performative Mockup*' designed for the two South/Southwest-oriented canopy modules.

Mechanical Leaves (Team: Diogo Bulhões and Louay Youssef)

According to the weather and environmental analysis produced by Ladybug, the canopy's rooftop module was the element that had a lesser influence on the thermal comfort of its occupants. Driven by the environmental data analysis, the rooftop's partial shading would not induce any significant improvements for the canopy's users. The idea for this triangular frame was to design an electronic control shading system (sustained by a photovoltaic solar panel) that could enable canopy users full sunlight exposure or total blackout, according to sun exposure intensity and its individual comfort sensation. The *Mechanical Leaves* solution was rooted in the interactive movement that occurs among the natural leaves of palm trees (Figure 5.0:10).

In order to increase sunlight exposure to the lower levels of the leaves of the palm trees, leaves produce some overlapping movements enabling the passage of sun radiation. A reinterpretation of their common development and a mechanical plan led to the *Mechanical Leaves* system arrangement. Composed by two symmetrical fans, formalized by five blades each, the fans were fixed to two opposite edges of the canopy rooftop frame; the first blade of each fan is static (Figure 5.0:11). Static blades were positioned at the south and southwest edges of the canopy's triangular frame. The determinant conditions for the material choice were to avoid unwanted deformation due to deflection and to decrease the friction effect. An eight millimeters thick red fiberwood board was the selected material for the symmetrical fan systems. The development of the mechanical system faced several challenges: the availability of a restricted number of linear motors, its own weight, and its dimension, were the most significant. With the availability of one motor per group, the challenge was about how to design the mechanical system in a closed circuit, powered by a linear motor, enabling the production of a bilateral symmetry movement in the two fans. Looking into the animal kingdom, most animals have bilateral symmetry. For instance, a peacock has a heavy tail, that produces an upward movement, followed by a symmetrical fan movement, or even butterflies that fold their wings upward, perfectly matching in size and patterns. In both referred examples, the fan movement has its origin on a center axis of the animal's gravitational center and moves according to a 90º angle. Picking the idea of an overlap process of the shading system, the Lemniscata (Latin designation, for a geometric curve with an eight shape – the infinite symbol) case was selected as the natural inspirational source example. Its symmetrical principle only requires one-directional movement distributed into two opposite directions. The system fans were parametrically modeled, predicting possible physical constraints between the two fans and crashes between the blade elements and the pre-existing structure. To calculate strength and material resistance, as well as assembly constraints between blades and the canopy's structure, a 1:1 prototype was fabricated. Inspired by the Lemniscata circuit, the symmetrical fan systems were composed of a single linear motor, connected to a continuous lashing wire rope, activated by a pulleys circuit, attached to the first blade of each fan (Figure 5.0:12). The fiberwood blades were connected to each other by cotton rope (providing a soft closure and avoiding relaxation), leaving only the necessary length of rope for them to slide over each other. In order to provide electric energy to the fan systems, a PV panel linked to a power supply and a switcher was attached to the frame structure to provide the canopy's inhabitants with the options of opening and closing the rooftop (Figure 5.0:13).

Figure 5.0:10. Palm trees overlap[1].

[1] *Palm trees*, n. d., photograph, viewed 21 November 2018, <https://www.amazon.com/Artificial-Greenery-Flowers-Arrangement-Decoration/dp/B073WZY98F>

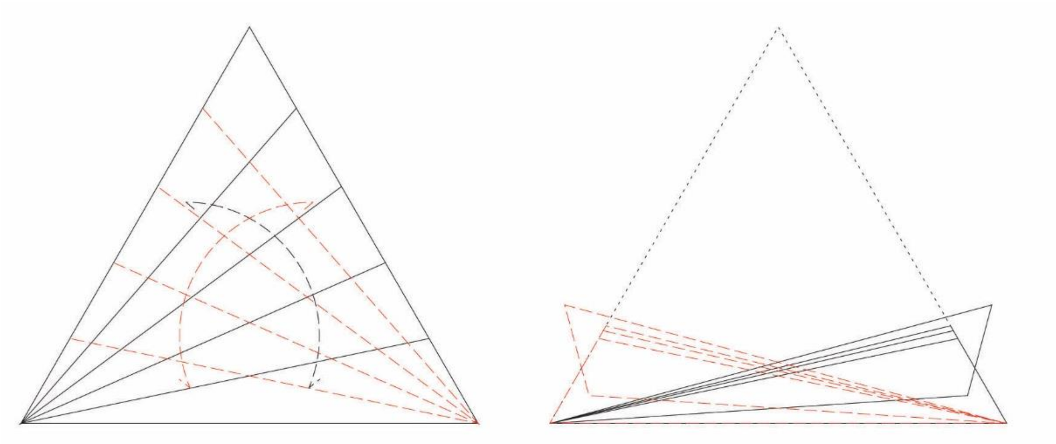

Figure 5.0:11. Mechanical Leaves blades system.

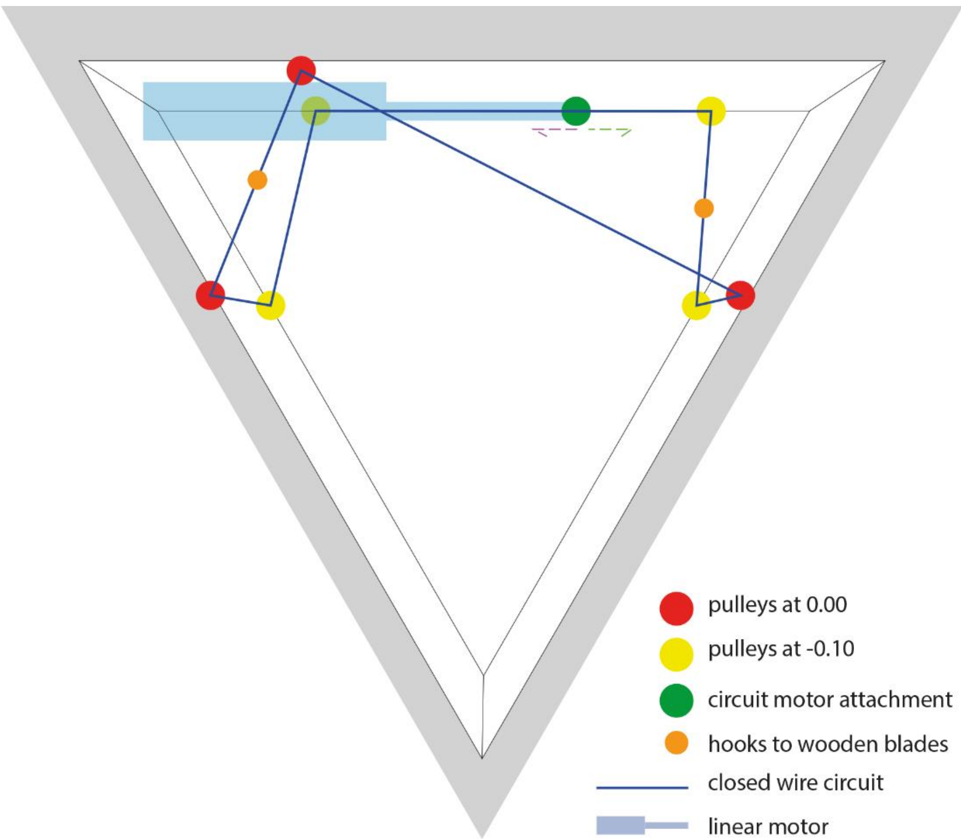

Figure 5.0:12. Mechanical Leaves, mechanical system diagram.

Figure 5.0:13. Mechanical Leaves.

The Lotus Project (Team: Luísa Almeida and Adriana Coutinho)

Developed for the west triangular module of the canopy façade, this was the frame that had to ensure the highest protection against wind and sun exposure. Environmental analysis, radiation, and sun path graphics revealed that while the south edge of this west-facing surface required larger areas of sun entrance, the north corner of the surface needed to be strongly protected, providing clues for less and smaller openings. *The Lotus Project* system found its essential hypothesis on the Codariocalyx motorius plant (Figure 5.0:14A), in which each leaf is equipped with a hinge that enables it to rotate to receive more sunlight, and the Neblumbo nucifera (commonly known as the Lotus flower) that performs daily exposing its petals to the sun and closing them at sunset (Figure 5.0:14B). Their routine could only be broken by the intervention of an external event, such to deter potential predators.

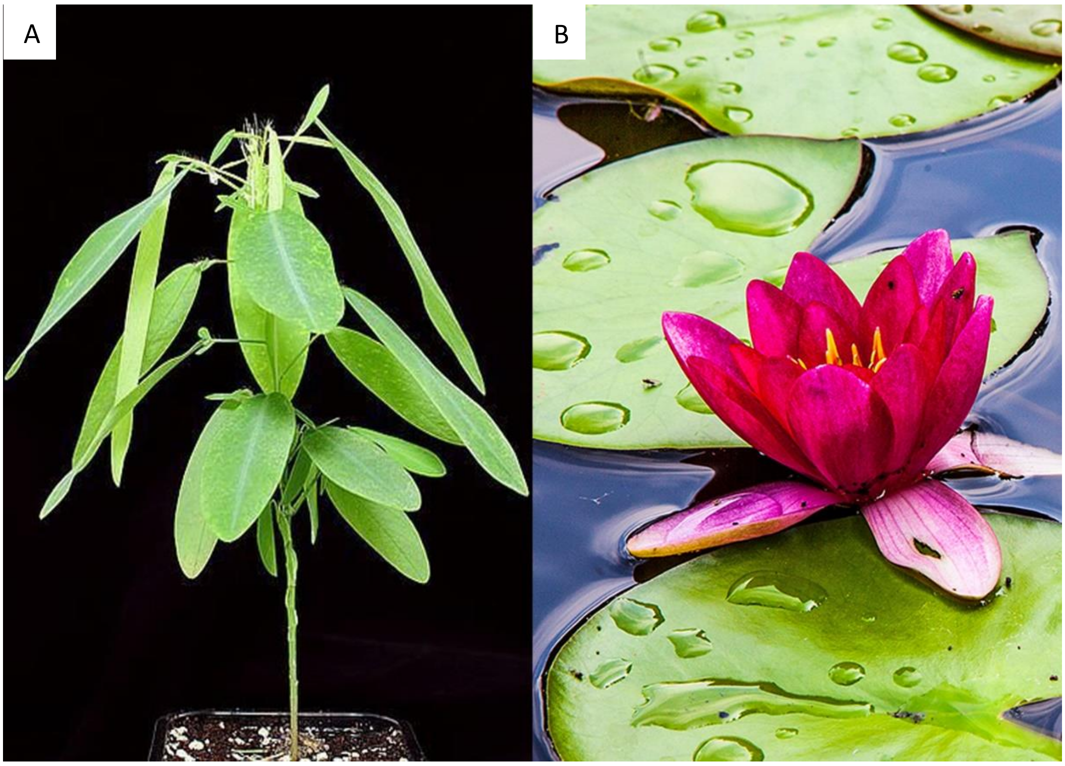

Figure 5.0:14. A - Codariocalyx motorius[2]; B - Neblumo nucifera[3].

The idea was then to develop a shading system that could enable sun exposure through the façade, and yet provide to the canopy's users the possibility to block sun and wind exposure. The conceived system had the ability to perform autonomously, establishing a direct connection with its surrounding environment, but also provide to the canopy inhabitants the possibility to interrupt the feedback loop to improve its individual comfort. To rule and sustain the parametric development of the patterned façade, a parametric definition was developed, based on the radiation and wind graphics analysis, providing adequate control coordination between the sizes of the different openings and their proximity relations. Smaller offset spinning elements filled the designed openings in order to produce a filtered direct sun and wind exposure effect inside the canopy (Figure 5.0:15). Considering that this was the most volatile façade of the canopy, the surface was materialized by an eight-millimeter perforated fiberwood panel reinforced by a thirty-millimeter insulation board of expanded cork agglomerate. Beyond providing a more controlled comfort fluctuation inside the canopy, this double skin revealed to be a valuable add-on by hiding the rotation blocking system while sustaining the metallic axis of the spinning elements. The blocking system was composed of bidimensional Y-shaped

[2] Dancing Tree Dancing Grass Telegraph Plant, n. d., photograph, viewed 16 July 2019, <https://www.amazon.es/Dancing-Telegraph-Codariocalyx-Motorius-HG/dp/B009GPINT0>

[3] A self-repairing surface that stays clean and dry, n. d., photograph, viewed 16 July 2019, <https://www.economist.com/science-and-technology/2017/05/11/a-self-repairing-surface-that-stays-clean-and-dry>

elements, controlled by a cylindrical left-right turn button enabling the canopy's users to lock/unlock the spin elements and so interrupt the 'natural' spin system. In *The Lotus Project* façade system, the spin elements establish a trilogy relationship between light, void, and surface. The proportion between the spin elements and their correspondent openings ranges between 25% and 90%, depending on the position angle of the spin element. A CNC machine cut fiberwood and cork agglomerated boards, and Y-shaped MDF blockers were fabricated by laser cutting. Conceived as a passive dynamic shading system, *The Lotus Project* engaged form, material, and environmental conditions, enabling its users to interact and intersect the 'natural' system behavior (Figure 5.0:16; Figure 5.0:17).

Figure 5.0:15. The Lotus Project spinning elements and projected shade[4].

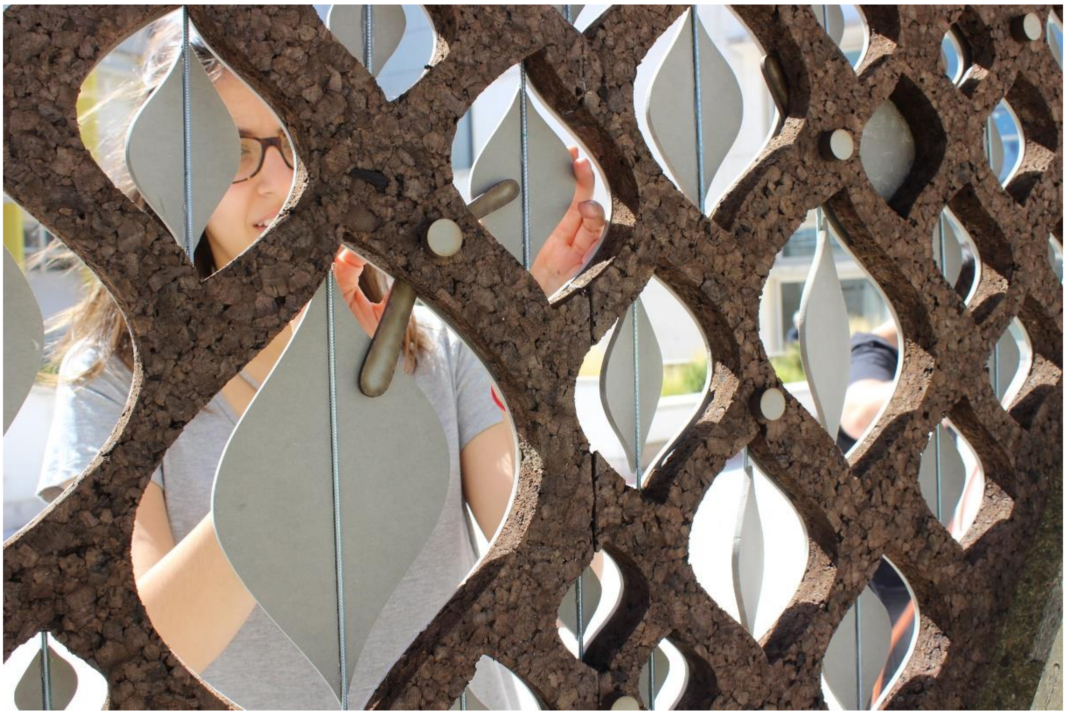

Figure 5.0:16. Blocking system, Y elements, controlled by a cylindrical left-right turn bottom[5].

[4] Almeida, Luísa, *The Lotus Project units and shade*, photography.
[5] Almeida, Luísa, *The Lotus Project – spinning elements*, photography.

z

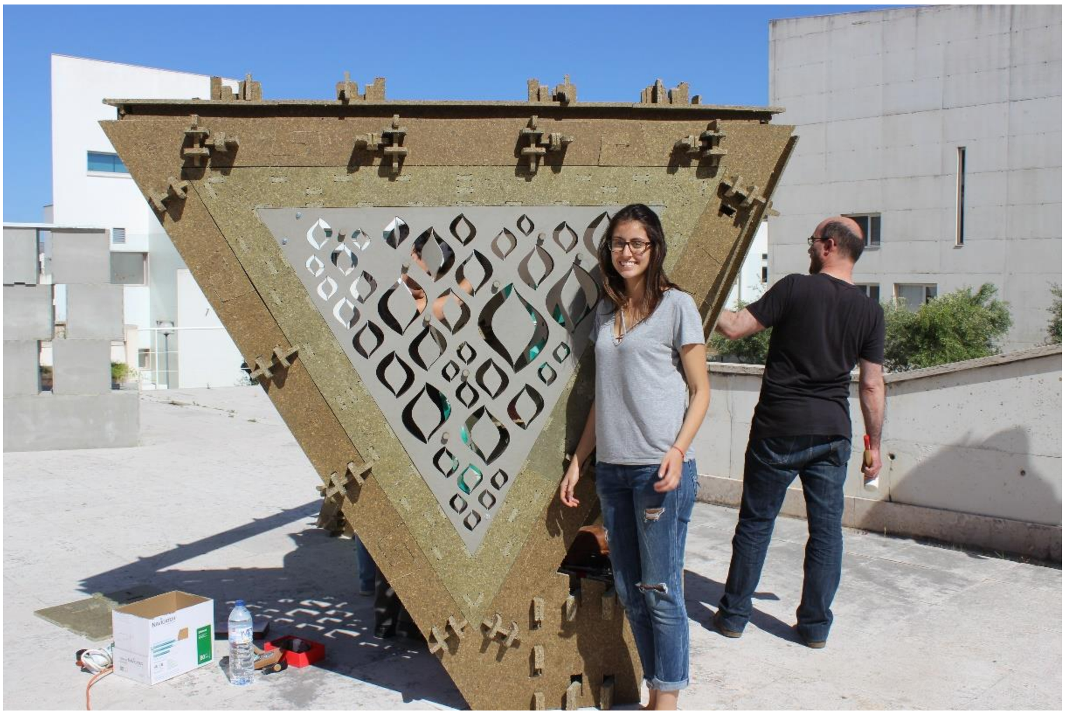

Figure 5.0:17. The Lotus Project[6].

Bioshading – A Performative Mockup (Team: Carmo Cardoso, Pedro Sequeira and Tania Papasotiriou)

Two triangular frame modules were attributed to this group. Facing South/Southwest sunlight, this façade experienced extreme levels of radiation. From an environmental analysis, while radiation graphics revealed major incidences of radiation crossing southwestern limits, it also showed that the passage of some controlled radiation could benefit afternoon users, increasing the canopy's comfort values. The group's instant idea was to develop a system that could rapidly produce an open/close movement while enabling some indirect light through the system. Looking into Nature, eye pupils seemed to provide an inspirational activity. Compared to a camera aperture, pupils play a crucial role as an adjustable opening that controls the intensity of light allowed to enter the eye. Most terrestrial vertebrates have slit-shaped pupils. While nocturnal predators, such as canines, felines, geckos, some snakes, and birds, have vertical slit pupils, other species such as frogs and humans have horizontal slit pupils. Amazingly, the open/close geometric membrane of amphibious eyes (Figure 5.0:18) also produces a retractive movement. To produce an open/close movement and create a prominent retraction movement, a tridimensional structure was designed.

[6] Almeida, Luísa, *The Lotus Project*, photography.

Figure 5.0:18. Amphibious eyes.

The tridimensional units were composed of two pyramids of different sizes attached to each other by two common vertices, establishing a structural rotation axis. The structural axis enables a rotational movement, producing a fast change of state of the system – a closed and pyramidal shape or an opened diamond frame. The *Bioshading* system needed to cover two triangular canopy modules, and at the same time, work individually at different levels in the two different modules. Therefore, the idea was to introduce hierarchy to the system through two strategies: i) by regulating the area of the voids, using the intensity of shade and radiation as a measure of proportion, and ii) by establishing a progression relationship between the different void levels of the panels, designing a progressive hierarchy void grid structure (Figure 5.0:19). *Bioshading* modules faced sun exposures between 70º and -50º. Pyramidal units covered 75% to 85% of the total area of each module. Although the *Bioshading* openings enable a conditioned solar ray passage between 20% to 50% of its total area, these low percentages of direct exposure enable the managing of a fulltime controlled and filtered system (Figure 5.0:20). The integration of this shading system into the canopy structure increases shading benefits in 2º to 3º Celsius, which translates in a 20% to 25% of comfort improvement, according to the Ladybug simulation.

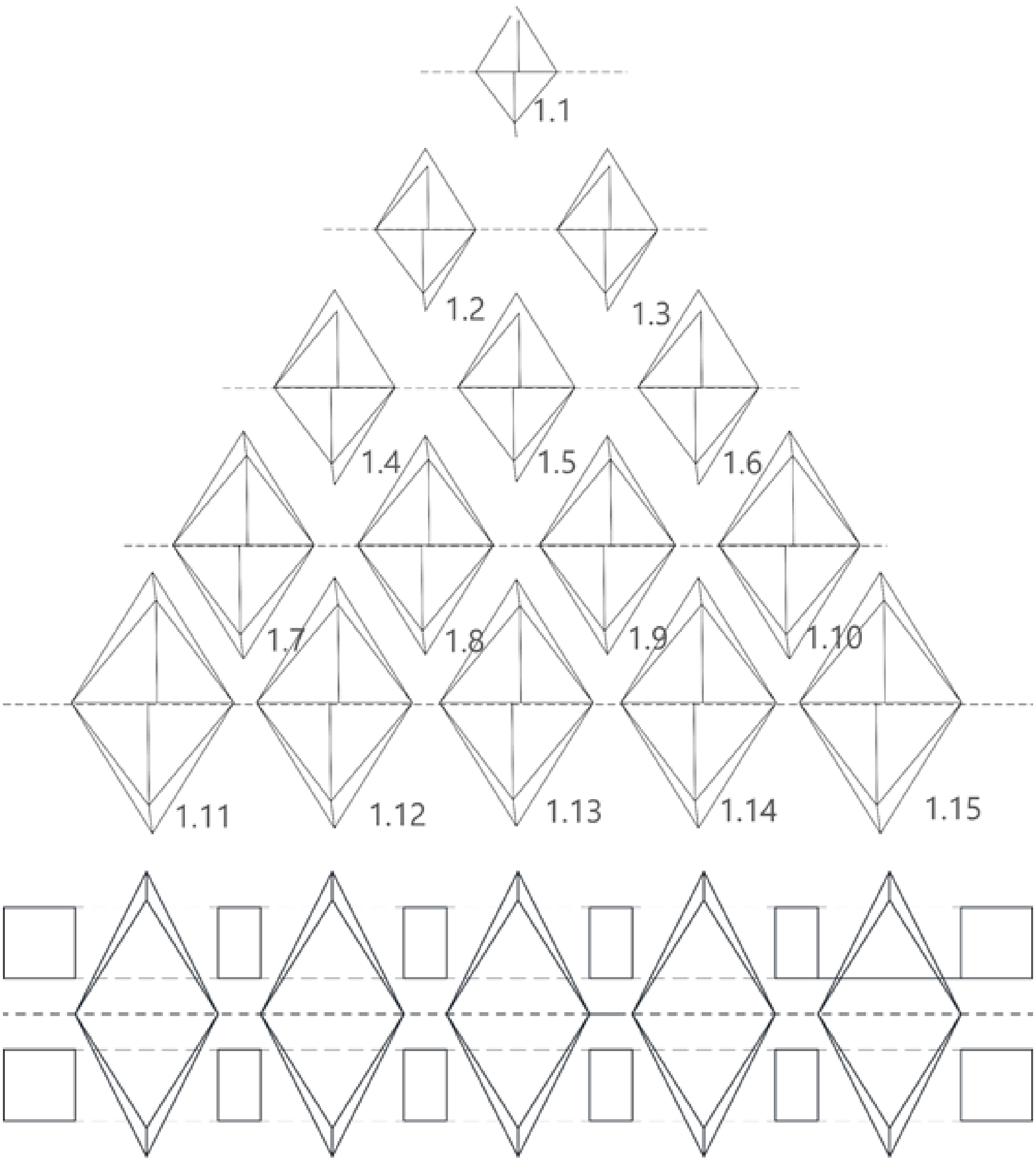

Figure 5.0:19. Progression and sizing scale of the units on the right module.

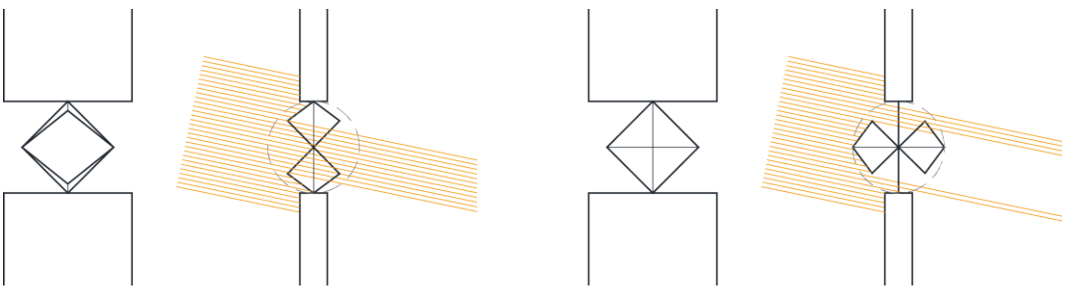

Figure 5.0:20. Conceptual diagram of the light filter system.

Both *Bioshading* modules were composed of a double MDF layer. The module voids followed a linear proportional size and bottom-up direction, respecting the previous radiation evaluation (Figure 5.0:21). The shading 'eyes' units were materialized into foldable laser-cut plan sheets, assembled and aligned in horizontal lines by threaded rods, defining a simultaneous rotation movement per line. Working inside the MDF layers, the threaded rods were supported by a wood pulleys network. Produced by using translucent green polypropylene, the eyes were attached to the threaded rods with a bolt and nut system that also fixed a constant space between the eyes while constraining the final geometry (Figure 5.0:22).

Figure 5.0:21. Bioshading unit's construction and assemblage.

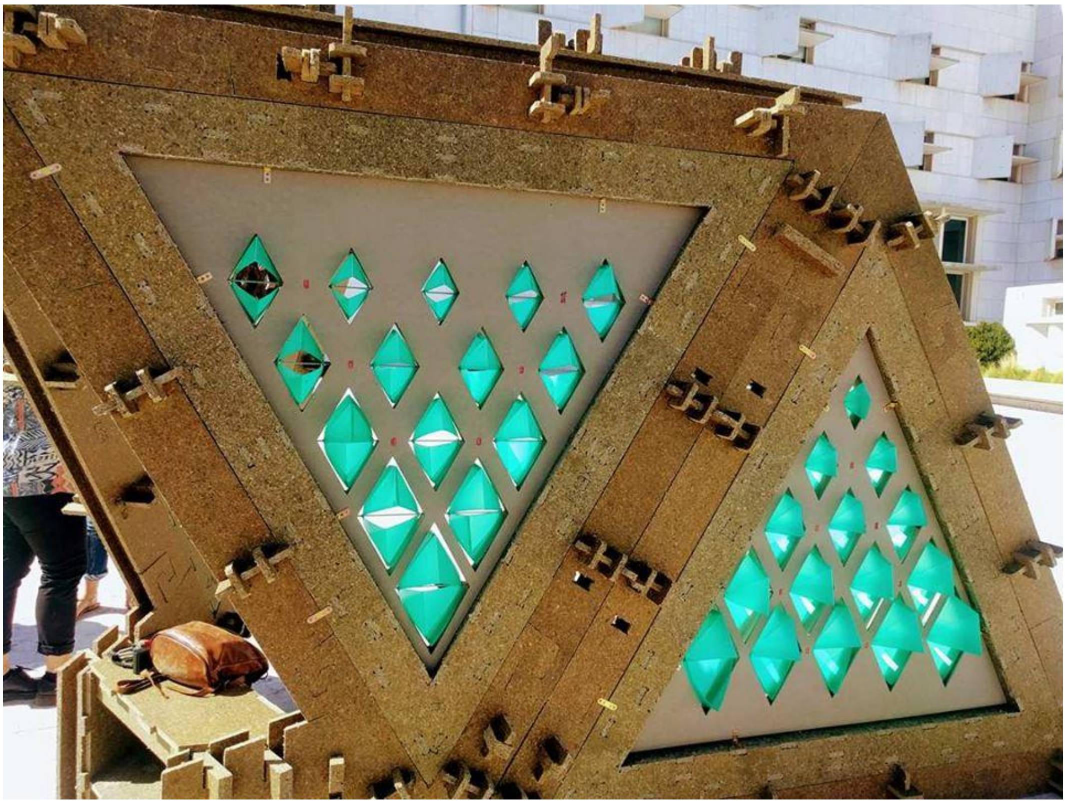

Figure 5.0:22. Bioshading[7].

[7] Cardoso, Carmo, *Bioshading Mockup*, photography.

Combining Mechanical Leaves, The Lotus Project and Bioshading

All the Shading System ISS projects were launched with the same initial Ladybug environmental/weather analysis, with the same physical and structural constraints, and with the same location issues. From the first diagnosis, the groups worked over their façade's specificities, balancing strong winds and intensive sunrays of the late Summer afternoon, as well as strong solar radiation from the south/southwest. Also to consider was the general light entrance mediation improving the canopy's comfort, which was needed for the rooftop. Aiming to produce a 100% passive shading control system, human intervention was a common requirement in which the three groups considered essential. On its whole, the canopy enables human intervention and interaction, in different degrees of influence, in the well-functioning of the different systems. *Mechanical leaves* lets users determine its state – open, closed, semi-opened; *The Lotus Project* autonomous system could be blocked by users' intersection; while *Bioshading* accepts real users' interaction, by enabling a time-limited blocking or accelerating the effect. However, if users stop interacting, the system reorganizes itself, returning to its natural dialogue with the surrounding environment (Figure 5.0:23).

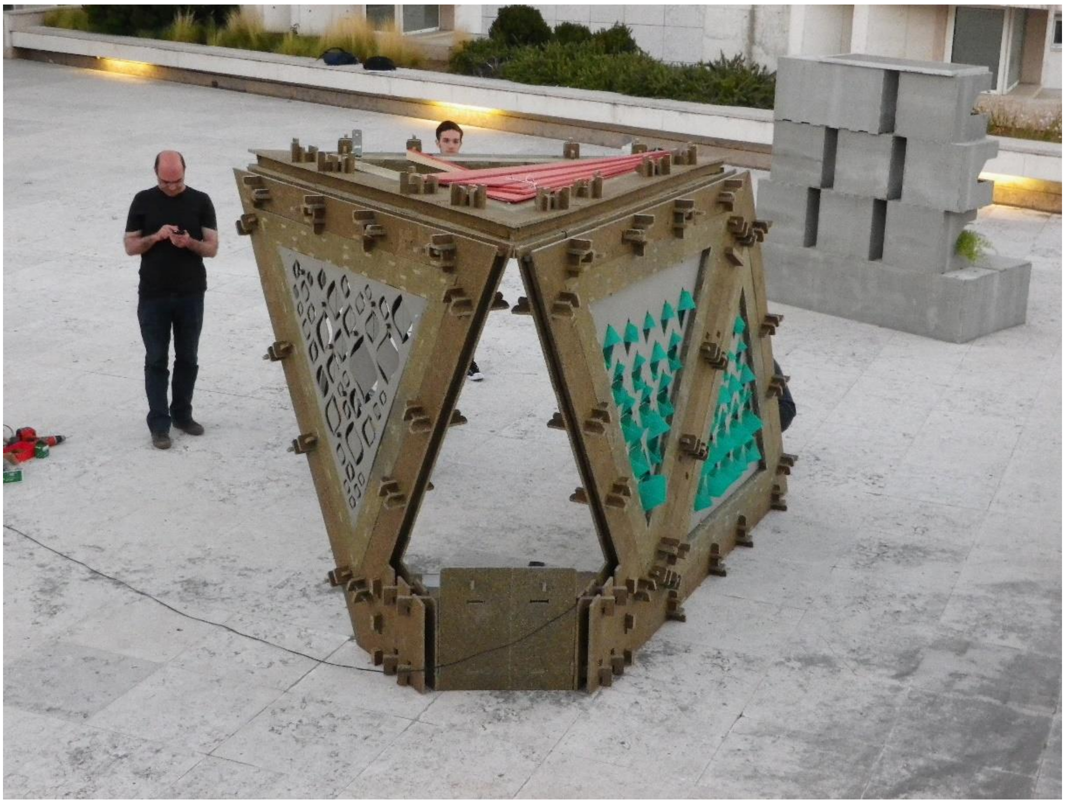

Figure 5.0:23. [SIS]'17 Shading System canopy, completed by the three passive shading systems proposed solutions.

5.4 Insights

The three shading systems were up to each specific challenge, and on the whole, the canopy was successful. The above comment is sustained by the different responses produced by the three shading projects to four main questions: 1- Did the project answer to the context's premises (local solar geometry and orientation, and the previously designed and installed canopy skeleton); 2- How was the project conditioned by the fabrication premise (materials, processes and assembly); 3- What were the project's weaknesses; and finally, 4- What were the project's strengths?

Regarding the context questions, *Mechanical Leaves* was designed for the horizontal surface, which was the one that had less impact on the canopy's solar radiation incidence inside the pre-establish canopy; therefore, this was the design that had more freedom in dealing with solar geometry. However, the weight of the physical and mechanical components required special considerations. On the other hand, *The Lotus Project* was designed to be applied in the West-facing panel of the canopy, and in this way, the guiding geometry for each shading unit of the system (the spin elements) had to be oriented vertically. The canopy's triangular base geometry conditioned the size of the shading units that decreased towards the south edge of this panel, ensuring the adequate shading levels inside the canopy. *Bioshading* reached a final design solution for the shading units, which was not conditioned by local solar geometry, but through the rotation based on a horizontal axis that allowed its effective functional performance in different latitudes. The triangular canopy frame geometry conditioned the parallelogram shape of the shading pyramidal units.

Concerning the fabrication, material, and assemblage constraints, the most crucial challenge of *Mechanical Leaves* was the idealization of the mechanical system itself. In order to have an operable symmetrical fan system, the selected materials had to ensure mechanical strength, adding extra weight (motor self-weight). *The Lotus Project* group saw in these premises an opportunity to optimize material usage and conditioned the geometry of the spinning shading units by only varying its size, maintaining the same shape. One of the constraints created by the *Bioshading* group was the conception of tridimensional units attached to a rotational system. These volumetric units required a light-weight foldable material in order to reduce the number of joints and its resistance to wind. Therefore, this system had to use four different types of materials, adding extra complexity to the fabrication and construction processes.

Mechanical Leaves' major weakness was its heavy self-weight complete system. On top of the double fans made of eight-millimeter fiberwood blades, the mechanical components of the system added considerable weight to the shading solution. In *The Lotus Project*, the defined pattern, together with the need to ensure the operability of the spinning units, prevented the possibility of a complete blockage of solar radiation and wind. The dynamic rotation of the *Bioshading* group was hampered and not always functional by the wind force, even though this was a design criterion materialized by a common rotation axis for all the shading units in the same horizontal row.

Despite what was said above, *Mechanical Leaves* was the most efficient solution from the biomimetics perspective, because it emulated the superimpose dynamic effect of palm trees and developed an autonomous system, based on a PV panel energy supply. *The Lotus Project* developed its strength based on its own biggest weakness: exploiting the fact that the system does not allow a complete sun block, it created interesting light patterns inside the canopy as a result of the wind-induced movement of each shading units. From the emulation of Nature examples to the creation of the mechanical system, *Bioshading* accomplished all the established goals of the main challenge – to design and build a biomimetic-based passive shading system (Figure 5.0:24).

During [SIS]'17 ISS, tutors and participants looked into Nature, intending to achieve possible and improved design solutions. In order to lead participants to accomplish the goal of designing and building a biomimetic passive shading system, a gauge that encompassed climate analysis, examples of interpretations and redesign of natural systems, users' environmental comfort analysis parameters, and practical tools of how to materialize, fabricate and build were provided to each group. [SIS]'17 ISS stage one was imperative, not only due to the available time to develop the shading solutions, but also to map and analyze possible design, fabrication, and assemblage processes. This stage not only 'framed' the shading systems' possible solutions, but it also improved the success rate of the shading solutions combination. Through the nine days of the design studio, ISS tutors conducted participants through a predefined script: 1- analyze the problem and its context; 2- structure problem issues and possible Nature solutions; 3- subdivide the solutions, decomposing them through several natural strategies; 4- (re)focus on the main goal of the challenge; 5- brainstorm, debating possible designs, systems, and mechanical emulation processes; 6- evaluate and improve possible solutions; 7- combine solutions and 8- prototype. This eight-step methodology was determinant to engage, not only participants but also tutors into a systemic production delivery of subsequent tasks. Even considering limiting individual time creation, as well as material, systems, and mechanical problems, all developed successful shading solutions.

Figure 5.0:24. [SIS]'17 Shading System canopy[8].

The above tested and validated described methodology was a fundamental motto for the developed concept design methodology proposed in this thesis. From this previous experience three fundamental phases stood out: i) Architecture – the analysis of climate and environmental context is essential to empower and establish a sustainable feedback loop between users and context environment, through the architectural construction; ii) Nature – although there is a wide range of information in the world wide web, if the methodology user is not an expert, search could be a hard task to perform so, it revealed to be necessary the creation of a database that could support the methodology users, guiding them through their posterior autonomous research; and iii) Artifact – the physical construction of a prototype is essential to the designer, because only at this phase are considered and revealed issues related to the physical matter, mechanisms, and assemblage.

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[8] Costa, Vasco, *[SIS]'17 Shading System canopy,* photography.

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SECTION IV
NATURE

6.0 Plants

6.0 PLANTS

Plants are living organisms that will serve as the basis for this research. More specifically, the biomimetic processes used are focused on terrestrial plants with a vascular system. The study of the functioning and survival events[1] of these organisms is crucial in order to establish a link between the biological and the architectural lexicons. This chapter intends to contextualize these living organisms through their geographical context, their categorization, and groups, leading to the systematic presentation of their most significant characteristics. In turn, this systematization enables the elaboration of a creative and imaginary library of individual images - *Memes*[2].

6.1 Planet Gaia

In 1998, the chemist James Lovelock wrote: "*The idea that the Earth is alive may be as old as humankind*" (Lovelock, 1998, p. 486). This affirmation could be considered the motto of the Gaia[3] hypothesis. Formulated by Lovelock and co-developed by the biologist Lynn Margulis during the '70s, the Gaia hypothesis proposes that living organisms co-evolve with their surrounding environment – organisms influence their abiotic[4] environment, and the environment influences the biota[5]. The hypothesis sees the biota, the temperature, the planet liquid, solid surfaces, and the air as a unique entity. The Gaia hypothesis has a profound significance for biology, and directly affects Darwinistic visions, for no longer it would be enough to say that organisms that are able to generate progeny will succeed in their surrounding environment. According to the Gaia hypothesis, organisms that are able to generate progeny will succeed so long as they do not adversely affect their environment. Geophysical systems always begin with the action of an individual organism, which means that Earth (Gaia) works from an act of an individual organism that develops and influence a global system.

Because humans are mainly city dwellers, they are so disconnected from the world of Nature that few could name wildflowers or insects from their own context environment, or even notice their extinction. Not considering a humanistic philosophy, the Gaia hypothesis establishes an optimistic perspective over the Earth's future. Moreover, it establishes an optimistic human role over the Earth's future. If each human being performs a task, develops an activity, an action that contributes to the increase of the Earth's

[1] Events are defined as natural systems, organisms, organs or even different types of adaptations.
[2] Memes are units of meaning that can express any idea, behavior or design. Like genes, memes can replicate and be transmitted and even compete with other memes for survival. Regarding its functionality, the meme is a cultural assessment unit that can be used as a self-propagating way. Memes can be ideas or parts of ideas, languages, sounds, drawings, skills, values, aesthetics, and morals, or anything else that can easily be visualized and transmitted as an autonomous unit. The study of evolutionary information transfer is known as memetics.
[3] In Greek mythology, Gaia was the goddess who personified Earth.
[4] Abiotic components are non-living chemical and physical parts of the environment that affect living organisms and the functioning of ecosystems.
[5] Biota is the set of all living beings in a given environment or period.

homeostasis, our planet can be preserved for our descendants and evolve in a much healthier and sustainable way (Lovelock, 1998).

The research developed in this thesis intends to be a contribution to a sound relationship between humans and the planet by developing an architectural design methodology based on vascular plant events. Architects are the great thinkers and builders of space. If architects could shape their constructions based on the “minimum inventory, maximum performance Nature” motto, human constructions could not only improve human health, spatial conditions, and functional adaptation, but also improve a building’s life cycle by relating and integrating its environmental resources and the inhabitants’ needs while decreasing greenhouse gas emissions, energy consumption, resource usage, waste generation, among others.

6.2 Climatic zones

The climatic characteristics of a region are conditioned by its location and geography. The duration and intensity of solar radiation are dependent on the latitude. Also, the types of air mass and the wind fronts are conditioned by the location of the region. Among the geographic factors of significant influence, six stand out: latitude, continentality, orography, sea surface temperature, altitude, and nature of the surface (the type of material covering the surface). Latitude and relief, in the mountainous regions, the thermal averages are lower than in the neighboring plains having an arid climate, due to the rarefied water vapor that the atmosphere suffers, as the altitude increases. On the other hand, continentality is commonly characterized by its dry air, inducing more extreme temperature variations. Slopes perform a determinant role in the geographic orography. According to its orientation, slopes can work as barriers, causing a climatic asymmetry between shaded and exposed slopes. In the first case, shaded slopes have lower temperatures that will favor air condensation and the occurrence of precipitation, while due to its direct solar radiation exposure, exposed slopes have higher temperatures and consequently quick dry out. Sea surface proximity and temperature directly influence terrestrial climate, making it more humid and moderate. However, sea temperature is related to sea currents. For instance, considering two cities with the same latitude, New York City, in the U.S.A., and Figueira da Foz, in Portugal, both have different sea temperatures due to the Gulf stream that flows down alongside North America and flows up alongside the Portuguese coast. As for altitude and nature of the surface, the air temperature in forests is lower, throughout the year, than in other areas lacking a dense vegetation coverage. A natural sandy surface, without vegetation, will have a high reflection of incident solar radiation and also some absorption of heat in the first layers. Due to its high thermal conductivity, rock formation surfaces store high amounts of heat.

Köppen-Geiger[6] considers five climatic types due to its seasonality, annual and monthly average values of air temperature, and precipitation (Figure 6.0:1). The tropical climate is a megathermic climate, with average temperatures during cold months above 18 ºC and intense annual precipitation. It is the climate of monsoons, rain forests (Eastern Amazonia, Guianas, Venezuela, Equatorial Africa, etc.) and savannas (Deccan, Sudan, Congo Basin, Bolivia, Central Brazil). The arid climate: characterized by its dry climate, it can be divided into two different types, i) climate of the steppes - semi-arid regions, low rainfall (Kazakhstan, Turkmenistan, Kyrgyzstan, Uzbekistan, Tajikistan, Mongolia, the Western United States, the Northeast of Brazil); and ii) desert climate - arid, near-zero rainfall (Sahara, Arabia, Arizona, Kalahari, Central Australia). The temperate climate usually defines mesothermic and humid climates with winter temperatures oscillating between -3 ºC and 18 ºC degrees and well-defined summer and winter seasons. Three types of temperate climate are distinguished: i) mesothermal climate with dry winter (central China, Ganges region, Libya, Brazilian highlands); ii) mesothermal climates with no dry season (southern plateau of Brazil, southeast of USA and China, Australia); iii) Mediterranean climate with dry summers (Mediterranean basin, California, central Chile). The continental climate, also defined as microthermic climate, its characterized by the cold forests of the northern hemisphere, with negative temperatures below -3 ºC, and maximum temperatures exceeding 10 ºC. Summer and winter seasons are well defined. Two types of continental climate can be identified: i) micro-thermal climates with wet winters (Canada, Russia, Siberia); ii) micro-thermal climates with dry winters (Norway, Sweden, and Northeast Asia). The fifth type of climate is the glacial climate, typical of polar and high mountain regions where each month has air temperatures below -10 ºC. The Summer season is ill-defined or indistinctive. Two types can be identified: i) tundra climate, with warmer mean temperature above 0 °C (marginal areas to the Arctic and Iceland); and ii) perpetual ice climate, with average temperatures never above 0 °C (Antarctica, inland Greenland) (Figure 6.0:2) (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006).

[6] Climate classification of Köppen-Geiger, is the global classification system of climatic types most used in geography, climatology and ecology. The classification was proposed in 1900 by the Russian climatologist Wladimir Köppen. which he perfected in 1918, 1927 and 1936 with the publication of new versions, prepared in collaboration with Rudolf Geiger (hence the name Köppen-Geiger) (Classificação climática de Köppen-Geiger, 2018).

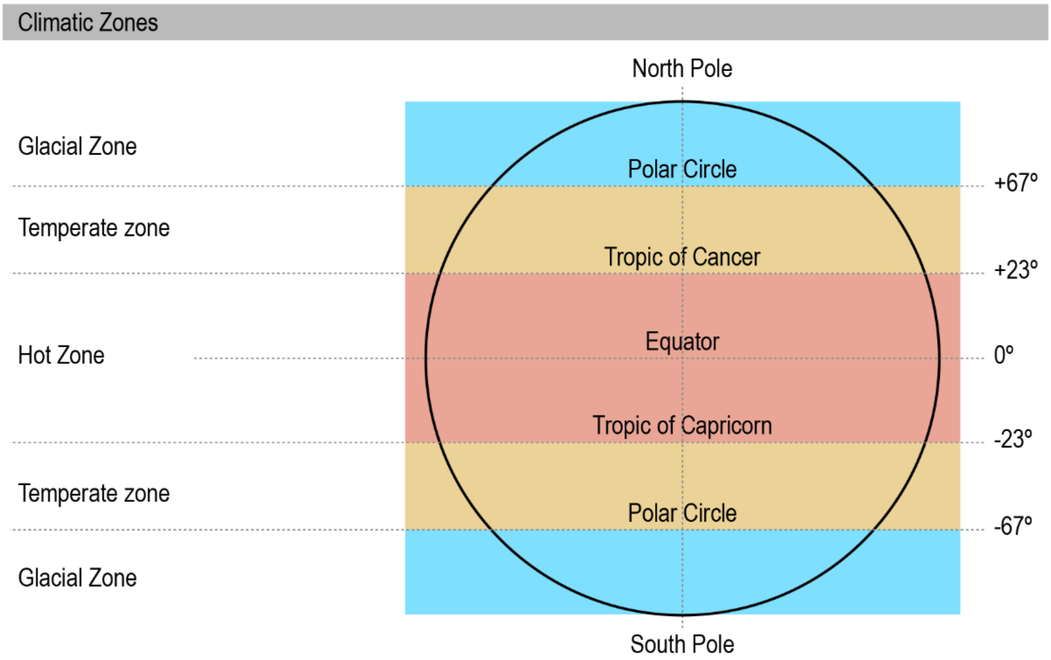

Figure 6.0:1. Climatic Zones.

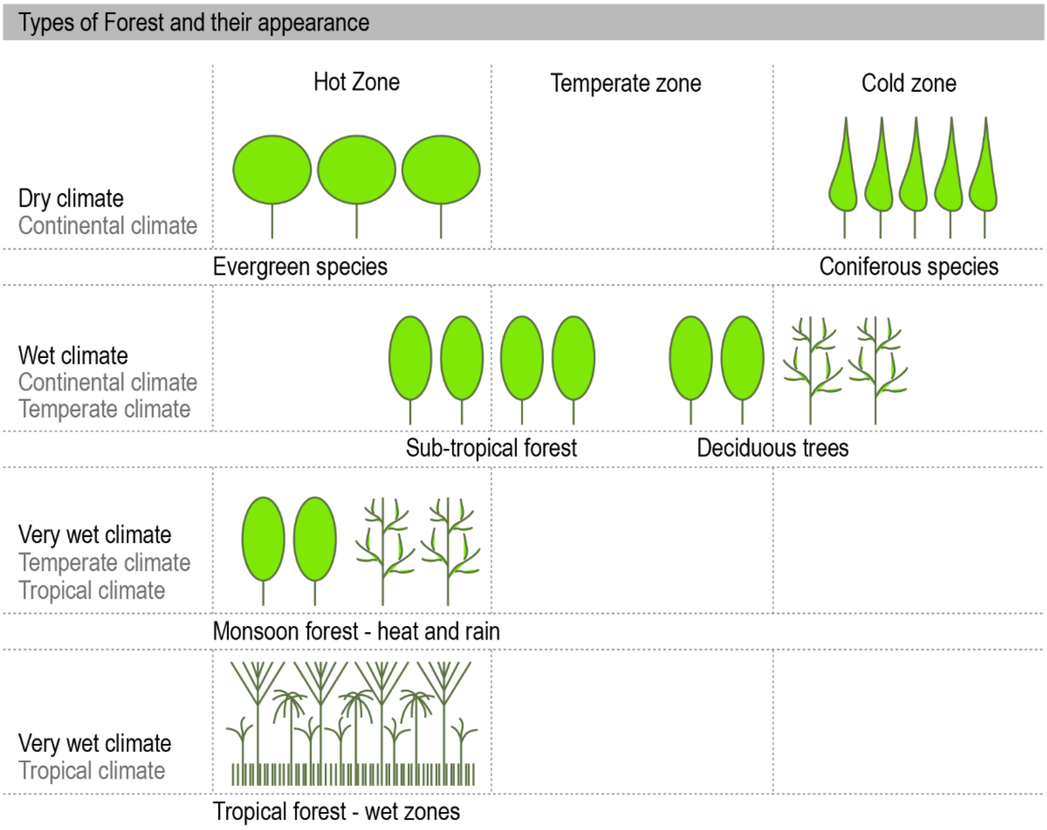

Figure 6.0:2. Types of Forest and their appearance (adapted from Dicionário de Botânica, 1983).

6.3 About Plants

Climate, physics, and biota are the main components of Nature. Climate could be described as the state of the atmosphere and its relationships with the Earth's surface (the hydrosphere and the pedosphere). It is most commonly characterized by temperature, solar radiation, airflow, and humidity. Physics refers to Earth's geological processes, matter, and energy. Biota, or more commonly designated as living organisms, refers to animals and plants. Their evolution is related to the oxygenation of the atmosphere and, consequently, with the ability to perform photosynthesis by prokaryotic cyanobacteria[7] that grew in the sunlit surface layer, using water as the hydrogen source to convert CO_2 into organic matter (Smetacek, 2012). This event has triggered the progressive occupation of land by living organisms, increasing its independence from water for reproduction. Animals and plants are generally categorized into two families: vertebrates and non-vertebrates, and vascular (Pteridophytes) and non-vascular (Bryophytes), respectively. According to the Gaia theory, there are no singular actions/events without consequences/repercussions; thus, in order to provide a clearer and more sustained contextualization of plants, a brief history of its evolution will be presented.

6.3.1 Plants Categorization and Major Groups

Terrestrial plants date their evolution from 500 million years (Paleozoic Era), during the Silurian-Holocene temporal range. Today set by the oldest fossil crustaceans, mollusks diversification, and the appearance of the first fossil plants, this period started with a major extinction event. The climate’s physical conditions in that era included mild temperatures, shallow seas, and generally flat continents. Out of the water, plants faced a new challenge: they needed to live in two different environmental conditions, in the soil and the air. From the soil they can extract water, minerals and structural stability, while from the air, they capture light and carbon dioxide for photosynthesis and oxygen[8] for respiration. Some terrestrial plants have responded to the challenge by developing a vascular system, constituted by roots, stems, and leaves connected by vessels[9].

In response to this challenge, terrestrial plants evolved developing new skills and adaptation strategies. Today, terrestrial plants are categorized into two major groups: non-vascular and vascular organisms. Also known as the pioneer species that moved into inhospitable territories, terrestrial non-vascular plants (*Bryophytes*) are composed of a structure of *phyllis* (similar to leaves), single sheets of cells with no internal air space. Mosses are non-vascular plants. Seedless and flowerless plants, composed only of a series of *phyllis,* attached to a stem with the role of conducting water and nutrients. Usually,

[7] Also known as blue-green algae.
[8] Like animals, plants cells perform cellular respiration, which requires oxygen.
[9] The first terrestrial vascular plant fossil dates from the Silurian period.

after fertilization, mosses develop sporophytes (also known as *seta*), which grow on or under the soil, and are rarely seen. Terrestrial non-vascular plants are restricted to small sizes and moist environments since these do not have a vascular system. Conversely, terrestrial vascular plants have responded to the challenge by developing a vascular system, constituted by roots, stems, and leaves connected by a vessel system. Defined by its lignified tissues, which distribute resources through the plant (water, nutrients, minerals, and photosynthesis products), terrestrial vascular plants can be categorized into three major groups: ferns, conifers and flowering plants (Cazadero Nature Program, 2005). Ferns (*Pteridophytes*) are constituted by leaves, stems, and roots connected by a vascular system composed of vessels (xylem and phloem). Ferns do not produce seeds or flowers, and so they reproduce asexually by spores born in *sori* on the undersurface of mature leaves. Conifers, or gymnosperms, are plants that produce 'naked seeds' contained within a cone. The male cones produce pollen grains that are blown by the wind onto female cones. In fact, this is a very inefficient process, so the conifers must produce a substantial amount of pollen to ensure the fertilization of the female cones. These seeds are multicellular, containing the necessary nutrients for the new plant, all within a protective coat. Flowering plants refer to the angiosperm group. The development of flowers set an important advance in plant evolution. The flower attracts animals, which could assist in pollination, increasing the success rate against the gymnosperm family. Pollination by animals is called zoophilia. Among the primary pollinators are birds, bats, humans, and insects. After successful pollination, the seed grows in the plant's ovary, becoming a fruit that assists seed dispersion.

6.3.2 Vascular Organisms

Like many others, organisms' plants have evolved over time. Due to their immobility, plants cannot hide or seek protection from other elements, making them into exceptional biological sources for detecting climatic changes. This condition enables an easy comparison to buildings since both lack movement and remain exposed to environmental changes in a specific location. On the other hand, over millions of years, plants have developed characteristics, properties, and behaviors enabling environmental adaptation. Lacking from the same proportion of time, but supported by technological research and evolution, buildings did not. An in-depth analysis and evaluation of vascular plant adaption strategies to their environment is the unlock key to this research.

Plant colonization of the land is frequently related to the evolution of structures in obtaining water and minimize its loss. A plant's body may be understood through the evolutionary transformations involved in the geographic and climatic evolution of where it developed. The basic requirements of a photosynthetic organism are water, light, oxygen, carbon dioxide, and minerals. Land provides or enables the provision of light, oxygen, carbon dioxide, and minerals, with water remaining the challenge. Unlike animals, that are mobile organisms, or even fungi that remain below the soil's surface feeding on any type of organic material, plants have to use an alternative strategy – roots. Plants' roots not only anchor them to the ground, but they are responsible for the collection of water for body preservation and photosynthesis. Stems are responsible for the support of the photosynthetic organs - the leaves (Evert & Eichhorn, 2012, p. 6). The aboveground portions of the plant involved in photosynthesis are coated by waxy cell layers that retard water loss, named epidermis. However, epidermis also delays the gas exchange between the plant and its surrounding environment, which is necessary both for photosynthesis and respiration of the organism. Plants have dealt with this dilemma by developing the *stomata*[10]. The *stoma* consists of a pair of epidermal cells with a small opening between them, that opens and closes in response to environmental and physiological inputs, helping the plant regulate water loss and oxygen/carbon dioxide balance. Stems, composed by a vascular system, are the conductive system between the photosynthetic and the non-photosynthetic parts of the plant's body. The vascular system is composed of the xylem and the phloem. The xylem enables the water circulation through the plant´s body, and the phloem enables the flow of food manufactured in leaves and other photosynthetic parts of the plant. This extremely efficient system is what gives the name to this main group of plants – Vascular plants (Figure 6.0:3).

[10] Stomata (singular stoma) are pores found in the epidermis of leaves, stems and other organs that enable gas exchange.

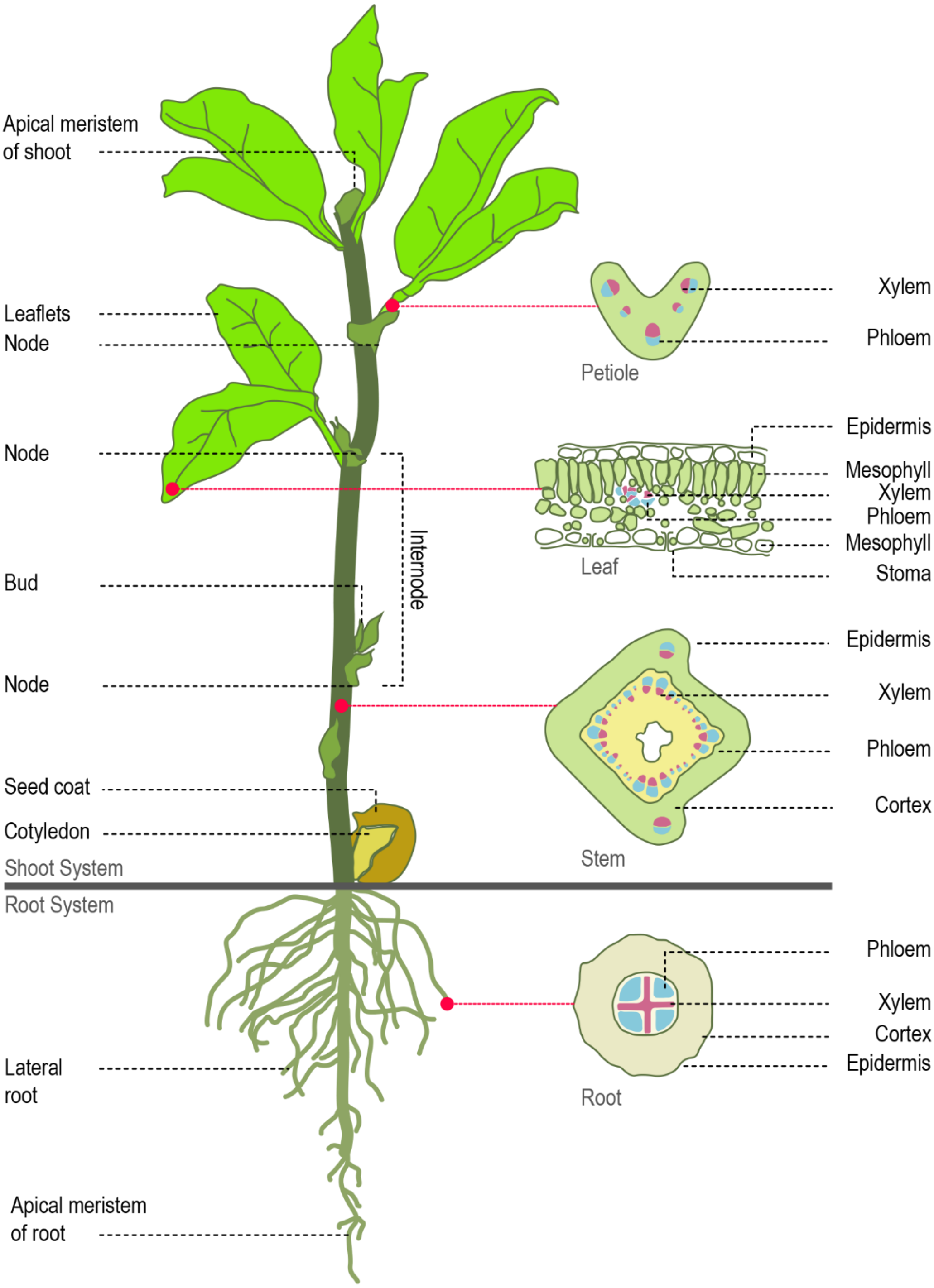

Figure 6.0:3. Vascular plant (adapted from Evert & Eichhorn, 2012).

Summarizing, vascular plants are plants that have specialized tissues (phloem and xylem) for conducting water, minerals, and photosynthetic products. Figuratively, it is an organism composed by a stem that contains two main channels, connected to underground roots and higher leaves, enabling a constant flux of water, nutrients, and energy inside the organism, regulating and stablishing its homeostasis. The reproductive cells are protected by a multicellular structure, and in seed plants, the embryos are covered by resistant coats

(Evert & Eichhorn, 2012, p. 9). From the perspective of this research work, plants are the living organisms that most resemble human-made buildings. Mainly terrestrial vascular plants, which are rooted, composed by an exchange gas system, and exposed to its context environment and its inhabitants. The following sections will contribute to the construction of a plant biology data survey, organized by types of adaptation and strategies. This plant biology data survey is composed of several aspects that are part or define several terrestrial vascular plant events: chemical and physical properties, systems, organs, family types, among others. In order to build a hybrid lexicon that could bridge plants' biology with architecture, the data survey will describe the events, contextualizing it in its cause or intention, without providing any images of reference. The fundamental idea of the survey is to provide its users the essential information about the terrestrial plants' events enabling an individual and personalized creation of figurative memes associated with each specific event.

6.3.3 Plants Adaptation Strategies

Nature is demonstrably sustainable. Its challenges have been resolved over eons to enduring solutions with maximal performance using minimal resources. Unsurprisingly, Nature's inventions have eternally inspired human achievements and have led to the creation of exceedingly effective and efficient materials and structures, as well as methods, tools, mechanisms, and systems by which to design them (Oxman N. , 2010). Insights from the study of biomimetic strategies are significant, not only from a scientific perspective but also in the context of their application to the design of balanced and sustainable environments. Biology is the science that studies life and the living. The present investigation has as one of its main foundations the understanding of the adaptation phenomena of terrestrial plants. Like buildings, plants are organisms exposed to their environment. Unlike animals, plants do not have the ability to move in search of better environmental conditions or food. In this way, terrestrial plants had to develop different adaptation strategies that allowed them to survive, respond, and interact with their surroundings. In this regard, terrestrial plants have developed three major adaptation strategies: morphological, physiological, and behavioral.

Morphological adaptation strategies of plants

Plant morphology [Gk. Morphe, form + Logos, discourse] "*represents a study of the development, form, and structure of plants, and, by implication, an attempt to interpret these on the basis of similarity of plan and origin*" (Bold, Alexopoulos, & Delevoryas, 1987). There are four major fields of study in plant morphology. One is comparative, meaning that the morphologist examines structures in many different plants of the same or different species, then draws comparisons and formulates ideas about similarities. A second one is vegetative (somatic), and reproductive. The vegetative structures of vascular plants include the study of the shoot system, composed of stems and leaves, as well as the root system. The reproductive structures are more varied and are usually specific to a group of plants, such as flowers and seeds, fern *sori*, and moss capsules. Another major field of study is about scale, from the smallest scale to general structural features. At this structural scale, plant morphology overlaps with plant anatomy as a field of study. At the largest scale, the study of plant growth habits overlaps with the architecture of a plant. The fourth major field of study concerns the pattern of development, which is the process by which structures originate and mature as the plant grows. Plants continuously produce new tissues and structures throughout their lives. This area of plant morphology overlaps with plant physiology. In short, a morphological adaptation is a structural feature that enhances the adjustment of organisms to their surrounding environment and enables better functionality for survival. Several morphological features influence organisms' adaptation, like shape, size, pattern, and structure (Badarnah, 2012). As an example, the hairy leaves of *Actinotus helianthin* (Figure 6.0:4) are used to reflect sunlight from their surfaces.

Figure 6.0:4. Actinotus helianthi[11]

[11] Stewart, A., Actinotus helianthi – Flannel Flower, photograph, viewed 1 October 2018 <https://www.gardeningwithangus.com.au/actinotus-helianthi-flannel-flower/>

Physiological adaptation strategies of plants

Physiological adaptation is a chemical process, an organism, or a systemic response of an individual to a specific external stimulus in order to maintain homeostasis (López, Rubio, Martín, & Corxford, 2017). Physiology is about the regulation of the different functions that allow them to adjust to environmental changes (Schmidt-Nielsen, 2007). An example of a physiological adaptation is the salinity tolerance of the mangroves. Mangroves inhabit the inter-tidal zones along the coast with high salinity levels. Its biochemical and molecular mechanisms enable mangroves to cope with salt stress. Another example, the Cam photosynthesis (Crassulacean Acid metabolism) is a carbon fixation pathway that can be found in some plants, such as the *Echeveria Glauca* (Figure 6.0:5), as an adaptation to arid conditions.

Figure 6.0:5. Echeveria Glauca[12]

[12] Echeveria glauca, aka blue echeveria, n. d., photograph, viewed 1 October 2018, <https://www.pinterest.pt/pin/341992165432263803/?lp=true>

Behavioral adaptation strategies of plants

Behavioral adaptations are internal and/or external body actions or changes that organisms perform for survival. It is a necessity of a balance between an organism and its environment (Piaget, 2012 [1947 in French, 1967 translated]). To cope with the new situations that the environment generates, the organism can behave accordingly by reacting to stimuli, creating an appropriate behavioral response for an optimal result. This physical response is linked to a feedback signal, enabling the interaction between the organisms and their surrounding environment. Some examples could be the inward fold of Mimosa Pudica (Figure 6.0:6), as a reaction to physical contact, or even the heliotropic plants' movement along the day, tracking sunlight to capture the highest percentage of light exposure.

Figure 6.0:6. Mimosa Pudica[13]

The above categorization finds its origins on the results obtained from a biophysical dataset of plants. Below (Table 6.0:1, Table 6.0:, and Table 6.0:), a list is presented with several events related to plant biology, organized by three fields of adaptation. The

[13] Shirley, P., Mimosa Pudica, photograph, viewed 1 October 2018 <https://paulshirleysucculents.wordpress.com/2013/10/06/mimosa-pudica/>

collection of data happened upon the investigation of terrestrial plants with vascular systems.

Table 6.0:1. Plant Adaptation Strategies – Morphological

MORPHOLOGICAL		
Designation	Description	Cause/Intentions
Asymmetry	Zero planes of mirror image, on leaves, petals, sepals, or stems).	Asymmetry could be related to the direction of the tendril, the direction of the contortion, or even with stem coiling.
Canopy Plants	Increase radiation capture by multilayer arrangements of leaves with loose distribution.	Give rise to a higher density of elements, allowing access to illumination in all layers.
Carnivorous Plants	Adapted to grow in soils that are deficient in nutrients, these plants get their nutrients from trapping and consuming animals or protozoans.	Usually located in poor soils, these plants get their nutrients from trapping and eating animals, so they can obtain nitrogen in order to grow.
Climbing Plants	Long-stemmed rooted in the soil at ground level and uses trees or other vertical supports to climb up to get access to light.	Plants climb for sunlight.
Deciduos Plants	Plants that lose all their leaves for part of the year (the drop of a part that is no longer needed).	Plants lose their leaves to conserve water or to better survive winter weather conditions.
Fractal	Plants that are composed of similar parts – self familiar.	Increase packing order and optimize space occupation; plants with fractal distribution also receive light evenly.
Hydrotropism	Hydrotropism is a plant's direction of growth, determined by a stimulus in water concentration.	Plants recognize water in their environment, and in order to absorb it for metabolic purposes, they send a signal to elongate part of the root.
Inflorescence (Figure 6.0:7)	Inflorescence is a group or cluster of flowers arranged on the stem of a plant.	Inflorescence is the reproductive portion of a plant that bears a cluster of flowers in a specific pattern.
Continue…		

MORPHOLOGICAL		
Designation	Description	Cause/Intentions
Packing structures	Maximizing strength while reducing materials by incorporating tetrahedral elements that can be stacked in hexagonal containers.	Could be found either at the micro or macro scale of the plant. Its essential function is to provide a higher resistance and a shorter and easier distribution of nutrients.
Phyllotaxis (Figure 6.0:8)	Phyllotaxis is the arrangement of leaves on a plant's stem.	Phyllotaxis enables plants of modification. These modifications can involve the length and nature of the internodes and the phyllotaxis, as well as variations in the proportions, compressions, swellings, adnations, connations, and reduction of main and secondary axes.
Spermatophytes	Also known as "seed plants", are composed by Gymnosperms and Angiosperms: Gymnosperm – Has naked seeds. Seeds develop either on the surface scale, or leaf-like appendages of cones, or at the end of short stalks; Angiosperm – Has seeds or ovules enclosed during pollination. Their seeds have three parts: (1) an embryo, (2) a supply of nutrients for the embryo, and (3) a seed coat – they are flowering plants.	Reproduction system. Gymnosperm - During pollination, pollen grains are physically transferred between plants from the pollen cone to the ovule. Pollen is usually moved by wind or insects. The essential feature of angiosperms is the flower; its function is to ensure the fertilization of the ovule and the development of fruit containing seeds.

Table 6.0:1 (Cont). Plant Adaptation Strategies – Morphological.

MORPHOLOGICAL		
Designation	Description	Cause/Intentions
Stoma	Tiny opening or pore that is used for gas exchange.	Found in the epidermis of leaves, stems, and other organs, a stoma is a pore bordered by a pair of guard cells that are responsible for regulating the size of the stomatal opening.
Succulent	Reduce exposure through a reduced projected area for radiation.	Succulents increase their volume, usually to retain water in arid climates or soil conditions.
Symmetry	Proportional and harmonious, characteristic present on leaves, petals, sepals, and stems.	Plants exhibit radial and bilateral symmetry, often at the same time. In flowers, symmetry is directly linked with a pollination strategy; in a stem, the distribution of weight in a symmetrical way is a balance factor.
Tracheid	Long cell in the Xylem system of vascular plants. Tracheid transports water and mineral salts and retains water against gravity when transpiration is not occurring.	Tracheid transports material and provides structural support.
Understory Plants	Increase radiation exposure by monolayer arrangements of leaves with dense distribution.	Although these plants need some radiation, there are cool and shady plants, that avoid direct sunlight.
Vessels	Are the water-conducting tissue of plants, one of the cell types found in xylem.	Commonly found on flowering, vessels are thought to have evolved from tracheids.
Whorl	A whorl is an arrangement of sepals, petals, leaves, stipules, or branches that radiate from a single point and surround or wrap around the stem.	Increases plants' physical balance by distributing several elements by different levels, enabling scale variations.

Table 6.0:1 (End). Plant Adaptation Strategies – Morphological.

Table 6.0:2. Plants Adaptation Strategies – Physiological.

PHYSIOLOGICAL		
Designation	Description	Cause/Intentions
Anthocyanins	Water-soluble vacuolar pigments that, depending on their PH levels, may appear – red, blue, or purple – on leaves.	Anthocyanins result as a camouflage protecting the plants from insects, making them more vulnerable to predators by inhibiting the reflecting of green wavelengths (Evert & Eichhorn, 2012, p. 490).
CAM Plants (Crassulacean Acid Metabolism)	CAM plants are adapted to dry, desert habitats. CAM plants use a method of carbon fixation and osmoticium, allowing the separation of uptake and assimilation of atmospheric CO_2 with water-saving daytime stomatal closure and osmotic acquisition of water.	CAM plants manage the dilemma of desiccation or starvation by nocturnal malic acid accumulation in the vacuoles.
Chloroplasts	These are small organelles inside the cells of plants and algae. Chloroplasts are responsible for the conduction of photosynthesis (Evert & Eichhorn, 2012, p. 102).	A chloroplast is a type of organelle known as a plastid, characterized by its two membranes and a high concentration of chlorophyll. Highly dynamic, chloroplasts circulate and move around within plant cells, and occasionally pinch in two to reproduce. Their behavior is strongly influenced by environmental factors like light color and intensity.
Endothermic	A process or reaction in which the system absorbs energy from its surroundings in the form of heat (Evert & Eichhorn, 2012, p. 97).	Endothermic reactions absorb energy from the surroundings and lower the temperature. They are a type of endogenic reaction. In biology, anabolic processes are examples of endothermic reactions.
Continue…		

PHYSIOLOGICAL		
Designation	Description	Cause/Intentions
Epidermis	Epidermis is a layer of cells that covers the leaves, flowers, roots, and stems of plants, forming a boundary between the plant and the external environment.	The epidermis prevents water loss, regulates gas exchange, secretes metabolic compounds, and absorbs water and mineral nutrients (fundamentally roots).
Exothermic	A process or reaction that releases energy from the system, usually in the form of heat (Evert & Eichhorn, 2012, p. 97).	To survive in ice environments, and some plants to spread smells attracting pollinating insects.
Meiosis	A type of sexual reproduction in which the number of chromosomes is reduced by half through the evaporation of homologous chromosomes producing two haploid cells – number of divisions 2; Daughter cells 4 haploid cells (Mixing chromosomes).	Meiosis process occurs in all sexually reproducing single-celled and multicellular eukaryotes, namely in animals, plants, and fungi.
Mitosis	A process of asexual reproduction in which the cell divides in two, producing a replica, with an equal number of chromosomes in each resulting diploid cell number of divisions 1; Daughter cells 2 diploid cells (crossing over cannot occur).	Mitosis is a part of the cell cycle when replicated chromosomes are separated into two new nuclei. Cell division gives rise to genetically identical cells in which the number of chromosomes is maintained.

Table 6.0:2 (Cont.). Plants Adaptation Strategies – Physiological.

PHYSIOLOGICAL		
Designation	Description	Cause/Intentions
Osmosis	Refer to a spontaneous movement of water crossing a membrane from a region of low salute concentration to a more concentrated solution. This equalizes concentrations on both sides of a membrane.	Osmosis is a vital process in biological systems, as biological membranes are semipermeable. These membranes are impermeable to large and polar molecules, such as ions, proteins, and polysaccharides, while being permeable to non-polar or hydrophobic molecules like lipids as well as to small molecules like oxygen, carbon dioxide, nitrogen, and nitric oxide.
Phloem	Transportation of food and nutrients such as sugar and amino acids, from leaves to storage organs and growing parts of plants. This bidirectional movement (it moves up and down the plant's system from 'sauce to skin' of substances in called translocation).	Composed by living-cells, Phloem transports sap, the water-based solution, rich in sugars made by photosynthesis.
Superhydrophilic	Surface layer that attracts water.	Superhydrophilic plants absorb water through their epidermis. In superhydrophilic matter, the contact angle of water is equal to 0º.
Superhydrophobic (coating)	Surface layer that repels water.	Plants with superhydrophobic epidermis have the ability to maintain their body completely dry, regarding their climatic and environmental context. The contact angle of a water droplet is >150º.

Table 6.0:2 (Cont.). Plants Adaptation Strategies – Physiological.

PHYSIOLOGICAL		
Designation	Description	Cause/Intentions
Thermogenesis	Plants that can raise their temperature above that of the surrounding air.	It is a survival strategy. When increasing their body temperature, plants spread chemicals that attract animals, increasing pollination rates.
Trichomes	Described as fine outgrows on plants, trichomes have variable shapes, cytology, and functions.	These elements could appear on different surfaces of most of the angiosperms, contributing to light piping, protecting the plant against temperature stress by increasing water loss reduction.
Table 6.0.2 (End). Plants Adaptation Strategies – Physiological.		

Table 6.0:3. Plants Adaptation Strategies – Behavioral

BEHAVIORAL		
Designation	Description	Cause/Intentions
Bark	The outermost layer of stems and roots of woody plants.	Keeps surface cool by minimizing the absorption of solar light and maximizing thermal emission.
Bioluminescence	Bioluminescence refers to the production/emission of light by a living organism.	It occurs when a fraction of the stored energy is (re)converted to light energy. Bioluminescence is an accidental product of energy exchanges in most luminescent organisms.
Cactus (Cacti)	Adapted to live and prosper mostly on dry environments, cactuses have thickened, fleshy parts adapted to store water – Spines.	Spines help prevent the plants from becoming dry' by reducing airflow close to the Cactus, providing some shade.
Continue…		

BEHAVIORAL		
Designation	Description	Cause/Intentions
Diaheliotropism	Plants that orient their leaves to receive maximum sunlight.	Diaheliotropic plants grow toward the sunlight in order to maximize their solar radiation capture.
Gravitropism (geotropism)	Growth movement by a plant or fungus in response to gravity (Evert & Eichhorn, 2012, p. 662).	The redirection of the growth movement occurs in consequence of root or steam growth outside
Heliotropism	Heliotropism is a diurnal or seasonal movement in plants that is induced by sunlight (Evert & Eichhorn, 2012, p. 680).	Heliotropic plants track sunlight during the day period in order to maximize its exposure.
Nyctinastic movements	Leaves of plants respond to the daily alternation between light and darkness by moving up and down.	Survival mechanism associated with diurnal light, temperature, and air velocity change
Paraheliotropism	Plants that move their leaves to avoid sunlight (reducing dehydration).	Paraheliotropism helps to minimize excess light absorption, reducing plants' dehydration by orienting their leaves parallel to incoming sun rays.
Phototropism	Phototropism is a growth movement induced by any light stimulus.	Phototropic plants orient their growth into light exposure.
Roots (Figure 6.0:9)	In vascular plants, the root is the organ of a plant that typically lies below the surface of the soil. They can also be aerial or aerating.	To collect water and nutrients essential for growth and survival.
Skototropism	Growth away from the light (movement towards darkness).	Minimize light exposure and increase moisture effect.
Thigmotropism	A response to contact with a solid object.	Thigmotropism is a response that occurs due to unilateral growth inhibition.
Vernation (Figure 6.0:10)	How the leaves are arranged on the buds, folding or curling.	Vernation is a form of balance leaf and flower distribution, ensuring a balanced distribution of water and nutrients.

Table 6.0:3 (Cont.). Plants Adaptation Strategies – Behavioral.

BEHAVIORAL		
Designation	Description	Cause/Intentions
Xylem	Vascular system that transports water and minerals from roots to aerial parts of the plant.	Part of a plant's transport system for water, nutrients, and minerals.
Table 6.0:3 (End). Plants Adaptation Strategies – Behavioral.		

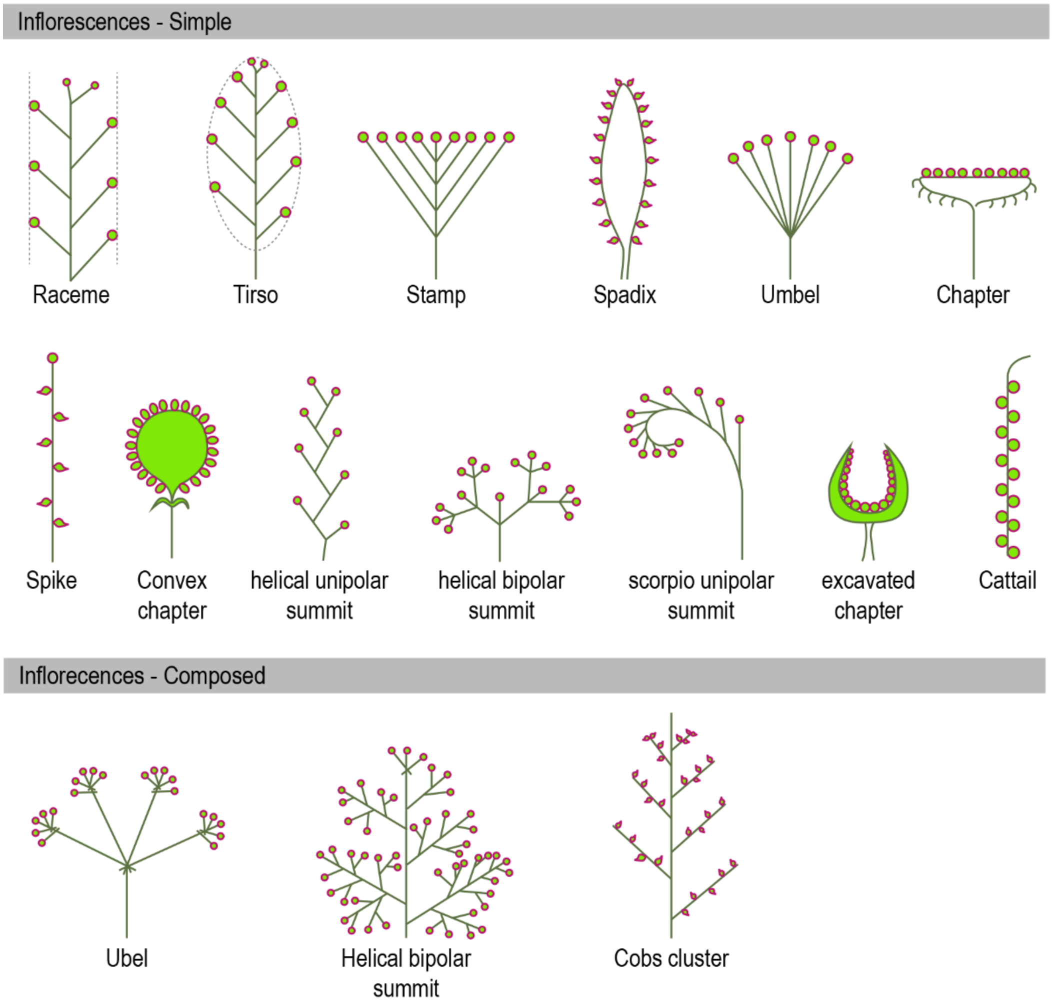

Figure 6.0:7. Types of Inflorescences (adapted from Dicionário de Botânica, 1983).

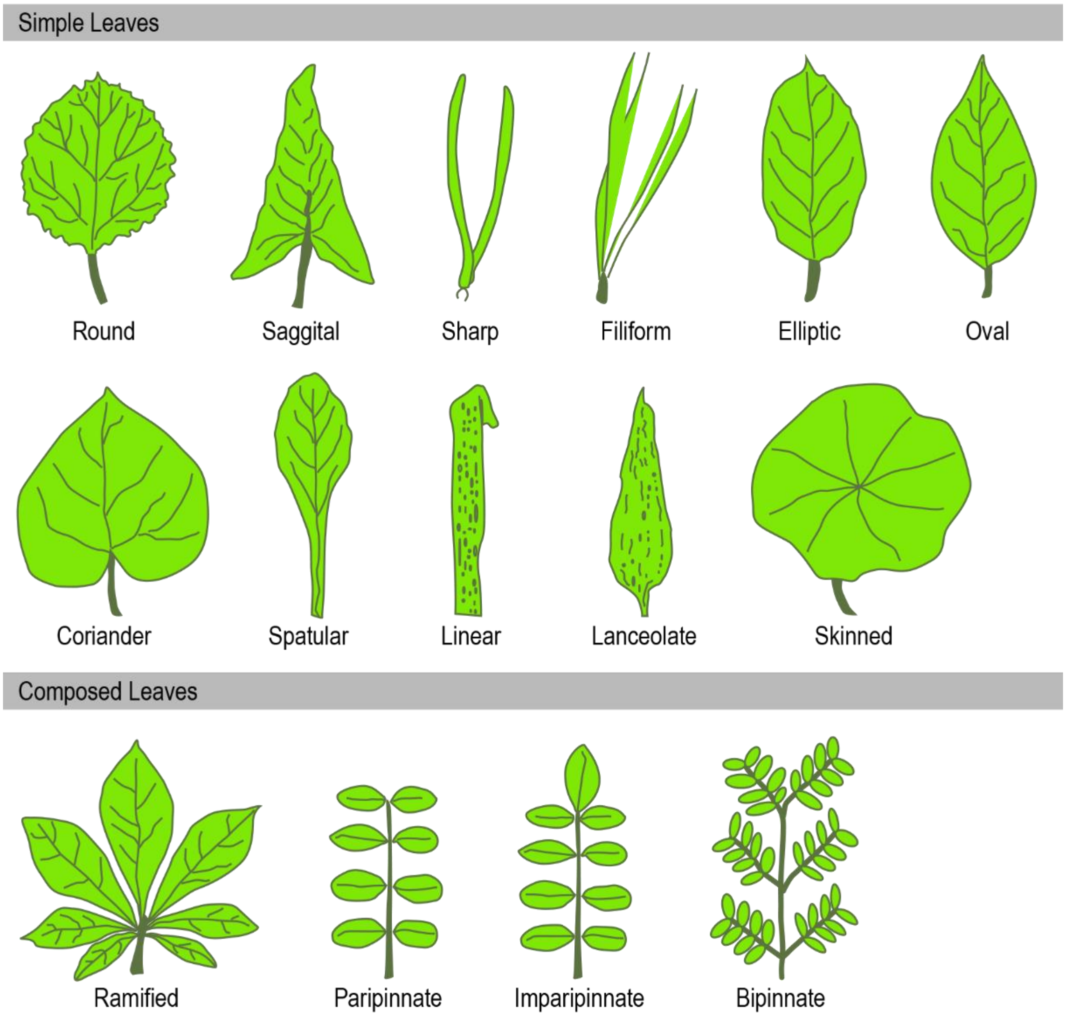

Figure 6.0:8. Phyllotaxis.

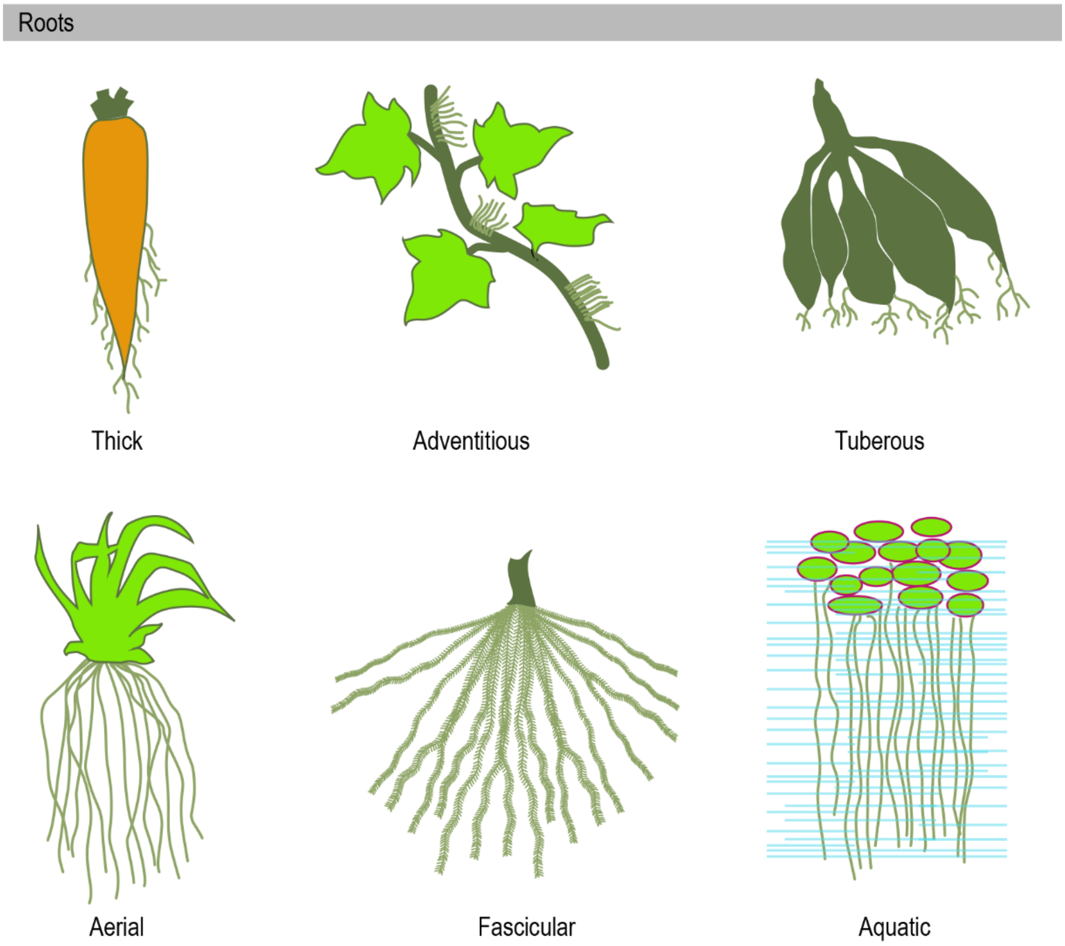

Figure 6.0:9. Types of Roots (adapted from Dicionário de Botânica, 1983).

Vernations

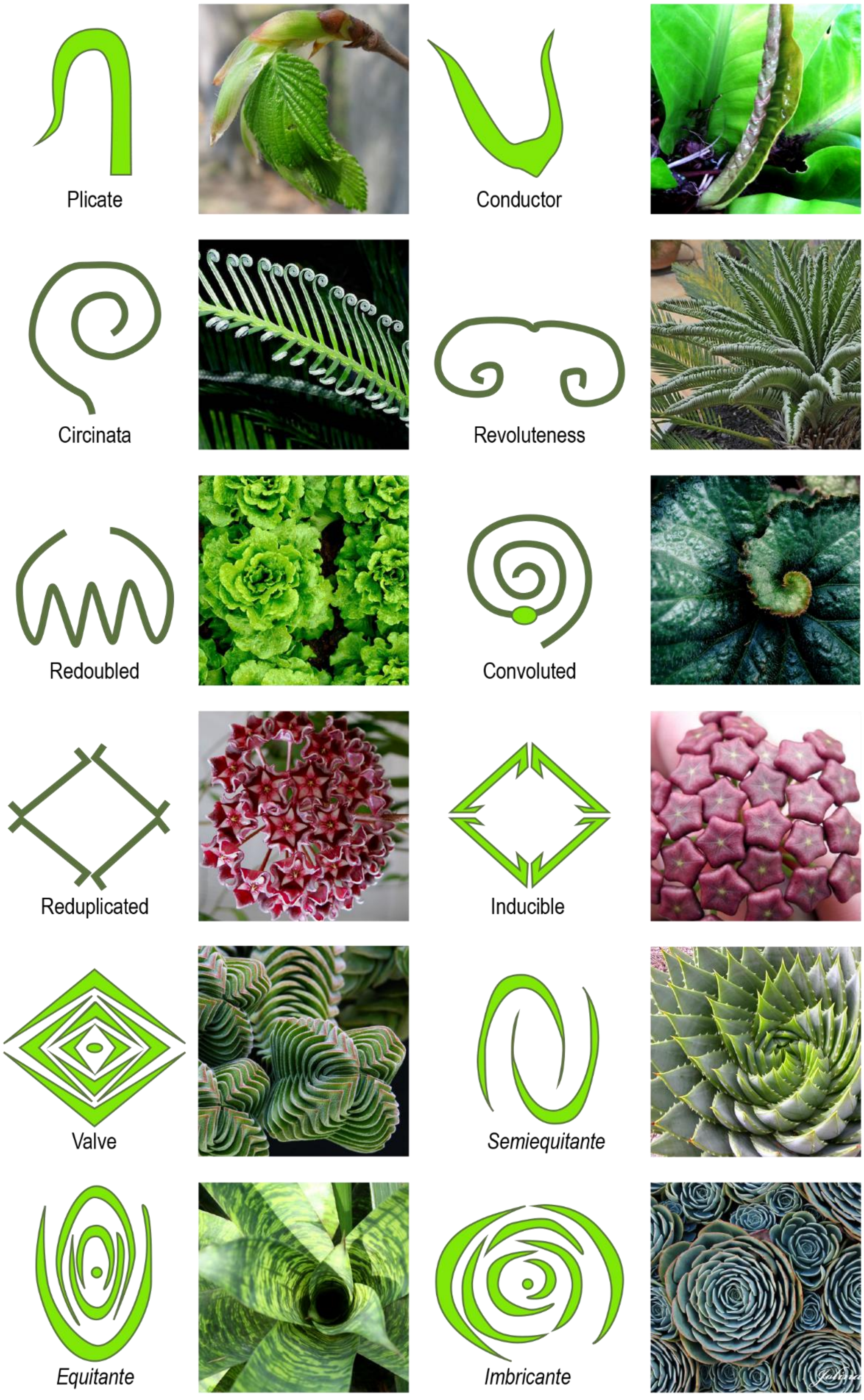

Figure 6.0:10. Types of Vernations.

6.3.4 Strategies categorization: Dynamic and Static systems

A dynamic system is a concept in which a function describes the time relationship of a point in a geometric space. These systems evolve according to a rule that links the present state to the past states. Plants' dynamic systems correspond to a physical movement as a response to an external stimulus. Also called tropisms or nasties, these movements depend on a direction or a specific position of the stimulus. These plants exhibit rapid and reactive movements in a humanly visible time-scale. Plants' reaction to temperature and light occurs through reactive mechanisms that can be observed at macro and microscale levels. The pollination of pine trees (Figure 6.0:11) is triggered by the opening of the pinecone, through its valve mechanism, enabling the use of gravity, wind, and animals for its dissemination; this is an example of a macroscale dynamic strategy. Stomatal movements (Figure 6.0:12) in response to temperature, light, and carbon dioxide are an example of dynamic mechanisms at the microscale.

Figure 6.0:11. Pinecones pollination[14]

[14] Pine Pollination, n. d., photograph, viewed 31st August 2019 <http://www.tezhler.am/index.php/event/pine-pollination/ >

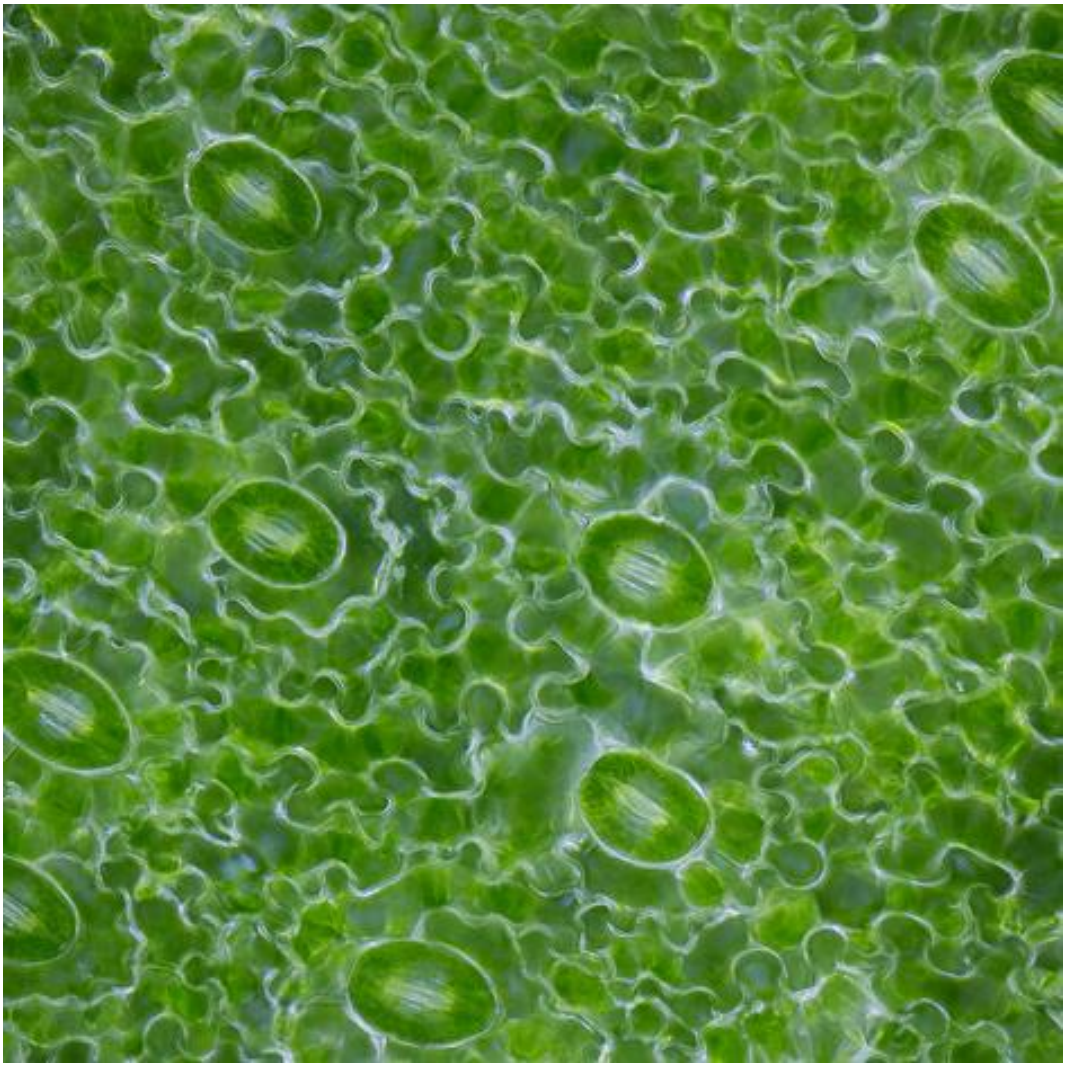

Figure 6.0:12.Stomata[15]

Static system focuses on multifunctional properties, such as surface structures of plants. Plants' static systems correspond to a physical characteristic, or its development, or internal response to an external stimulus. These processes occur on a microbiological level, developing and triggering a chain of events that enable the organism to optimize its performance to its surrounding condition. Plants' surfaces offer several solutions for environmental conditions, such as reflection, superhydrophobic, or superhydrophilic surfaces. These strategies could be detected at a macro or micro scale level depending on the organism and its technique. *Salvia officinallis* (Figure 6.0:13) hairy leaves reflect visible sunlight. This reflective structure is an example of a static system at a macroscale level. The lotus effect is probably one of the most famous and well documented static strategies that occur at the nanoscale; it refers to a self-cleaning property that removes dirt particles from water droplets due to its minimal adhesion to the surface. One of the oldest living

[15] Nell, W., Fern stomata, photograph, viewed 8 October 2018 <
http://www.photomacrography.net/forum/viewtopic.php?p=132965&sid=649e47508313c8f7afcde49e0ea0207a>

examples is the *Ginkgo biloba* (Figure 6.0:14) - a gymnosperm, unchanged since the Jurassic Era.

Figure 6.0:13. Salvia officinallis[16]

[16] Salvia officinallis, n. d., photograph, viewed 8 October 2018 <https://www.plantnmore.com/products/sage?variant=3549652811816>

Figure 6.0:14. Ginkgo biloba[17]

6.4 Insights

The analysis of the mechanisms through which plants adapt to their environment is a fundamental component of this research. In biology, ‘adaptation’ is a process by which a living organism becomes fitted to its environment. Firstly used in the 18th century to describe the relationship between what we today call ‘design’ and ‘function’, or how something fits into something else, adaptation, in biology, has three different fields of application: morphological, physiological, and behavioral (Gittleman, 2018). In order to create an essential data survey of events related to terrestrial vascular plants, three tables, focusing on the three fields of application, where created. To improve the accuracy of understanding and interpretation, dynamic and static system strategies were also defined.

[17] Butterfield, R., Ginkgo biloba, photograph, viewed 8 October 2018 <http://pinguicula.typepad.com/blog/2006/11/ginkgo.html>

From these two elements, the user of this methodology will be able to conceive and create in their mind the necessary *memes* that will enable them to link specific adaptations to architectural functions, materials, systems, components, etc..

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SECTION V
ADAPTATIVE BUILDING ENVELOPES

7.0
Shading Systems

7.0 ABOUT BUILDINGS

Cities never sheltered such a large portion of human beings. By 2015, the most populous city on the planet, Tokyo, had 37.2 million inhabitants, followed by Delhi with 25.9 million and Shanghai with 23.5 million (Smith, 2017). By 2035, the population of large cities is estimated to grow by about 37% (Smith, 2018). The future of civilization will be determined by and within cities. Our cities are major contributors of greenhouse gas emissions (Kamal-Chaoui & Robert, 2009). The European Council estimates that our buildings are responsible for 40% of the European Union's primary energy consumption and 36% of its CO_2 emissions. To improve energy performance of buildings the European Union has not only fixed a legislative agenda, that includes the Energy performance of buildings directive (EPBD - 2018/844) and Energy efficiency directive (EED - 2012/27/EU) but also has been developing several funding programs for research and innovation, such the Horizon 2020[1] (European Commission, 2019), which includes energy efficiency as one major priority. In what energy is concerned, the R&D programs funded by the European Commission are primarily targeted at three main goals: improve the energy efficiency of new buildings as well as of the existing building stock, reducing the heating and cooling loads through better design (e.g., passive design strategies); increase the energy efficiency of equipments and appliances; drastically increase the use of renewable energy sources (Stevanović, 2013).

Building envelopes define a physical barrier that separates the indoor and outdoor environments of a building. Therefore, building envelopes, façades, skins, or shading systems perform a significant role in the regulation and control of energy consumption by acting like filters between external environmental conditions and desired requirements inside (Kuro, Fiotito, Olfield, & Bonser, 2018). These architectural elements are essential design components determining the indoor physical environment, thus affecting energy usages in buildings (Oral & Yilmaz, 2003). Shading systems enable the control of the amount of solar radiation that enters a building, thus determining the ability to boost solar gains in the heating season and to avoid these same solar gains in the cooling season. In the last decades, shading systems have defied architects to explore new forms and strategies of technological integration and usage, trying to achieve greater efficiency and performance in terms of energy, comfort and structure, by lowering the energy usage and enhancing the indoor comfort (Selkowitz S. E., 2001) (Selkowitz, Aschehoug, & Lee, 2003).

[1] Horizon 2020 is the European Union framework Program for Research and Innovation. The program is centered on three main areas: 'Excellent Science', the 'Industrial Leadership', and the 'Societal challenges'.

7.1 Shading Systems

Our surrounding environment is always changing. Solar radiation, temperature, relative humidity, rainwater, wind, air quality, and noise are the most common environmental issues affecting buildings occupancy. As a consequence, these are issues that perform a critical role in buildings' performance and in its inhabitant's comfort demands. 60% of the energy consumed in buildings is for heating and cooling (Omrany, Ghaffarianhoseini, Ghaffarianhoseini, Raahemifar, & Tookey, 2016). A well-designed shading system reduces building peak heat gain and cooling requirements, improving natural lighting quality in the building interiors. Several reports have affirmed that depending on the amount and location of the openings, adapted shading systems have contributed 5% to 15% of energy consumption reductions. More than offering the opportunity of differentiation through the building skin, shading systems devices can also improve inhabitants' visual comfort by controlling glare and reducing contrast ratio, leading to an increase of satisfaction and productivity (Uspenskiy, 2013).

The use of shading control systems is a determinant aspect of many project strategies of energy efficient-buildings. Buildings that use passive solar heating or daylight, frequently depend on well-designed shading devices. During the summer season, an external window shading is an excellent strategy to avoid unwelcomed solar heat gain inside a conditioned space. The design of effective shading devices will depend on the solar orientation of a specific building's façade. Considering a South façade in the North hemisphere, simple fixed protrusions are effective for shading. This is true (depending on the location's latitude) due to the solar radiation high angles. However, during peak periods of heat gain in the summer, the same solution is ineffective in blocking afternoon low-altitude sun in west façades. For this west façade, vertical shading elements will be required in order to block afternoon low radiation angles. Shading control can be provided by several building components and surrounding natural elements. Landscape properties, such as trees and exterior overhangs or vertical fins, reflexive surfaces, low shading coefficient glass, and interior control brightness devices, like Venetian blinds or adjustable louvers, are additional elements that could provide solar shading control improvements (Prowler, 2016).

7.1.1 Shading systems types

A shading system can perform as a building's protective skin, not only protecting transparent but also opaque surfaces (façades and roofs), improving energy usage by reducing: i) cooling loads during the summer, ii) heat loads during the winter, and iii) the necessity of artificial lighting by redistributing daylight. There are five main types of shading systems: 1- Fixed (static elements during day and season), that mainly respond to a defined period of the year; 2- Adjustable (manually or automatically), can respond to sun path, allowing direct and diffuse radiation control; 3- Overshadowing from surrounding vegetation and urban morphology; 4- Advanced Glazing Systems (AGS); and 5- other shading technologies, like Transparent Insulation Materials (TIM).

Internal and external shading devices are effective against diffuse solar radiation, due to its different angles of incidence, and against direct solar radiation, due to its direct intersection and dissipation of radiation, before it reaches the internal building surfaces. Therefore, solar heat gain is prevented from hitting the building, reducing cooling loads.

Daylighting performance is often defined differently by different stakeholders. For an electrical engineer, the daylighting performance is often defined in terms of achieving Zero Net Energy, while an architect defines it in terms of aesthetic qualities of daylight distribution and perceived level of visual interior-exterior connection. The building's client may define daylighting performance based on the requirements of green building certification, or other specific requirements, while building users may define and evaluate daylight performance based on their perception of daylight efficiency, visual comfort, views or even the control level of adjustability to the dynamic environmental conditions (Konis & Selkowitz, 2017). Four main events directly affect building energy use: 1- thermal heat transfer, 2- solar heat gain, 3- airflow, and 4- lighting loads. Architects can use several strategies to improve buildings' performance. For instance, improving wall insulation will reduce conductive heat losses; the usage of solar shading and special glazing will enable the control of solar heat gain; proper window system design (directly related to space subdivision) will improve cross-ventilation; and optimizing the daylighting in the interior spaces will reduce the need for electric lighting (Aksamija & Perkins+Will, 2013). In this chapter, the functions, actions, and agents of shading systems are discussed, together with their different types of structures and actuators, influencing their design.

7.1.2 Shading systems functions

Shading systems' fundamental functions are related to the different types of solar radiation, visual comfort, visual connection with the outdoor, ventilation, and its architectural integration. Solar radiation affects our buildings and its inhabitants through direct, diffuse, and reflected radiation. Also called direct beam radiation, direct radiation is usually described as a straight line with a defined direction from the Sun into the Earth. Diffuse radiation is generally described as the light scattered by molecules and particles in the atmosphere. The third component is reflected by surrounding surfaces, reaching the buildings' surfaces. As direct radiation has a defined direction, an object can completely block it, producing shadows. However, while direct radiation can be easily blocked, diffuse radiation is harder to deal with, due to the microscopic irregularities of the interface. For instance, when light strikes a rough/granular surface, light bounces off in all directions. This light scattered effect is one of the main causes of visual discomfort in the urban areas.

Directly linked to the visual comfort and the daylight transmission balance, the glare is often described as the difficulty of seeing caused by a ratio of luminance between the task plane and the glare's source. Glare is divided into three categories. 1- Disability glare, defined as the visual system failure, due to the light scattering in the eye (usually from very bright sources); 2- Discomfort glare, caused by excessive contrast or non-uniform light distribution in a determined field of view; and 3- Veiling glare, characterized by the contrast reduction of an image (e.g. the reflection of a window on a computer monitor) (Konis & Selkowitz, 2017).

Today, as a result of research in the field of environmental psychology, people know more about the importance and effects of windows in their surrounding environment. The provision of windows for all building inhabitants is an essential component of people's performance, health, and well-being. Windows support several functions such as views, stimulation (by colors, objects, other living organisms), and the perception of space, providing sunlight and daylight exposure. Beyond the provision of views, a visual connection to the outdoors fills relevant biological needs for environmental information, such as location, time, weather, enclosure, visual, olfactory and auditory stimulation, a possible connection to other living beings, and also places to refuge in time of perceived danger (Konis & Selkowitz, 2017). Shading systems can also perform an essential role as ventilation systems, regulating the process of air renewal from an indoor space reducing cooling loads, and enhancing air quality. Acting as a double-skin façade, exterior shading systems can control and mediate natural ventilation through the façade. Furthermore, it can work as a sound filter element, preventing sound from passing through the exterior wall of the building.

Shading systems can perform more efficiently when designed integrated with the whole building conception. Effective and well-integrated shading systems, combined with other design options (e.g., material properties, thermal inertia), enable a significant reduction in the building's energy consumption. The reduction and management of energy losses and gains can be achieved through the integration of operable openings to reduce cooling and ventilation loads and through daylight optimization, in detriment of electrical lighting.

In order to achieve an effective shading system, architects need to consider the exterior environment, building's orientation and proportion, as well as the aims for inhabitants’ comfort. Table 7.0:1 shows how factors such as air temperature, solar radiation, humidity, wind speed, ground reflectiveness, and location can influence thermal and visual comfort (Aksamija & Perkins+Will, 2013).

Table 7.0:1. Environmental conditions and properties affecting thermal and visual comfort based on (Aksamija & Perkins+Will, 2013, p. 22).

Environmental conditions	Thermal comfort	Visual comfort
Outdoor	Solar radiation Sun and wind obstructions; Building orientation; Air temperature (range); Relative humidity (range); Wind speed.	External horizontal illuminance; Ground reflectivity.
Indoor comfort	Air temperature; Relative humidity; Air speed; Mean radiant temperature; Layer thickness; Solar heat gain coefficient.	Glare index; Window definition – size, location, and shape; Glass thickness and color; Visual transmittance; Reflectance.
Opaque façades	Material properties; Amount of insulation;	Window/wall ratio.

In short, depending on each building's specific case and conditions, an effective shading system should actively respond to some of the following functions: i) allow entry or ii) block direct solar radiation; iii) control and manage diffuse solar radiation; iv) balance transmission through glare control; v) ensure exterior views of the buildings; vi) provide natural ventilation; and lastly vii) it should be designed having in mind good and adequate architectural integration.

7.1.3 Shading systems actions and agents

An action is a process of doing something to achieve a goal. Considering the previous referred functions, six essential actions can be related: i) permeability; ii) reflection; iii) refraction; iv) intersection; v) material; and vi) scale. Permeability relates to almost all of the functions, from direct radiation entry and blockage, to diffuse radiation control, exterior views, natural ventilation, and architectural integration. Permeability is related to visual and physical connection. Reflection refers to the amount of radiation that is not transmitted or absorbed. The light reflection angle is generally the same as the angle of incidence. Therefore, when surfaces are smooth, light reflection is uniform (specular reflection). However, when the surface is rough, light reflects through a set of different angles. This happens because the angles of incidence are also different as a function of the surface irregularity. Refraction is the change of direction of a ray of light when it travels through different physical states (e.g., when light travels from air into water). The change of direction is an adaptation caused by the change of speed of the light ray. Intersection refers to the contact points between light rays and the impact surface. Material selection relates to all the functions, being one of the most important actions that will influence shading system performance. Material refers to a physical condition of matter. Scale relates to size and proportion. Scale concept can be applied to single elements or groups.

An agent is an entity that takes an active role in producing a specific effect during an action. In order to perform each of the above-referred actions, a shading system can and should consider some essential agents: i) translucency; ii) opacity; iii) morphology; iv) structure; v) density; vi) pigment; vii) pattern; viii) orientation; ix) roughness; and x) air flow. Agents are empowering tools for actions. For instance, permeability can be achieved through translucent materials, enabling a visual permeability. Nevertheless, it also can be achieved through a design pattern, enabling physical and visual permeability. Reflection can be achieved through pattern, density, and orientation, while intersection can be powered by translucency, density, and orientation. Shading systems can perform vital functions in a building ecosystem. To accomplish these functions, several actions have to be taken. These actions are supported by several agents that enable their development. This chain process also enables the success of the shading system's elected functions.

7.1.4 Shading Systems Structures

In the last two decades, architects have looked more deeply into shading systems as valuable assets of buildings. With the overall goal of managing buildings' energy demand, building envelopes are often designed considering shading systems strategies that affect building thermal performance, heat loads, and light requirements. Nowadays, most shading systems can be categorized into four main types of structure: 2D and 3D open/close structures, inflatables, flexible, and tensegrity structures.

2D Open/Close Shading Systems

2D open/close shading system types of structures are usually composed of flat elements, that through bidimensional movements produce an open/close effect in the building façade. The building inhabitants can operate these types of structures, but it is also common to respond to environmental conditions by automated mechanisms using monitor sensors.

Located in Essen, Germany, and designed by SWD Architekten and Chaix & Morel et Associés, the awarded Q1 Headquarters (2010) presents a singular envelop (Figure 7.0*:1*). Q1 Headquarters envelope was designed to provide highly efficient sun protection. The adopted strategy consisted of the design of 400.000 triangular stainless steel lamellas oriented in response to solar altitude and azimuth, enabling light redirection and preventing view blockage. The triangular lamellas are attached to the plumb lines of a structural squared grid, producing an XY rotation movement perpendicular to the building's façade.

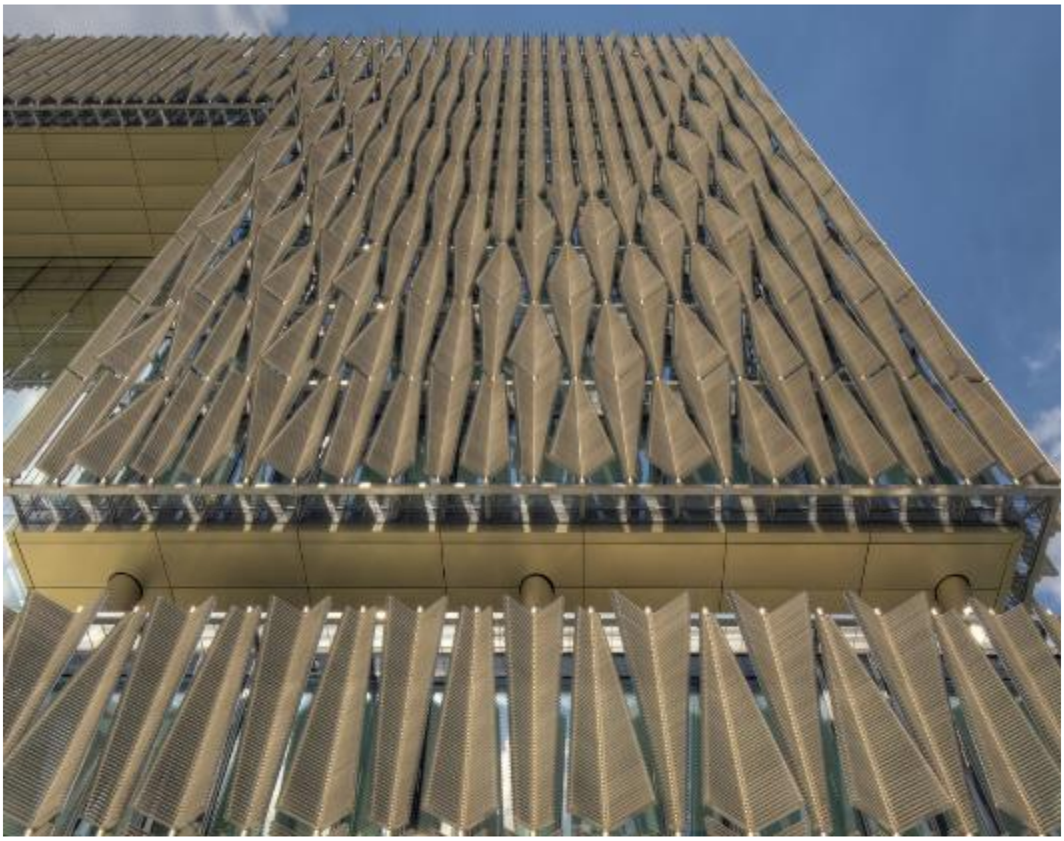

Figure 7.0:1. Q1 headquarters (2010), by SWD Architekten and Chaix & Morel et Associes, in Essen, Germany[2].

Another relevant example of 2D open/close shading systems is the 2012 project from Sean Godsell, the Royal Melbourne Institute of Technology (RMIT) Design Hub (Figure 7.0:2). The goal of the building was to accommodate and centralize design research tools and resources that, until then, were sprawled in several different places. The building holds several sustainable strategies, like energy waste, water, and recycling management, although its shading system represents the most expressive energy-efficient strategy. Composed of thousands of automated solar circular units that include photovoltaic cells, evaporative cooling, and natural ventilation, the shading system improves indoor air quality, reducing energy costs. Exclusively designed for the building, the solar units can be easily replaced as research into solar energy achieves better and improved technologies.

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[2] *Q1 headquarters building in Essen Germany*, 2012, n.d., photograph, viewed 5th August 2019, <http://getyourimage.club/resize-1-august.html>

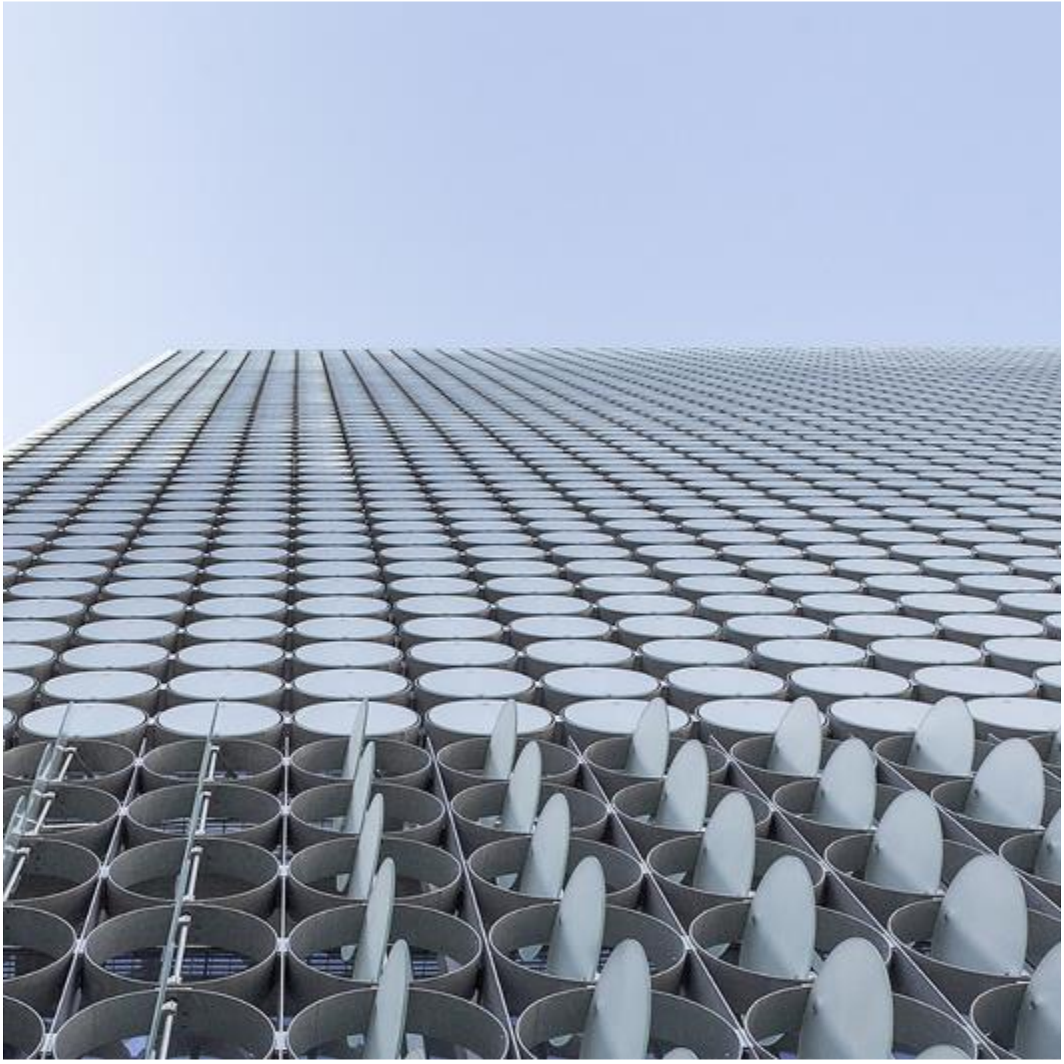

Figure 7.0:2. The Royal Melbourne Institute of Technology (RMIT) Design Hub (2012), by Sean Godsell Architects, in Melbourne, Australia[3].

Designed by Pattern Design Limited, the Hazza Bin Zayed Stadium (Figure 7.0:3) was completed in 2014. Located in Al Ain, Emirate of Abu Dhabi, well known for its palm plantation, the building is inspired by the rotating fractal geometry of the date palm fronds. The main function of its outer skin is to perform as a passive cooling device, shading the building during intense heat while enabling the air flow. Due to the building's orientation, the shading system works in a horizontal axis, easily blocking high solar rays. Each shading unit responds individually to the daylight exposure, regulating the entry of radiation inside the building.

[3] Jonathan P, 2018, *RMIT Design Hub*, photograph, viewed 5th August 2019, <http://www.throughvinslens.com/rmit-design-hub.html>

Figure 7.0:3. Hazza Bin Zayed Stadium (2014), by Pattern Design Limited, in Al Ain, Emirate of Abu Dhabi, United Arab Emirates[4].

3D Open/Close Shading Systems

3D open/close shading systems can be composed of bidimensional or three-dimensional objects, that through linear or nonlinear motion, perform an open/close tridimensional effect on the building's façade. Usually, this type of structure is equipped with technological components, performing complex effects using simple mechanisms. Despite all the technological advances, the idea of adaptive building envelopes is not new. Wheels and hinges are basic mechanic components that can create adaptive and transformable environments (Kolarevic & Parlac, 2015). Built in 2007, the Kiefer Technic Showroom (Figure 7.0:4), in Bad Gleichenberg by Ernst Giselbrecht + Partner Zt Gmbh, is an office building and showroom for a product representation of a metal company. Covered

[4] Gilbert, Dennis, 2014, *Hazza Bin Zayed Stadium*, photograph, viewed 5th August 2019, <https://www.archilovers.com/projects/156284/gallery?1314510>

by foldable steel planes, the glass curtain wall is continuously changing, either adapting to individual changes and needs, or if users are not present, controlled by a computer program.

Figure 7.0:4. Kiefer Technic Showroom (2007), by Ernst Giselbrecht + Partner ZT GmbH, in Graz, Austria[5].

Still in its prototype stage, the Flare Façade Module (Figure 7.0:5), developed by WHITEvoid interactive art & design Berlin (since 2008), is an iconic façade experience of three-dimensional motion elements. The computer-controlled Flare system consists of an infinite array of stainless-steel flakes that can be attached to any building façade. Reflecting its surrounding light, each flake reflects sunlight when standing in its vertical position, and when tilted downwards, its face is shaded from the skylight appearing as a dark pixel. Flare establishes an impermeable relation with its inhabitants while establishing an elegant dialog with the surrounding environment light.

[5] *Kiefer Technic Showroom*, 2008, n.d., photograph, viewed 5th August 2019, <https://worldarchitecture.org/architecture-projects/hvfv/kiefer-technic-showroom-project-pages.html>

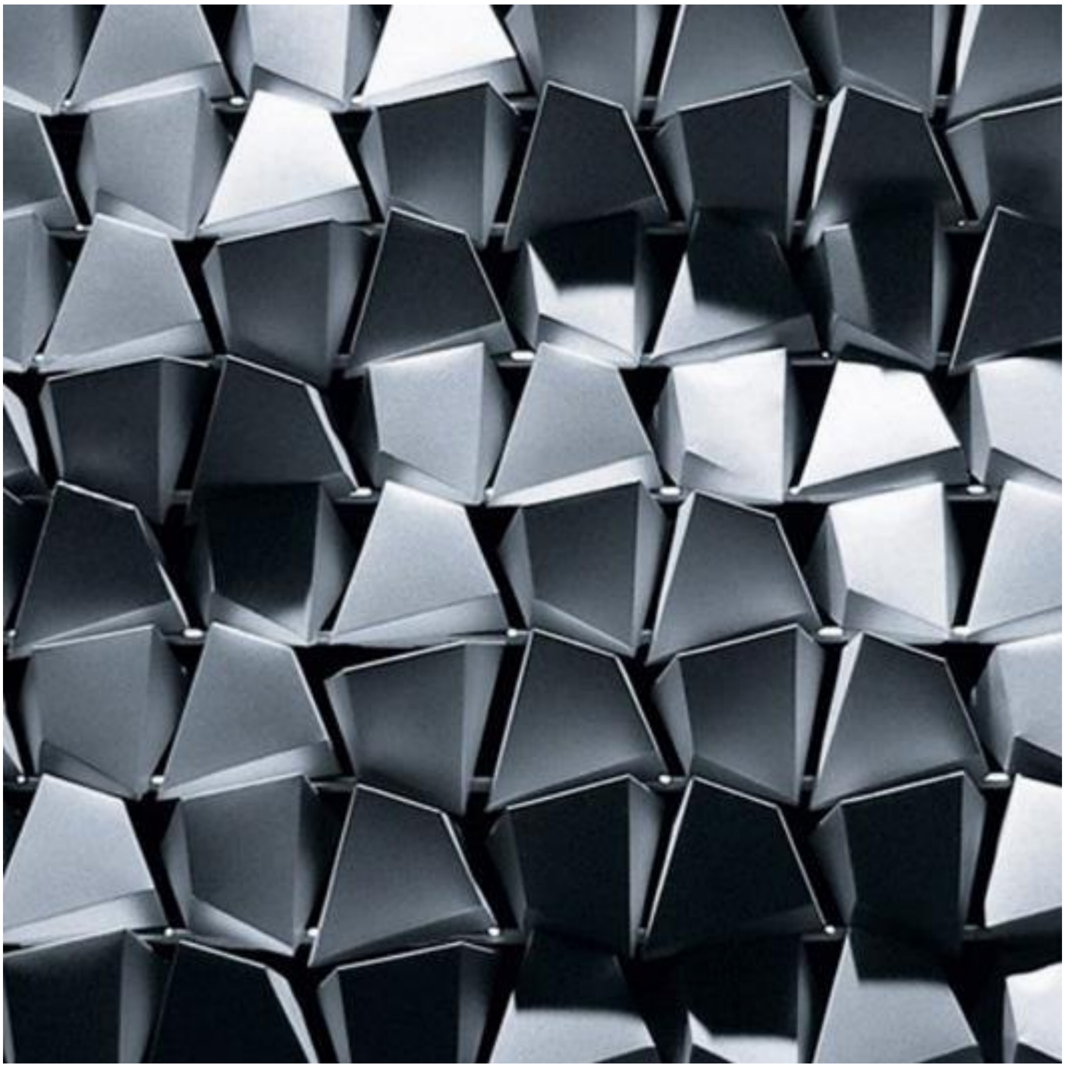

Figure 7.0:5. Flare prototype (2008), by WHITEvoid interactive art & design Berlin (2008), in Berlin, Germany[6].

Winner of the 2009 AA's Nicholas Pozner Prize for Best Single Drawing of the year, Hellberg's design for a Japanese Embassy in London celebrates the tension between the natural and the artificial. The Tower of the Folding Stones (Figure 7.0:6) is covered by an arboreal structural metaphor, materialized through umbrellas structures. These structures replicate the blooming moment of the chrysanthemum flower. The umbrellas open and close, adapting to its surrounding environment, mediating the daylight entry inside the tower.

[6] WHITEvoid, 2008, *FLARE_07_large*, photograph, viewed 5th August 2019, <https://www.flickr.com/photos/whitevoid/7247794434>

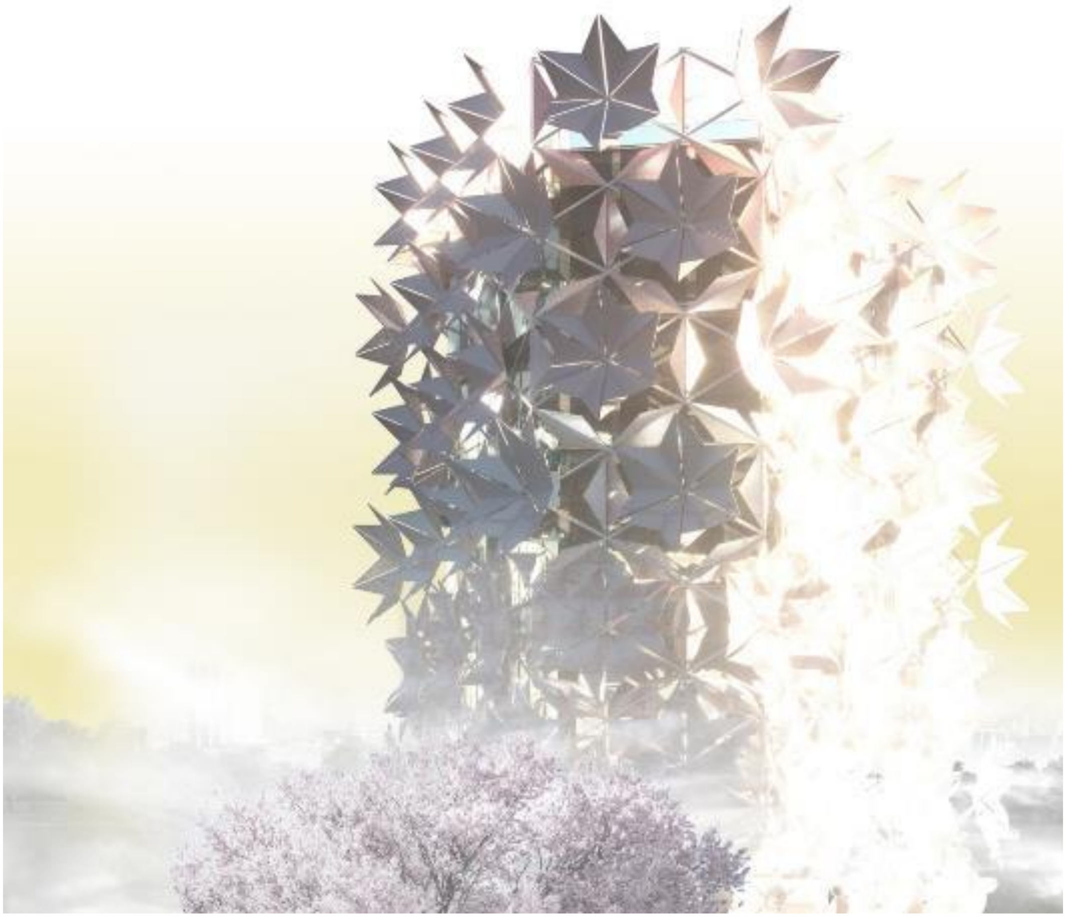

Figure 7.0:6. Tower of the Folding Stones – Japanese Embassy (2009), by Fredrik Hellberg, London, United Kingdom[7].

Inflatable Shading Systems

Inflatable architectural structures (also known as air structures) have enabled the construction of many utopian projects. Otto's and Füller's large city enclosures are now possible through the use of the air-filled pillows of Vector Foiltec's Ethylene Tetrafluoroethylene (ETFE) technology. ETFE cushions structures are inflated by air, creating a building skin that is waterproof, UV-resistant transparent, and lightweight. ETFE cushions may have two or more printed layers, enabling the variable air pressure to create a thermally dynamic building façade (McLean & Silver, 2015).

[7] Hellberg, F., 2010, *Tower of the Folding Stones*, Render, viewed 5th August 2019, <http://projectsreview2010.aaschool.ac.uk/submission/uploaded_files/DIP-13/fredrik.hellberg-CFVH_WEB_03.jpg>

Described by Phillipe Starck as *'a minimal architectural gesture with maximum poetry'*, completed in 2004, 'Le Nuage' fitness center (Figure 7.0:7), authored by him, is recognized as the first inflatable building in France. Created in collaboration with the Roxim Group, the five-story fitness complex finds its roots in an aerial sense of lightness and transparency. The ETFE cushions façade acts as a variable screen, filtering sunlight during the day and expressing its dynamic character through its RGB façade during the night.

Figure 7.0:7. Le Nuage (2004), by Philippe Starck, in Montpellier, France[8].

The Allianz Arena – Football Stadium (Figure 7.0:8) opened in Munich in 2005. Designed by Herzog & De Meuron, the football arena was completed in just 30 months. One of the great attractions of the project is the diamond-shaped composition, cushioned-shells, composition attached to a metal grid, representing a smooth exterior translucent envelope. A 2 millimeter ETFE (Ethylene Tetrafluoroethylene) membrane, extremely lightweight, self-cleaning, and continuously ventilated, covers 2874 inflatable panels. The 98% translucent ETFE allows daylight reaching the football stadium grass. One of the building's most striking features is the color-changing façade that reflects the respective home team using the arena - red for Bayern Munich, blue for TSV, and white for the German national football team.

[8] *Philippe Starck Aasarchitecture*, 2019, n.d., photograph, viewed 5th August 2019, <http://postal.striucken.com/index.php?main_page=product_info&products_id=23660>

Figure 7.0:8. Allianz Arena (2005), by Herzog & Meuron, in Bavaria, Germany[9].

Designed by Diller Scofidio + Renfro with the Rockwell Group joint venture, the Shed's (Figure 7.0:9) opening occurred in New York in the beginning of 2019. The Shed is a nonprofit cultural organization that develops, presents, and commissions several artistic expression forms in all fields of art. The iconic element of the building is the large-scale open stage for performances, installations, and concerts, the McCourt. The McCourt is a 1600m^2 space featuring light, sound, and temperature control. The space was created through the deployment of the telescopic outer shell, gliding along rails onto the adjoining plaza (DillerScofidio + Renfro, 2019). Based on gantry crane technology, usually found in railway systems, the movable shell slides on a double-wheel track. The movement is triggered by a rack-and-pinion, enabling the shell to move back and forward on four single-axle and two double-axle bogie wheels. The exposed steel diagrid frame of the movable

[9] *Allianz Arena Designed by Herzog & de Meuron*, 2019, n.d., photograph, viewed 5th August 2019, < https://medium.com/@mariodisibio/auxetic-materials-for-inflatable-structures-964067943bd0>

shell is cladded in translucent cushions of durable and lightweight ETFE. With the thermal properties of insulating glass at a fraction of the weight, the translucent ETFE allows light to pass through and can withstand hurricane-force winds.

Figure 7.0:9. The Shed (2019), by Diller Scofidio + Renfro and Rockwell Group's, in New York City, US[10].

Flexible Shading Systems

Flexible architecture is a concept that requires design theory, conceptual framework, mechanics, and structural engineering. As it has been stated, a building mediates a highly dynamic relationship between its inhabitants and the environment. *"(…) there are two overarching factors driving building design today: (1) the critical need for sustainable solutions; and (2) the power of computation. The convergence of these two is leading to a new generation of adaptive technologies (…)"* (Hoberman, 2015, p. 116).

Gardens by the Bay in Singapore (Figure 7.0:10), designed by Wilkinson Eyre Architects, completed in 2012, features a double-glazed roof with an external shading system composed of a fabric diamond mesh. Exterior sensors monitor the environmental conditions (temperature, humidity, and light levels), controlling the extended/rolled up state of the shades. As light increases, the external shading expands. When deactivated, the

[10] Bann, I., 2019, *The Shed, New York NY*, photograph, viewed 7th August 2019, <https://dsrny.com/project/the-shed>

shades are rolled up and concealed under structural components. The expand/contraction shade effect also provides visitors a light visual spectacle experience (Kolarevic & Parlac, 2015).

Figure 7.0:10. Gardens by the Bay (2012), by Wilkinson Eyre and Grant Associates, in Singapore[11].

Another iconic example of flexible architecture through the design of its shading system is the Aldar Central Market (Figure 7.0:11), completed in Abu Dhabi in 2010 and designed by Foster + Partners. ABI[12] Permea^{TM} was applied as an exterior shading roof in the three public squares of the Aldar Central Market. Permea^{TM} is a unitized, motor-driven, self-contained system that individually controls the three roof squares permeability, resembling a traditional coffered Islamic roof.

[11] *Gardens by the Bay is World Building of the Year*, 2012, n.d., photograph, viewed 5th August 2019, <https://wordlesstech.com/gardens-by-the-bay-is-world-building-of-the-year/>
[12] Adaptive Building Initiative – a joint venture between Buro Happold and Hoberman Associates

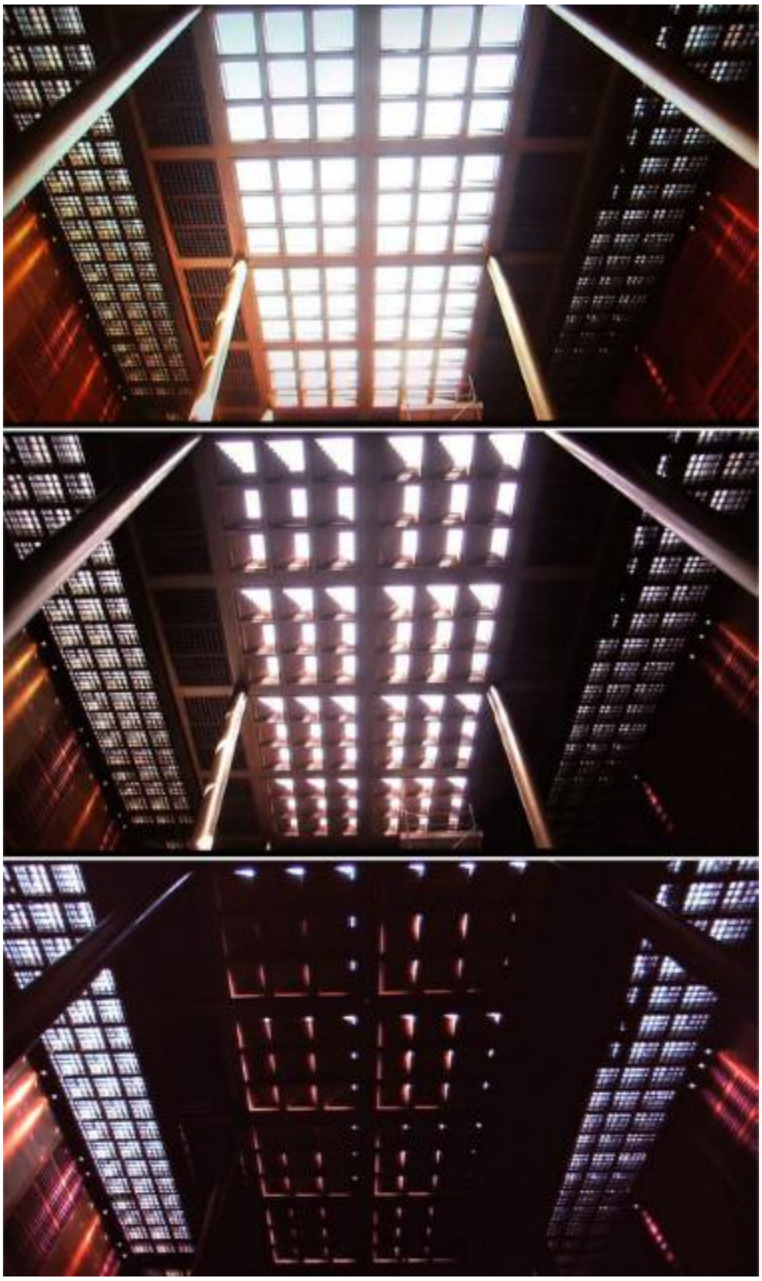

Figure 7.0:11. Abu Dhabi Central Market (2014), by Foster + Partners, in Emirate of Abu Dhabi, United Arab Emirates[13] (Hoberman, 2012, p. 12).

Using a different approach, the Snapping Façade uses a "snapping-induced motion" to open and close a shading structure, not requiring mechanical actuators to operate or to facilitate its complex maintenance. Developed in 2018 by Jin Young Song + Jongmin Shim and Dioinno Architecture PLLC, the Snapping Façade prototype explores elastic instability to create dynamic motion on the building's façade (Figure 7.0:12). The

[13] Adaptive Architecture - Aldar Central Market, photographs, 2014, n.d., viewed 5th August 2019, <http://www.hoberman.com/soq/HobermanSOQ.pdf>

prototype uses plastic instability (relaxation) to produce deformation with minimal stimulus. The Snapping Façade takes advantage of the elastic instability by applying it as an opening and closing mechanism, using embedded energy within the materials. The idea is that the building's inhabitants can participate in the dynamic movement, either to play or for energy saving. The project is still ongoing.

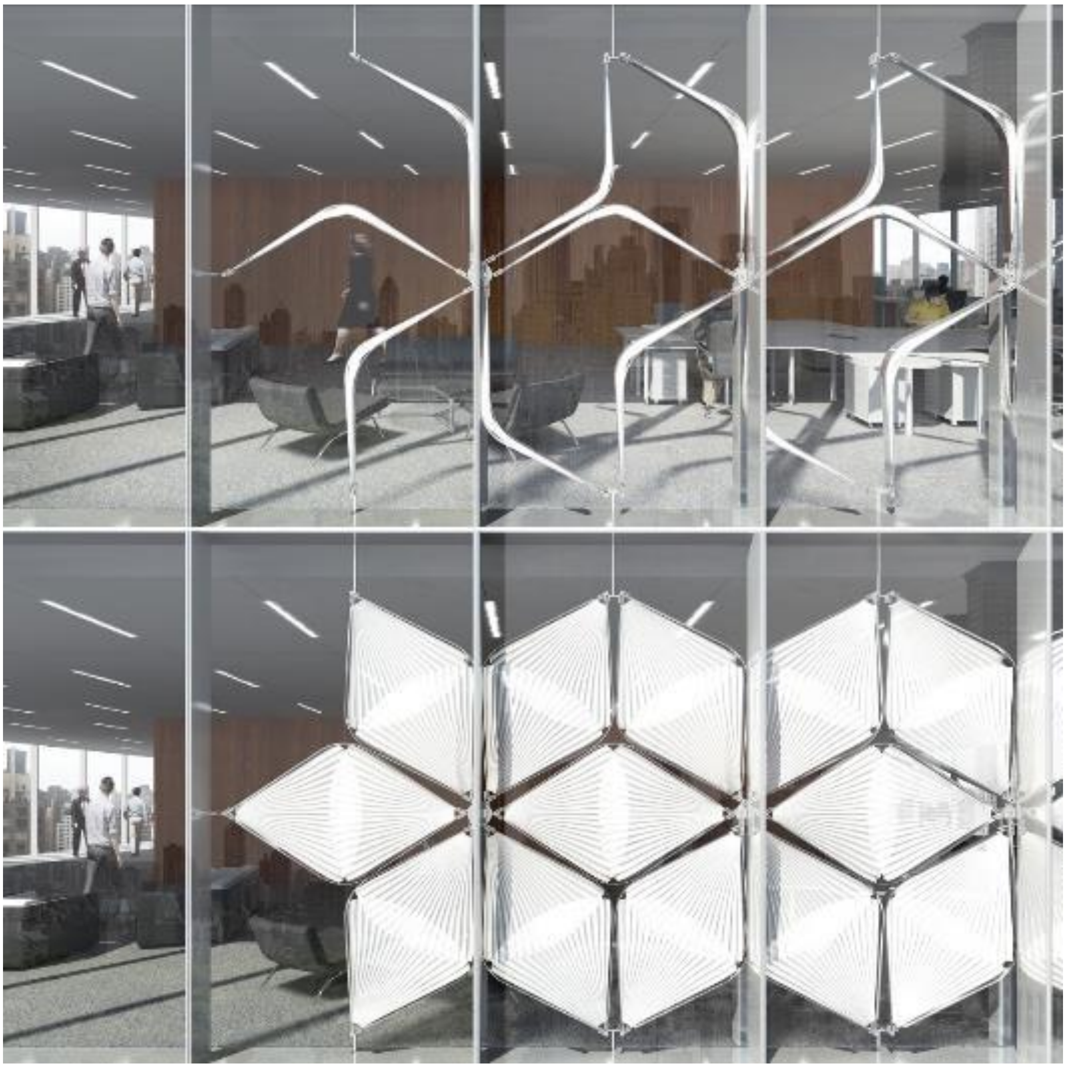

Figure 7.0:12. Snapping Façade prototype (2018), by Jin Young Song + Jongmin Shim and Dioinno Architecture PLLC, in Buffalo, NY, United States[14].

Tensegrity Shading Systems

The last type of structure reported in this thesis is the tensegrity shading systems. Tensegrity (tension + integrity of a body) is a matrix that combines traction and compression in order to enhance objects' stability and strength. In 2000, the architect Fruto

[14] Song, Jin Y., Shim, J., *Snapping Facade / Building shade*, photograph, viewed 5th August 2019, <https://ifworlddesignguide.com/entry/230325-snapping-facade>

Vivas, under the guidance of Frei Otto, designed the Expo 2000 Venezuelan pavilion (Figure 7.0:13). Displayed in the Hannover Expo, and under the motto of the biodiversity of the country, eight giant petals around a central mast of eighteen meters high covered the pavilion's exhibition spaces. The giant petals produced an opened/closed effect through a vertical movement, according to the exterior climatic conditions, favoring the pavilion's indoor comfort. The Petals are cabled by a tubular support structure and remain invariable during their movement to a new position (García-Diego, Llorens, & Poppinghaus, 2001).

Figure 7.0:13, Venezuelan Pavilion - Expo 2000 (2000), by Fruto Vivas + Frei Otto, in Hanover, Germany[15]*.*

Considered as a pioneer building in the context of Riyadh's urban space, the King Fahad National Library (Figure 7.0:14) designed by the Gerber Architekten and completed

[15] *Venezuela pavilion at the 2000 World Expo*, 2000, n.d., photograph, viewed 5th August 2019, <https://www.pinterest.pt/pin/821555156996009094/?lp=true>

in 2013, is a squared plan building covered by a filigree textile façade. The filigree textile façade follows the traditional middle-eastern architectural patterns, here linked to contemporary art and technology. The façade was developed based on a rhomboid textile awning, notable in its play of revealing and concealing. Similar to the traditional Arabian tent, the white membranes, supported by a three-dimensional steel cable structure, perform as a technological version of this type of sunshades. At night, the colorful and bright façade is the city's newest cultural icon.

Figure 7.0:14. King Fahad National Library (2013), by Gerber Architekten, in Riyadh Saudi Arabia[16].

Working at a totally different scale, Lumen installation (Figure 7.0:15) was an emblematic tensegrity example of shading structures. Lumen, designed by Jenny Sabin and her multidisciplinary team, was the 2017 winner of the Museum of Modern Art's PS1

[16] Richters, C., 2014, *King Fahad National Library*, 2014, photograph, viewed 5th August 2019, <https://www.archilovers.com/projects/113487/king-fahad-national-library.html>

in the Young Architects Program category. Held in tension within the PS1 courtyard walls, Lumen was a social and environmental responsive installation that adapted heat and sunlight to its users. Lumen was composed of a lightweight knitted fabric of responsive tubular structures and a canopy of cellular components, photo-luminescent, and solar wires that collected and delivered light. The installation was generated under the motto of adaptative materials and architecture, combining code, pattern, human interaction, environment, and matter in a conceptual design space.

Figure 7.0:15. Lumen (2017), by Jenny Sabin Studio, in The Museum of Modern Art (MoMA), New York City, US[17].

[17] Enriquez, P., 2017, *Interactive Spatial Installation: Lumen by Jenny Sabin Studio*, photograph, viewed 5th August 2019, < https://www.detail-online.com/article/interactive-spatial-installation-lumen-by-jenny-sabin-studio-30389/>

7.1.5 Shading systems actuation types

In the last two decades, we have witnessed a remarkable development in the building industry. New materials and technologies have found their role in building envelopes leading to an unprecedented tectonic evolution in façade engineering. The incorporation of electronically controlled, mechanically activated shading and ventilation systems brought to reality the dynamic façades and the high-performance building envelopes. Regarding the dynamic façades and the high-performance building envelopes concepts, the fundamental idea behind these systems is that buildings should dynamically respond to their surrounding environment in several energy-efficient ways (Kolarevic & Parlac, 2015). To make a shading system dynamic, their elements need to have movement capabilities such as rotate, twist, shrink, stretch, etc.

An actuator is a machine component responsible for triggering and controlling the movement of a system. An actuator requires an input signal and an energy source. The dynamic property is not related to the element itself, translating a signal to actuation, but rather to how the actuation is produced. Four main types of actuation will be explored through building examples: motor-based, hydraulic, pneumatic, and material-based.

Motor-Based Actuation (Between layers)

Electrical actuation is powered by a motor that converts electric energy into mechanical force. Mechanical Venetian systems, inside double-layered façades, are the most common motor-based actuation system (electrical current energy source). These systems can significantly reduce glare effect and solar heat gain, and they are often automated, whereby a Building Management System (BMS) tracks sun position, monitoring temperature, daylight, and interior light conditions in order to adjust the Venetian tilt.

The KFW Westarkade office building (2010) in Frankfurt, Germany, is one of the first skyscrapers in the world that runs on less than 100 kWh/m^2 of primary energy per year (Figure 7.0:16). Designed by Sauerbruch Hutton, the skyscraper is coated by a wind-pressurized double-skin façade, that regardless of the exterior climatic conditions, ensures natural ventilation, high insulation performance, and solar screening efficiency. Double skin façade houses several mechanical blind devices controlled by BMS. This motor-based actuation combines rotational and linear vertical movements. Another motor-based actuation example is Tesselate. Developed in 2010, by the joint venture between ABI and A. Zahner Company, Tesselate (Figure 7.0:17) is an adaptive façade system, contained in a double-glass façade, that consists of bidimensional perforated panels that move, overlapping each other in order to create kaleidoscopic patterns. Based on linear horizontal movements, this motion system applied to overlapping panels enables the control of light and solar gain, natural ventilation, and visual connection.

Figure 7.0:16. KFW Westarkade (2010), by Sauerbruch Hutton, in Frankfurt, Germany[18].

Figure 7.0:17. The Tesselate Adaptive Façade (2010), by ABI in collaboration with A. Zhaner Company[19].

[18] Bitter, J., 2010, *KfW Westarkade, Frankfurt*, photograph, viewed 5th August 2019, <http://www.sauerbruchhutton.de/en/project/kfw>
[19] *Zahner, Tessellate - Adaptive Shading System by Zahner And Adaptive Building Initiative (Abi)*, n.d., photograph, viewed 5th August 2019, <https://www.pinterest.pt/pin/147563325269066484/?lp=true>

Motor-Based Actuation (External devices)

Adaptive shading systems can be either internal (embedded in the building's façade) or external to it. Featuring an adaptive external shading system is the Al-Bahr Towers (Figure 7.0:18) in Abu Dhabi, designed by AHR office, completed in 2012. The towers exhibit operable triangular umbrellas, organized into hexagonal shade units through an origami folding effect, attached to a glass façade. A BMS that tracks the Sun's position provides instructions to the umbrellas, that can reconfigure themselves, by open/close linear actuation. By minimizing the solar heat gain, the system reduces cooling loads by about 25%, thus reducing energy consumption (Ghabra, 2017). Due to its fiber-glass surfaces, the system diffuses direct solar radiation, enabling visual connection from the inside to the surrounding cityscape.

Figure 7.0:18. Al Bahr Towers (2012), by AHR, in Abu Dhabi, United Arab Emirates[20].

Completed in 2014, the SDU Campus Kolding (Figure 7.0:19) designed by Henning Larsen Architects, in Kolding, Denmark, with its triangular shape, stands out as a landmark in the city center (Henning Larsen, n.d.). Apart from its distinctive architecture, the energy consumption of the campus is so low that the building is classified as Energy

[20] *Sunshades on the Al Bahr Towers, Abu* Dhabi, n.d., photograph, viewed 5th August 2019, <https://www.reddit.com/r/ArchitecturePorn/comments/5ohagn/sunshades_on_the_al_bahr_towers_abu_dhabi_3500/>

Class 1[21]. One of the elements responsible for this classification is related to the building's façade. During the day, 1600 triangular perforated steel shutters, directly respond to daylight, in order to regulate the amount of light and energy allowed to flow inside the building. The triangular units are individually anchored to the façade by a pivoting system, enabling synchronized or independent rotational movement. This dynamic shading system provides daylight and comfortable temperature indoor spaces, while at the same time providing indoor/outdoor visual connection (Henning Larsen, n.d.).

Figure 7.0:19. SDU Campus Kolding (2014), by Henning Larsen Architects, in Kolding, Denmark[22].

Hydraulic Actuation

Hydraulic actuators use hydraulic fluid pressure as their primary energy source. Hydraulic actuation can be translated into a linear, rotational, or oscillatory mechanical motion. Designed by Mick Pearce and completed in 2006, the CH2 (Council House 2) in Melbourne (Figure 7.0:20), features an external dynamic shading system moved by a computer-controlled hydraulic system. The shading system consists of pivoting timber shutters that respond to direct sunlight exposure. In the morning, the shutters are entirely open, and as the sun moves to the West, they slowly close perpendicular to it (Kolarevic & Parlac, 2015). Considered one of the 'greenest' buildings in Australia, the CH2 also features the control of lighting and ventilation systems.

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[21] This classification is based on the Energy Requirements of BR18 - A quick guide for the construction industry on the Danish Building Regulations 2018.
[22] *Henning Larsen Architects_University of Southern Denmark in Kolding*, 2019, n.d., photograph, viewed 5th August 2019, <https://mipsbe.com/post/>

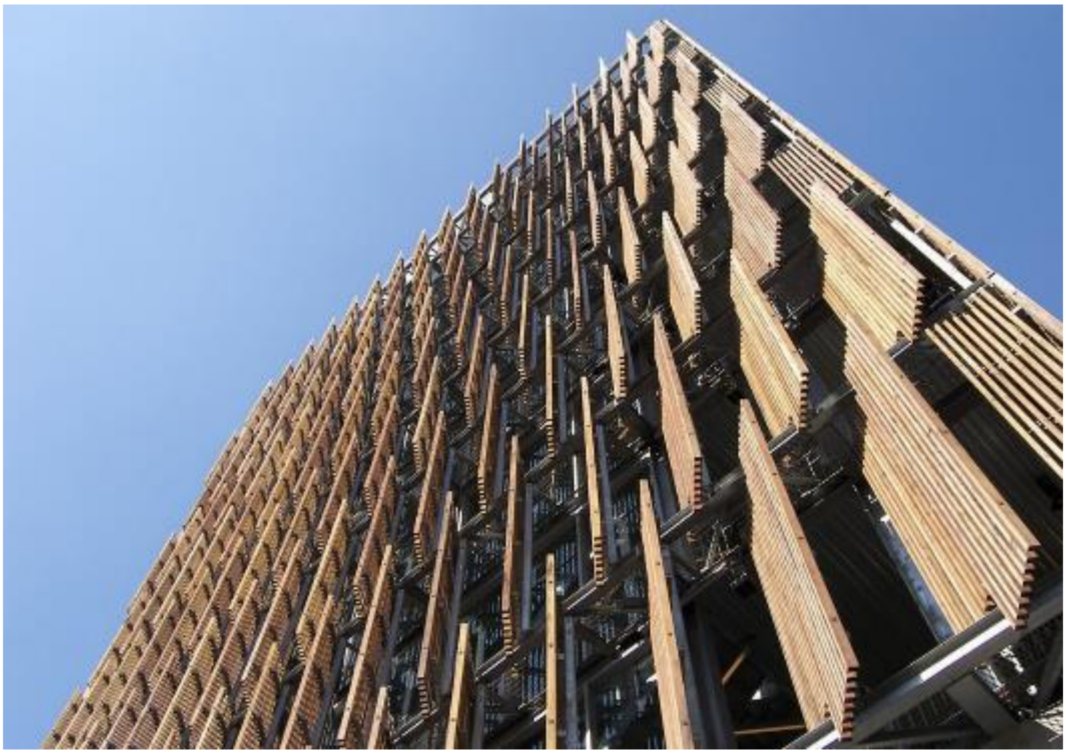

Figure 7.0:20. Council House 2 (CH2) (2006), in Melbourne, Australia[23].

Born from a conflict between the Nasher Sculpture Center (designed by Renzo Piano) and the Museum Tower (designed by Sasaki Associates), Surya concept design (Figure 7.0:21) is an iconic urban scale sculpture, sun-responsive shading screen designed by REX/Front, that aimed to accomplish three objectives: i) protect Nasher's galleries all year round; ii) produce a minimal impact at the real estate value of the Museum Tower, and iii) be a positive addition to the Dallas Art District. After an exhaustive sun analysis impact study on both buildings, a vertical oval silhouette was designed between the two buildings. The silhouette was composed of variably dimensioned umbrellas that 'blossom' in a precise composition when undesired reflections from the Museum Tower are sensor-detected, contracting when reflection is harmless (REX, 2019). In 2012, Surya was dubbed 'a bizarre plan' by the Wall Street Journal, and the project was never built.

[23] *CH2: Australia's greenest building*, 2007, n.d., photograph, viewed 5th August 2019, <https://inhabitat.com/ch2-australias-greenest-building/>

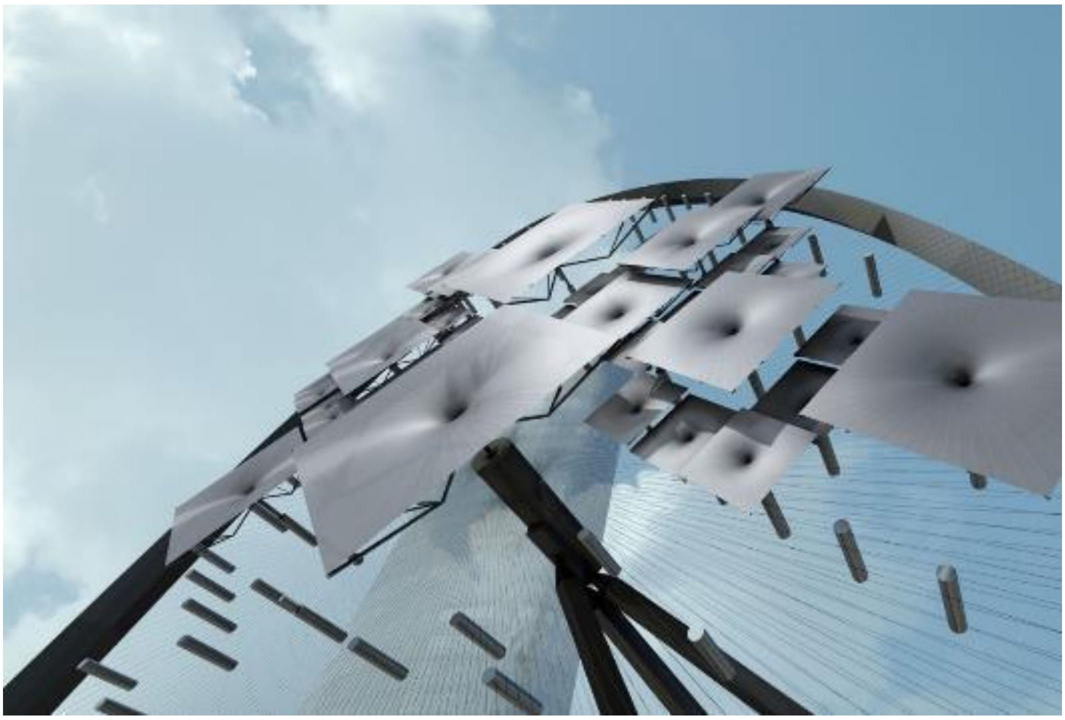

Figure 7.0:21. Surya (2012), by REX / Front, in Dallas, United States[24].

Pneumatic Actuation

Pneumatic actuation converts energy formed by low-pressure (vacuum) or high-pressure (compressed) air into linear or rotatory motion. Built in 2008, the Watercube (Figure 7.0:22) was Beijing's 2008 Olympic Games Aquatic Center winning proposal by the CSCEC + PTW + CCDI and ARUP joint venture. The goals were to create a visually striking, energy-efficient, and ecological building. One of the main features of the building is the maximization of its daylight exposure by capturing solar energy to heat the interior spaces and the pools. Acting as a giant greenhouse, the exterior ETFE cushions envelope allows high thermal efficiency while the concrete pool structures act as thermal mass, retaining heat during warm days and releasing it gradually over the cold nights. By varying the amount of light and solar radiation entering the building, through varying the translucent and transparent foils, the envelope has three levels of operation, allowing the building to adjust to winter, summer, and midseason conditions.

[24] Luxigon, 2013, *Surya: REX*, render, viewed 5th August 2019, <https://www.archdaily.com/447891/surya-rex-front-s-400-foot-solution-for-dallas-disputed-hot-spot>

Figure 7.0:22. Watercube (2008), by PTW Architects, in Beijing, China[25].

Media-TIC in Barcelona (Figure 7.0:23), designed by Enric Ruiz-Geli, is an exceptional example of pneumatic actuation. Completed in 2011, the environmentally responsible and responsive building features a South-East façade made of inflatable ETFE cushions that act as a variable screen. The cushions regulate the sunlight entry along the different seasons, enabling more permeability during the Winter for solar heat gain and become opaquer in the Summer period in order to protect and shade the building's internal environment. The opacity of the ETFE cushions consists of three layers of plastic with two air chambers between them that can be inflated/deflated as needed. This "inflate/deflate effect" is controlled by a differential movement, that by varying the internal air pressure, can be moved further together or apart to create solar shade. The shade effect occurs due to the different patterns of the cushions – layer one is completely transparent, while layers two and three have a reverse pattern that creates shade when inflated (Architizer, Inc, 2018).

[25] *Beijing National Aquatics Center*, n.d., photograph, viewed 5th August 2019, <https://www.caleffi.com/nederland/nl/case-study/beijing-national-aquatics-center>

Figure 7.0:23. Media-TIC (2011), by Enric Ruiz Geli, in Barcelona, Spain[26].

Material Based Actuation

Material based actuation is developed with materials that respond to a stimulus in the form of a change in its properties such as form, dimension, viscosity, among others. The stimulus can be based on electric or magnetic current or field and temperature change. The most common material actuators are the Shape Memory Alloys (SMA), Magnetostrictive Materials, Piezoelectric & Electrostrictive Materials, Electrorheological, and Magnetorheological fluids (Shebina, 2014).

In 2004, Ned Kahn, in collaboration with Koning/Eizenberg, developed the Articulated Cloud (Figure 7.0:24). The Articulated Cloud is an environmentally responsive sculpture façade that is integral to the Pittsburgh Children's Museum. One of the aims of the project was to incorporate environmental awareness into the building and exhibits, and to foster a sense of environmental stewardship among Pittsburgh's children. Composed of thousands of translucent white plastic squares that move in the wind, the sculpture façade is intended to suggest a digitized cloud that envelopes the building. The internal lighting and transparent/translucent skin allow the building to emit a bright but gentle lantern-like

[26] *Media-TIC*, 2017, n.d., photograph, viewed 5th August 2019, <https://www.reddit.com/r/bizarrebuildings/comments/5lev7p/mediatic_by_enric_ruiz_geli_barcelona_spain/>

glow lightening Allegheny Square at night. It is also intended to serve as an actual and metaphorical beacon in the Northside neighborhood. The optical qualities of the skin change dramatically according to the weather and the time of day. An aluminum space frame supports the articulated skin, so it appears to float in front of the building (Bruner Foundation, Inc., 2007).

Figure 7.0:24. Articulated Cloud (2004) - Pittsburgh Children's Museum, by Ned Kahn, in Pittsburgh, United States[27].

Looking into the 'organic' or biological paradigm of kinetic adaptation, other kinds of building adaptive materials are emerging out. In 2013, the architecture office Splitterwerk, in collaboration with ARUP, Colt International, and the Strategic Science Consult (SSC), completed BIQ, a five-story high passive building (Figure 7.0:25), built for the 2013 International Building Exhibition (IBA). BIQ was the first building in the world to have a bioreactor façade as part of a holistic regenerative energy concept:

Microalgae are cultivated inside a double glass panel, arranged on the South-West and South-East façades, in order to force the living organisms to grow and developed inside it, producing biomass and heat through photosynthesis and solar thermal energy. Algae are cultivated for the generation of energy but also to control the light inflow and shading of the building. As a result of the consistent growth of the algae, the façade is continuously in motion and changing its color. In this way, regenerative energy production does not occur in an invisible energy center but is an explicit component of the architectural concept.

[27] Schultz, M., 2018, *Articulated Cloud*, photograph, viewed 5th August 2019, <https://jerusalemhouseministries.net/image/ned-kahn>

Figure 7.0:25. The BIQ residential building (2013), by Splitterwerk Architects, ARUP, Colt International and Strategic Science Consult, in Hamburg, Germany[28].

7.2 Insights

Shading systems are determinant project elements of sustainable building construction. Today's industry provides several types of shading devices, from fixed to adjustable, from AGSs to TIMs. Their fundamental functions are based on solar radiation, visual comfort, and ventilation. Shading systems' primary functions are to mediate and control direct solar radiation entry or blockage, diffuse radiation and glare, assuring natural ventilation and external views according to the inhabitants' needs and requirements, ensuring a complete and successful architectural integration. To achieve those functions, several actions can be taken into account: permeability, reflection, refraction, intersection, material, and scale, are the main actions considered in this research. To perform those actions, several agents can be elected. Considering the above-referred actions, the fundamental agents are: translucency, opacity, morphology, structure, density, pigment, pattern, orientation, roughness, and air flow. Currently, there are four different types of shading system structures: open/close structures (that can be separated in bidimensional or three-dimensional compositions); inflatable – lightweight based air structures; flexible – shape-changing, retractable structures; and tensegrity – tensioned, traction and compressive body structures. These different types are enriched by four main actuation

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[28] *The green façade means the green energy*, 2016, n.d., photograph, viewed 5th August 2019, <http://trendnomad.com/the-green-facade-means-the-green-energy/>

types: motor-based (mostly electrically powered); hydraulics (liquid fluids); pneumatics (air compression); and material-based (respond to a stimulus in the form of mechanical property).

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SECTION VI
A BIOMIMETIC DESIGN METHODOLOGY

8.0
Proof of Concept

8.0 NATURALIZING ARCHITECTURE DESIGN

In 1917, D'Arcy Thompson, in his *On Growth and Form*, established the theoretical problematic of design, conceptualizing that the evolution of form over time is based on an initial structural pattern (Thompson, 1942). The relationship between form and environment, the conception of evolutionary design as an evolutive pattern, and the limitations of technology as generative and evolutionary processes were some of the fundamental issues for the development of nature-based theories and practices into contemporary design. More than morphological studies of shape and structures, Thompson's work launched the basis for a clear understanding of the growth and adaptation of form in specific site conditions in what is known as form-finding processes (Oxman R. , 2013). There are innumerous aesthetic ideas and formal references in art and architecture inspired by Nature. From Sullivan's (1856-1924) *'Golden Door'* organic ornamentation (Figure 8.0:1), Wright's (1867-1959) organic architecture praxis, to Gaudí (1852-1926) catenary curve models made with weighted hanging chain, wire and rope, exploring and studying structural processes (Figure 8.0:2), and Otto (1925-2015) and the Institute of Light-weight Structures (ILS) experiments on structures and gravity using analogical form-finding models (Figure 8.0:3). The precedent mentioned works could be considered as the 'classical' basis for computational models of form-finding.

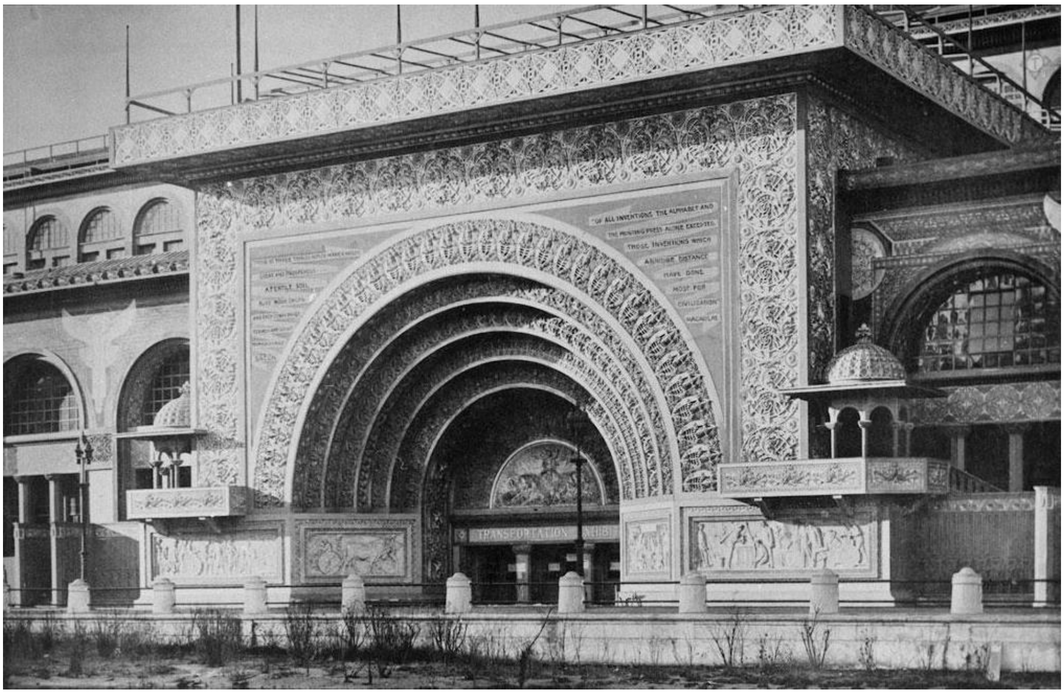


Figure 8.0:1. Sullivan's Golden Door[1].

[1] Nickel, R., (2011), *Golden Door*, photograph, viewed 17 April 2019, <https://explore.chicagocollections.org/image/artic/85/4747h6v/>

Figure 8.0:2. Gaudí's catenary arch[2].

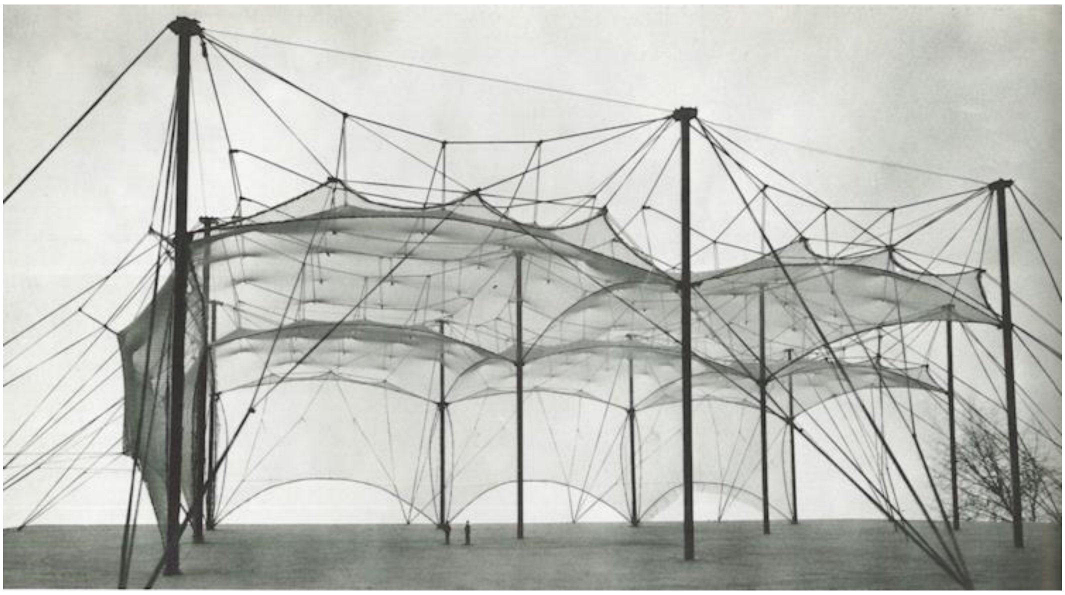


Figure 8.0:3. Otto's light-weight structures[3].

More than reproducing a natural form, a natural morphological pattern that creates organic architectural shapes, new emerging methods and generative design theories look into Nature as a set of processes, described through the employment of scripting and coding techniques, which in turn describe and reproduce relationships between a variety of systems, not only natural but also artificial ones. This link between mathematical models based evolutionary adaptations, informed by the natural environment, is producing a *naturalizing-architecture*. First used by Frèdèric Migayrou and Marie-Ang Brayer in 2013, *Naturalizing-Architecture* is a term that derives from our ability to digitally model and fabricate based on similar phenomena of the natural environment. To Migayrou (2003), the

[2] Dragicevic, P., (2015) Gaudí catenary arch, photograph, viewed 17 April 2019, <http://dataphys.org/list/gaudis-hanging-chain-models/>
[3] *Otto light-weight structures*, n.d., retrieved from The Work of Frei Otto. Museum of Modern Art, (1972), viewed 17 April 2019 < https://magazine.sangbleu.com/2014/04/29/dead-loads/>

creation of representative models of natural complexity of growth is among the main issues of *natural* digital modeling of form and structures (Migayrou, 2003). In the same year of 2013, Oxman goes further, arguing that today's architecture requires an *informed process* that encompasses a model that should link analysis and synthesis, performance and generation, tectonic integration of form, structure, and material. Oxman's *informed processes* integrate four phases: 1- the formation of the process (parametric design) is sustained by mathematics, geometry, and topology; 2- the performative component (performance-based), supported by analysis and synthesis; 3- Generative techniques and; 4- Fabrication tools. Parametric design is a mathematical model of shape forming, which can be defined as a topological differentiation process based on computational models of associative geometry. The impact of a given environmental context on the sustainability and efficiency of a project should be considered even during its formulation phase. Performance-based design is achieved when computational analysis and simulation are integrated with the generative design process (Kolarevic & Malkawi, 2005) (Oxman N. , 2010). Generative evolutionary processes require the understanding of design as an algorithmic process. Fabrication requires material, assembly, and construction strategies, as well as expertise in order to master this design field (Oxman R. , 2013).

Nature provides a remarkable database of possible adaptation strategies that can be implemented in biomimetic design of shading systems. However, at this moment, successful design methods are conditioned to limited knowledge and ability to emulate Nature's strategies to meet corresponding functional needs. The implementation of biomimetic processes has as some significant challenges: 1- the search and selection, among several databases, of appropriate strategies adopted by Nature; 2- difficulties in reading, interpreting, and translating to different scales; 3- connection problems between concepts and material premises. The selection of Nature models is a prevalent situation among architectural projects. Form, structures, motion, processes, morphologies, and systems are available mimicking strategies that could be implemented at different scales, contexts, materials, elements, among others. As already referred to and detailed in the previous *Section II Chapter 3.0 Background: Fundamental of Biomimetics*, from the literature, two main approaches are noticed in biomimetics, problem-based and solution-based (Vattam, Helms, & Goel, 2009). The problem-based approach works by analogy, seeking a solution from Nature for a specific and particular problem. Solution-based works by induction, being inspired by and observation in Nature, which could lead to technological design.

The presented research investigation aims to present a Bioshading System Design Methodology, developed on a problem-based approach. Starting with the architectural challenge of design, solutions will be sought in Nature to solve specific Bioshading systems performative requirements. The hypothesis that sustains the methodology development lies over an *informed process* that integrates and interrelates three domain areas: 1- Architecture; 2- Nature; and 3- Artifact. In this context, *the Architecture* domain roots its basis on the formation of the process, computational environmental analysis, and diagnosis. This formation process is conducted through environmental analysis software, integrated through parametric design tools. *The Nature* domain is defined through an abstraction process. Sustained by the plants mapping process table (*presented on Section IV, Chapter 6.0 Plants*), the creation of a *meme's* semantics[4] should trigger a performance-based design process. Performance-based design is achieved when computational analysis and digital simulation are integrated with the exploration of shape and structure through generative design processes. The Artifact domain is the physical materialization of the design concept that enables its evaluation and emulation. Performance-based design processes and digital fabrication tools are integrated components, supporting the creation of the artifact. It was intended that both academics and professionals of architecture would be used by the presented methodology. In this perspective, the methodology will be supported by a digital toolkit. The idea is that the toolkit will allow greater proximity between the students and the process, working as a pedagogical vehicle of information, promoting debate between working groups, and facilitating the development and organization of the different tasks to be carried out during the process. Therefore, in order to elaborate and validate the final methodology and its toolkit components, a real-time proof of concept was conducted.

8.1 Proof of Concept (PoC) 1.0

PoC 1.0 was conducted through two separate four-hour sessions. Ten voluntary participants, students and professionals of the architectural field, organized in pairs, carried out this experience. None of the participants had knowledge or base experience in the field of biomimetics (Table 8.0:1.). For this purpose, a computer laboratory was used.

The main goal for this experience was for participants to be able to develop a shading system to a pre-determined building and defined context, using the Bioshading System Design Methodology, version 1.0. PoC 1.0's sessions aimed at testing and evaluating the methodology considering three criteria: 1- *Methodology Clarity* (evaluated by the participants at the end of the experience); 2- *PoC 1.0 sessions* [participants were invited to evaluate i) the clarity of the oral presentation methodology and the supplied digital material regarding the methodology, ii) time of session and iii) the available means]; and finally 3- *Method Operability and its Outputs* (evaluation performed by the team involved in the development of the methodology, about each developed project, about their method's

[4] In this context, a memes semantics represents a set of imaginary images related or derived from each other, which include an idea or interpretation of an event or its consequence occurring in Nature.

clarity and applicability, goal definition, biomimetic *meme* path matrix generation, design solutions, and its technical implementation).

Table 8.0:1. PoC 1.0 – Participants data.

Personal data			Type/time of experience in architecture?				On a scale of 1 to 5, what is your experience in biomimetic projects?					On a scale of 1 to 5, what is your experience in projects that equate solar control?					If you have answered the previous question from 2 to 5, please state succinctly how solar control studies are included in the projects.	On a scale of 1 to 5, what is your experience in projects that equate climate analysis?					If you have answered between 2 and 5, the previous question, indicate which analysis software you use.	On a scale of 1 to 5, what is your experience in digital fabrication?					If you have answered between 2 and 5 to the previous question, please indicate what type of machinery you use/used.	What is your level of experience with parametric modeling software?					If you have answered between 2 and 5, the previous question, please indicate which software you use.
Name	Age	Gender	St	P<5	P<10	P>10	1	2	3	4	5	1	2	3	4	5	Description	1	2	3	4	5	Description	1	2	3	4	5	Description	1	2	3	4	5	Description
Ana C.	34	F		X			X					X					none	X					none		X				3D Printer	X					none
Carlos S.	38	M			X			X					X				none	X					none			X			CNC; Laser, 3D Printer			X			Grasshopper
Diana G.	31	F		X				X				X					none	X					none			X			CNC; Laser	X					none
Filipa O.	38	F				X	X								X		From the knowledge acquired during the degree and from professional practice, I take project options experimentally and through 3D models.	X					none				X		CNC; Laser				X		Rhino | Grasshopper
João P.	21	M	X				X					X					none	X					none		X				Laser, 3D Printer	X					none
João S.	29	M			X		X					X					none		X				Ecotect, Archicad					X	CNC; Laser; 3D Printer, Robotic Arm			X			Archicad, Rhino, Grasshopper
Luisa A.	23	F	X				X					X					none	X					none				X		CNC; Laser; 3D Printer		X				Rhino + Grasshopper
Pedro F.	34	M		X			X					X					none	X					none	X					none	X					none
Raquel M.	26	F		X			X					X					none	X					none		X				CNC; Others			X			Grasshopper
Susana N.	30	F		X			X							X			When taking into account the solar orientation of each project and the impact that this has on the experience of the space.	X					none					X	CNC; Laser; 3D Printer; Others			X			Grasshopper

Bioshading System Design Methodology relies on a circular order of nine phases, equally distributed by three domains: *Architecture*, *Nature,* and *Artifact* (Figure 8.0:4). Initiating its journey with the *Architectural* domain, the created and applied methodology has a problem-based concept design approach. The first session guided the participants through the *Architecture* and *Nature* domain phases, in order to, respectively, define the shading system goals and to create its concept design *Biomeme.* The *Goals definition* consisted of determining the main *functions* of the future designed shading system, as well as the *actions* that will support them and the *agents* that will enable it. The *Biomeme* is composed of the creation of a *fictional meme*[5], which is a product of the studied vascular plant events (see chapter IV) combined with the aimed *functions* of the shading system. The second session was essentially focused on the *Generation* and *Simulation* phases of the *Artifact* domain, and it was strongly devoted to the digital design project, considering types of structure, actuation, fabrication, and materials.

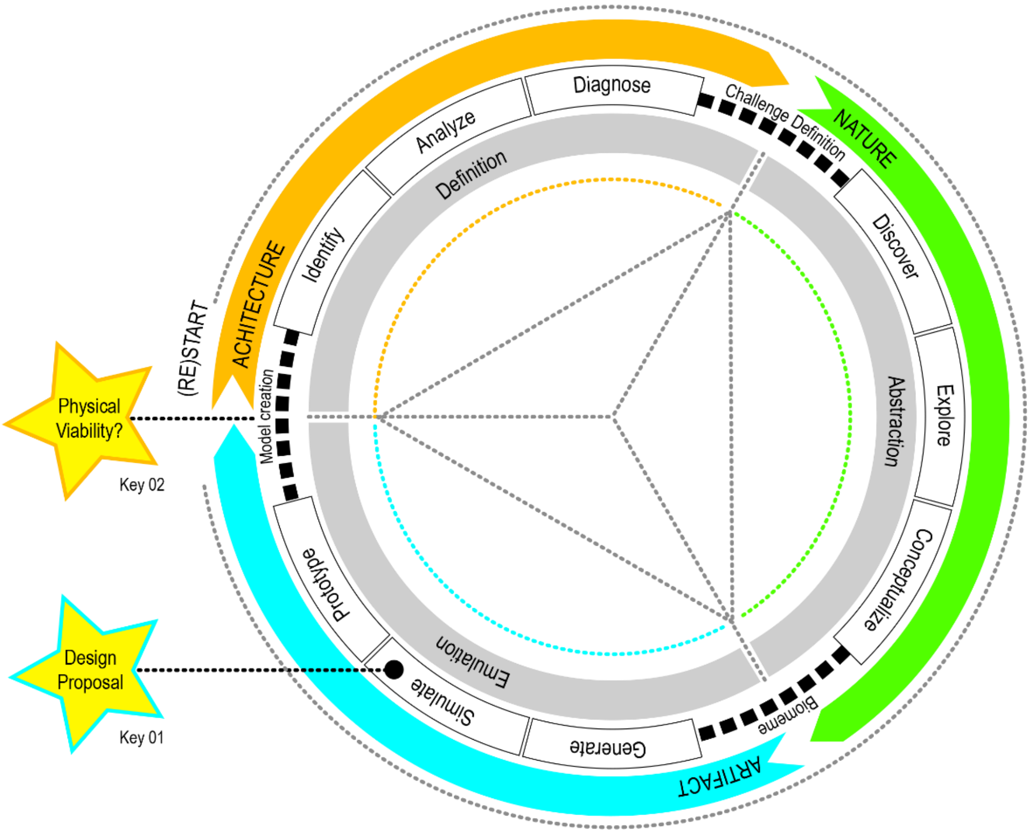


Figure 8.0:4. Bio-Shading Concept Design Methodology.

The experience was conducted through a defined time script (Table 8.0:2) having a digital kit (see Annexes 11.0) as support. The digital kit was composed of several folders containing: i) the digital 3D model of the case study building and its context surroundings, ii) the Climate Consultant 6.0 graphic analysis of Lisbon's climate, iii) Ladybug graphical analysis of the studied building's south façade, iv) tables and diagrams containing shading façade essential functions, actions, and agents, v) a list containing several terrestrial plant types and adaptation strategies, vi) a *Biomimetic meme path matrix* diagram in order to help the participants define its fictional *Biomeme,* and vii) two tables listing the main shading systems types of structure and actuation.

[5] It is called *fictional meme*, because it is a conceptual representation that derives from the interpretation of various ideas from different semantics.

Table 8.0:2. PoC 1.0 - time script.

PoC 1.0 1st SESSION SCRIPT

Session 01* - June 24th		period 18:30 - 22:30
Framework: Architecture + Nature+ Digital Tools Relationship	Material to present / make available	Dedicated time
1- Given the current context, what is the relevance of this relationship? 2- Frame the relationship between Architecture/-Terrestrial Plants, justifying the relevance of this relationship; 3 - Current design, analysis and CAM tools.	- Oral presentation, supported by images and diagrams of the covered subjects	30' min
Architecture domain		
Phase 01: Identify Present the main goal of the experience - develop a shading system design proposal, to a given building south facade biomimetic based;	- Climate Consultant 6.0 Analysis Charts; 3D Modeling (Rhinoceros 6.0 and Autocad 2018)	20' min
Phase 02: Analyze Analysis of the built environment, understand the impositions and requirements of the bulding façade;	- Present Ladybug climate analysis diagrams and analyze it with participants;	10' min
Phase 03: Diagnose Shading system functions presentation, its possible associated actions, and their relationship to possible agents;	- Functions + Actions + Agents	20' min
CHALLENGE DEFINITION Participants should dissect the model and select the functions and intentions of their project;	- Participants should draw up their own intentions matrix.	30' min
Nature domain		
Phases 04+05: Discover and Explore Introduction to terrestrial vascular plants - adaptation systems, strategies, principles and distinctive features	- Presentation of the vascular system of plants, expressing possible analogies between the natural and the constructed system; Plant adaptations data survey; The *meme* characterization; Online resources for exploring possible events, organs and systems that make up vascular plants;	30' min
Phases 06: Conceptualize The creation of the Biomimetic *meme*	- Fulfilment of the biological *meme* path matrix thus creating the *meme* that will support the design;	20' min
BIOMEME Approach to Open Studio Design	- Dedicated period to creation of the *Biomeme*, throught the *Biomimetic Meme path matrix*;	1h00' min

PoC 1.0 2nd SESSION SCRIPT

Session 02* - June 26th		period 18:30 - 22:30
Artifact domain		
Phases 07: Generate New data are presented - several types of structures and actuation are expected to influence system design will be presented; The digital design process is conducted;	- Some of the most common types of structure mechanisms and actuators in shading systems are presented; Two documents synthetizing this information and listing their pros and cons its supplied; Design studio dedicated time;	2h00' min
Phases 08+09: Simulate & Prototype It would be interesting to be able to rehearse some of the ladybug solutions with the participants so they can see the results and / or build small manual prototypes of the solutions…	- Run analysis settings and support shading system prototype planning;	1h00' min (depending on time and available resources)
DEBATE AND OPINION OPEN SESSION Participants will be invited to give their opinion on the experience and above all to give feedback on gaps, errors or possible improvements to the process - conclusion.	- MMcBeth multicriteria evaluation: 1- Method Clarity; 2- P.O.C. sessions.	40' min

*Both sessions had a 20' min coffee-break.

The first PoC 1.0 session opened with a 30 minutes introduction of biomimetics and architecture. It was a chronological presentation aimed at contextualizing the application of biomimetic values and principles not only in architecture but also in other relevant fields as mechanics, design, and materials' science. The relationship between architecture and terrestrial vascular plants was pointed out as a case study and as an inspirational motto, and its link was justified based on plants' and buildings' similar physical condition. Finally, a brief presentation of the most used design and analysis tools, as well as the current CAM resources[6] that today enable architects to perform diagnostic analysis and evaluation on architecture, were also presented and discussed, identifying its strengths and weaknesses, during the architectural design process (see Annexes 11.1.1).

Entering the *Architectural* domain, at the *Identification* phase, PoC participants were presented to the case study building and its context. The selected case study building integrates a proposal for a university residency program, which also houses coworking and services spaces. Located in Lisbon, inside the Cidade Universitária Campus, the analysis target was the south façade of the case study building[7]. To the participants was given a three-dimensional model of the Cidade Universitária Campus. A complete climate analysis of the city of Lisbon - conducted through Climate Consultant 6.0 (CC) software - was presented and explained to the participants[8]. The participants' supplied CC material contained annual temperature, radiation, illumination, and wind velocity range graphics, sun shading, and psychrometric charts, among other information. In the second phase, *Analysis,* participants were introduced to the Ladybug analysis charts and diagrams. Based on parametric information, Ladybug can perform real-time analysis, providing the possibility to extract two or three-dimensional diagrams, schemes, and charts into/over the three-dimensional model. Dry bulb temperature, irradiation, total direct and diffuse radiation, urban shade benefit, shading comfort façade design, wind speed, and air temperature roses were the diagrams and charts that were provided to the participants. A process of interpretation and analysis was conducted. After a context/climatic study and analysis, participants were invited to *Diagnose,* which were, in their perspective, the shading system's main *functions* for that case study façade. Three base tables (Figure 8.0:5) were supplied, i) containing the shading system's main *functions*, ii) pointing some of the most relevant shading systems *actions*, and iii) enumerating some of the agents that could trigger these *actions* (see Section V, Chapters 7.1.2 and 7.1.3). During the *Diagnose* phase, participants started working in pairs, which triggered some effective discussions over their

[6] CAM (Computer Aided Manufacture) resources, in this context refers to the current CAM available machinery – CNC (Computer Numerical Control); laser cutters, 3D Printers, vinyl cutters, robotic arms, among others.
[7] All the information provided about the case study building, not yet built, is based on a rendered image published in "Universidade de Lisboa constrói 1700 novas camas", in Expresso Journal, November 3rd, 2018.
[8] The CC analysis used the ASHRAE standard 55 and the Current Handbook of Fundamentals Model. This comfort model defines that thermal comfort is based on dry bulb temperature, clothing level, metabolic activity, air velocity, humidity, and mean radiant temperature.

intentional aspects regarding the shading system pairs proposals. From this brainstorm, the five groups were able to define their shading system's main goals, as well as their functions>actions>agents' semantic relationship, achieving at the end of this phase the so-called *Challenge definition*.

	Functions
1	Dir. Rad. entry
2	Dir. Rad. blockage
3	Diffuse Radiation
4	Glare control
5	External views
6	Natural ventilation
7	Architectural integration
8	Others

	Actions
A	Permeability
B	Reflection
C	Refraction
D	Intersection
E	Material
F	Scale
G	...
H	...
I	...
J	...

	Agents
a	Translucency
b	Opacity
c	Morphology
d	Structure
e	Density
f	Pigment
g	Pattern
h	Orientation
i	Roughness
j	Air flow
k	...
l	...
m	...

Figure 8.0:5. Functions>Actions>Agents tables.

The second part of the first PoC 1.0 session was all about the *Nature* domain. An oral presentation, supported by images and diagrams, aimed to expose and explain terrestrial plants' vascular system, its relevance and main functional organs and features (see Annexes 11.1.1 Phase 2). During the presentation, several analogies between plants events and features, and the man-built environment functions performed a major contribution to initiate an individual and creative link between the natural and the humanmade systems. To engage the working groups at the *Discover* and *Exploration* phases, an introduction to plant adaptation strategies (morphological, physiological, and behavioral) was made, in order to present and explain how to analyze the supplied plant adaptation data survey in its digital format (based on Section IV, Chapter 6.3.3, Tables 6.0:1, 6.0:2 and 6.0:3), as well as how and where to search for the presented data or search for other adaptation events (fundamental online resources such AskNature[9], Biomimicry 3.8[10], Basic Biology[11], among others). Given the resources, it was necessary to clarify the creation process of the *Biomeme*. From the several available surveys, each group was invited, at the *Exploration* phase (considering the previous *Challenge Definition* results), to

[9] AskNature - https://asknature.org/
[10] Biomimicry 3.8 - https://biomimicry.net/
[11] Basic Biology - https://basicbiology.net/biology-101/introduction-to-biology

elaborate a *Meme* event table (Table 8.0:3), where they selected the plant adaptation events that could resemble their shading system's defined functions.

Table 8.0:3. Meme Events Table example.

***Meme* Event**	**Adaptation**	**Strategy**	**Main principles**	**Main features**
Bioluminescence	Behavioral	Dynamic	Occurs through a chemical reaction that produces light energy within an organism's body.	Photosensitive
Epidermis	Physiological	Static	Epidermis is a layer of cells that covers the leaves, flowers, roots, and stems of plants, forming a boundary between the plant and the external environment.	Multi-layer
Nyctinastic movements	Behavioral	Dynamic	The leaves of plants respond to the daily alternation between light and darkness by moving up and down.	Movement, open-close,
Vernation	Behavioral	Static	How the leaves are arranged on the buds, folding or curling.	pattern

In order to dissect the selected *meme* events, participants stratified the events according to its type of adaptation, strategy, main principles, and features. This stratification is essential for the methodology user. This process allows not only to extract the several characteristics and properties of each of the selected *memes*, as well as transport them through interpretation to the architectural lexicon. Adaptation and strategy will enable the *meme* categorization in the fields of its actuation. Principles are the BSDM user's first approach to an individual interpretation of the *meme* event, while features are the pattern, material, and performative characteristic observed by the BSDM user in that specific *meme*. After completing this task, the groups were ready to *Conceptualize* their *Biomeme*. The *Biomeme* conceptualization was produced with the completion of the *Biomimetic Meme path matrix* (Table 8.0:4). In PoC 1.0, the *Biomimetic Meme path matrix* crossed the shading system's main functions with the selected *meme* events. Extracted from the previous *meme* events table, and in addition to the shading system selected functions, the *Biomimetic Meme path matrix* also crossed other inputs *meme* events information, such as adaptation and strategies types, pattern, material, and performative features. Through this process, each group achieved its *Biomeme* through a majority accounting process.

Table 8.0:4. Biomimetic Meme path matrix example provided to the PoC 1.0 participants.

selected functions	A meme	B meme	C meme	... meme	**Biomeme**
1	X				X
2		X			X
3			X		X
4				X	X
Meme Strategies					
Dynamic	X	X		X	X
Static			X		
Meme Adaptation					
Morphological	X		X		X
Physiological				X	
Behavioral		X			
Meme Pattern features					
xxx	X				
xxx			X	X	X
Meme Material features					
xxx	X	X			X
xxx			X	X	X
Meme Performative Features					
xxx	X		x	x	x
xxx		x			

After a one-day reflection gap between sessions, PoC 1.0's second session was entirely devoted to the *Artifact* domain. The session was initiated by an oral presentation supported by several reference images regarding shading system types of structures, mechanisms, and actuations (see Annexes 11.1.2 Phase 3). An oral debate was encouraged in order to promote brainstorming between the groups. Two digital documents were supplied to the groups, containing synthesized information about shading systems structural types and possible types of actuation. The shading system types of structure document contained a short description, pros and cons of the mentioned type of structure, and possible actuation clues for its implementation. The actuation types document also contained a brief description of the actuation, its pros and cons, and some required resources and knowledge for its implementation. The following period was completely devoted to the groups' shading systems design. As it is represented in the PoC 1.0 time script, one hour of the second session was programmed to be dedicated to the *Simulation* phase; however, participants required it for the *Generate* phase design process. The last 40 minutes of this session intended to hear the PoC 1.0 participants' opinions about the experience, but also it was intended for them to evaluate the *Methodology Clarity* and the *PoC 1.0 experience*. From the PoC 1.0, five different projects, with different levels of development, emerged. Letters, A, B, C, D, and E, will be used to mention them. A brief description of the groups' produced work follows.

Group A (Luísa Almeida and Ana Castanho)

Group A's shading system's selected functions were related to the system's ability to block/let pass the direct solar radiation, enabling a convenient and constant external view connection, ensuring the building's natural ventilation. In order to achieve these performative functions, the selected actions were: permeability, intersection, material, and scale. Their idea was to design a system that could be either permeable or opaque to light in different moments of the day. Materials would perform a significant role during this action, while scale was the key action that would enable natural ventilation. Their system was rooted in three fundamental agents: density, scale, and pigment. Density was based on the repetition of the same element at different scales; pigment was related to the visual permeability of elements but also with the chromatic composition of the façade; and pattern composition was linked to the form and motion of the elements of the shading system. During the *Nature* domain, the group's selected *memes* were: bioluminescence, epidermis, nyctinastic movements, and vernations. Their fictional *Biomeme* (Table 8.0:5*)* was a system with permeable/opaque ability, scale variations, with dynamic strategies and behavioral adaptation abilities, that should be materialized through a multilayer and perforated system, using porous material properties and open/close mechanisms.

Table 8.0:5. Group A's Biomeme.

Group A - Biomimetic *Meme*	
Functions/actions	Permeability
	Scale
Strategies	Dynamic/Static
Adaptation	Behavioral
Pattern Features	Multilayer
	Perforated
Material Features	Porous
Performative Features	Open/Close

During the *Generate* phase, the designed system was a triple-layered façade, composed of bi-directional radial foldable elements, organized by three different scales (Figure 8.0:6). Different scale elements were arranged in the three layers façade, producing several overlapping areas in the final composition. The foldable elements were composed of triangular frames, coated by two different materials. When rotated clockwise, the elements exhibit a perforated textile; when rotated counter-clockwise, the elements exhibit an opaque textile. The system was conceived to respond to the sunlight position automatically.

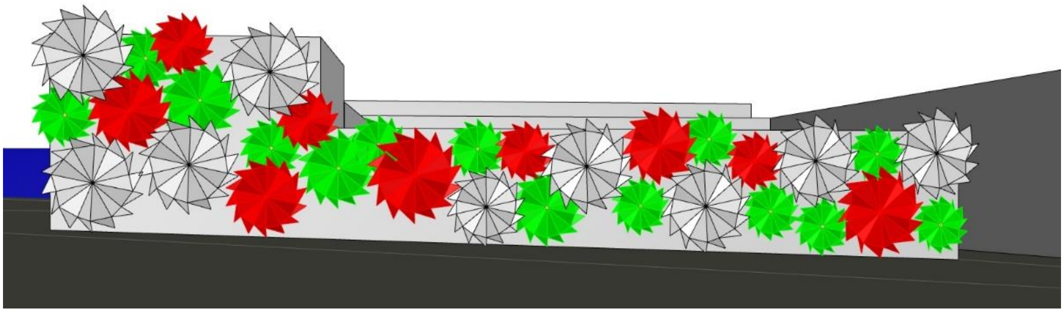


Figure 8.0:6. Group A - PoC project: Shading system design proposal.

Group B (Susana Neves and João Parcelas)

After a careful analysis of the CC and Ladybug supplied material, Group B considered that the most relevant shading system functions for the case study façade should privilege the external views, natural ventilation, and convenient architectural integration. It is important to refer that these functions are always rooted in the solar radiation control context. Their selected actions were permeability and material. Permeability enables the connection between interior and exterior, natural ventilation, and material opens a wide range of possibilities for the shading system's performance and to its proper architectural integration. In order to perform the selected actions, morphology and opacity were the elected agents. Morphology enables the creation of material/structural/motion integration and opacity, and adds a new layer to the material action. Having created a very flexible combination of elements during the *Architecture* domain, the group needed to be more accurate during the *Nature* domain phases. The selected *memes* were: trichomes, nyctinastic movements, and diaheliotropism. The defined *Biomeme* (Table 8.0:6), privileged external views connection, natural ventilation, and architectural integration, using dynamic strategy and behavioral adaptation, through an adaptive pattern, composed of flexible material with tracking features.

Table 8.0:6. Group B's Biomeme.

Group B - Biomimetic *Meme*	
Functions/actions	External views
	Natural ventilation
	Arch. Integration
Strategies	Dynamic
Adaptation	Behavioral
Pattern Features	Adaptative
Material Features	Flexible
Performative Features	Tracking

The proposed solution was a stretched/bent vertical system composed of perforated and translucent flexible materials (Figure 8.07). The façade was cladded with vertical strips (all of which with the same width), and the system worked in one stretch/bend consequent loop. A sun-tracking system controlled this loop. When direct sunlight needed to be blocked, the translucent material was stretched and the perforated was bent; when sunlight represented no harm, perforated material was exposed and the translucent material was bent.

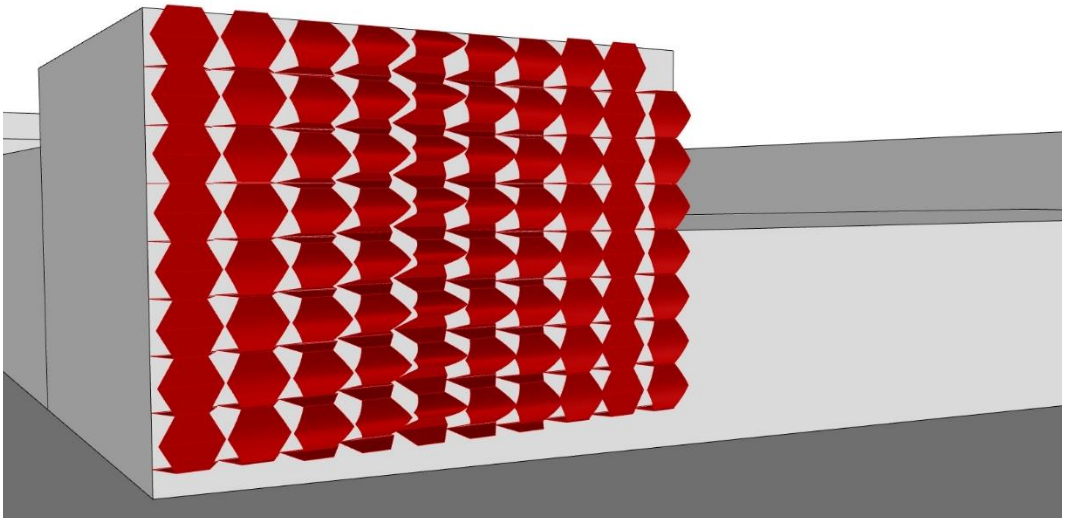


Figure 8.07. Group B - PoC project: Shading system design proposal.

Group C (Raquel Martins and Carlos Sequeira)

Direct radiation entry, diffuse radiation, glare control, and natural ventilation were the main *functions* considered by Group C. In order to perform these *functions*, the selected *actions* were permeability, material, and scale. The selected *agents* were density, pattern, opacity, and structure. Permeability was worked by density and pattern, material by the opacity, and scale through the structure. This was a group that dedicated some quality time to the *Discover* and *Exploration* phases, during the *Nature* domain period. The selected *memes* were: canopy plants, endothermic, xylem, superhydrophillic, phloem, and bioluminescence. The created *Biomeme* (Table 8.0:7) aimed to manage the direct and diffuse radiation entry, glare control, and to ensure natural ventilation through the façade. The intended strategy was dynamic, with physiological adaptations. Features should resemble a multilayer bubbles pattern, using flexible and/or sponge materials, enabling unidirectional movements and storage behavior.

Table 8.0:7. Group C's Biomeme.

Group C - Biomimetic *Meme*	
Functions/actions	Dir. Rad. Entry
	Diffuse Radiation
	Glare Control
	Natural ventilation
Strategies	Dynamic
Adaptation	Physiological
Pattern Features	Multilayer
	Bubbles
Material Features	Flexible
	Sponge
Performative Features	Unidirectional Mov.
	Storage

The fundamental idea was to create a living curtain façade that, using solar radiation, could heat collected rainwater for domestic use. Thus, the project was composed of double-layered vertical pipes, punctuated by double-skin rubber spheres equipped with individual heat sensors (Figure 8.0:8). Every time a bubble intersects direct solar radiation, stored water enters through the pipes and inflates the rubber bubble, that using solar radiation heats the water. Sensing the direct solar radiation or the intense diffuse radiation, bubbles enable the entry of water inside them, inflating; as a consequence, this creates a physical and visual barrier between the indoor and the outdoor (Figure 8.0:9). Furthermore, as the pattern is spherical, there is no total 'blackout', and ventilation is assured. During the night, with no sense of solar radiation, the deflated bubbles glow, creating an iconic lighting effect (the glow process was intended to be produced by the material properties - but the theme was not developed).

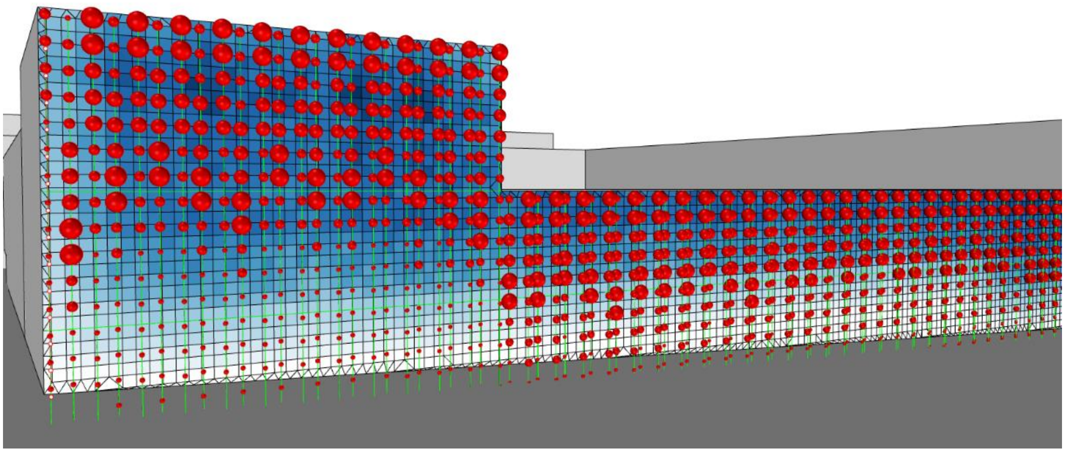


Figure 8.0:8. Group C - PoC project: Shading system design proposal.

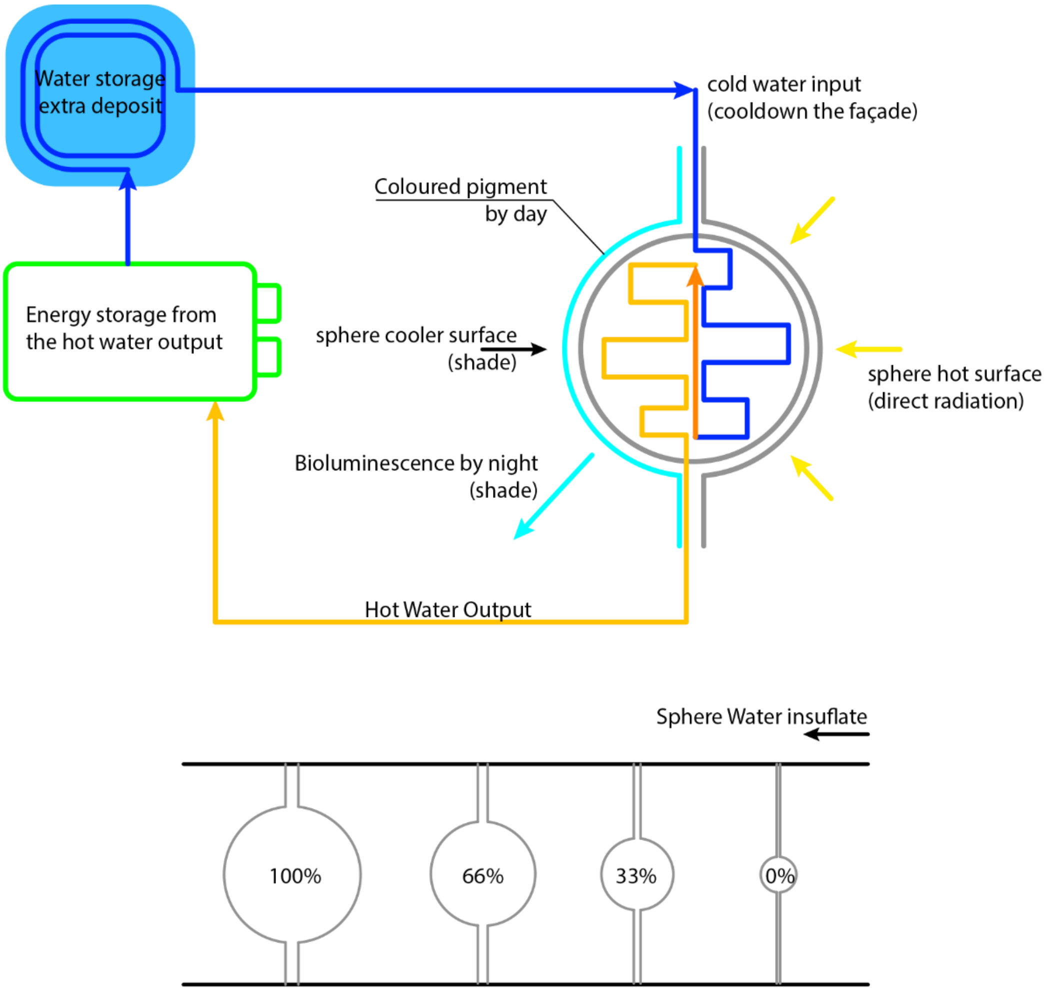


Figure 8.0:9. Group C - Shading system functional diagram.

Group D (Diana Gabão and João Sousa)

Group D diagnosed the case study façade with the necessity of direct radiation blockage, external views connection, natural ventilation, and a convenient and adequate architectural integration. In order to achieve these *functions*, their selected *actions* were: permeability, reflection, refraction, and material. Since a very early stage, material was an important factor due to its potential to transform and achieve almost infinite viable combinations. To perform the pointed *actions*, the elected *agents* were translucency, morphology, pattern, and density. At the *Nature* domain, the group focused on morphology, pattern, and density actions, and selected diaheliotropism, endothermic, asymmetry, stoma, and epidermis as their *memes*. Their *Biomeme* (Table 8.0:8) aimed at responding to direct radiation, maintaining external view connection, not forgetting the architectural integration. In order to design the shading system, a static strategy was conceived using morphological and physiological adaptations. The shading system would operate through a multilayer pattern, composed of hard material, with concentric movements and/or cellular performative features.

Table 8.0:8. Group D's Biomimetic Meme.

Group D - Biomimetic *Meme*	
Functions/actions	Dir. Rad. Block.
	External views
	Arch. Integration
Strategies	Static
Adaptation	Morphological/Physiological
Pattern Features	Multilayer
Material Features	Hard
Performative Features	Concentric Movement
	Cellular performance

The presented shading system design was based on a main hexagonal grid, sub-divided in triangular parts (Figure 8.0:10). This subdivision represented the cellular division of an element. This cellular subdivision was ideally conceived through the same material, but each triangular cell had different levels of translucency (three different levels would be needed), producing a visual multilayer effect. In interspersed areas of the façade, combinations of triangular cells would rotate, thus opening a visual and physical channel between indoor and outdoor spaces. These openings were designed to produce movement in two different directions, one diagonally, intended to block western solar radiation when opened, and another horizontally, blocking the high southern solar rays. The translucent triangular elements would follow the shading comfort diagram of the façade from the Ladybug analysis. Darker translucent triangular elements would be presented in more critical shading areas, medium-dark in regular shading areas, and lighter elements in parts with low demand for shading areas.

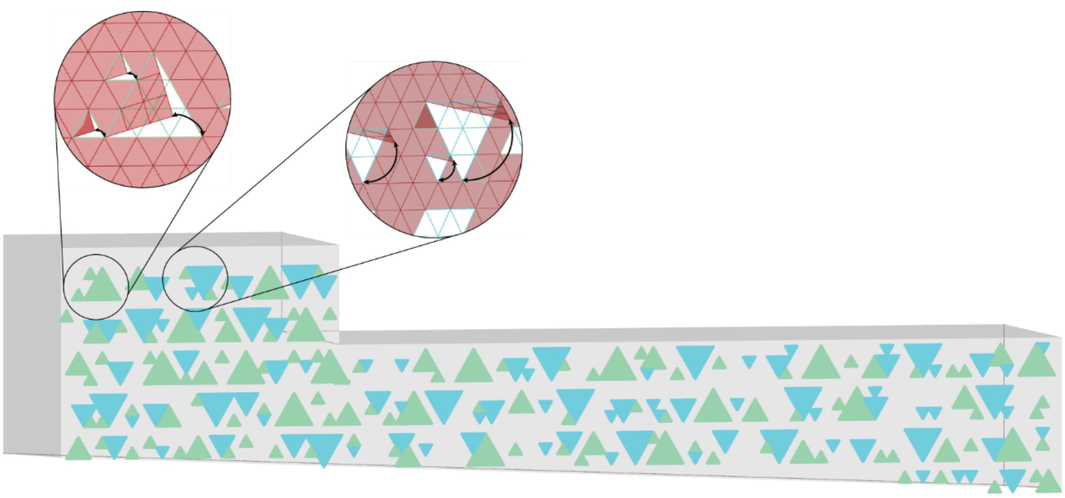


Figure 8.0:10. Group D - PoC project: Shading system design proposal.

Group E (Filipa Osório and Pedro Frutuoso)

Group E began their project studying the sunrays of the southern façade during summer and winter solstices. Their selected *functions* were the ability to control entry and blockage of solar radiation as well as indoor glare control. To achieve these *functions*, the selected *actions* were permeability, reflection, intersection, and material. The group's action>agent strategy was based on material translucency, a structure capable of producing intersection and reflection, and a pattern with an adequate density enabling. Their selected *memes* were the deciduous plants, whorl, bark trees, diaheliotropism, and the nyctinastic movements. The conceived *Biomeme* (Table 8.0:9) aimed to control not only entry and block solar radiation as well as the glare effect, using dynamic strategies, through the implantation of behavioral adaptations. The shading system would have a random pattern, made of flexible materials, in order to enable a bidirectional movement.

Table 8.0:9. Group E's Biomimetic Meme.

Group E - Biomimetic *Meme*	
Functions/actions	Dir. Rad. Entry
	Dir. Rad. Block.
	Glare Control
Strategies	Dynamic
Adaptation	Behavioral
Pattern Features	Random
Material Features	Flexible
Performative Features	Bidirectional. Mov.

The designed system was composed of a diamond-like mesh, which had its main axes aligned with the angles of the solstices' solar radiation rays (Figure 8.0:11). Each shading system unit corresponds to a single diamond capable of performing two perpendicular movements (Figure 8.0:12). The idea was that each diamond performed its movement independently from its neighbors, responding according to its individual sensor reading.

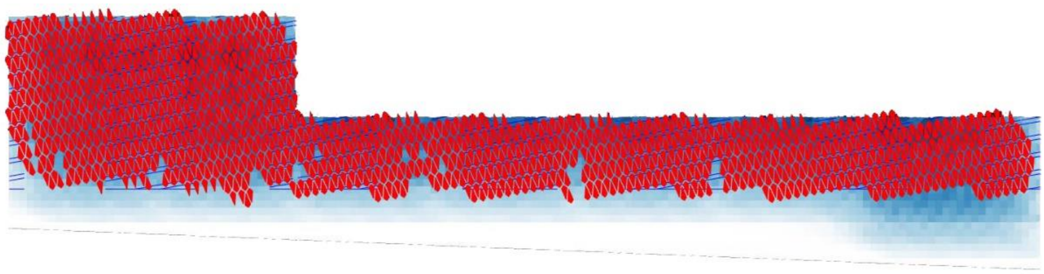


Figure 8.0:11. Group E - PoC project: Shading system design proposal.

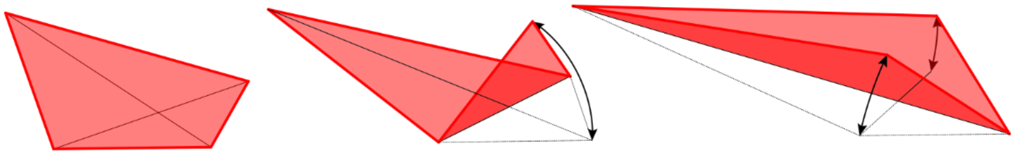


Figure 8.0:12. Group E - PoC project: diamond perpendicular movements.

8.2 PoC 1.0 evaluation

The previously reported experience aimed to evaluate: 1- the methodological clarity; 2- the PoC 1.0 sessions (both items – 1 and 2 – evaluated by the PoC 1.0 participants), and 3- the methodological operability and applicability (evaluated by the researchers). In order to conduct these evaluations, three assessment models were created using the Macbeth software. Macbeth (Measuring Attractiveness by the Categorical Based Evaluation Technique) is an interactive approach that only requires qualitative judgments about differences in attractiveness to help a decision-maker or a decision support group to quantify the relative attractiveness of the options. As the judgments are introduced, their consistency is automatically checked. As output, a numeric scale is generated, entirely consistent with all judgments of the decision-maker. The weights attributed to the criteria were generated through a similar process. Macbeth was chosen because of its ability to incorporate various types of information (qualitative and quantitative) built through pairwise comparison judgments. In this way, the evaluation model can be shaped, in order to match the several types of analysis, through a co-participative decision-making process (Stellacci, Rato, Poletti, Vasconcelos, & Borsoi, 2018).

8.2.1 Methodology's Clarity (participants' evaluation)

For the methodology's clarity, five evaluation criteria were defined, being evaluated on a scale from 1 to 5:

1- Identify/analyze: Participants were questioned, if the theoretical material of introduction to the methodology, and the provided digital resources (analysis diagrams and three-dimensional modeling) were adequate for the general contextualization of the challenge and for the comprehension of the tasks;

2- Diagnose: The participants were asked how easy or difficult they found the process of shading system functions, actions and agents diagnostics, to be;

3- Discover/Explore: these criteria aimed to evaluate how easy/difficult was the *Discover* and *Explore* phases through the plants available and presented surveys;

4- Conceptualize: how easy/difficult was the process of creation of the *Biomeme*;

5- Generate: How much the previous phases influenced/helped in the design process of the shading system.

The ranking given to each criterion (from 1 to 5) is translated to a percentage scale ranging from -62.5% to 100%, considering that 0% equals to 3 (3 was considered the acceptable minimum of success, below it was considered trash results). A weight of 20% was attributed to each criterion in order to achieve a final average. At the end of the PoC 1.0, each participant was asked to evaluate the experience, assigning a value from 1 to 5 (where 1 was very weak, and 5 was very good) to each of the criteria. The results are reflected in the ranking table (Table 8.0:10).

Table 8.0:10. Methodology's Clarity[12].

Methodology Clarity - Ranking Table				
Id/An (20%)	**Diag** (20%)	**Dis/Ex** (20%)	**Conc** (20%)	**Gen** (20%)
Id/An 5	**Diag 5**	**Dis/Ex 5**	**Conc 5**	**Gen 5**
AnaC	AnaC	CarlosS	AnaC	FilipaO
DianaG	FilipaO	FilipaO	CarlosS	JoãoP
JoãoP	LuísaA	LuísaA	DianaG	JoãoS
JoãoS	**Diag 3**	PedroF	FilipaO	LuísaA
LuísaA	CarlosS	RaquelM	JoãoS	SusanaN
PedroF	DianaG	AnaC	LuísaA	**Gen 3**
RaquelM	JoãoP	DianaG	PedroF	AnaC
CarlosS	JoãoS	JoãoP	SusanaN	CarlosS
FilipaO	RaquelM	JoãoS	JoãoP	DianaG
SusanaN	PedroF	SusanaN	RaquelM	PedroF
Id/An 3	SusanaN	**Dis/Ex 3**	**Conc 3**	RaquelM

Legend:
Id/An - Identification and Analysis
Diag - Diagnose
Dis/Ex - Discover and Exploration
Conc - Conceptualize
Gen - Generate

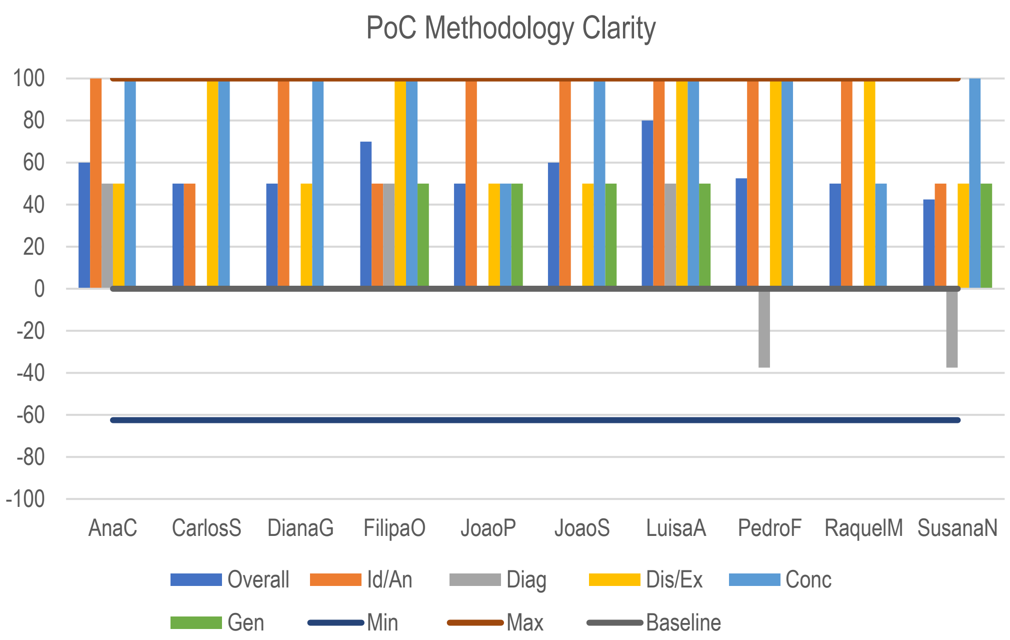
5 (Very good)
4 (Good)
3 (Moderate / minimum acceptable)
2 (Weak)
1 (Very Weak)

From the previous table, it is clear that the most fragile phase of the methodology was the *Diagnose*. During the evaluation session, the participants were asked why it was so difficult for them to understand and accomplish the *Diagnose* phase (Architecture domain). The unanimous response was the lack of a diagram that explained how they should link the relations *Functions* > *Actions* > *Agents*, extracting the most relevant elements in order to proceed to the following phases. Some of the participants also pointed

[12]Ranking Table The name of each participant has been abbreviated: AnaC (Ana Castanho); CarlosS (Carlos Sequeira); DianaG (Diana Gabão); FilipaO (Filipa Osório); JoãoP (João Parcelas); JoãoS (João Sousa); LuísaA (Luísa Almeida); PedroF (Pedro Frutuoso); RaquelM (Raquel Martins); SusanaN (Susana Neves).

out that they struggled to extract the most relevant *Functions* that, à posteriori, should link to the Discover/Exploration phases of the *Memes*, suggesting that, instead, it would be more intuitive the connection of the *Actions*. Another participants' input was related to the completion of the *Biomimetic meme path matrix*. It was suggested that a scheme that could relate the *Memes* events table with the *Biomimetic Meme path matrix*, could increase the creation efficiency of the *Biomeme* saving non-creative time during the task. *Generation* was also considered a weaker phase due to the devoted period during the PoC 1.0 session, but its results will be more detailed in the PoC Session participants' evaluation report. *Identification* and *Analysis* phases (*Architectural* domain), *Discover* and *Exploration* phases (*Nature* domain) were highly punctuated, and no necessary alteration or improvement has been pointed out. Overall, the participants' evaluation was strongly positive (Graph 8.0:1).

Graph 8.0:1. PoC Methodology Clarity[13].



8.2.2 PoC session (participants' evaluation)

PoC Session participants' evaluation was defined by three evaluation criteria:

1- Clarity presenting the methodology: the participants were asked, if, in an overall view, the presented methodology, its phases, and tasks, were presented in a clear and comprehensively way;

2- Time for the session: in this criterion, the participants were asked if the time for the PoC sessions (total: 8h00) was adequate;

[13] The presented graph was generated in an Excel environment, based on numeric values extracted from the Macbeth software.

3- Available means: this criterion aimed to evaluate the physical resources available for the PoC Sessions – room, computers, software, etc.

The ranking given to each criterion was similar to the Methodology Clarity, from 1 to 5, but in this case translated to a percentage scale ranging from -100% to 100%, again considering that 0% was equal to 3. Different weights were attributed to the three criteria; 46% - the highest percentage - was attributed to the *Clarity Presenting the Methodology*, and 27% to both *Time* and *Means* criteria. Similarly to the previous review, each participant was asked to evaluate between 1 and 5 (where 1 was very weak, and 5 was very good). The results are in the PoC Session ranking table (Table 8.0:11).

Table 8.0:11. PoC session - Ranking Table.

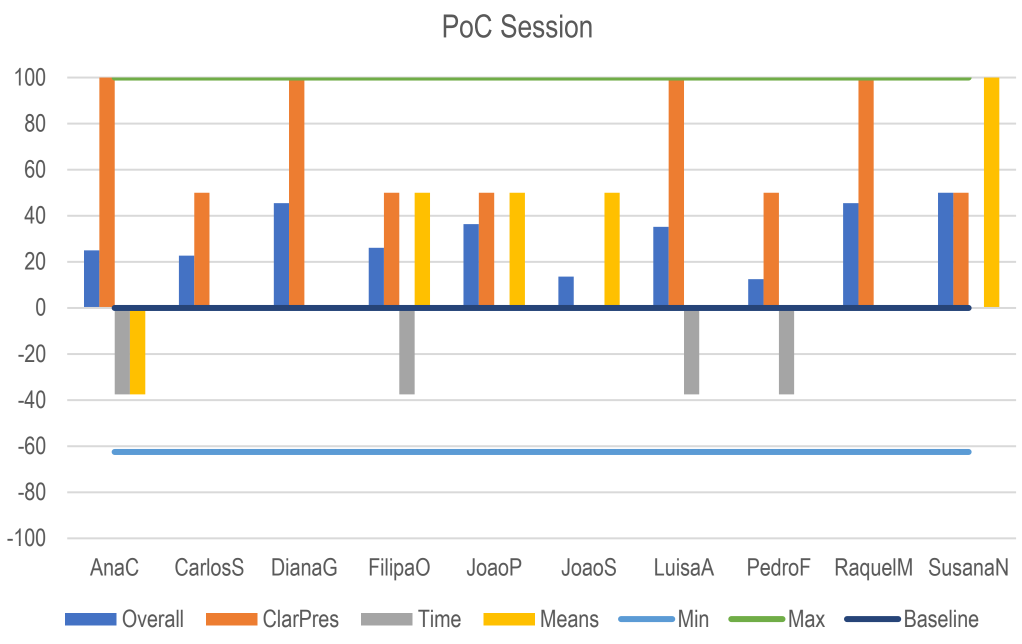
PoC session - Ranking Table		
ClarPres(45.46%)	**Time**(27.27%)	**Means**(27.27%)
ClarPres 5	**Time5**	**Means5**
AnaC	Time3	SusanaN
DianaG	CarlosS	FilipaO
LuísaA	DianaG	JoãoP
RaquelM	JoãoP	JoãoS
CarlosS	JoãoS	Means3
FilipaO	RaquelM	CarlosS
JoãoP	SusanaN	DianaG
PedroF	AnaC	LuisaA
SusanaN	FilipaO	PedroF
ClarPres3	LuísaA	RaquelM
JoãoS	PedroF	AnaC

Legend:
ClarPres - Clarity Presenting Methodology
Time - Time
Means - Means

5 (Very good)
4 (Good)
3 (Moderate / minimum acceptable)
2 (Weak)
1 (Very Weak)

During the PoC Session evaluation, *Clarity Presenting the Methodology* was the most well-scored criterion. However, as previously reported, participants felt a lack of procedural diagrams that could explain the connection *Function* > *Action* > *Agent*. Means were also pointed out as limited. Time was the poorest punctuated criterion. Participants reported that more time was needed to the *Generate* phase. Again, and overall, as it can be confirmed in Graph 8.0:2, participants' evaluation of PoC sessions was very positive.

Graph 8.0:2. PoC session.



8.2.3 Projects (researchers' evaluation)

In order to evaluate the success of the methodology, it was fundamental to evaluate the resulted projects. To evaluate the produced five projects, first, it was fundamental to determine the two dimensions of its creations. The first dimension was linked to the *Operability* of the methodology and the second to the produced *Outputs*. These two dimensions provided the four projects criteria of evaluation:

1- Methodology Clarity: it is the only criterion extracted from the *Operability* domain, this criterion aimed to evaluate from the methodology's creator point of view, how it was understood and conducted by the participants;

2- Goal definition: from the dimension of the *Outputs*, the objective was to evaluate the level of coherence and understanding of the phases regarding the *Architecture* domain, as well as the definition of the *functions>actions>agents* relationship;

3- *Biomeme:* it aimed to evaluate the ability of abstraction, logical and deductive reasoning, as well as the creative individuality within the *Nature* domain;

4- Technical implementation: aimed to evaluate the emulation degree of the design project, considering the implementation of potential technical and performative features.

Each of the above criteria contributed with 25% for the final evaluation. In order to produce a fair and complete evaluation of the *Outputs*, it was necessary to separate the information and analyze it.

Group A had a linear path. The pair soon understood the logic of the *Goal's definition* and the creation process of the *Biomeme*, although, during the exploration phase, their search was limited, which then reflected in the abstraction period of the *Nature* domain. This limitation was transported to the *Artifact* domain, where the group struggled to design their fragmented ideas. The project was only developed in the 'conceptual and formal' plans, disregarding fabrication, or technical implantation. Even considering that it would be an open/close three-dimensional structure, the idea of how the mechanism could be assembled and operated in the whole system would be essential for a more defined design project. Group A's output evaluation can be checked in Table 8.0:*12*.

Table 8.0:12. Group A - Output evaluation.

Ana Castanho + Luisa Almeida	**Architecture**						*Qualitative Quote*
	Climatic analysis	*Selected Functions*	*Selected Actions*	*Correspondence*	*Selected Agents*	*Correspondence*	
	2	Dir. rad. Blockage	Permeability	4	Density	3	Medium
		Dir. rad. Entry	Intersection		Pigment		
		External views	Material		Pattern		
		Natural ventilation	Scale				
					Goal Definition	3	
	Nature						*Qualitative Quote*
	Auton. Exploration	*Meme features caracterization*		*Biomimetic Meme*		*Meme creation*	
	2	Bioluminescence	4	*Functions/actions*	Permeability	3	Medium
		Epidermis	3		Scale		
		Nyctinastic Mov.	5	*Strategies*	Dynamic/Static		
		Vernations	2	*Adaptation*	Behavioural		
				Pattern Feat.	Multilayer		
					Perforated		
				Material Feat.	Porous		
				Performative Feat.	Open/Close		
					Biomimetic *Meme*	2.83	
	Artifact						*Qualitative Quote*
	Climatic consid.	*Functions + Actions reflectance*		*Agents reflection*	*Conceptual Design*	*Tech.+Fab.Consid.*	
	2	3		3	3	1	Medium
					Technical Implementation	2.4	
					Global appreciation:	**2.74**	**MEDIUM**

0 < 1	**Very Low**	**1.1 < 2**	**Low**	**2.1 < 3**	**Medium**	**3.1 < 4**	**High**	**4.1< 5**	**Very High**

Group B had a difficult start-up; the shading system *Goal definition* was their most arduous task. Although, after the task was completed, the following *Nature* domain phases provided them a fresh boost. *Discover* and *Exploration* phases were appropriately conducted, and the creation of the *Biomeme* resulted from an outstanding abstraction capacity. During the *Generate* phase, the group was able to design a primary mechanism, expressing some movements and material notes, but still, the global functioning of the system and its effect was unclear, as well as its mechanical system. Their complete evaluation can be checked in Table 8.0:13. Group B - Output evaluation*.*

Table 8.0:13. Group B - Output evaluation.

Susana Neves + João Parcelas	**Architecture**						*Qualitative Quote*
	Climatic analysis	*Selected Functions*	*Selected Actions*	*Correspondence*	*Selected Agents*	*Correspondence*	
		External views	Permeability		Morphology		
	2	Natural ventilation	Material	2	Opacity	3	Medium
	....	Arch. Integration	....		....	....	
					Goal Definition	2.33	
	Nature						*Qualitative Quote*
	Auton. Exploration	*Meme features caracterization*		*Biomimetic Meme*		*Meme creation*	
	2	Trichomes	2	*Functions/actions*	External views		
		Nyctinastic Mov.	5		Natural ventilation		
		Diaheliotropic	5		Arch. Integration		
	....	....	....	*Strategies*	Dynamic	4	High
				Adaptation	Behavioural		
				Pattern Feat.	Adaptative		
				Material Feat.	Flexible		
				Performative Feat.	Tracking		
					Biomimetic *Meme*	3.33	
	Artifact						*Qualitative Quote*
	Climatic consid.	*Functions + Actions reflectance*		*Agents reflection*	*Conceptual Design*	*Tech.+Fab.Consid.*	
	2	2		2	3	3	Medium
					Technical Implementation	2.4	
					Global appreciation:	**2.91**	**MEDIUM**

0 < 1	**Very Low**	**1.1 < 2**	**Low**	**2.1 < 3**	**Medium**	**3.1 < 4**	**High**	**4.1< 5**	**Very High**

Group C developed one of the most impressive projects of the PoC 1.0. During the *Goal definition* phase, the group followed the instructions and achieved an adequate result. Proceeding to the *Nature* domain, the group produced one of the most accurate researches, studying events and conceiving an astute strategy that enabled them, at this early stage, to connect their results to the *Generate* phase. This designing strategy enabled them to more rapidly connect their *Biomeme* to an innovative mechanism that sustained the design project. In this way, the technical implementation did not come as an à posteriori design solution; instead it gave rise to it. As a result, the three hours shading system proposal, ensured an accurate challenge definition by framing the architecture challenge and defining its goals, a solid abstract biomimetic connection through the study of plants adaptations events, and an optimized technical implementation, providing the fundamental clues to its physical construction (Table 8.0:14).

Table 8.0:14. Group C - Output evaluation.

	Architecture						*Qualitative Quote*
Raquel Martins + Carlos Sequeira	*Climatic analysis*	*Selected Functions*	*Selected Actions*	*Correspondence*	*Selected Agents*	*Correspondence*	High
	3	Dir. Rad. Entry	Permeability	3	Opacity	4	
		Diffuse Radiation	Material		Structure		
		Glare Control	Scale		Density		
		Natural ventilation			Pattern		
					Goal Definition	3.33	
	Nature						*Qualitative Quote*
	Auton. Exploration	*Meme features caracterization*		*Biomimetic Meme*		*Meme creation*	Very High
	4	Canopy Plants	3	*Functions/actions*	Dir. Rad. Entry	5	
		Endothermic	4		Diffuse Radiation		
		Xylem	5		Glare Control		
		Superhydrophilic	5		Natural ventilation		
	....	Pholem	1	.... *Strategies*	Dynamic		
		Bioluminescence	4	*Adaptation*	Physiological		
				Pattern Feat.	Multilayer		
					Bubbles		
				Material Feat.	Flexible		
					Sponge		
				Performative Feat.	Unidirec. Mov.		
					Storage		
	....	....	....		Biomimetic *Meme*	.... 4.22	
	Artifact						*Qualitative Quote*
	Climatic consid.	*Functions + Actions reflectance*		*Agents reflection*	*Conceptual Design*	*Tech.+Fab.Consid.*	High
	4	3		4	5	4	
					Technical Implementation	4	
					Global appreciation:	**3.85**	**HIGH**

0 < 1	Very Low	1.1 < 2	Low	2.1 < 3	Medium	3.1 < 4	High	4.1< 5	Very High

Group D's shading design proposal initiated its *Architectural* domain based on a growing scale. The lack of some fundamental knowledge related to building climatic analysis was on the base of their difficulties. However, during the deductive process, information was linked, and the relationship *functions>actions>agents* was appropriately defined. *Nature* domain phases were conducted successfully, leading to a coherent and adequate *Biomeme*. Their entire shading system proposal was designed through parametric tools, which conducted them to the conceptual idea of a possible technical implementation, by designing a motion intention. The complete *Output* evaluation can be consulted in Table 8.0:15. Group D - Output evaluation.

Table 8.0:15. Group D - Output evaluation.

Diana Gabão + João Sousa	**Architecture**						*Qualitative Quote*
	Climatic analysis	*Selected Functions*	*Selected Actions*	*Correspondence*	*Selected Agents*	*Correspondence*	
	2	Dir. Rad. Block.	Permeability	3	Translucency	4	Medium
		External views	Reflection		Morphology		
		Natural Ventilation	Refraction		Pattern		
		Arch. Integration	Material		Density		
					Goal Definition	3	
	Nature						*Qualitative Quote*
	Auton. Exploration	*Meme features caracterization*		*Biomimetic Meme*		*Meme creation*	
	2	Diaheliotropic	3	*Functions/actions*	Dir. Rad. Block.	4	High
		Endothermic	5		External views		
		Asymmetry	5		Arch. Integration		
		Stoma	3	*Strategies*	Static		
		Epidermis	4	*Adaptation*	Morph+Phys.		
				Pattern Feat.	Multilayer		
				Material Feat.	Flexible		
				Performative Feat.	Concentric Mov.		
					Cellular perform.		
					Biomimetic *Meme*	3.33	
	Artifact						*Qualitative Quote*
	Climatic consid.	*Functions + Actions reflectance*		*Agents reflection*	*Conceptual Design*	*Tech.+Fab.Consid.*	
	3	4		5	4	3	High
					Technical Implementation	3.8	
					Global appreciation:	**3.38**	High

0 < 1	Very Low	1.1 < 2	Low	2.1 < 3	Medium	3.1 < 4	High	4.1< 5	Very High

Potentially due to the participants' more extensive experience, Group E had no difficulties during the entire methodology process. A correct and efficient response to the *Architecture* domain phases empowered them for the *Nature* domain, which was skillfully worked to boost them to the *Generate* phase. During this phase, the group integrated the *Goal definition* constraints into a parametric model and designed a morphological proposal. The proposal offered not only a formal solution but also a structural and motion solution. Output evaluation can be checked in Table 16. Group E - Output evaluation.

Table 8.0:16. Group E - Output evaluation.

Filipa Osório + Pedro Frutuoso	**Architecture**						*Qualitative Quote*
	Climatic analysis	*Selected Functions*	*Selected Actions*	*Correspondence*	*Selected Agents*	*Correspondence*	
	3	Dir. Rad. Entry	Permeability	4	Translucency	5	High
		Dir. Rad. Block.	Reflection		Structure		
		Glare Control	Intersection		Density		
			Material		Pattern		
					Goal Definition	4	
	Nature						*Qualitative Quote*
	Auton. Exploration	*Meme features caracterization*		*Biomimetic Meme*		*Meme creation*	
	2	Deciduous Plants	4	*Functions/actions*	Dir. Rad. Entry	4	High
		Whorl	5		Dir. Rad. Block.		
		Bark Trees	4		Glare Control		
		Diaheliotropic	3	*Strategies*	Dynamic		
		Nyctinastic Mov.	4	*Adaptation*	behavioural		
				Pattern Feat.	Random		
				Material Feat.	Flexible		
				Performative Feat.	bidirectional. Mov.		
					Biomimetic *Meme*	3.33	
	Artifact						*Qualitative Quote*
	Climatic consid.	*Functions + Actions reflectance*		*Agents reflection*	*Conceptual Design*	*Tech.+Fab.Consid.*	
	5	5		4	4	3	Very High
					Technical Implementation	4.2	
					Global appreciation:	**3.84**	High

0 < 1	Very Low	1.1 < 2	Low	2.1 < 3	Medium	3.1 < 4	High	4.1< 5	Very High

The five groups presented a shading system design proposal, based on environmental and climatic analysis, exploring plant adaptation events, studying and abstracting its features, considering motion hypothesis and mechanical implementation (Table 8.0:17). Although, based on our evaluation scale, two of the projects are not considered positive. The projects from groups A and B had negative scores: Group A's design proposal lacked ideas for technical implementation; and Group B had unclear goals and, similarly to Group A, lacked structural and technical implementation strategies (Graph 8.0:3). Based on the overall participation, the final evaluation of the projects reflects a successful experience.

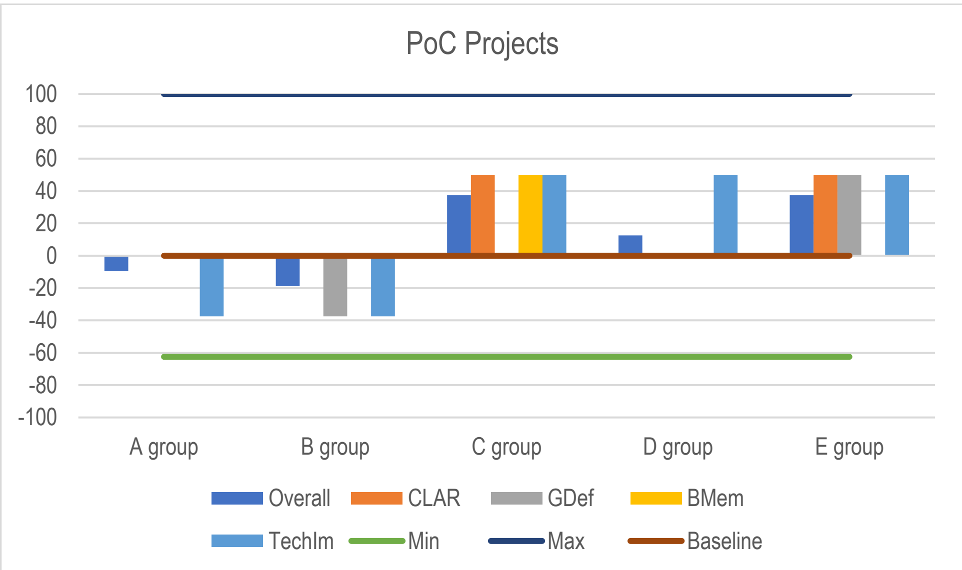
Table 8.0:17. PoC 1.0 Projects - Ranking Table.

Ranking Table			
Clar (25%)	**GDef** (25%)	**BMem** (25%)	**TechIm** (25%)
Clar5	**GDef5**	**BioMem5**	**TechImpl5**
Group C	Group E	Group C	Group
Group E	**GDef3**	**BioMem3**	Group D
Clar3	Group A		Group A Group E
		Group A Group C Group B	**TechImpl3**
		Group B Group D Group D	Group A
	Group D Group B	Group E	Group B

Legend:
Clar - Methodology Clarity
GDef - Goal Definition
BMem- Biomimetic Meme
TechIm - Technical Implementation

5 (Very good)
4 (Good)
3 (Moderate / minimum acceptable)
2 (Weak)
1 (Very Weak)

Graph 8.0:3. PoC 1.0 Projects – Final evaluation.



8.3 Insights

PoC 1.0 provided diverse and valuable pieces of information regarding the Bioshading Concept Design Methodology 1.0, but most of all, concerning its application procedure and digital tool kit. From the PoC 1.0 experience and from the participants' and researchers' evaluation, some changes and complementary material have to be (re)created for the Bioshading Concept Design Methodology 2.0:

1- During the *Architectural* domain, *Diagnose* phase, more than providing lists with the primary *functions*, *actions*, and *agents*, it is mandatory to explain those items and to show, by exemplifying their possible correlation. To explain the different *functions*, *actions*, and *agents*, a glossary should be created and open to the methodology users. In order to exemplify the correlation between the elements, an illustrative diagram should also be presented;

2- Regarding *the Nature* domain, a diagram that links the *Meme* events table, from the *Exploration* phase to the *Biomimetic Meme path matrix*, from the *Conceptualize* phase, would improve users' efficiency and optimize non-creative time during the process, accelerating the *Biomeme* creation;

3- The Artifact domain requires time. PoC 1.0 initially aimed to achieve the *Simulation* phase during the second session. However, PoC 1.0 participants used the *Simulation* assigned time (1 hour) for the *Generate* phase. Still, the designed projects were sustained by a context and climatic analysis, which make them more efficient and responsive to their surrounding environment context. Another important note about this phase is related to the high relevance of the users' experience. Skilled digital fabrication users more easily integrate technical information in their design, as well as skilled parametric designers, more easily design motion intentions.

The next chapter of this thesis will present the final Bioshading Concept Design Methodology 2.0, upgraded by the PoC 1.0 information and experience.

8.4 References

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SECTION VI
A BIOMIMETIC DESIGN METHODOLOGY

9.0
Bioshading System Design Methodology

9.0 BIOSHADING SYSTEM DESIGN METHODOLOGY

Bioshading System Design Methodology (BSDM) is an architectural problem-based methodology that uses Nature events as models and inspirational sources to develop and create performative and design solutions for responsive shading systems.

The design methodology is supported by a circular relationship between three main domains: *Architecture, Nature*, and *Artifact* (Figure 9.0:1). Each domain corresponds to a progressive formation process of the design methodology. T*he "Architecture" domain* corresponds t*o the "Definition*" process of the architectural challenge that the user aims to respond/solve; The *"Nature" domain* corresponds to the user*'s "Abstraction*" process, through which he/she will be able to create the *Biomeme* that will support the shading system design concept; and finally, the *"Artifact" domain* corresponds to the *"Emulation*" process, through which the user will be able to conceive the architectural design solution. Nine phases compose the BSDM. Each of the domains is divided into three consecutive phases (nine in total), that guide the user through the different processes of the design methodology.

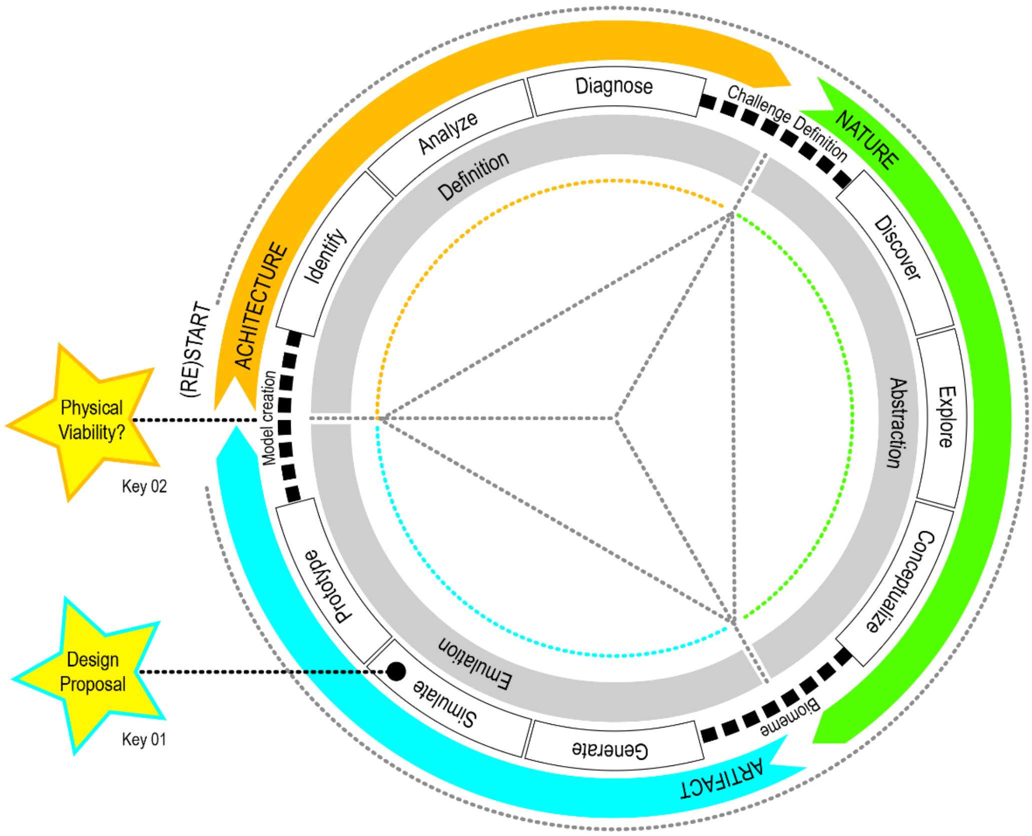


Figure 9.0:1. Bioshading system design methodology - workflow.

BSDM initiates with the Architecture domain. *Identification* and *Analysis* lead to the *Diagnose* of the shading system's main *Functions* (considering building usage, climate, and geographical position) that will be ensured by *Actions*, which in turn are only possible through the formalization of *Agents* in the field of the architectural lexicon. After this *Challenge Definition* process, BSDM users will enter the *Nature* domain. *Nature* domain is linked through an *Abstraction* process. The first two phases of *Nature* domain are *Discover* and *Explore*. These phases invite BSDM users to look inside terrestrial vascular plants' biological events, based on the previous extracted *Actions* and *Agents*, searching for similar natural conditions, potential strategies, principals, and features. At the final phase of this *Abstraction* process - *Conceptualization* - BSDM users create their Biomeme – a nature-based humanmade meme, completely tailored to the case study. Linked through an *Emulation* process, the *Artifact* domain engages with *Generate* and *Simulation* phases. At these phases, BSDM users (supported by shading system type of structures and actuators surveys, material, and CAM available resources) are designing and evaluating their shading system solutions through digital tools, refining the solutions and tuning them for the prototype phase. The prototype phase is the moment when the shading system is translated into matter. At this phase, it is crucial to evaluate possible material, mechanical, and/or electronic constraints, maintenance requirements and costs, system lifespan, among other related issues.

9.1 Architecture Domain – definition process

The *Architecture domain* operates in two main fields: context and potential. Its phases, *Identification* and *Analysis*, base its survey in the project context aims, constraints, and analysis of the urban and climatic environment and its functional program. The potential field provides proof regarding the opportunity that results from the previous analysis, enabling a final *Diagnose* based on generative analysis, bioclimatic factors and conditions, and other inhabitants' requirements. This *Definition* process enables an engagement since the very initial conditions of the project, from its environmental and contextual constraints to its individual potential, highlighting goal functions, possible improvements, and its own *Challenge definition*. This is the beginning of the construction of the *Bioshading lexicon*, which will provide the motto for the engagement of the consequent phases (Figure 9.0:2).

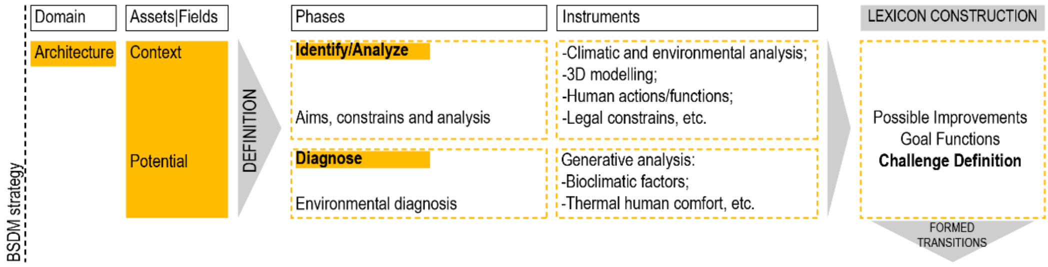


Figure 9.0:2. Bioshading System Design Methodology Strategy - Architecture Domain.

In order to conduct the *Definition* process, the first step is to *Identify* the building project and its target façade(s). It is necessary to identify not only its urban context, its climatic environmental conditions throughout the year, but also its inhabitants' type of use and spatial routines. It is recommended that the BSDM user have a 3D model, not only of the target building façade, but of its related urban context. The *Analysis* phase carries further meta-climatic analysis done through a building environmental software. The idea is to frame, locally, spatially, and climatically the environmental situation of the case study building. To produce this type of analysis, most of the climatic software only require the city weather file and the comfort model to be used. Temperature range values, radiation (Figure 9.0:3), and wind velocity graphics, extracted from Climate Consultant 6.0 (CC 6.0), are just some examples of the information that this type of meta-climatic analysis digital tools can provide to its users. This meta-analysis enables the user to look into its challenge from a higher perspective, enabling an extensive understanding and identification of the strengths, weaknesses, opportunities, and threats related to the building challenge.

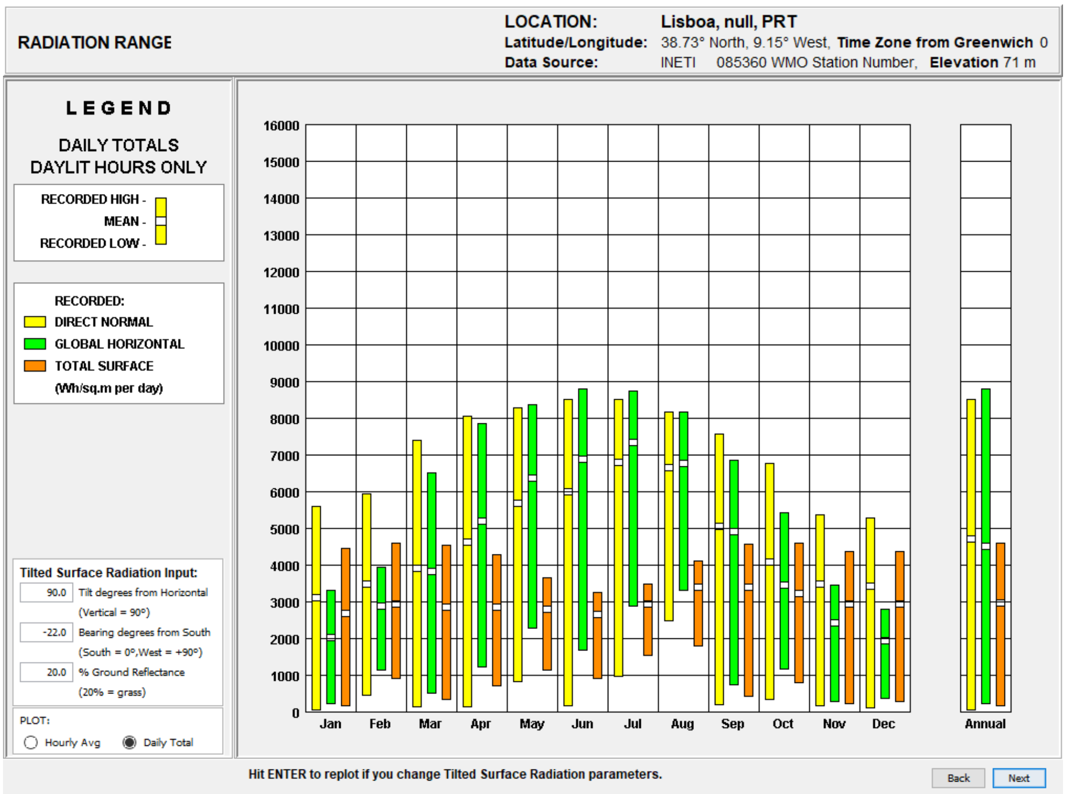


Figure 9.0:3. Climate Consultant 6.0 – Lisbon radiation range for vertical surface facing South/Southeast.

Zooming in from the urban into the building scale, it is necessary to analyze the building target façade(s). Several examples of software can produce this type of analysis, but this research will focus on Ladybug, which was the one that was used during the PoC 1.0 session. While meta-analysis software does not require the building's tridimensional model, providing a fast and broad climatic analysis, Ladybug analysis type of software are centered on the tridimensional model. This type of software requires not only the case study modeling but also its surrounding environment. Ladybug provides to its users several types of climatic and solar analysis, enabling its materialization into several forms of visualization – diagrams, 2D, 3D, and Psychrometric charts, among others. Radiation 3D charts are one of the most well-known and valuable tools of Ladybug analysis. To proceed through the BSDM *Definition* process, some charts are considered fundamental to the *Analysis* phase: Monthly/annual direct and diffuse radiation (Figure 9.0:4); radiation rose (Figure 9.0:5); shading comfort façade/window graphic, wind speed, and air temperature. However, users may feel the need for more information and analysis charts, according to the type and scale of the project. Being an environmental parametric analysis tool, Ladybug establishes a direct dialog with the virtual model geometry, enabling a precise visualization of its results over it, enabling a faster and more intuitive BSDM user analysis. From these analyses, at urban and building scales, BSDM users are expected to extract the necessary information regarding its shading system's main functions, adapted and personalized to its building case study. As it was already referred in Section V, Chapter 7.1.2, the fundamental *Functions* of a shading system are: Direct radiation entry and blockage; diffuse radiation and glare control; enable views to the external environment, natural ventilation and finally, and not less important, ensure its proper architectural integration.

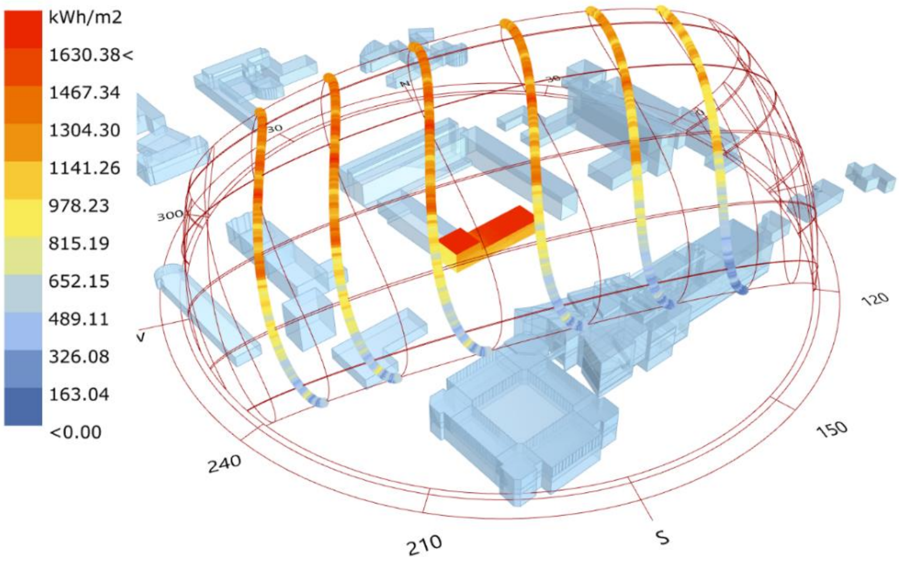


Figure 9.0:4. Ladybug: Radiation analysis (June to December period)[1].

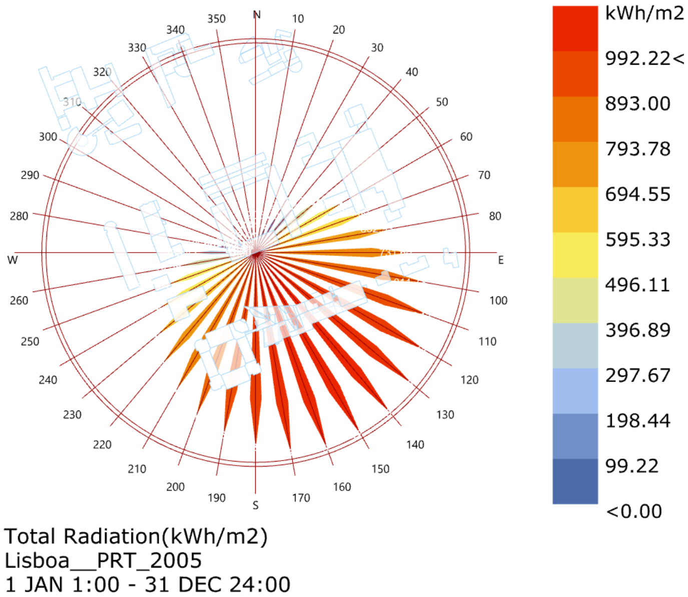


Figure 9.0:5. Ladybug Annual Radiation Rose[2].

[1] PoC 1.0 case study building. The caption considers a six-month period (June-December), focusing on a 5-hour range between 11 AM and 4 PM.
[2] PoC 1.0 case study building and urban context.

Some of the *Analysis* phase end questions should be: According to the previous analysis, where and when is it relevant to enable direct radiation entry? Where and when will building inhabitants want to block direct radiation? According to the building's functional program, when is glare control required? Moreover, regarding the external views connection, can the shading system empower it?

After the *Identification* and *Analysis* phases, the user will be prepared to engage with the *Diagnose* phase. The first step of this phase is to determine which are the main functions that the user needs to privilege in its shading system's façade. To help and guide the BSDM user in making this decision, two tables are provided, one containing the most relevant shading system *Functions* (Table 9.0:1) and another where the user will have to connect season and day period with building types, regarding use and solar orientation, attributing possible shading system functions to each situation (Table 9.0:2). In Table 9.0:2, the building *Function* fields should be adapted, highlighting the most relevant *Functions* for the user's case study building, including the type of climate. Table 9.0:2 is adequate for buildings located in the Northern Hemisphere. If the building is located in the Southern Hemisphere, the "south" should be replaced by "north" in the mid-lower part of the table.

Table 9.0:1. Shading System's main functions.

	Functions
1	Direct radiation - entry
2	Direct radiation - blockage
3	Diffuse radiation
4	Glare control
5	External views
6	Natural ventilation
7	Architectural integration
8	Others

Table 9.0:2. Shading System's functions according to building types, orientation, and season.

	building types of use					
season+period	residential	services	residential	services	residential	services
winter - day period						
winter - night period						
summer - day period						
summer - night period						
	east		south		west	

An example of the use of Table 9.0:2 is provided in Table 9.0:3, for the case of a mix-use, residential/services building located in Lisbon, Portugal. The target façade is facing south/southeast. Lisbon has a 3015 km^2 of metropolitan area, classified as a typical Mediterranean climate. With short and mild winters and warm summers, Lisbon's average annual temperature is 21.5 °C during the day and 13.5 °C at night. During January (considered the coldest month), temperatures range from 10 to 19 ºC during the day and 4 to 11 °C at night. During August (considered the hottest month), temperatures range from

24 to 28 °C during the day and about 15 to 19 °C at night (World Weather & Climate Information, 2010-2019).

In Table 9.0:3, the two building types of use were separated in order to focus on their particular needs and requirements. In Lisbon, a residential East façade requires diffuse radiation and glare control, external views communication, and natural ventilation during all the year. However, during the winter period, direct radiation should be able to enter the space, while during the summer period, it should be blocked, avoiding space overheating. In an office building, the East façade should control diffuse radiation, external views, and natural ventilation all year round, having in mind the Summer day period, when direct radiation can be harmful to the building's users. In a residential building's South façade, diffuse radiation control, external views connection, and natural ventilation are transversal requirements during all year. However, during the winter period, similar to what happens with the East façade, it is essential to let direct radiation enter the space in order to heat it for the following night period. During the summer period, the same direct radiation should be blocked, avoiding space overheating. In order to identify the most relevant façade *Functions*, a table crossing the building usage, orientation façade, and year season should be filled in (Table 9.0:4).

Table 9.0:3. Shading System functions example: a mix-used residential+services building located in Lisbon. (the numbers refer to the functions included in Table 9.0:1)

	building types of use			
season+period	residential	services	residential	services
winter - day period	1;3;4;5	3;5;6	1;3;5	1;3;5;6
winter - night period	6	0	6	0
summer - day period	2;3;4;5	2;3;5	2;3;5	2;3;5
summer - night period	6	6	6	6
	east		south	

Table 9.0:4. Shading System functions example – Crossing table.

	east - resid/serv						south - resid/serv					
winter - day period	x		x	x	x	x	x		x		x	x
winter - night period						x						x
summer - day period		x	x	x	x			x	x		x	
summer - night period						x						x
	1	2	3	4	5	6	1	2	3	4	5	6

Table 9.0:4 facilitates the Functions extraction. From the example, four functions are highlighted, diffuse radiation and glare control, external view connections, and natural ventilation (Table 9.0:5).

Table 9.0:5. Functions selection.

	Functions
1	Direct radiation - entry
2	Direct radiation - blockage
3	Diffuse radiation
4	Glare control
5	External views
6	Natural ventilation
7	Architectural integration
8	Others

Once the shading system's functions are defined, it is necessary to figure out what to do to achieve each one of the selected *Functions*. These are *Actions*. *Actions* are processes of doing something to achieve a specific *Function*. For the initial referred *Functions* (Table 9.0:1), six actions can be related: i) permeability; ii) reflection; iii) refraction; iv) intersection; v) material, and vi) scale (see Section V, Chapter 7.1.2). *One or more Action*s empower *each Function*. The following task invites the BSDM user to link the shading system *Functions* to its potential *Actions*. Based on the current example, a diagram that synthesizes the linkage process is presented (Figure 9.0:6).

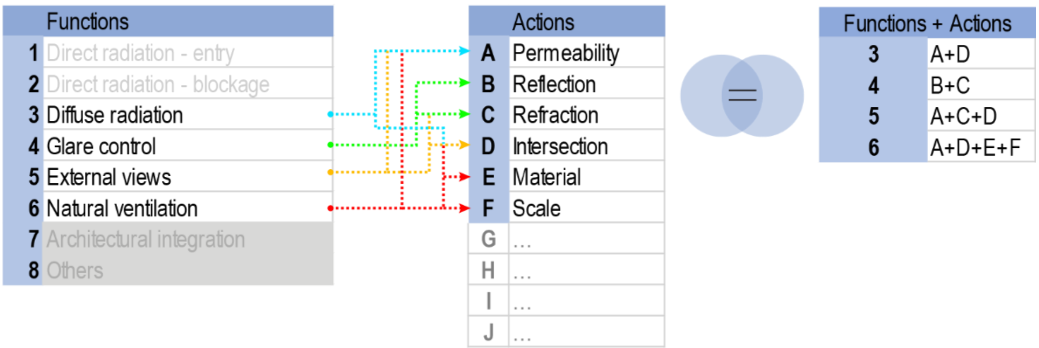


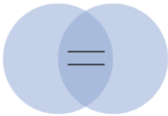
Figure 9.0:6. From Functions to Actions - a linkage task example.

In the example above, the user can conclude that the *Actions* that best fit the *Functions* that the shading system will have to ensure are *permeability* and *intersection* (present in three of the *Functions*), and with lower relevance *refraction* (present in only two *Functions*).

The final task of the *Diagnose* phase enables the discovery of the *Agents*, which will empower the shading system to perform its predefined *Actions* and, in its turn, its *Functions*. *Agents* perform an active role in order to produce a specific effect during a given *Action*. At this point, BSDM users will have to conduct a second link task, connecting its previous *Actions* to potential *Agents* (Figure 9.0:7).

	Actions
A	Permeability
C	Refraction
D	Intersection

	Agents
a	Translucency
b	Opacity
c	Morphology
d	Structure
e	Density
f	Pigment
g	Pattern
h	Orientation
i	Roughness
j	Air flow
k	...
l	...
m	...



Actions + Agents											
Actions	A	X	X			X		X			X
	C	X				X			X	X	
	D			X	X	X			X		
		a	b	c	d	e	f	g	h	i	j
		Agents									

Figure 9.0:7. From Actions to Agents – a linkage task.

From the connection of the shading system *Actions* with potential *Agents*, a table should be produced, in order to extract the most prominent *Agents*. In the above example, *translucency*, *density*, and *orientation* are the most relevant *Agents*.

It is important to refer that none of the provided tables are closed. BSDM users may find the need to add concepts and definitions, and they should feel free to do it.

At the end of the *Architecture domain*, by accomplishing the *Diagnose* phase, the BSDM user will be able to elaborate its case study *Challenge definition*:

1- A clear overview and understanding of the context environment (climatic and urban) of its building case study;

2- Diagnose shading system opportunities and possible contribution to improvements in its surrounding environment (e.g., by creating public shading opportunities in the building surrounding areas);

3- The shading system goal *Functions*;

4- A façade mapping that will provide information over the shadow necessity;

5- Define the shading system *Actions* and *Agents* that will enable the formed transition to the *Nature domain*.

The user is now ready to engage in the *Nature* domain.

9.2 Nature Domain – Abstraction process

Composed of three phases, *Discovery*, *Exploration*, and *Conceptualization,* progressively linked through an *Abstraction* process, the BSDM *Nature domain* is sustained, in this research, by the terrestrial vascular plant's biology (Figure 9.0:8). The terrestrial vascular plant's biology is a vast and amazing field of research. Architecture is one of the oldest forms of materialization and testimony of humankind's existence. From the combination of these statements, many dots are linked, sharing similar aims and properties (see Section IV, Chapters 6.3.1, 6.3.2 and 6.3.3) that support the idea of similarity between buildings and terrestrial plants.

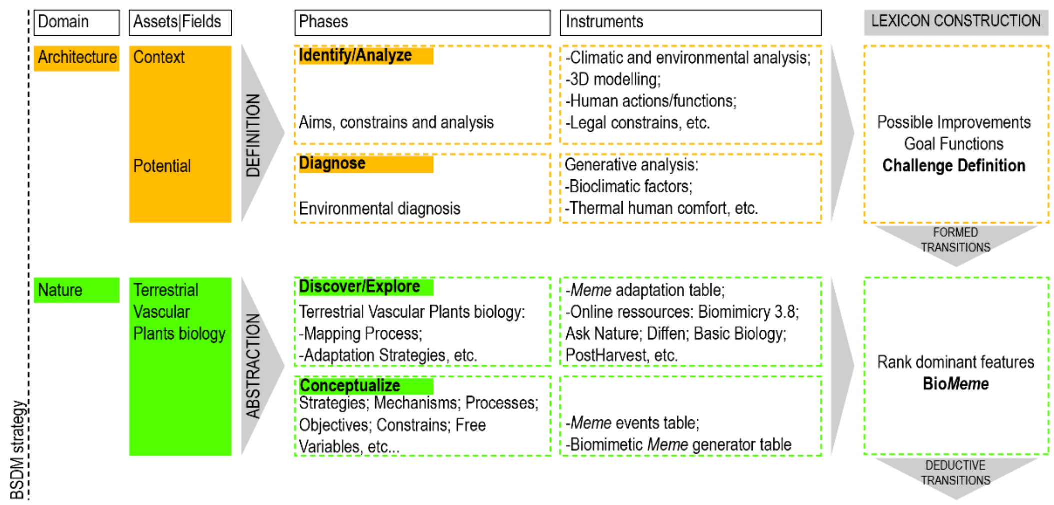


Figure 9.0:8. Bioshading System Design Methodology Strategy - Architecture and Nature Domain.

The first two phases of the *Nature* domain are the *Discovery* and the *Exploration* phases. During these phases, the BSDM user is invited to produce his/her own personal research based on the shading system goal *Functions*, *Actions* and *Agents* (extracted from the *Definition* process), the plants' adaptation events tables (Tables 6.0:1, 6.0:2 and 6.0:3 in Section IV, Chapter 6.3.3, also available with the BSDM toolkit), and several online database resources. At first, the BSDM user will have to look into the shading system *Actions* and *Agents*, abstracting from his/her previous conceived formal ideas and search through the available plants' adaptation event table for a possible connection between the concepts and terms. Every individual connects a personal and particular image (a figurative idea) to a specific term – a *meme* that is immediately linked to a definition. During these *Discovery* and *Exploration* phases, the BSDM toolkit does not provide any image reference over any of the terms; this is part of the *Abstraction* process that has to be made exclusively by the BSDM user.

At these phases, the BSDM user has to search in the *Plants Adaptation Events* tables the event that could match/correspond to the *Actions* of the shading system being developed. The *Agents* could help to increase the accuracy in the search by specifying particular properties of the event (Figure 9.0:9). In supporting this task, an online search is also essential to explore not only the listed *Plants Adaptation Events* but also to find new ones (Figure 9.0:10). The resulted product of this task is no longer a plant adaptation events list description, but a collection of *memes* that inform and reflect intentional shading system goals.

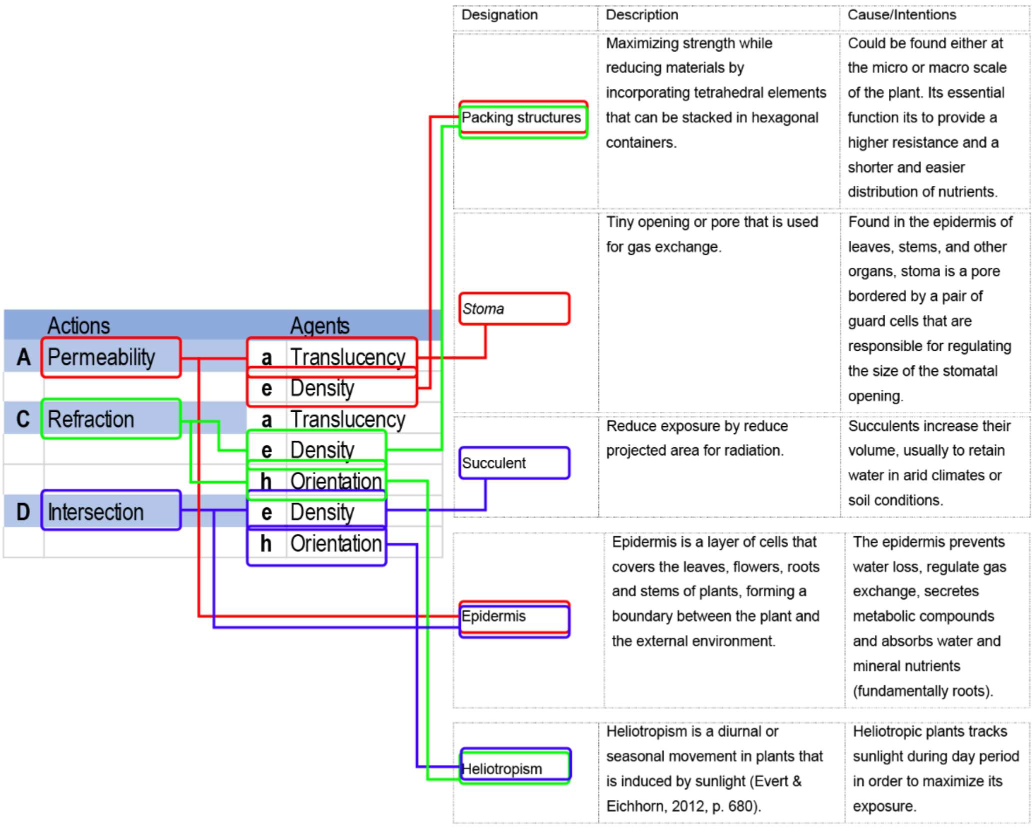


Figure 9.0:9. Connection example between shading Actions and Agents with Plants Adaptation Events.

Figure 9.0:10. Relevant search engines, to search and explore (new) Plants Adaptation Events.

After the *Discovery* and *Exploration* phases, the user enters the *Conceptualization* phase. The first task is to elaborate the *Memes* event table. Five fields compose this table: *Meme* event – the name of the selected *meme;* Adaptation – morphological, physiological or behavioral; Strategy – dynamic or static; Main principles - what are the main principles of each *meme;* and finally, Main features - which are its main features (pattern, material and performative features of each *meme)* (Table 9.0:6 and Table 9.0:7). A clear and synthetic understanding of the *meme* event's main principles and an adequate strategy categorization are determinant to perceive and extract its potential main features.

Table 9.0:6. Meme Events Table.

Meme **Event**	**Adaptation**	**Strategy**	**Main principles**	**Main features**
XXX	XXX	XXX	XXX	XXX

Considering the previous example, a possible *Meme Events* table filling is:

Table 9.0:7. Meme Events Table - Example.

Meme **Event**	**Adaptation**	**Strategy**	**Main principles**	**Main features**
Epidermis	Physiological	Static	The epidermis serves several functions such, water loss, regulates gas exchange, secretes metabolic compounds and (specially in roots) absorb water and mineral nutrients.	Permeability; Expandable; Intersection; Parallel divisions
Heliotropism	Behavioral	Dynamic	Leaves orient to track the course of the sun throughout the day.	Circular/Ellipse; Flexible; Lightweight; Intersection and tracking
Packing structures	Morphological	Dynamic	Packing structure, material minization	Hexagonal; Permeable; Lightweight; Storage
Stoma	Morphological	Dynamic	The thick elastic inner walls and thin elastic outer walls of the guard cells, ensure an uneven expansion when inflated, resulting in opening (Badarnah, 2012).	Circular/Ellipse; Permeable; Expandable; Open/close
Succulent	Morphological	Static	Pleated body morphology with surfaces almost parallel to radiation prevent excess heat loads (Badarnah, 2012).	Fractal; expandable; Opaque; Intersection; Storage

After completing the *Meme Events Table*, the BSDM user is now ready to create his/her *Biomeme*. The *Biomeme* is a conceptual *meme* created from attributes of the shading system: goals, *Functions*, *Actions*, and *Agents* combined with the plants' adaptation events. It is a humanmade conceptual creation based on human requirements, built and natural environments, and plants' biological events.

The Biomeme creation is rooted in an *Abstraction* process, supported by the filling of the *Biomimetic meme path matrix.* The *Biomimetic meme path matrix* is a bidirectional (vertical and horizontal) input table composed of the selected *Actions*, *memes,* and by the *Memes* events table properties and features (Table 9.0:8). Thus, to fill it in, the BSDM user will need the shading system *Actions* (from the *Diagnose* phase of the *Architectural domain*) and the *Meme events* table. From the *Meme events* table, the user will extract the discovered *memes*, their individual types of adaptation, and strategies. From the combination of the meme strategies with its main principles, BSDM users will be able to define the *meme*'s main features, extracting potential patterns, materials, and performative features (Figure 9.0:11).

Table 9.0:8. Biomimetic Meme Path Matrix – provided to the BSDM users during the Conceptualization phase.

selected Actions		A meme	B meme	C meme	... meme	**Biomeme**
	K1					
	K2					
	K3					
Meme Strategies						
	Dynamic					
	Static					
Meme Adaptation						
	Morphological					
	Physiological					
	Behavioral					
Meme Pattern features						
	xxx					
	xxx					
Meme Material features						
	xxx					
	xxx					
Meme Performative Features						
	xxx					
	xxx					

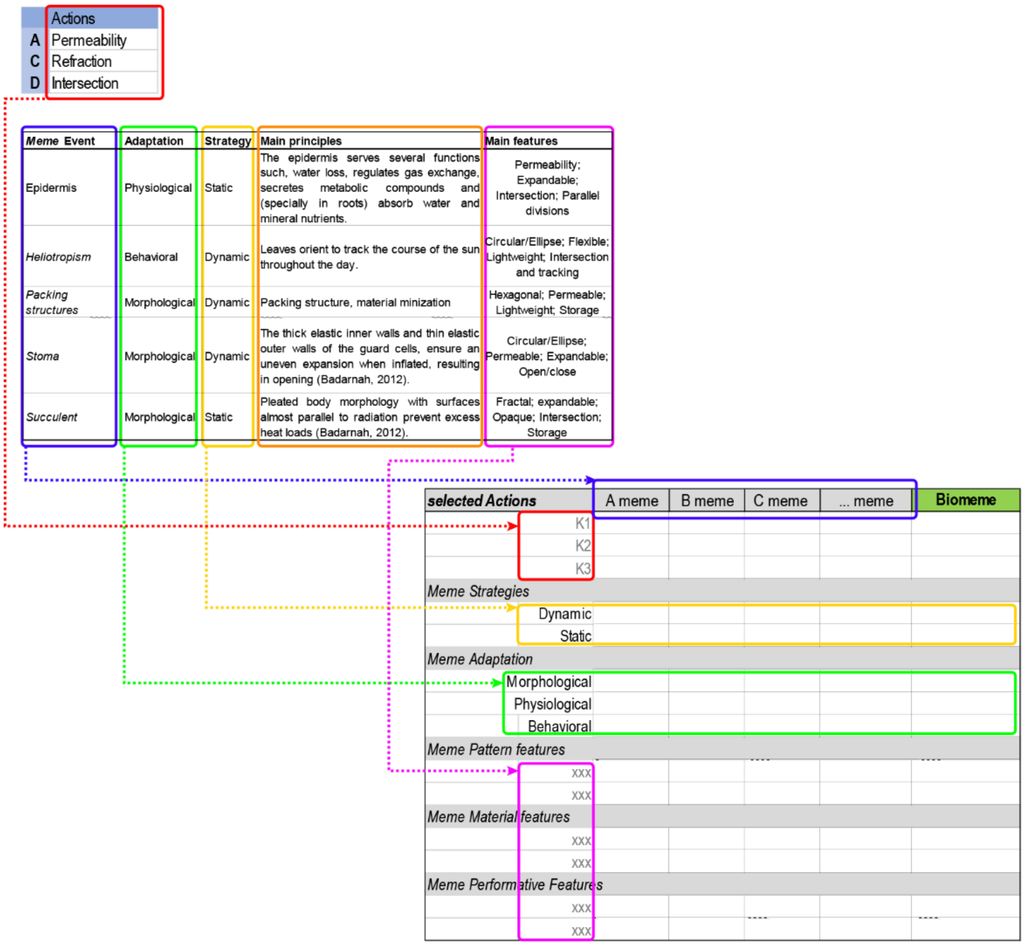


Figure 9.0:11. Biomimetic meme path construction - instructions.

After the insertion of the input data, the BSDM user needs to relate them, by checking the corresponding boxes. To achieve the *Biomeme* creation, the user needs to proceed through a counting process. The *Biomeme* creation arises from a horizontal counting, filtering the critical information through a majority or a tie result. Consider the below *Biomimetic meme path matrix* as an example (Table 9.0:9). The selected *Actions* are: *Permeability*, *Refraction*, and *Intersection*; and the selected *memes* are: *Epidermis*, *Heliotropism*, *Packing Structures*, *Stoma*, and *Succulent*. Connecting them through a conceptual relation, the most relevant *Actions* are *Permeability* and *Intersection*, with three checks each. Following through the *memes Strategies*, the majority of the selected memes perform through a *Dynamic* strategy, while regarding the *meme's* adaptation, the same selected *memes* perform mostly through *Morphological* adaptations. In analyzing *memes* pattern features, the most relevant will be the circular/ellipse characteristic with two checked boxes, while in the *meme's* material features, we can watch a typical example of a tie between all of the features. In this case, all the selected features are incorporated in the *Biomeme*. The last *Biomeme* parameter refers to its performative features, selecting *Intersection* and *Tracking* with two checks each.

Table 9.0:9. Biomimetic path matrix - Example.

selected Actions	Epidermis	Heliotropism	Packing structures	Stoma	Succulent	**Biomeme**
Permeability	X		X	X		**X**
Refraction		X	X			
Intersection	X	X			X	**X**
Meme Strategies						
Dynamic	X	X		X		**X**
Static			X		X	
Meme Adaptation						
Morphological			X	X	X	**X**
Physiological	X					
Behavioral		X				
Meme Pattern features						
Parallel divisions	X					
Hexagonal			X			
Circular/ellipse		X		X		**X**
Fractal					X	
Meme Material features						
Permeability	X			X		**X**
Flexible		X		X		**X**
Expandable	X				X	**X**
Lightweight		X	X			**X**
Meme Performative Features						
Intersection	X		X			**X**
Tracking		X			X	**X**
Storage					X	
Open/close				X		

At the end of the *Biomimetic meme path matrix* filling, the BSDM user has created his/her *Biomeme*. The *Biomeme* is the motto that launches the shading system design. By combining the architecture diagnosis with the Nature conceptualization, the BSDM user creates a Nature-based humanmade *meme*, completely tailored to the case study – The *Biomeme*.

Based on the above example, the to-be-designed shading system will be able to control diffuse radiation and glare, enabling external views and natural ventilation. The *Biomeme* has solar permeable and intersection action features that should be materialized through dynamic and morphological solutions. The shading system should privilege circular/ellipse patterns, as well as permeable, flexible, expandable, and lightweight materials, enabling intersection and tracking performative features.

This result expresses one of the goals of this thesis. However, it is important to say that these are architectural project principles that need to be validated through building behavior simulation. From the previous related experiences (Kine[SIS]tem'17 and PoC 1.0), the fundamental issue is that by applying the BSDM, users can improve their architectural propose to a more sustainable and efficient solution.

9.3 Artifact domain – Emulation process

The Artifact domain operates in the field of design and validation. The domain is divided into three progressive phases, *Generation*, *Simulation*, and *Prototyping*, leading the user through an *Emulation* process[3] (Figure 9.0:12).

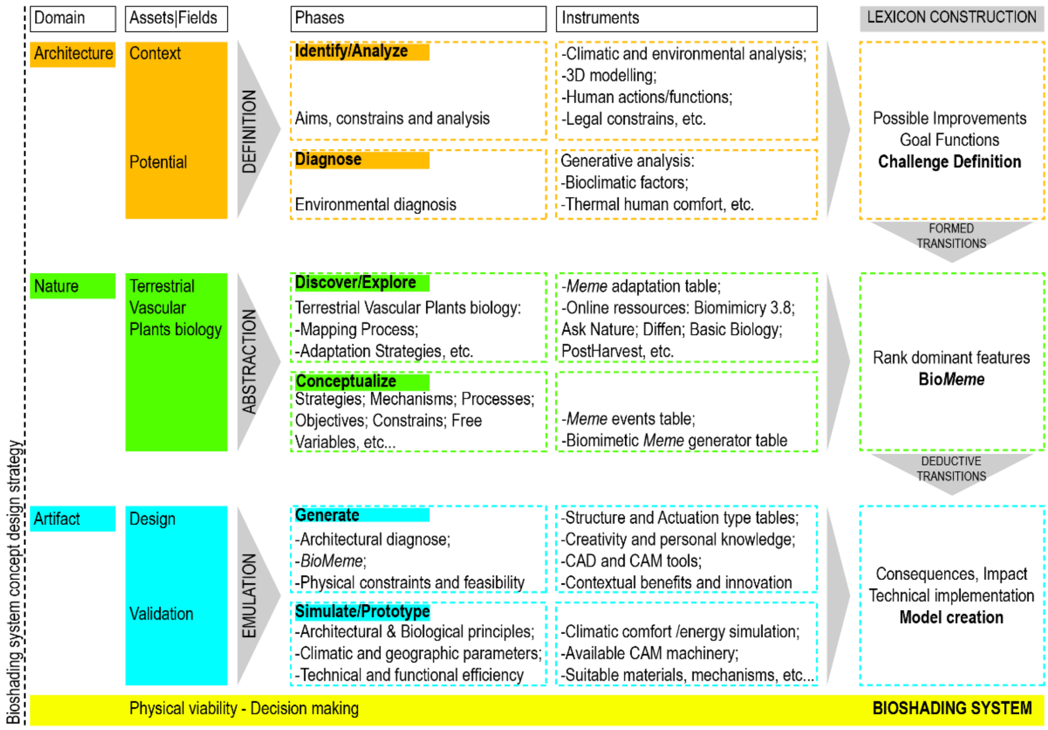


Figure 9.0:12. Bioshading System Design Methodology Strategy.

To go through the BSDM *Generate* phase, the user will need his/her previous architecture *Diagnose* and *Biomeme*. The *Generate* phase is one of the most personal and individual phases of the BSDM since it will depend not only on the semantic lexicon built up to this phase but also on the user knowledge and experience background. At this phase, it is expected that the BSDM user develops a design proposal for the shading system. To improve shading systems' responsiveness and physical viability, the BSDM provides to its users two instruments synthesizing the most relevant shading systems types of structures and actuation (Table 9.0:10 and Table 9.0:12) (see Section V, Chapters 7.1.4 and 7.1.5). Shading Systems Structures, Table 9.0:10, describes the five principle shading systems types of structures: open/close deployable and rotational structures, inflatable, flexible, and tensegrity. Shading systems actuation types, Table 9.0:11, describes the four most common types of actuation currently used for shading systems: motor-based, hydraulic, pneumatic, and material-based. Both tables list in each item a short description and its pros

[3]. This emulation process, more than imitate with an effort to equal nature biological events, aims to surpass its initial architectural diagnosis, by integrating physical constraints and potential.

and cons of application. In the type of structures (Table 9.0:10), possible actuation clues are also listed, while in the actuation table (Table 9.0:11), required resources and knowledge are referred. During the *Generate* phase, the BSDM user should consider both structural and actuation types, in order to anticipate and solve possible physical constraints of the shading system design model.

Table 9.0:10. Shading Systems Structures.

Type of structures	**Short description**	**Pros**	**Cons**	**Possible actuation**
<u>Open/Close structures</u> *Deployable sequences 2D – cylindrical scissor joint*	The structure is double-layered, of identical but inverted flat discs, made of curved plates which open in sequence reminiscent.	This type of structure has no gaps when closed and forms a perfect circle when open; It could function in a sandwich system.	The structure needs additional space, to expand - this expansion will trigger a structural overlap over the façade, inducing a sub sequential shading; Each cell of the system is composed of several units; if one fails, the entire cell will block; Friction of elements Highly maintenance; Needs its own structure.	These types of structures are usually performed by motor-based actuation; Hydraulic is also a possibility.
<u>Open/Close structures</u> *Rotation*	Actuation happens in the tridimensional space – usually, rotation occurs on the Z-axis, and the pattern elements/units could rotate between 0º to 360º; Rotation could also perform freely through autonomous units – eyes.	Usually, translated into monolayer structures, these elements could assume different shapes; These systems could be applied outside or inside the façade system; Patterns could close without gaps or could overlap; These systems are a synchronization of the unitary movement of its units; if one fails, the system could still perform.	This type of shading requires to be 24/7 updated - as the elements can rotate 360º, and are flat, they need to monitor the solar rotation on a daily basis, in order to minimize the entrance of heat/light in the summer and to facilitate the gains of heat/light in the winter; These systems are usually vulnerable to the external or internal environment elements; Needs its own structure.	
Continue...				

Type of structures	**Short description**	**Pros**	**Cons**	**Possible actuation**
Inflated	Inflated, also called pneumatic structures, could fulfill large areas with volumetric cushions.	Very versatile and highly durable; Fast erection and lightweight; Could achieve large areas and volumes; Although PVC is still one of the most used materials in this type of system, other more sustainable, such as ETFE, with properties at the level of solar gains, have been developed;	Requires its own structure; The manipulation of the air could be done through numerous techniques; After being inflated, super-pressured structures require a constant flow of air in order to maintain the shape of the envelope in its deployed state; The air intake duct creates permanent background noise.	Pneumatic Actuation; Inflatable structures could also result from the combination of pneumatics and tensegrity; Material-Based - recent material advances have developed 'smart-materials' with the same capacities, yet still scale limited.
Flexible	Due to its semi-rigid components, these structures may flex in defined directions; It is a deformable typology that undergoes deformation in a fluid and controlled manner.	This type of systems could cover large areas, using retractable structures; Multilayered compactable structures; Could accommodate rotation, translation, and linear movements;	Needs independent structures, and accurate mechanisms; These systems are usually vulnerable to the external or internal environment elements; Depending on its mechanisms, generally, these are heavy structures; Flexibility is provided by elastic materials.	Motor-based are the most common and explored actuation in these structures; Hydraulic; Pneumatic is less common in these types of structures, however, combined with motor-based actuation some retractable air-inflated experiences have been conducted; Material-based.
Tensegrity	Is a structural principle based on a set of discontinuous components in compression that interacts with a set of continuous tensile elements that are prestressed, thus generating stiffness in the structure while creating a stable volume in space.	Free-form expression, versatile and lightweight; Since the compressive elements are disjointed, this provides the possibility to fold these members , and hence the structure can be compactly stowed; These structures follow the principle of movability.	Tensegrity systems are limited due to the difficulty of controlling them at every stage of deployment; Usually exhibiting complex structural structures – mechanics and lots of joineries; These systems are habitually vulnerable to the external or internal environment elements;	Motor-based; Hydraulic; Manual

Table 9.0:12. Shading systems actuation types.

Actuation type	**description**	**pros**	**cons**	**required resources, knowledge**
Motor-based Between layers	- Motor-based actuation system, usually automated, can reduce glare and solar heat significantly with a BMS (building management system) that tracks the Sun's position and monitors light conditions.	- One-layer provides protection from the outside elements while the other protects from potential damage or interference with its operation	- Maintenance of the different units/elements could be conditioned by the space and the type of sealant between layers - High energy consumption demand	- Common mechanical knowledge
Motor-based Exterior		- Easier to carry out maintenance over the different units/elements	- Exposed to the external elements - Matter could get into mechanisms, causing malfunction - Shorter lifespan of the system - High energy consumption demand	
Hydraulic	- Confined pressurized systems that use moving liquids	- Liquids are not very compressible; there is no delay in the movement - Could be applied to a variety of actuations such rotation, linear movement, compression, etc.	- Uses several non-sustainable or recyclable liquids, like mineral oil, ethylene glycol, synthetic types, or high-temperature fire-resistant fluids to make power transmission possible.	- Advanced knowledge in Physics, Mechanics, and Electronics.
Pneumatic	- Confined pressurized systems that use moving air and other gases - Currently, the most sustainable solution to reduce heat gain by using lightweight ETFE air cushions	- Easily-compressible gas, like air or pure gas - Only need a compressor - Power: pneumatics uses pressures ranging from 36–45 Kg per each $6cm^2$	- Because gases can be compressed, there is a delay in the movement/force - Requires periodical maintenance - Requires a separate support system	- Average knowledge in Physics, Mechanics, and Electronics.
Material-based	- Smart materials – crossing different material properties, by adding features and characteristics from other materials and/or organisms	- Usually, this type of actuation generates low-energy systems - Capacities are built into the material, eliminating the need for complex mechatronic assemblies	- So far, unknown	- Large research team: material, physics, and chemical know-how. - Laboratorial resources

As soon as the design model is mature, digital *Simulation* is required (Figure 9.0:13). By simulating the environmental performance of the building with the new shading solution in place, the BSDM user will be able to identify unsolved issues, and also to adjust and improve the designed solution. *Simulation* aims to validate the BSDM user's design decisions as well as to evaluate the design solution's performative/responsive capacity. It is strongly recommended that this phase is conducted through parametric tools in order to optimize the relationships between the environmental context, the shading system design solution, and the time/production of the design proposal. This optimization will impact the final cost of the shading system's implementation as well as the building energy cost at medium/long-term.

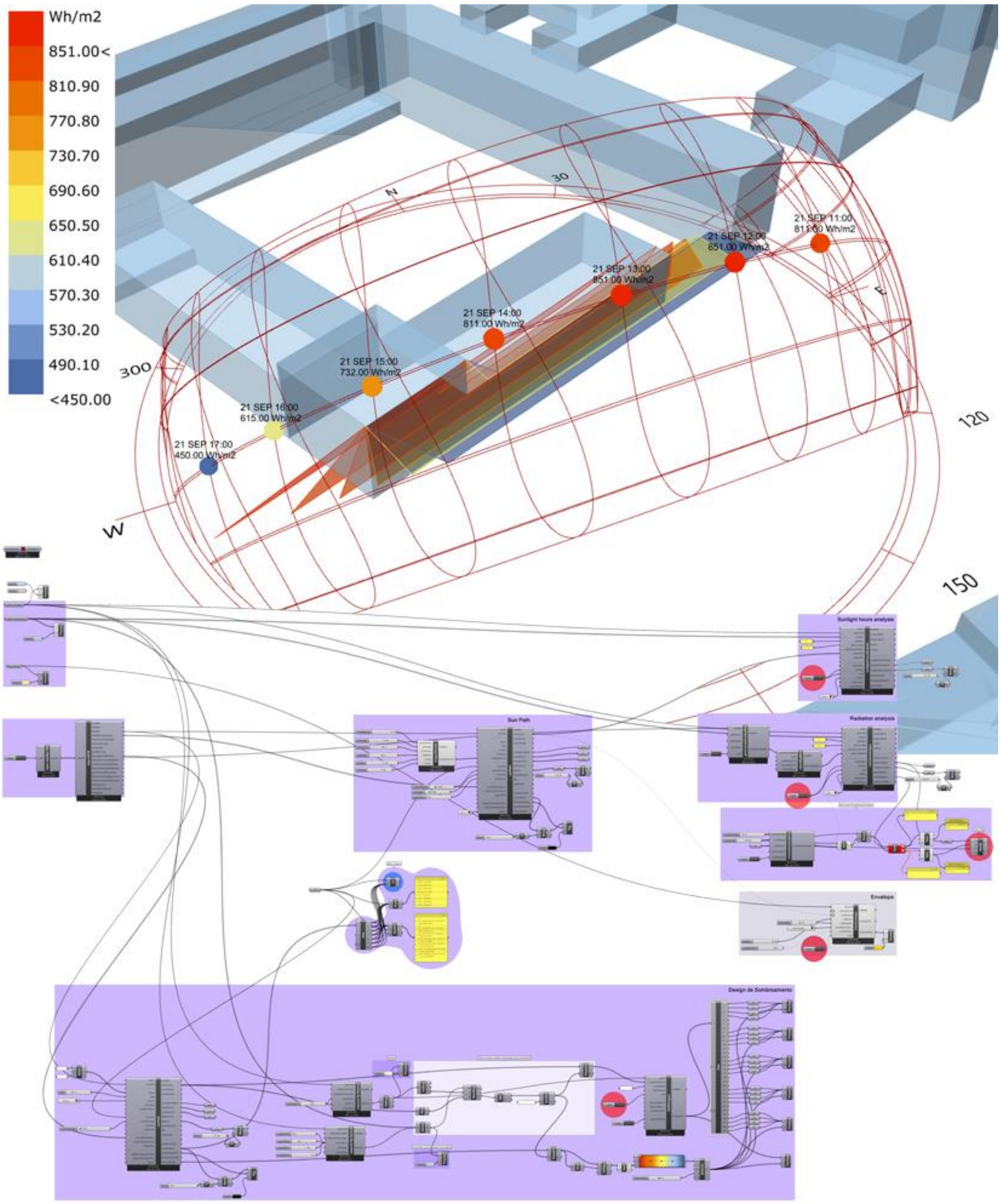


Figure 9.0:13. Shading system example: Ladybug analysis proposal.

The last phase of the BSDM is *Prototyping*. Not all of the possible problems and constraints are predictable and solved through digital *Simulation*. Materiality, fabrication, assembly, mechanics, and even knickknack objects only become a tangible issue when we start considering building something (Figure 9.0:14). To many, this may be a common statement, but it is important to emphasize it.

Figure 9.0:14. Kine[SIS] tem'19 prototype: stages of construction.

In the initial phase of *Prototype*, the designer has to consider the shading system's subdivision of the parts. In order to do this, it is essential to plan the several fabrication steps, considering the materials to be used and the necessary machinery to cut or build the several components of the shading system. The primary step is to unfold the designed solution, find its main joints, and plan its global assembly – firstly, considering the materials to be used, possible fittings, connection elements, and its structural integrity. After this previous task, it is necessary to develop a strategic plan for the different elements. Depending on the size of the available machinery and the size of the material to be fabricated, the shape and scale of the several shading system elements may vary as well. After fabricating the various pieces, it is necessary to finish and clean them. Only then, the assembly task can begin. By assembling the several pieces that compose the elements, the designer will find possible improvements, but most of all, he/she will be able to fully understand the potential and the weaknesses of the designed and produced elements. When the elements are ready, the assembly of the prototype and its potential mechanical implementation begins. Loads of information can be extracted from this task, such as design improvements, mechanical constraints, and its potentially better integration, operability, and forecast durability of the system, performative benefits, among other aspects.

It is evident that the final prototype is essential, but the most important thing for the BSDM is the richness of the information extracted and the experience assimilated in this phase, and that is why it is crucial for the success of the methodology. At the end of this phase, BSDM users will be capable of looking, analyzing, (re)configuring and improving their shading solution in a way that would not be possible had they not completed this phase. This enables the BSDM user to revisit the path of the methodology through its phases, now with a more accurate and critical sense, enabling it to be adjusted and reprogrammed. The final product is only ready when the designer has traveled all domains and respective phases fluidly, finding no flaws or deviations from any of the established principles.

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SECTION VII
SUMMARY

10.0
Contributions

10.0 CONTRIBUTIONS

10.1 Introduction

In the following chapter, we revisit the thesis' theoretical and methodological contributions. The implications of these contributions are considered in the context of architectural design training, research, and practice. Motivated by the desire to consider and to integrate the possible future contributions of the biomimetic field into sustainable design, the orientation of this research investigation was to propose a biomimetic design methodology as a means to achieve a novel shading systems design methodology based on terrestrial vascular plants' specific biological events.

Common to these contributions is the demand to promote a potentially sustainable design approach, inspired by terrestrial vascular plants, that supports the negotiation of multiple criteria (architectural uses, building inhabitants requirements, shading system functions, local solar radiation properties, etc.) in the several phases of the shading system design process. This design methodology has been coined by the author, Bioshading System Design Methodology.

The theoretical contributions refer to a body of research, experiments, and evaluation of the application of the methodology domains informed by their corresponding phases and progressive transitions. The keygen of the methodology is the *Biomeme* (created during the Nature domain abstraction process), informed by the architectural domain challenge definition and materialized through the artifact domain emulation process. *Biomeme* is viewed here as the enabling theoretical and technical approach for the Bioshading System Design Methodology.

Finally, the methodological contribution culminates with the creation of a step-by-step task path, informed by a three-domain circular board - Architecture, Nature, and Artifact - that guides its user through the several methodology phases and processes. The processes and their progressive transitions are sustained by several produced survey tables, diagrams, and path matrix to improve methodology user accuracy, time optimization, but most of all, individual user knowledge and creativity input.

10.2 Revisiting research questions

“How to develop architectural shading systems mimicking the adaptation strategies of terrestrial plants?” was the main addressed question of this research investigation. In order to answer it, four sub-questions were addressed and discussed throughout the previous chapters.

“What are the main advantages and gaps found in the current biomimetic design methodologies?". This is the main question addressed by our investigative research. Biomimetic design methodologies are being implemented in different fields of study at different scales. From the materials' chemical and physical composition micro-scale to the car industry's macro scale, biomimetic field has proved to be efficient and prolific. In the architecture field, problem-based methodologies are largely used for its objectiveness and easier relation with architectural goals. Usually applied at very early stages of the design process, biomimetic strategies are usually the inspirational kick-off for the design generation. However, in the architecture field, biomimetics approaches mainly focus on one single part rather than the whole of the design process. This lack of integration through the complete design process, weakens the projects' biomimetic intentions and roots, ending its influence in the conceptual phase of the design process.

The following question was, “*What are the shading systems' fundamental functions which fulfill the demands and the requirements of its inhabitants?".* This question was aimed to inform the methodology with the essential shading systems' parameters as its main performative functions. The shading systems' fundamental functions that best suit building inhabitants demands and requirements, are: direct radiation – by controlling its entry and blockage; diffuse radiation – by regulating the amount of light inside the space; glare control – regulating and improving visual comfort and daylight transmission balance; external views connection – by providing inside/outside visual contact; natural ventilation – by likely enhancing the air quality mediating natural ventilation through the façade; and an effective and global architectural integration.

After this, it was necessary to study and interpret vascular terrestrial adaptations strategies. "*What are the fundamental types of adaptation strategies and its categorization found in terrestrial vascular plants for implementation in shading systems?".* Found in Nature, the fundamental adaptations strategies are morphological, behavioral, and physiological. Morphological adaptations are the study of form, composition, and structure of the living organism. Physiological adaptation is a chemical process in response to an external stimulus that occurs inside the living organism in order to reestablish its homeostasis. Behavioral adaptations could be internal or external body actions or changes that an organism performs in reaction to an 'attack' to its overall integrity. Different adaptation strategies events can pursue two different strategies categorization: dynamic and static. Plants' dynamic systems respond to external physical stimulus, while static systems correspond to an internal response to an external stimulus.

The final research question was*, "How to translate and represent the plants' identified adaptation strategies into architects' design lexicon?”* Terrestrial vascular plants were studied from its micro to macro events, organs, and microsystems. Species, shapes, structures, organs, chemical processes, among other plant lexicons, were considered and organized in three adaptation tables and named as plant events. The developed Plants Adaptation Strategies tables are composed exclusively of three fields – designation, description, and cause/intention. Designation refers to the name of the plant event. Description, accommodates a short description of the event, avoiding excessive adjectives. Cause/Intention provides a simplified description of the possible cause/intention of the event. This survey, in text only, aims to instruct the methodology user so to avoid excessive figurative information. The images of the plant's events should be created and raised in the methodology user imagination – this is the moment of creation of the meme.

The presented methodology was conceived as a scheduled script. Divided into three main domains (architecture, nature, and artifact) with defined goals and outputs, each of the domains is constituted by three consecutive phases that promote a more structured, guided, and hierarchical information transition between the phases and the domains. BSDM presents to its users as a board game. The first two essential elements are the main strategic diagram that informs the BSDM user of the path that he/she will have to cover, and the BSDM concept design strategy that informs the methodology user about the fields of study, available surveys, potential instruments, formed and deductive transitions, and the global progression of the lexicon construction. For the architecture domain, the BSDM provides to its users shading systems functions, actions, and agents' tables. At the nature domain, *Plants adaptation strategies* – morphological, physiological, and behavioral tables are supplied, and at the artifact domain, *Shading Systems Type of Structures* and *Actuation Types* tables are also available to the BSDM users. None of the supplied material could be considered closed. This means that the BSDM user should use them as a work basis but should feel free to updated and enrich the supplied database.

10.3 Advantages and Limitations

The developed design methodology entirely covers the architecture conceptual design process. From the challenge definition, through analysis and diagnose, the abstraction through the conceptualization of a biomimetic meme, to the physical model creation, BSDM is a complete design methodology process that could be applied at academic and professional levels.

The presented work provides a selection of representative plant adaptation *events* based on a limited number of examples. At the moment, this limitation is filled by the available online resources. However, from the PoC 1.0 experience, the provided *Plant Adaptation Events* tables database are simpler and faster resources that BSDM users may find adequate. To raise a more elaborated and complete database, a more extensive collaboration with professionals of numerous areas will be required. Considering a more extensive database and since nature is always evolving and updating, it will be necessary to update constantly.

To correctly apply the BSDM, it is strongly recommended that the user has some basic knowledge about digital fabrication tools as well as access to this type of machinery. This will enable a more facilitated and efficient connection between the design and the physical model. Technical implementation will also be facilitated by improving the success rate of the artifact.

10.4 Potential Future Work

BSDM's last phase is the creation of a physical model. Some clues for its evaluation are provided; however, the presented methodology lacks a validation script.

The presented design methodology focuses on shading systems, terrestrial vascular plants, and physical condition for testing and as 'life proof'. However, several experience stages revealed some new pathways on a possible BSDM transformation/adaptation to other architecture functions. One of the future experiences could focus on the application of the design methodology, based on different architecture parameters, by replacing the shading system functional parameters.

10.5 Summary

This research investigation presented a shading system biomimetic design methodology, developed on a problem-based approach, termed by the author, Bioshading Systems Design Methodology. The new design methodology had as theoretical and methodological support, the combination of three complementary fields of study – Architecture, Biology, and Digital tools. This combination was designed to lead the BSDM user to the creation of more efficient and environmental responsive shading systems. Along the way, the most significant of the three fields of contribution was the dissolution of disciplinary boundaries and the creation of meaningful, rock-solid, open connections between architecture, biology, and digital tools. The transdisciplinary openness bridge condition granted the creation of a common lexicon that enables the creation of the *Biomeme* – the inspirational humanmade biological *meme* that provides the fundamental characteristics for the shading system, and also an easier and more efficient technical implementation since it is had in account during the *Biomeme* generation. Above all, BSDM has an open boundary condition. Based on a transdisciplinary lexicon, the presented methodology can potentially integrate other fields of study or adapt its initial architectural premises in order to create another tailored biomimetic design methodology.

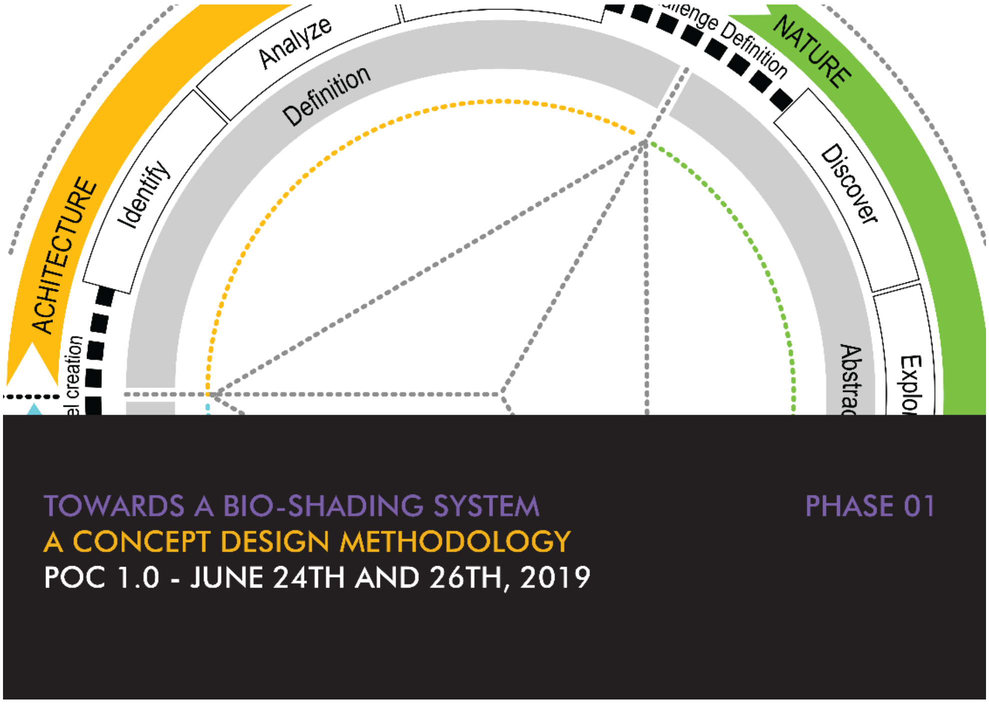
11.0

Annexes

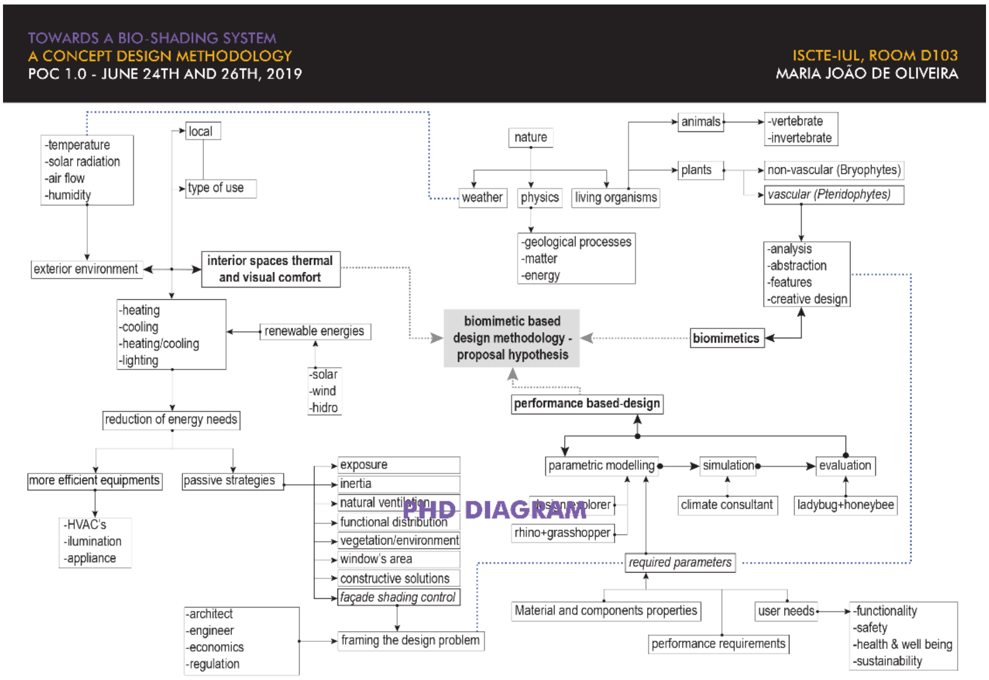
11.0 POC 1.0 DIGITAL KIT

11.1 PoC 1.0 presentation

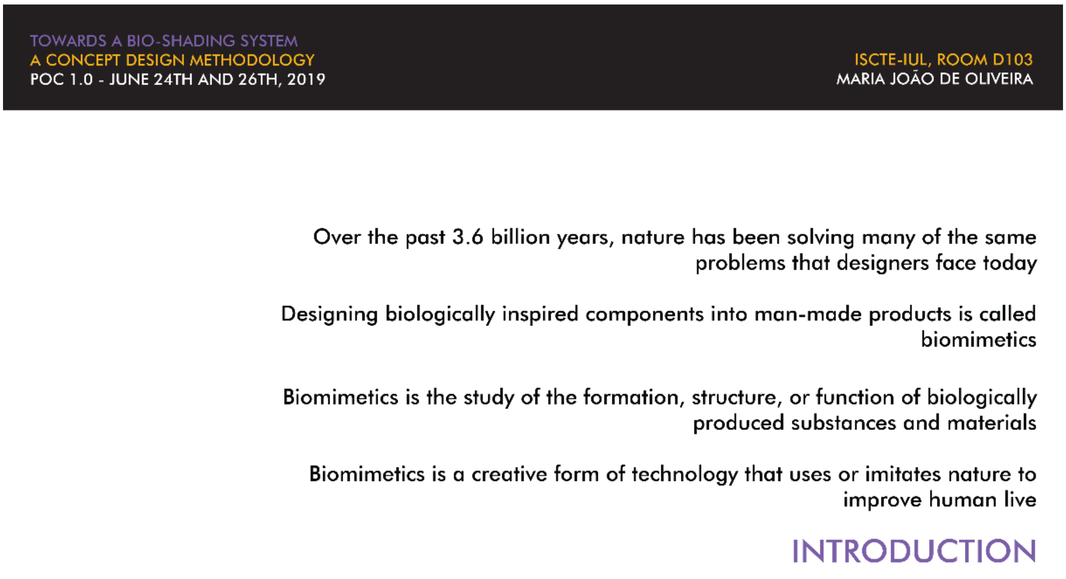
11.1.1 PoC 1.0 presentation (1st Session) – projection support



Slide 11.0:1. PoC 1.0 presentation: Cover.



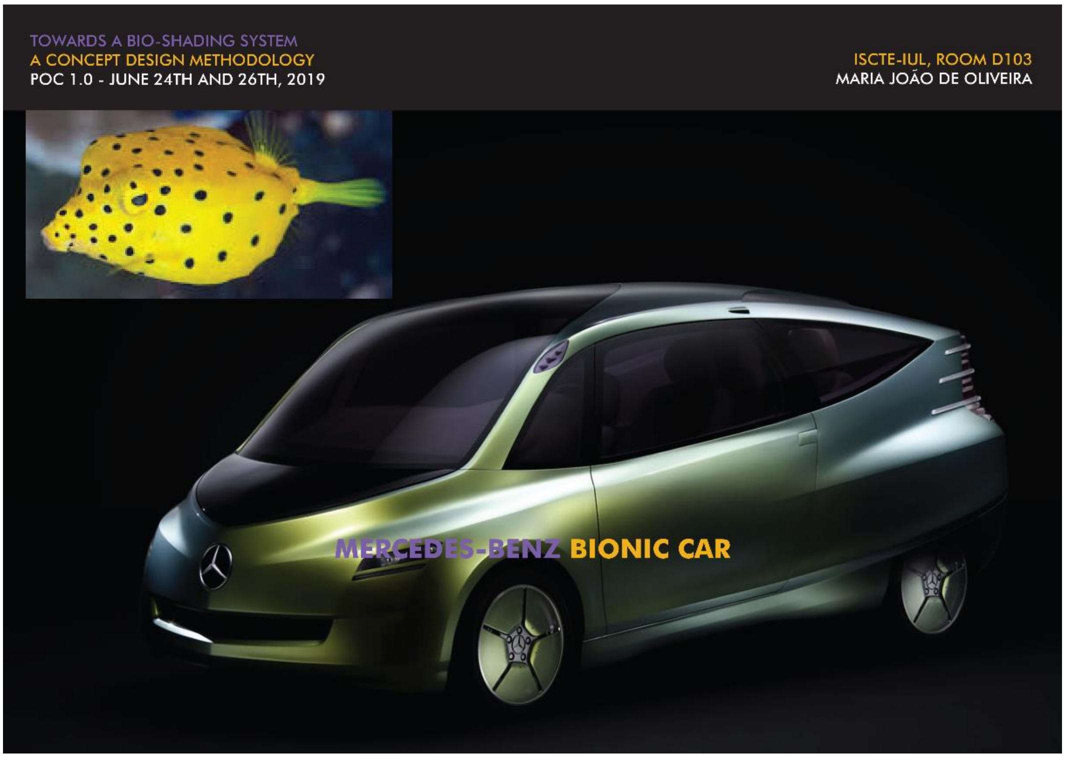
Slide 11.0:2. PoC 1.0 presentation: PhD Thesis propose.



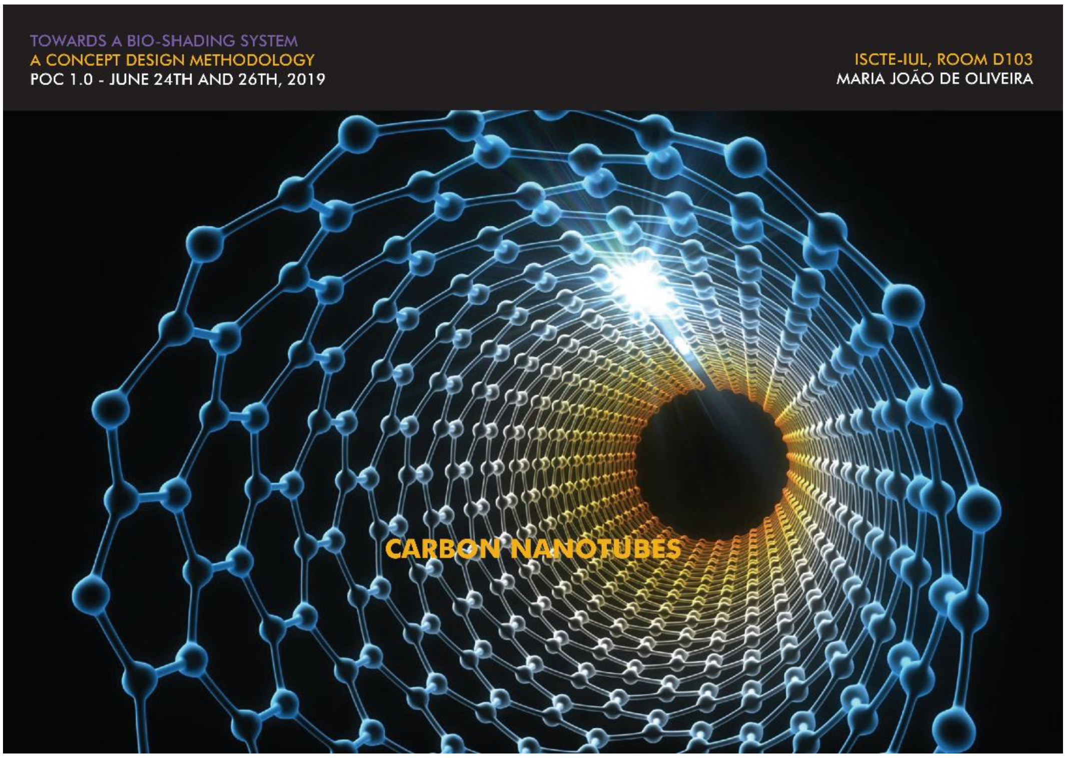
Slide 11.0:3. PoC 1.0 presentation: Introduction.

Slide 11.0:4. PoC 1.0 presentation: The Codex.

Slide 11.0:5. PoC 1.0 presentation: The Wright Brothers Airplane Flight.

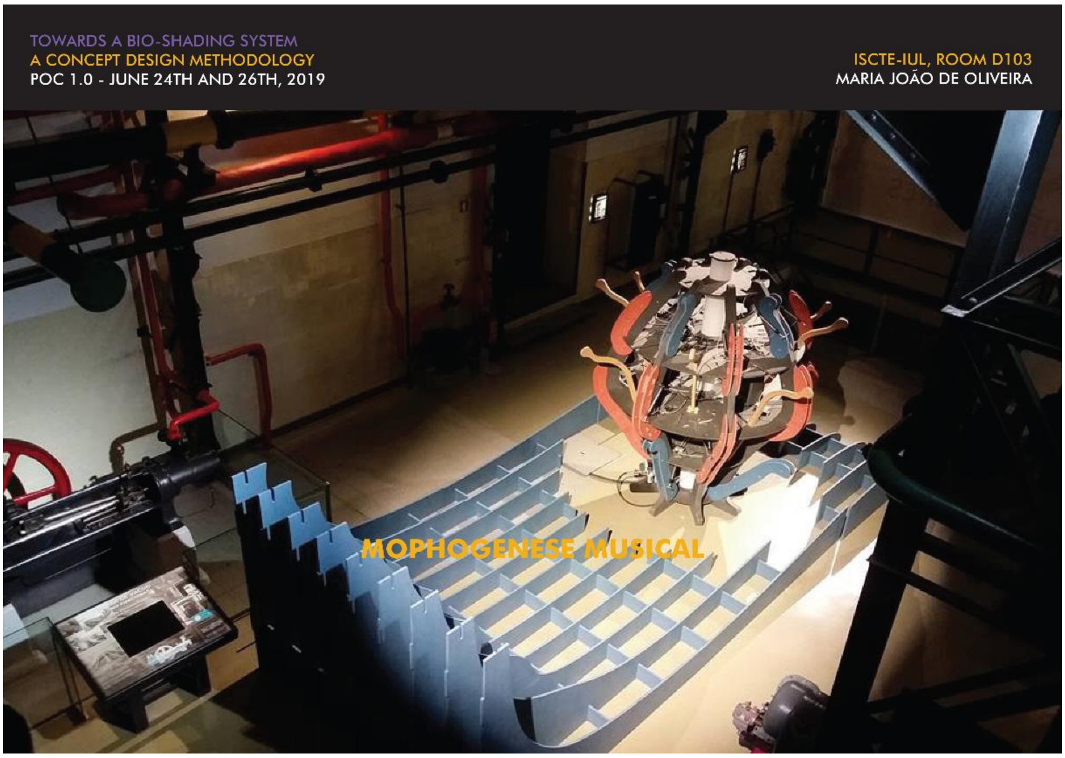


Slide 11.0:6. PoC 1.0 presentation: The Mercedes-Benz Bionic Car.



Slide 11.0:7. PoC 1.0 presentation: Carbon Nanotubes.

Slide 11.0:8. PoC 1.0 presentation: The Eden Project.

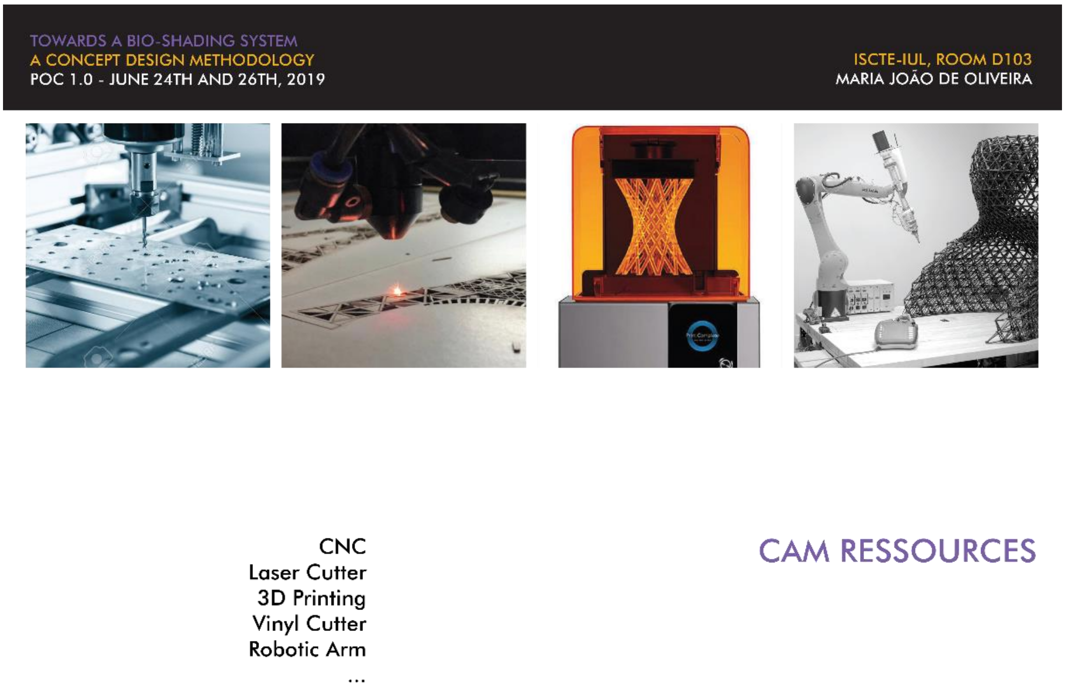


Slide 11.0:9. PoC 1.0 presentation: Musical Morphogenesis.

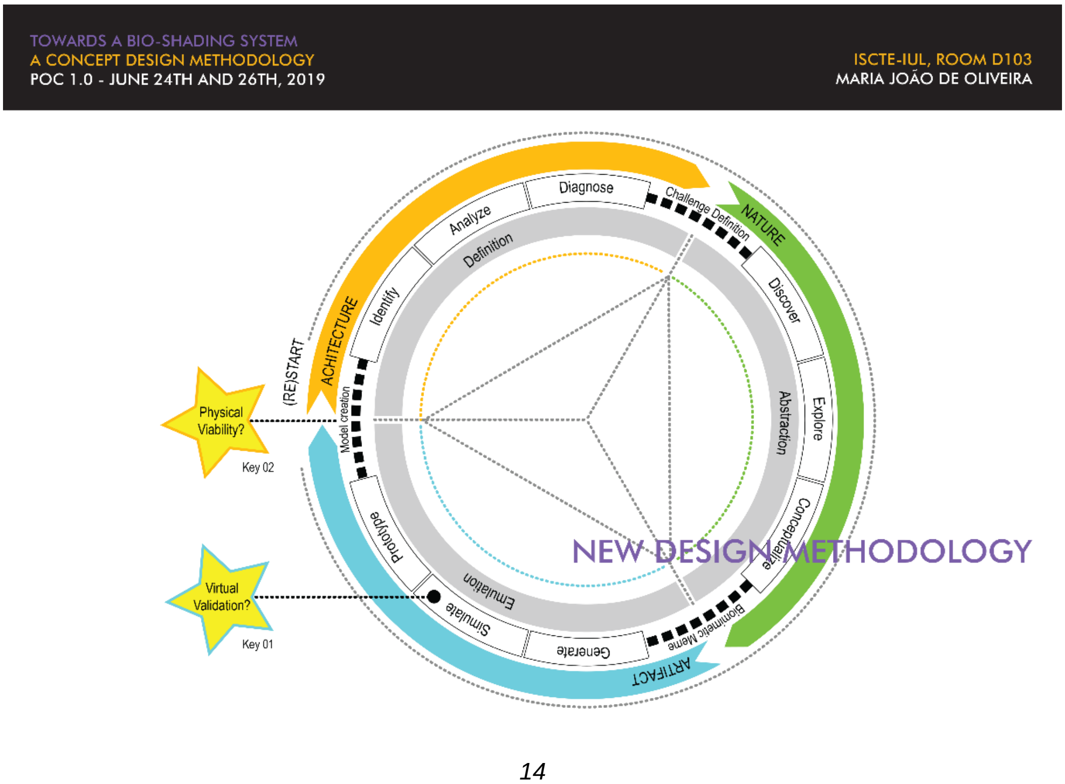
Slide 11.0:10. PoC 1.0 presentation: The Hylozoic Series.

Slide 11.0:11. PoC 1.0 presentation: Current Design Tools.

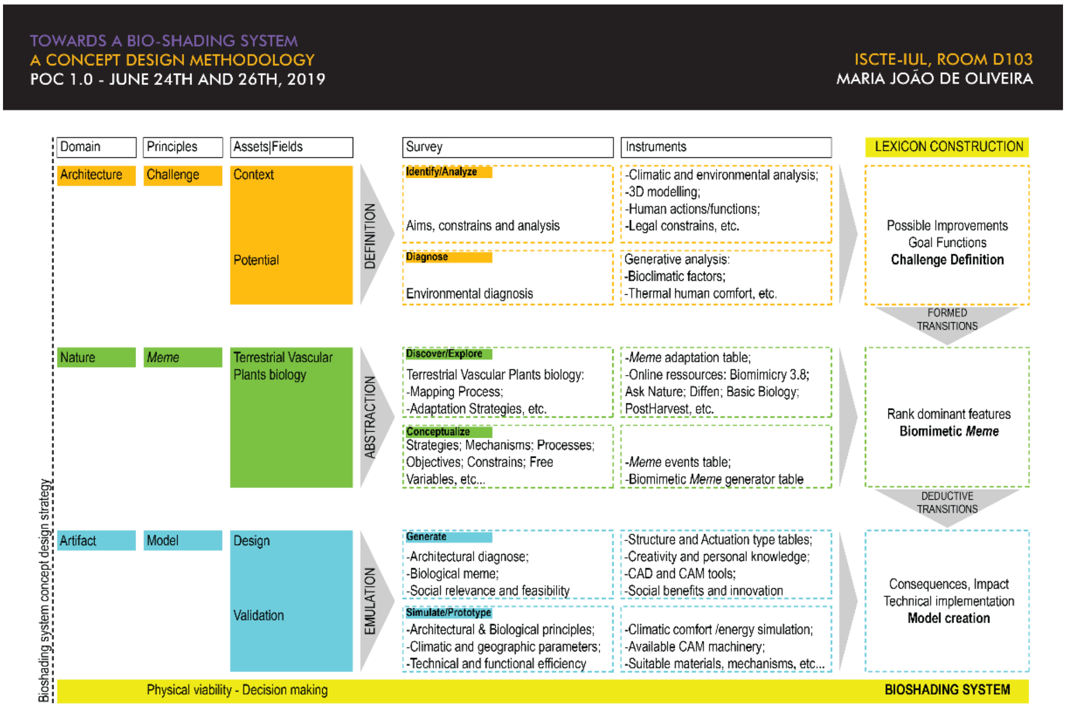
Slide 11.0:12. PoC 1.0 presentation: Analysis Design Tools.



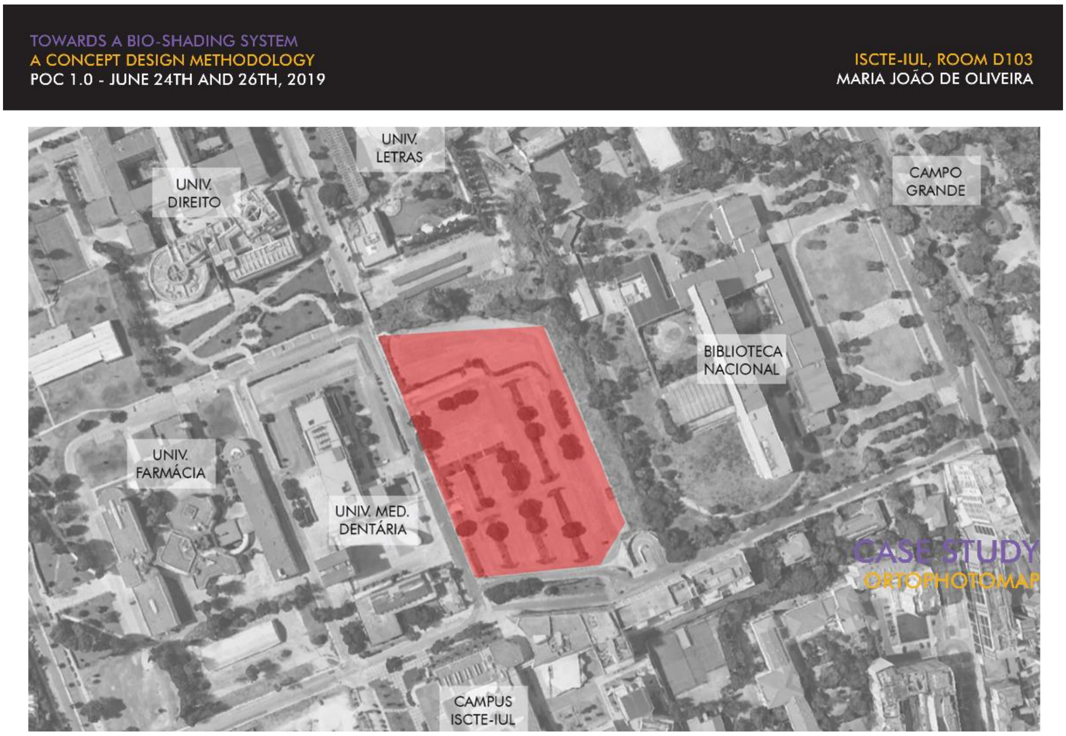
Slide 11.0:13. PoC 1.0 presentation: Computer-aided Manufacture Resources.



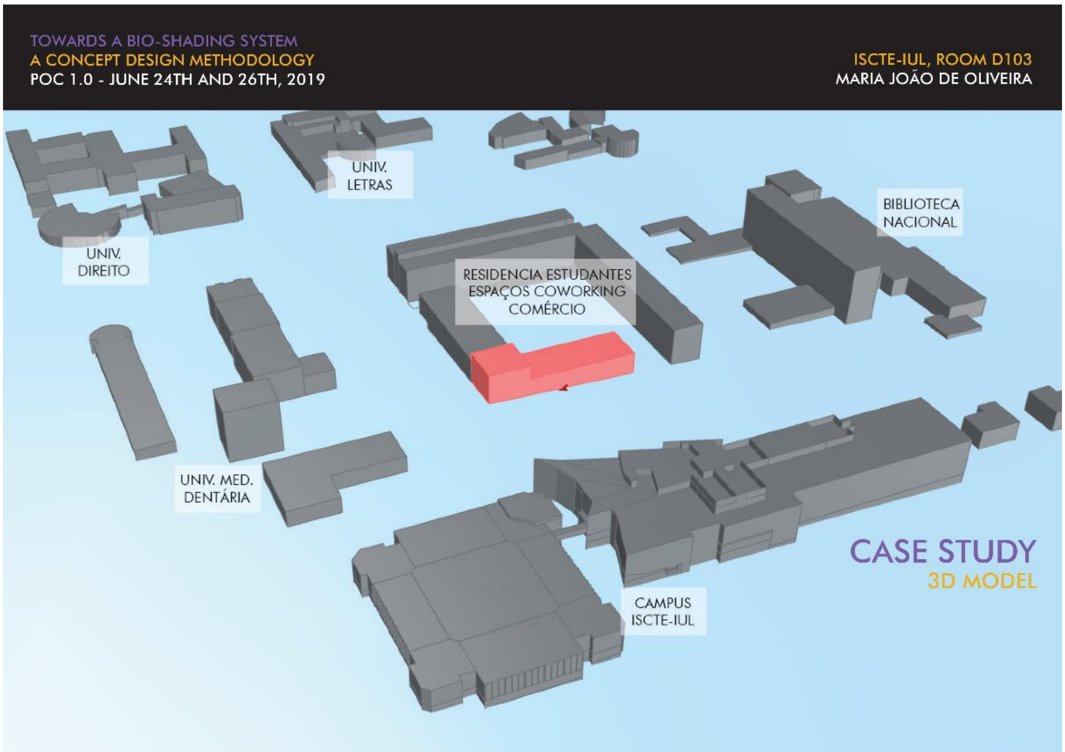
Slide 11.0:14. PoC 1.0 presentation: The Bioshading System Design Methodology fundamental Diagram.



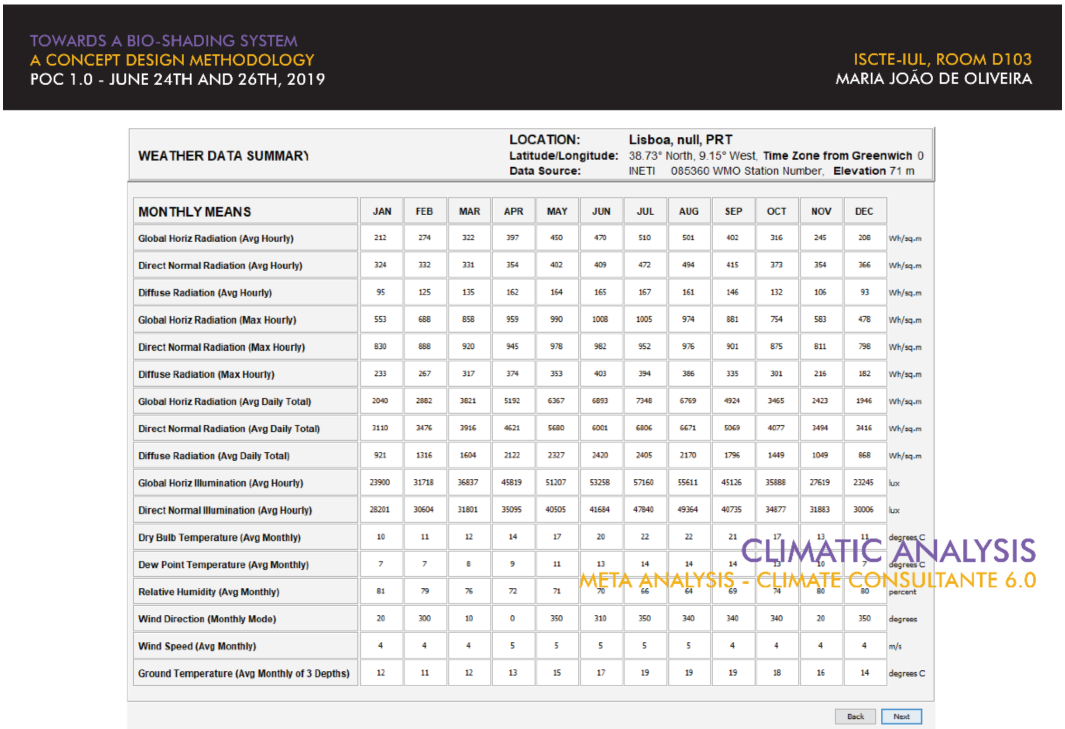
Slide 11.0:15. PoC 1.0 presentation: The Bioshading System Design Methodology matrix.



Slide 11.0:16. PoC 1.0 presentation: The intervention site location.



Slide 11.0:17. PoC 1.0 presentation: The case study building and its volumetric context.

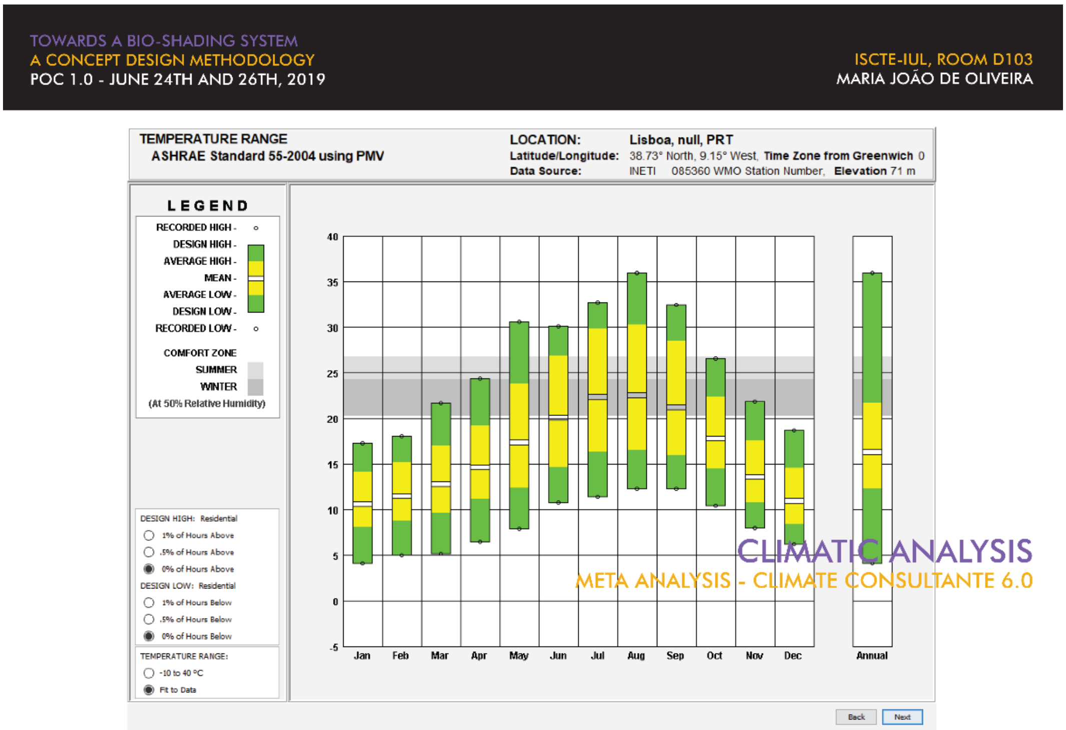


WEATHER DATA SUMMARY

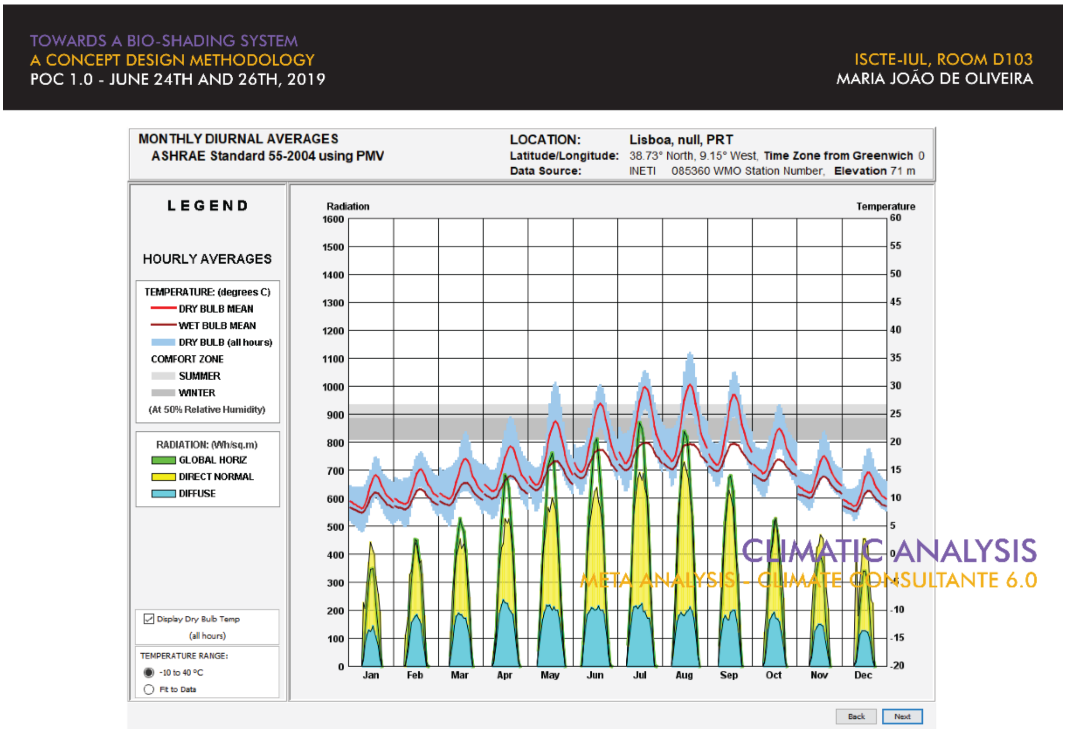
LOCATION: Lisboa, null, PRT
Latitude/Longitude: 38.73° North, 9.15° West, **Time Zone from Greenwich** 0
Data Source: INETI 085360 WMO Station Number, **Elevation** 71 m

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	212	274	322	397	450	470	510	501	402	316	245	208	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	324	332	331	354	402	409	472	494	415	373	354	366	Wh/sq.m
Diffuse Radiation (Avg Hourly)	95	125	135	162	164	165	167	161	146	132	106	93	Wh/sq.m
Global Horiz Radiation (Max Hourly)	553	688	858	959	990	1008	1005	974	881	754	583	478	Wh/sq.m
Direct Normal Radiation (Max Hourly)	830	888	920	945	978	982	952	976	901	875	811	798	Wh/sq.m
Diffuse Radiation (Max Hourly)	233	267	317	374	353	403	394	386	335	301	216	182	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	2040	2882	3821	5192	6367	6893	7348	6769	4924	3465	2423	1946	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	3110	3476	3916	4621	5680	6001	6806	6671	5069	4077	3494	3416	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	921	1316	1604	2122	2327	2420	2405	2170	1796	1449	1049	868	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	23900	31718	36837	45819	51207	53258	57160	55611	45126	35888	27619	23245	lux
Direct Normal Illumination (Avg Hourly)	28201	30604	31801	35095	40505	41684	47840	49364	40735	34877	31883	30006	lux
Dry Bulb Temperature (Avg Monthly)	10	11	12	14	17	20	22	22	21	17	13	11	degrees C
Dew Point Temperature (Avg Monthly)	7	7	8	9	11	13	14	14	14	13	10	7	degrees C
Relative Humidity (Avg Monthly)	81	79	76	72	71	70	66	64	69	74	80	80	percent
Wind Direction (Monthly Mode)	20	300	10	0	350	310	350	340	340	340	20	350	degrees
Wind Speed (Avg Monthly)	4	4	4	5	5	5	5	5	4	4	4	4	m/s
Ground Temperature (Avg Monthly of 3 Depths)	12	11	12	13	15	17	19	19	19	18	16	14	degrees C

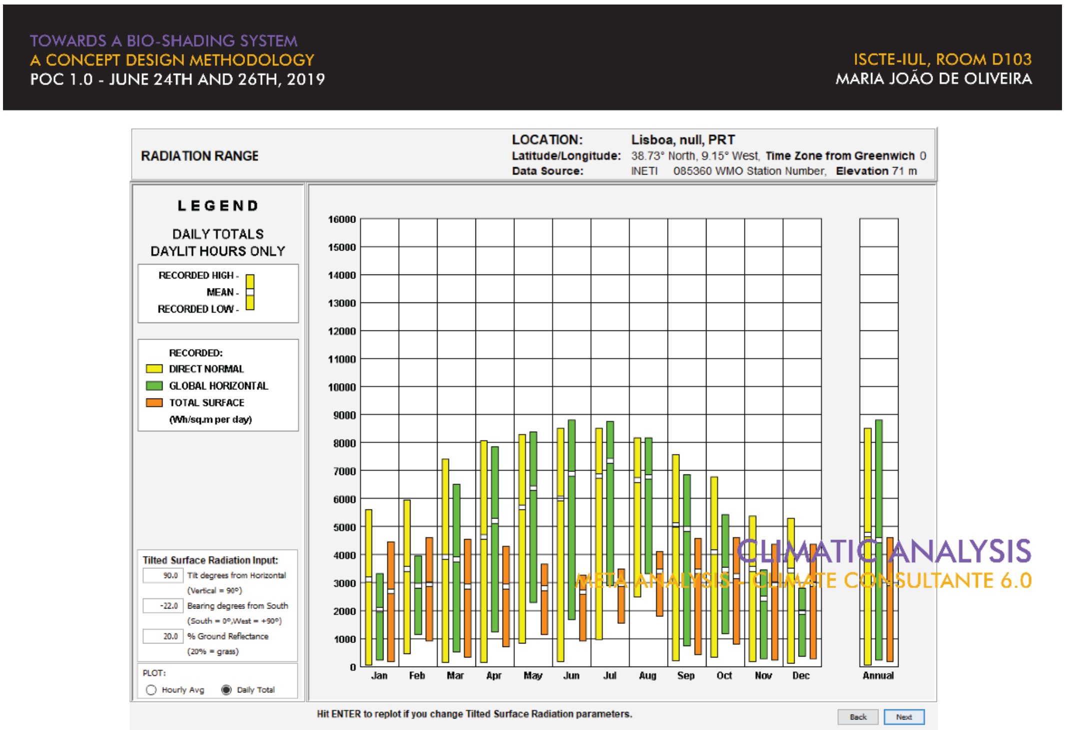
Slide 11.0:18. PoC 1.0 presentation: Climate Consultant 6.0 - data summary.



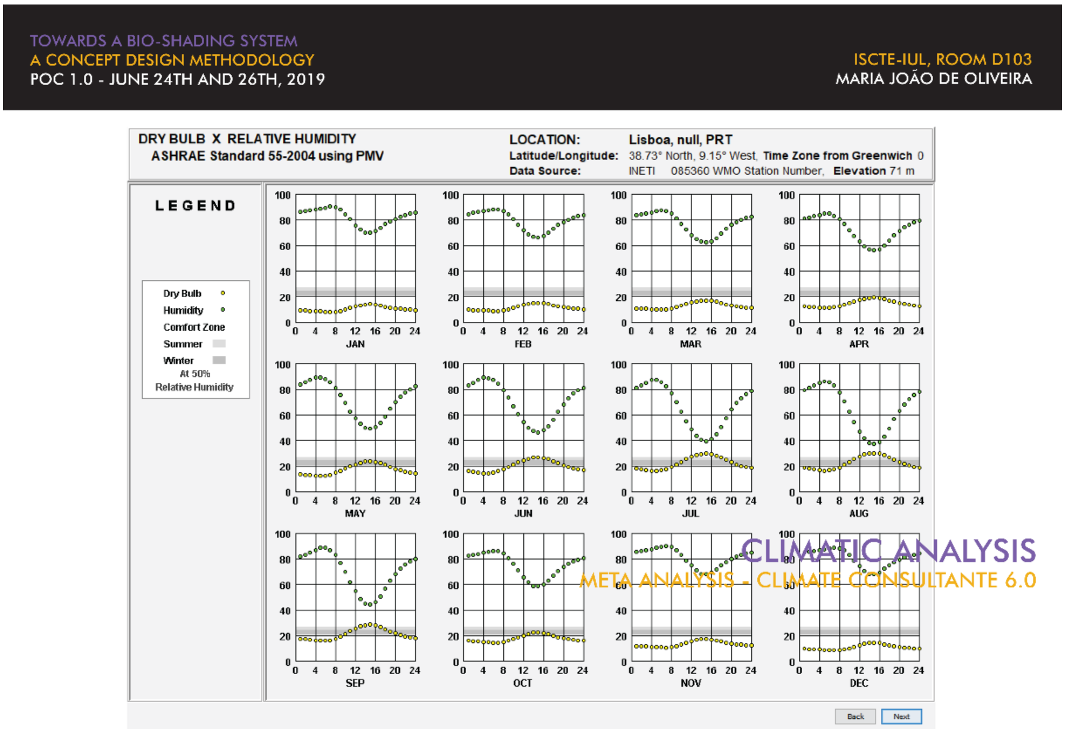
Slide 11.0:19. PoC 1.0 presentation: Climate Consultant 6.0 - data Temperature Range.



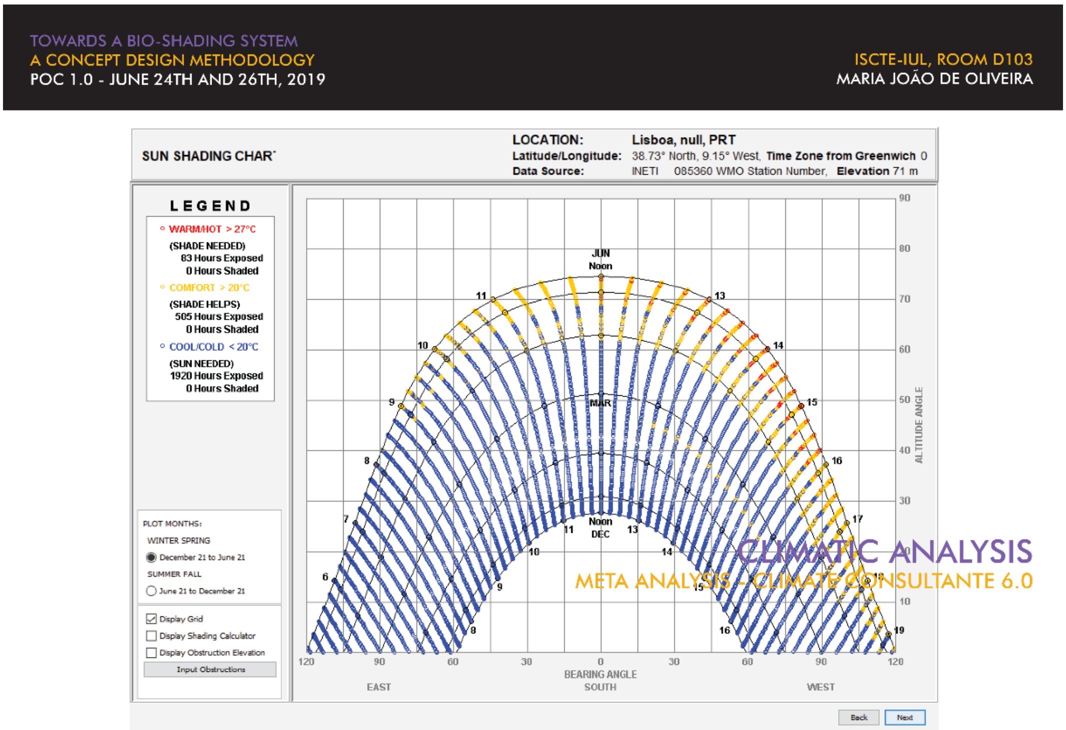
Slide 11.0:20. PoC 1.0 presentation: Climate Consultant 6.0 - data Monthly Diurnal Temperature Averages.



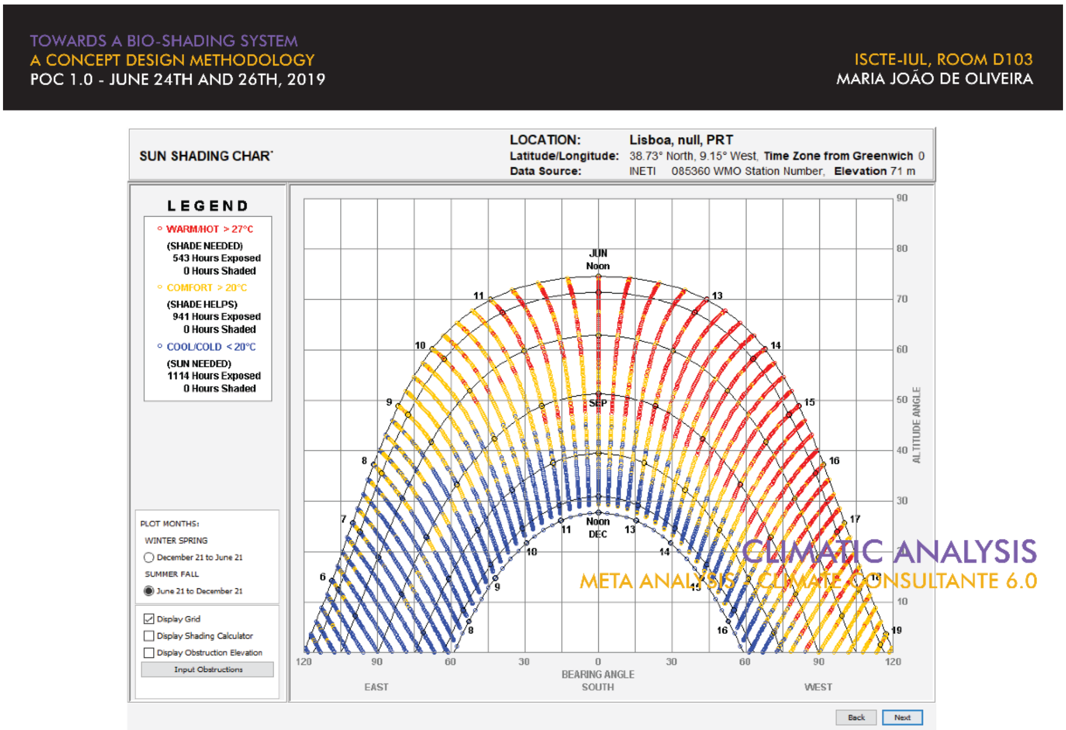
Slide 11.0:21. PoC 1.0 presentation: Climate Consultant 6.0 - data Radiation Range.



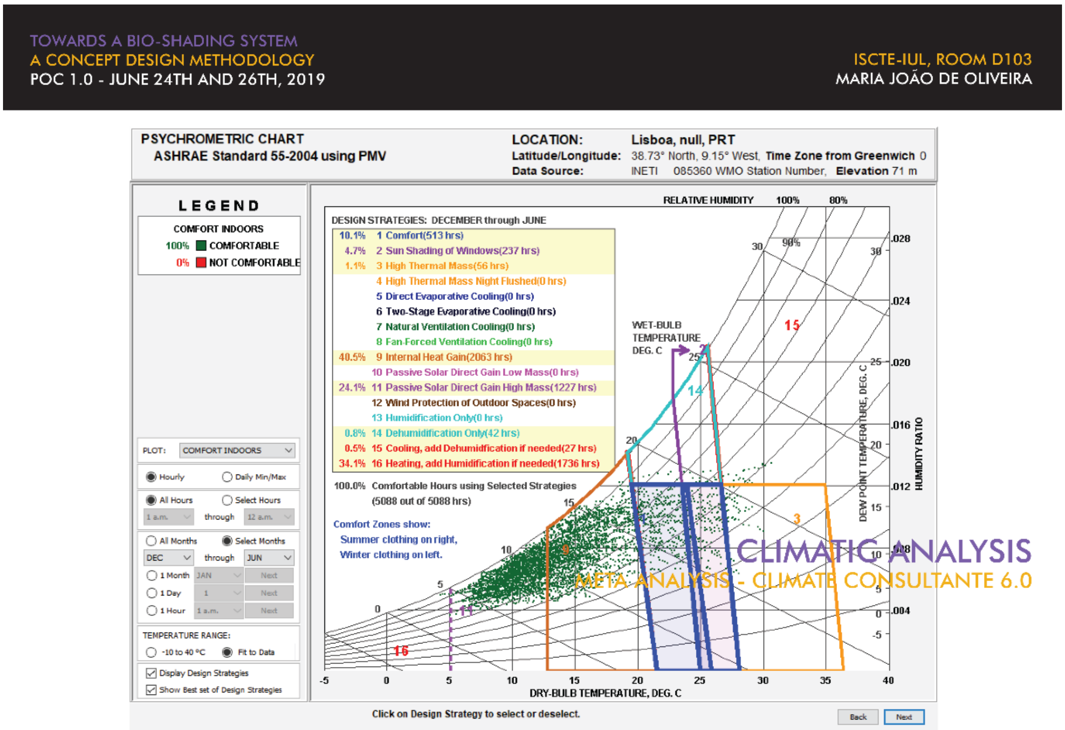
Slide 11.0:22. PoC 1.0 presentation: Climate Consultant 6.0 - data Dry Bulb vs Ralative Humidity.



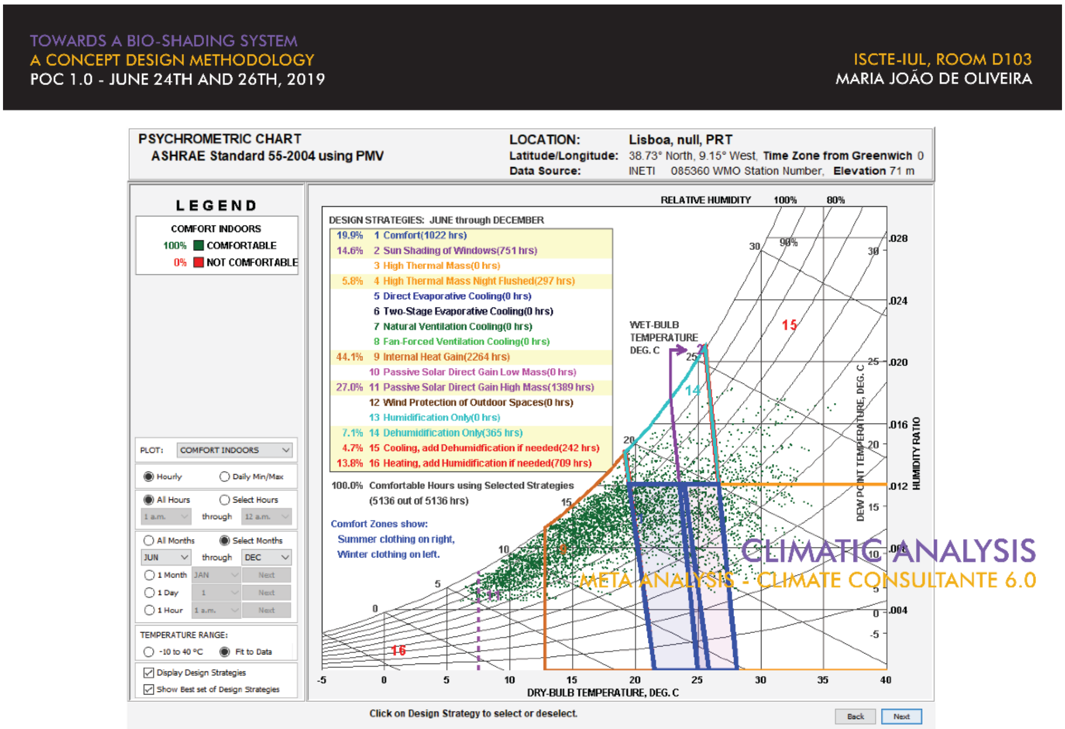
Slide 11.0:23. PoC 1.0 presentation: Climate Consultant 6.0 - data Sun Shading Chart – December to June.



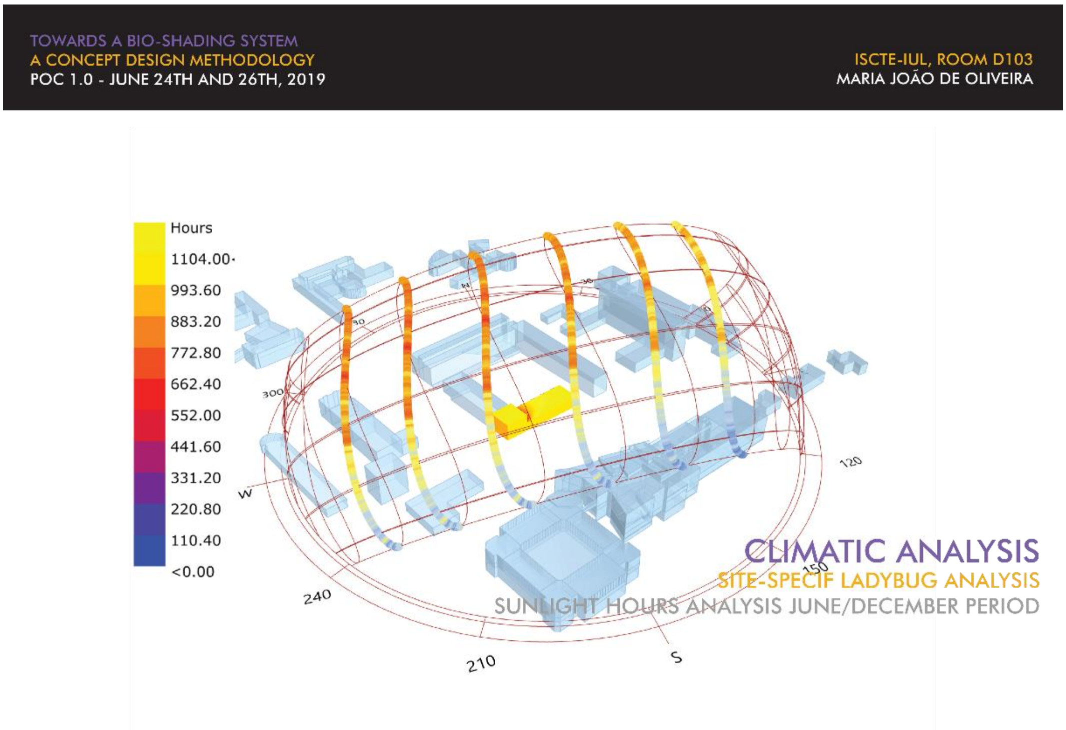
Slide 11.0:24. PoC 1.0 presentation: Climate Consultant 6.0 - data Sun Shading Chart – June to December.



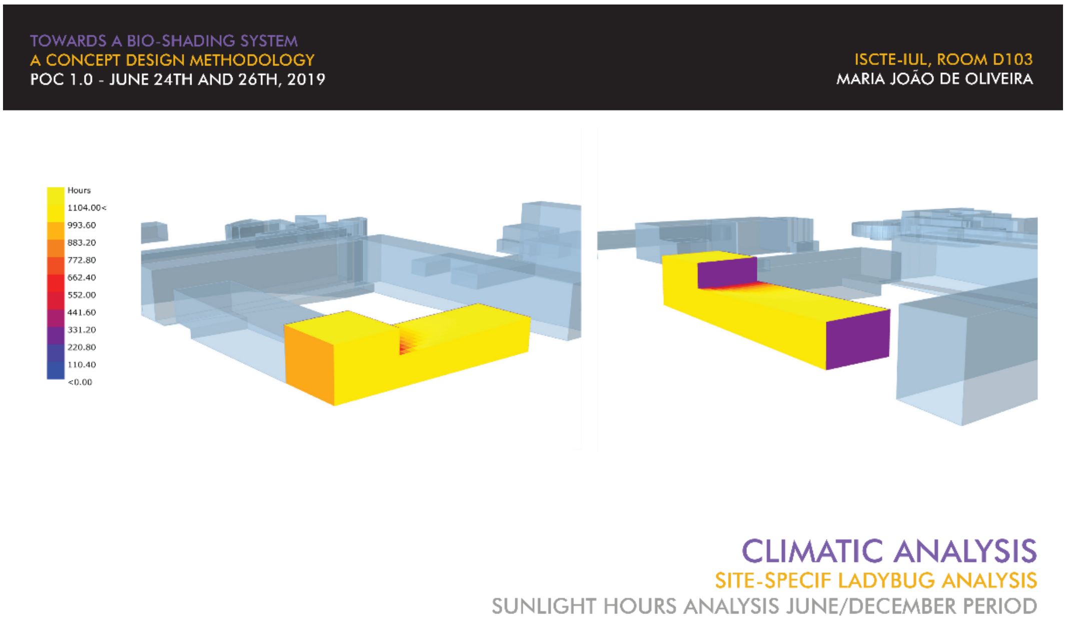
Slide 11.0:25. PoC 1.0 presentation: Climate Consultant 6.0 - Psychometric Chart - June.



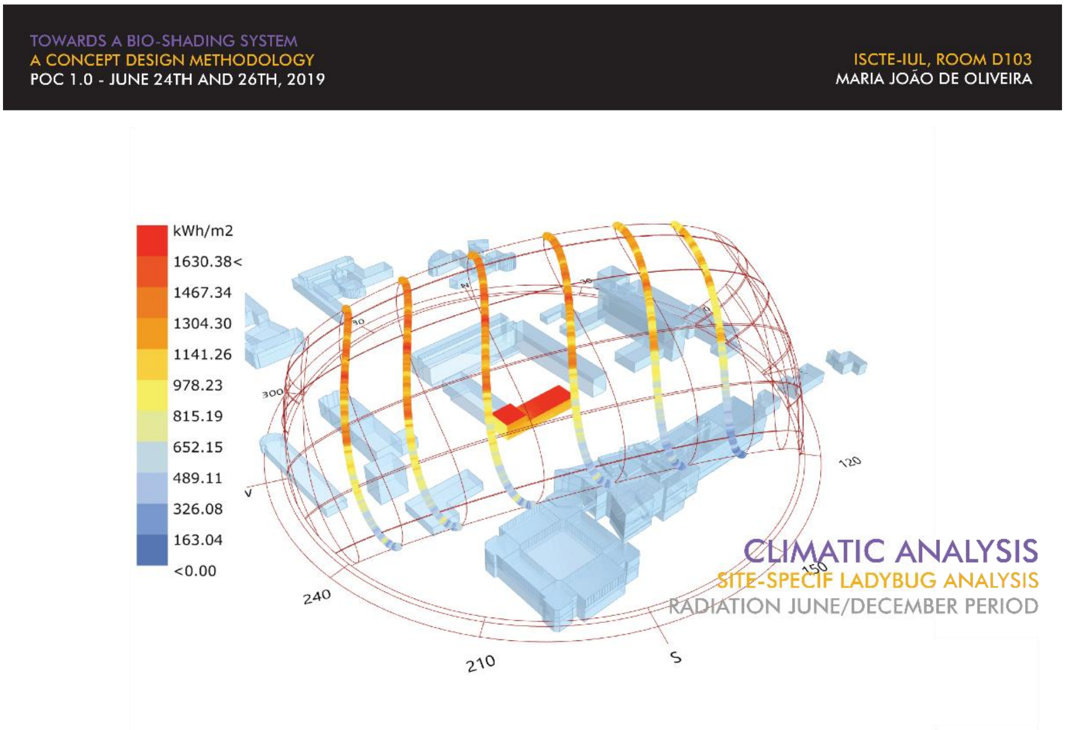
Slide 11.0:26. PoC 1.0 presentation: Climate Consultant 6.0 - Psychometric Chart - December.



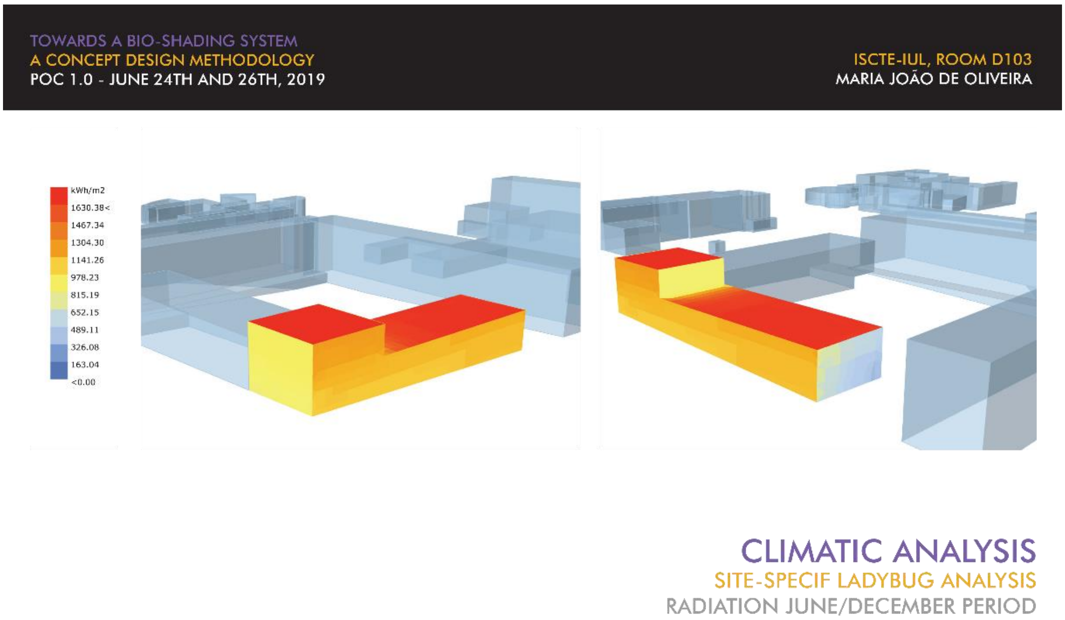
Slide 11.0:27. PoC 1.0 presentation: Ladybug Analysis – Sunlight Hours Analysis June/December.



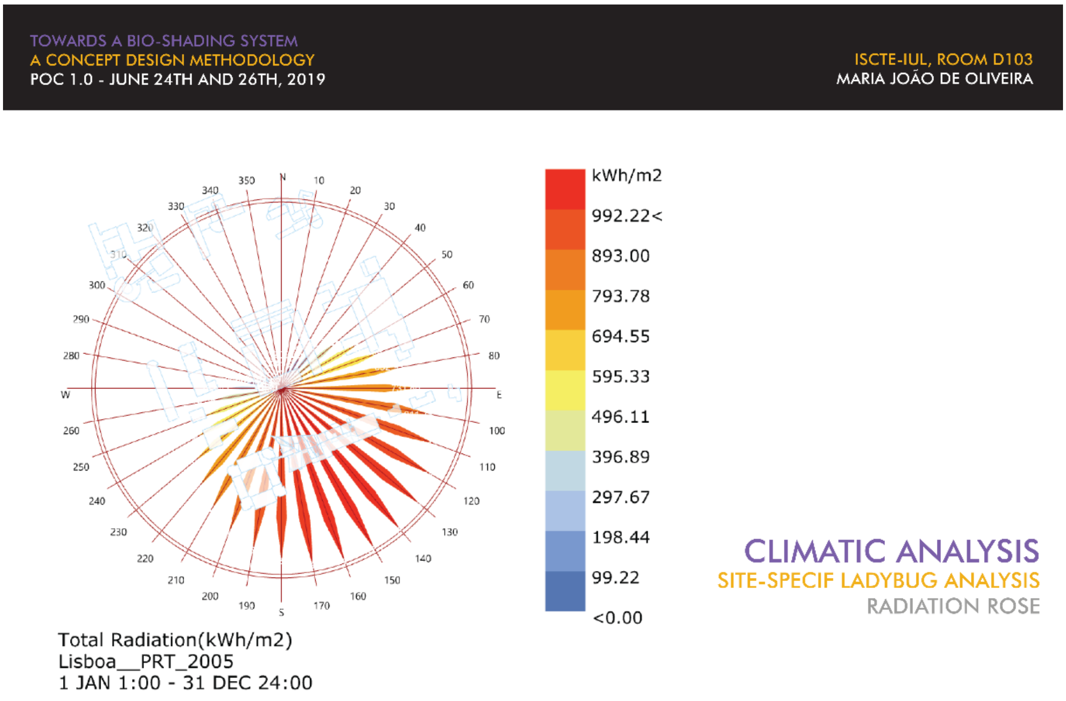
Slide 11.0:28. PoC 1.0 presentation: Ladybug Analysis – Façades Sunlight Hours Analysis June/December.



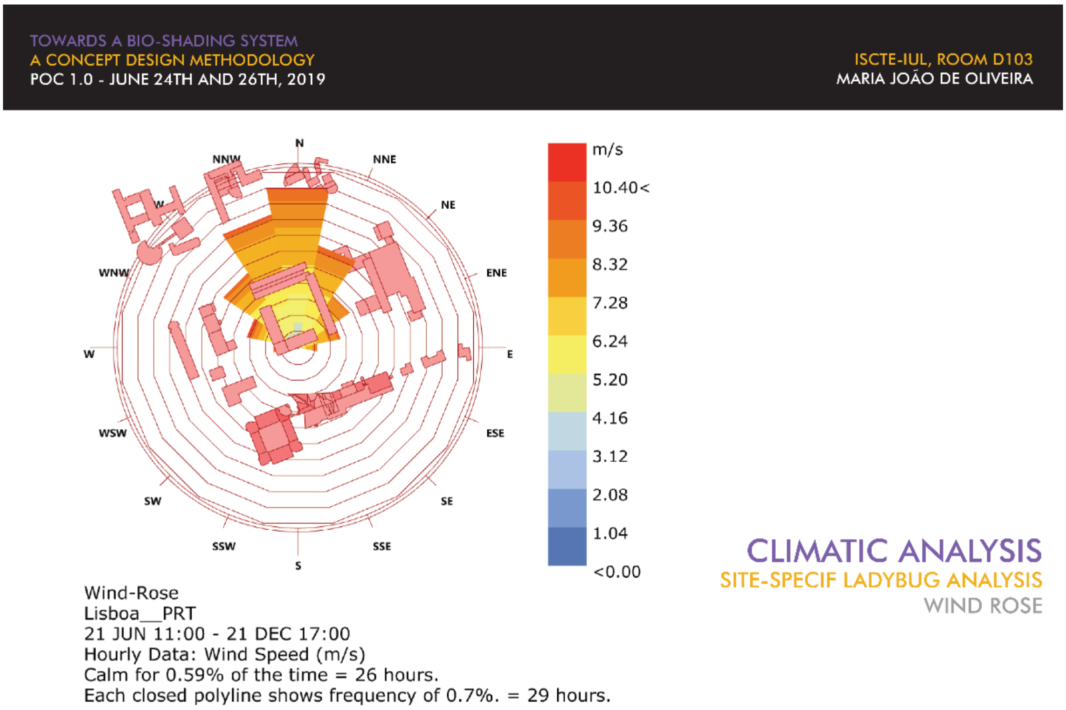
Slide 11.0:29. PoC 1.0 presentation: Ladybug Analysis – Radiation June/December.



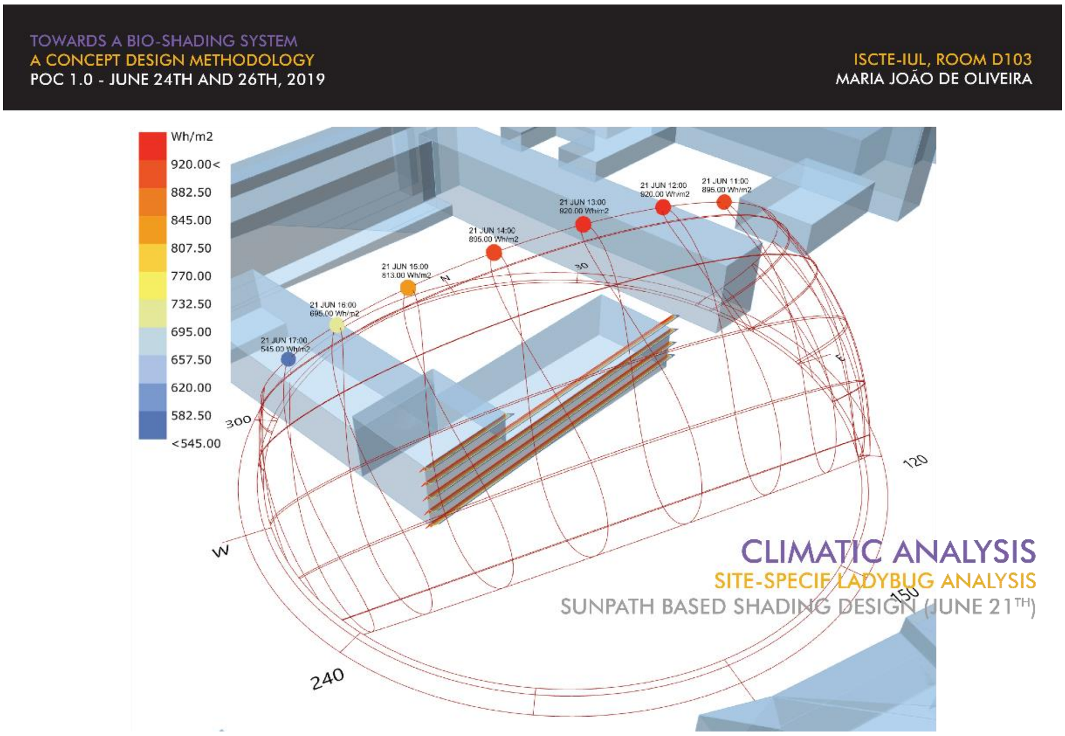
Slide 11.0:30. PoC 1.0 presentation: Ladybug Analysis – Façade Sunlight Hours Analysis June/December.



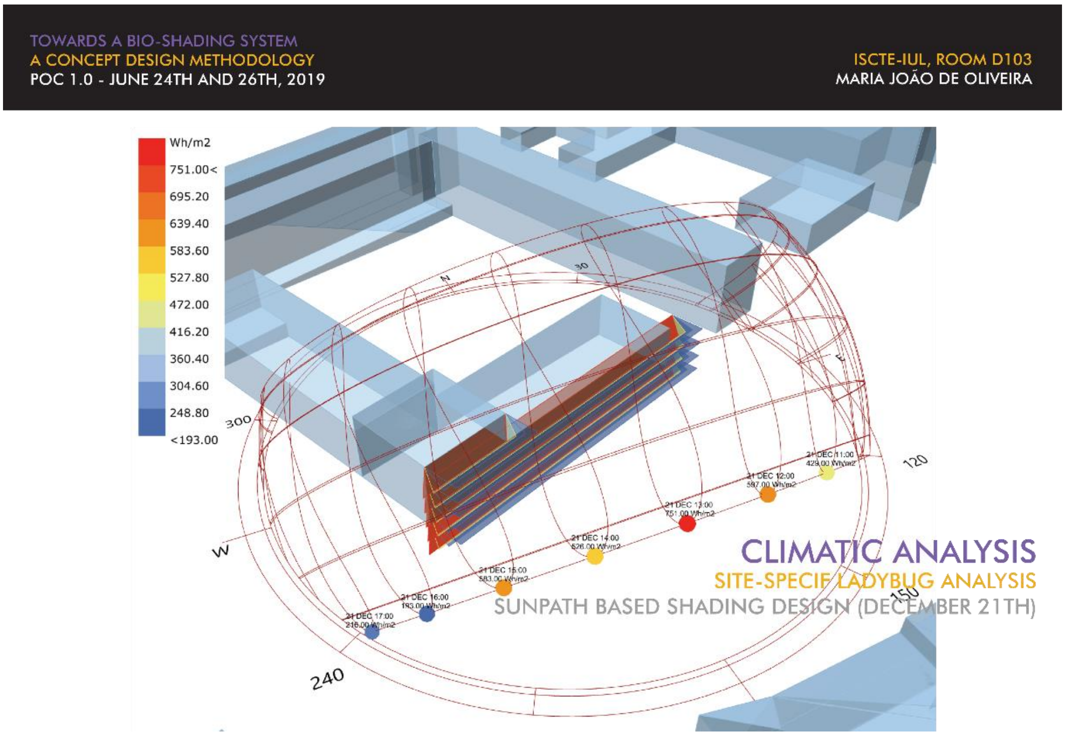
Slide 11.0:31. PoC 1.0 presentation: Ladybug Analysis – Annual Radiation Rose.



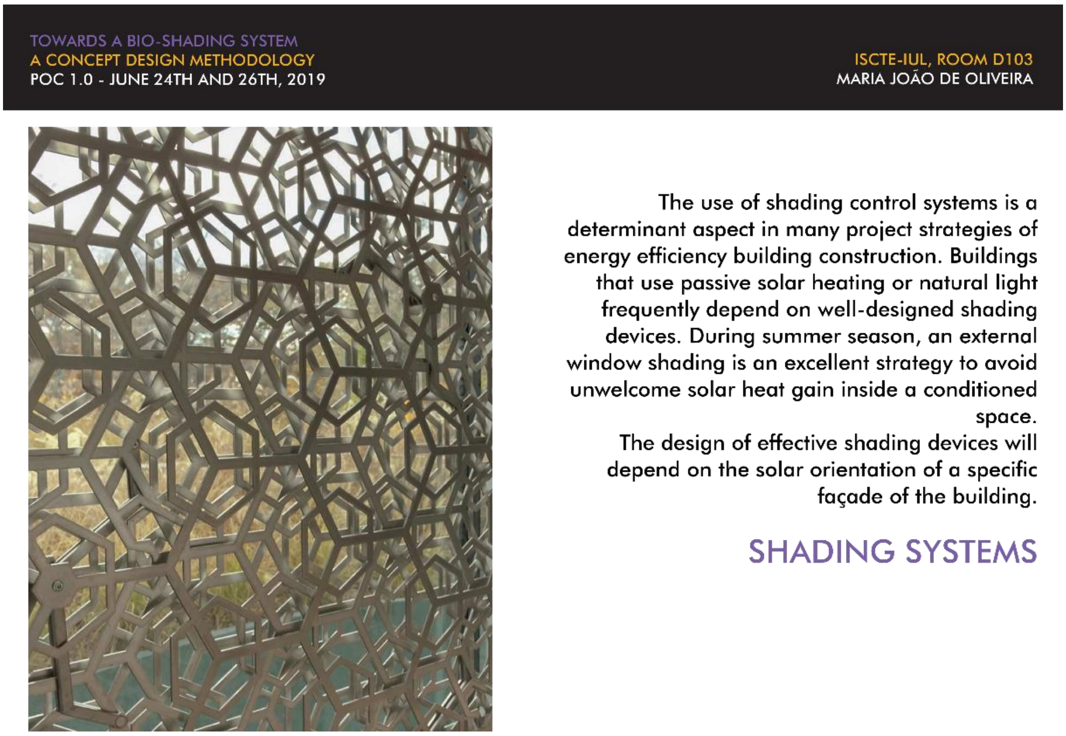
Slide 11.0:32. PoC 1.0 presentation: Ladybug Analysis – Annual Wind Rose.



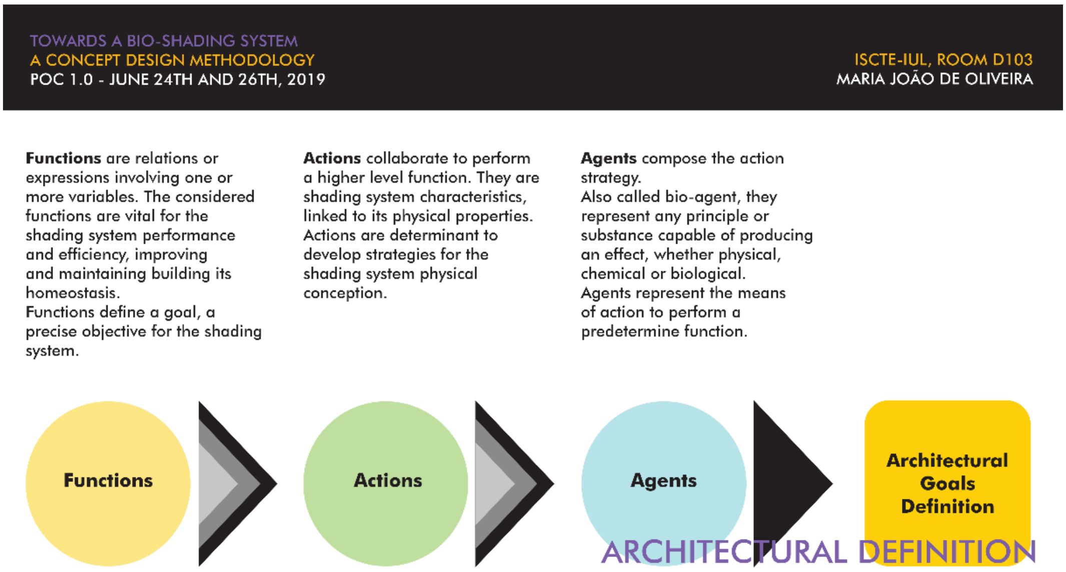
Slide 11.0:33. PoC 1.0 presentation: Ladybug Analysis – Sunpath Based Shading Design (June 21st).



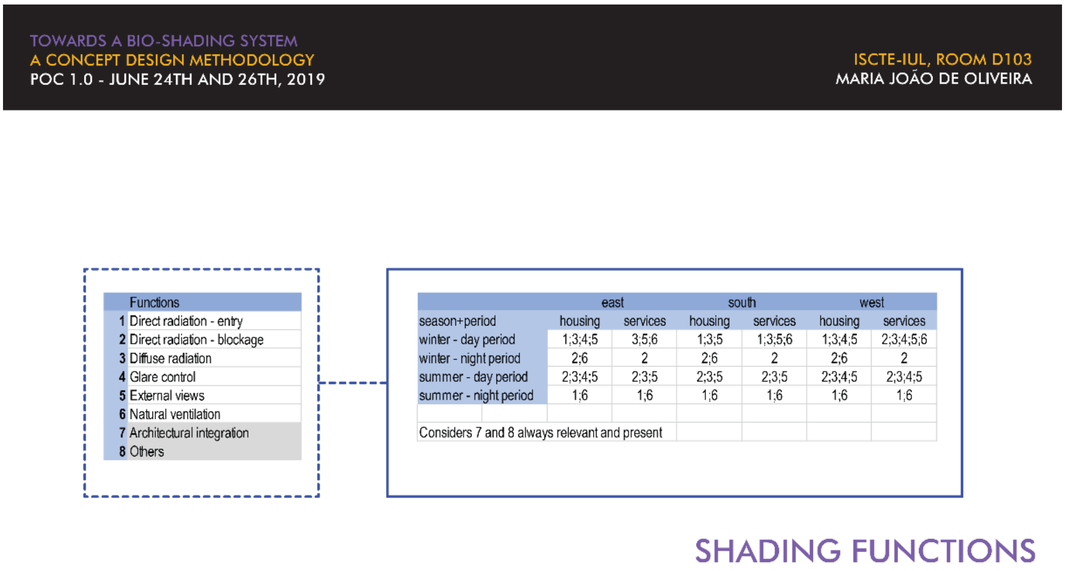
Slide 11.0:34. PoC 1.0 presentation: Ladybug Analysis – Sunpath Based Shading Design (December 21st).



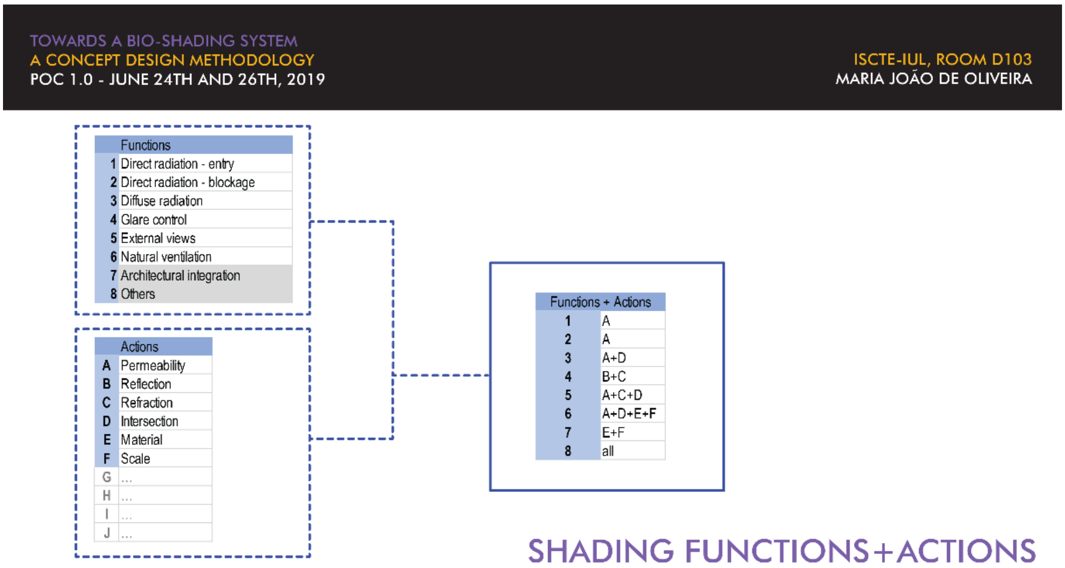
Slide 11.0:35. PoC 1.0 presentation: Ladybug Analysis - Shading Systems Introduction.



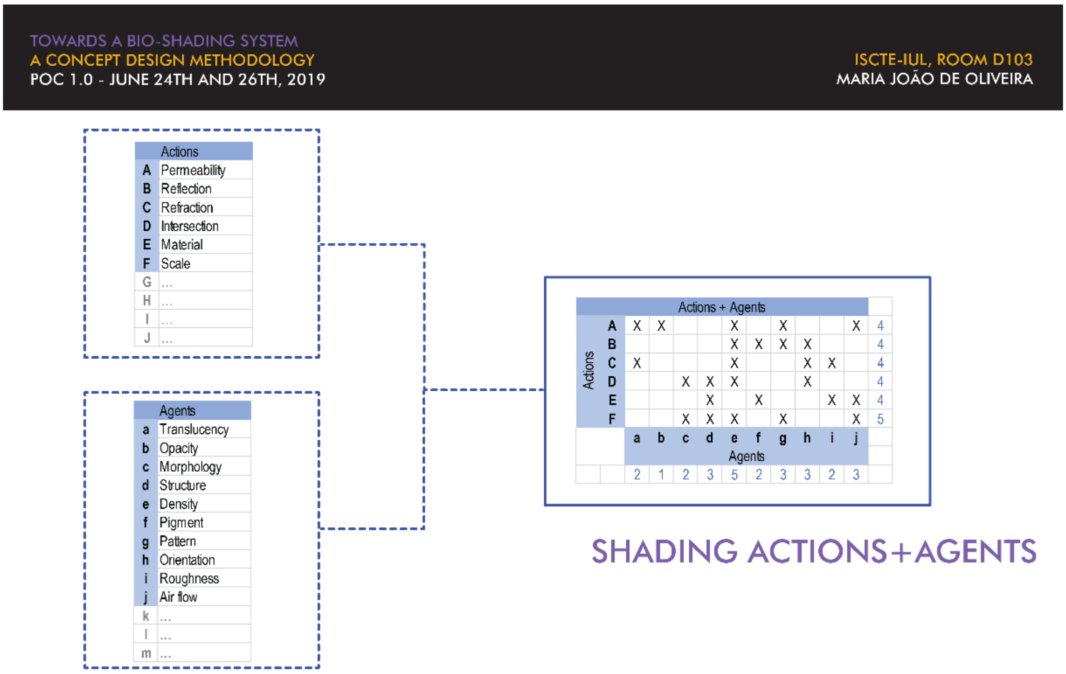
Slide 11.0:36. PoC 1.0 presentation: Ladybug Analysis – Shading Systems Function, Actions and Agents.



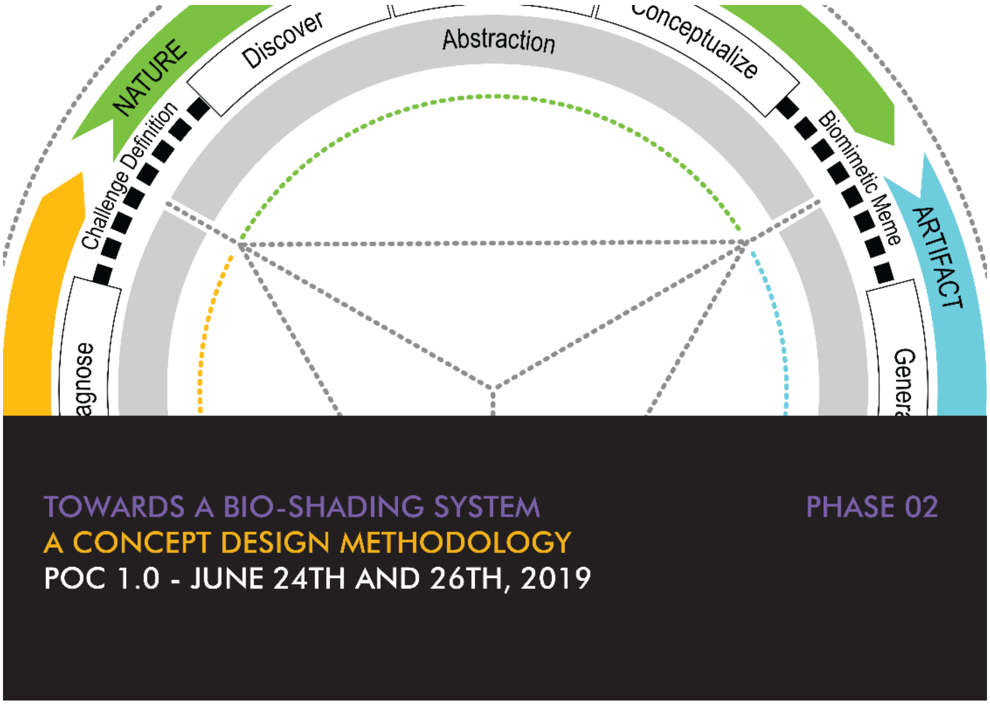
Slide 11.0:37. PoC 1.0 presentation: Ladybug Analysis - Shading Systems Functions.



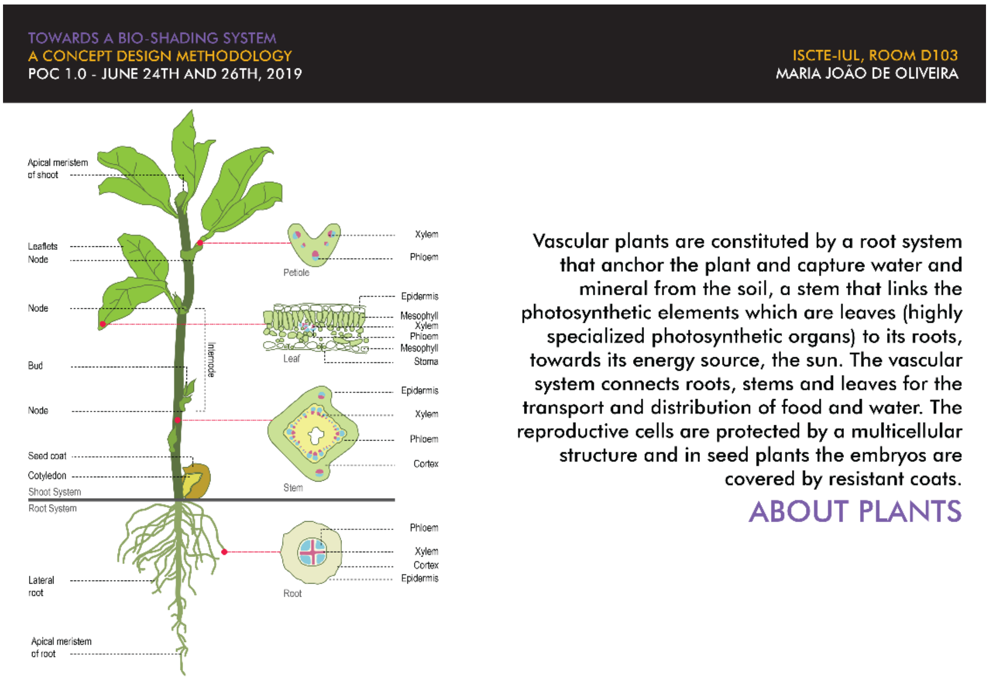
Slide 11.0:38. PoC 1.0 presentation: Ladybug Analysis - Shading Systems Functions + Actions.



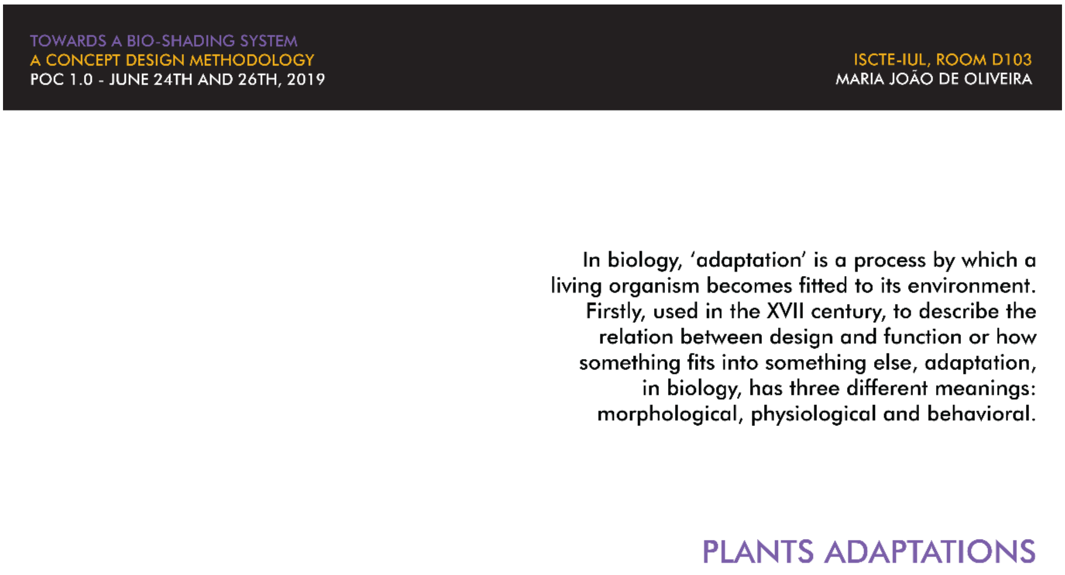
Slide 11.0:39. Ladybug Analysis - Shading Systems Functions + Actions Results.



Slide 11.0:40. Nature Introduction.



Slide 11.0:41. About Plants.



Slide 11.0:42. Plants Adaptations Introduction.

TOWARDS A BIO-SHADING SYSTEM
A CONCEPT DESIGN METHODOLOGY
POC 1.0 - JUNE 24TH AND 26TH, 2019

ISCTE-IUL, ROOM D103
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Morphological adaptation related to the form, size, pattern or structure of a feature that as evolved by natural selection for a specific function, for example the hairy leaves of Actinotus helianthin, that are used to reflect sunlight from their surface.

Physiological adaptation relates to an organism chemical processes in order to maintain homeostasis. Cam photosynthesis (Crassulacean Acid metabolism) is a carbon fixation pathway, that could be found in some plants, such Echeveria Glauca, as an adaptation to arid conditions.

Behavioral adaptation is driven by genetic variations among individuals that become adapted to a specific context, being frequently associated to an explicit and physical movement of the organism. This physical response is linked to a feedback signal, enabling the interaction between the organisms and its surrounding environment. A classic example could be the inward fold of Mimosa Pudica, as a reaction to physical contact.



Slide 11.0:43. Plants Adaptations – Morphological, Physiological and Behavioral.

TOWARDS A BIO-SHADING SYSTEM
A CONCEPT DESIGN METHODOLOGY
POC 1.0 - JUNE 24TH AND 26TH, 2019

ISCTE-IUL, ROOM D103
MARIA JOÃO DE OLIVEIRA

ASKNATURE
BIOMIMICRY 3.8
Postharvest management of Vegetables
BASIC BIOLOGY Inspired by Life
Diffen
BIOMIMICRY FOR SOCIAL INNOVATION
eol Encyclopedia of Life
BIOLOGY ONLINE

PLANTS ONLINE SURVEY

Slide 11.0:44. Plants Online Survey.

TOWARDS A BIO-SHADING SYSTEM
A CONCEPT DESIGN METHODOLOGY
POC 1.0 - JUNE 24TH AND 26TH, 2019

ISCTE-IUL, ROOM D103
MARIA JOÃO DE OLIVEIRA

***Meme* Event**	**Adaptation**	**Strategy**	**Main principles**	**Main features**
Anthocyanins	Physiological	Static	One of the flavonoids, which are water soluble pigments present in the vacuoles of plant cells.	Range in colors from red, purple to blue; Spectrum; Radial
Asymmetry	Morphological	Static	There are no mirror matching in the plant structure and morphological pattern.	Asymmetry
Bioluminescence	Behavioral	Static	Occurs through a chemical reaction that produces light energy within an organism's body.	Self-luminous; Color Range
Carnivorous Plants	Morphological	Dynamic	Exists five types: Pitfall traps, Flydader traps; Snaptraps; Bladder traps; Lobster pot traps.	Open-close; Cover systems; Bending
CAM Plants (Crassulacean Acid Metabolism)	Physiological	Dynamic	Opening stomata at night to prevent water loss, when ambient temperatures and water vapor concentration difference between the tissues and ambient air are low (Badarnah, 2012).	Permeability; Storage
Nyctinastic movements	Behavioral	Dynamic	Leaves are oriented horizontally during the day and vertically at night.	Rotation; Inclination; Open-close; Synchronization
others	…	…	…	…

PLANTS *MEME* EVENTS

Slide 11.0:45. Plants Meme events.

TOWARDS A BIO-SHADING SYSTEM
A CONCEPT DESIGN METHODOLOGY
POC 1.0 - JUNE 24TH AND 26TH, 2019

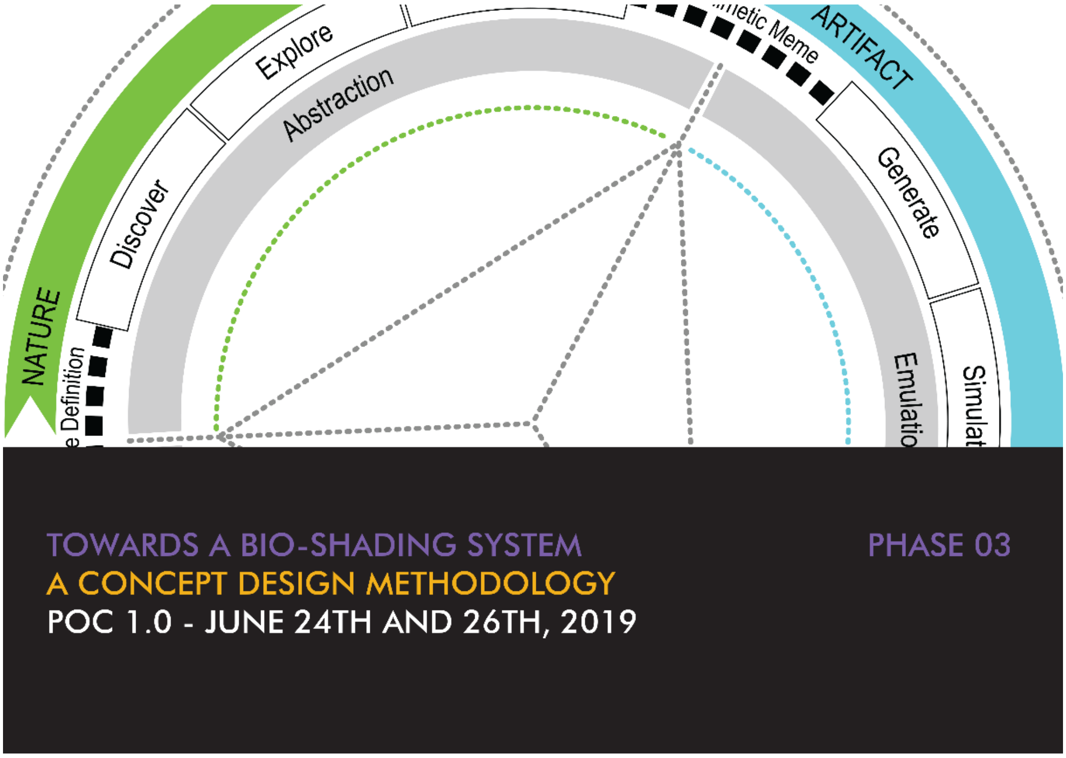
ISCTE-IUL, ROOM D103
MARIA JOÃO DE OLIVEIRA

selected actions	A meme	B meme	C meme	... meme	**Biomimetic meme**
A	X				X
B		X			X
C			X		X
D				X	X
Meme Strategies					
Dynamic	X	X		X	X
Static			X		
Meme Adaptation					
Morphological	X		X		X
Physiological				X	
behavioral		X			
Meme Pattern features					
Loose	X				
Multilayer			X	X	X
Hexagonal		X			
etc...					
Meme Material features					
Flexible	X	X			X
Translucent			X	X	X
Hard					
etc...					
Meme Performative Features					
Tracking	X				
Bending		X		X	X
Unidirectional movement				X	
etc...					

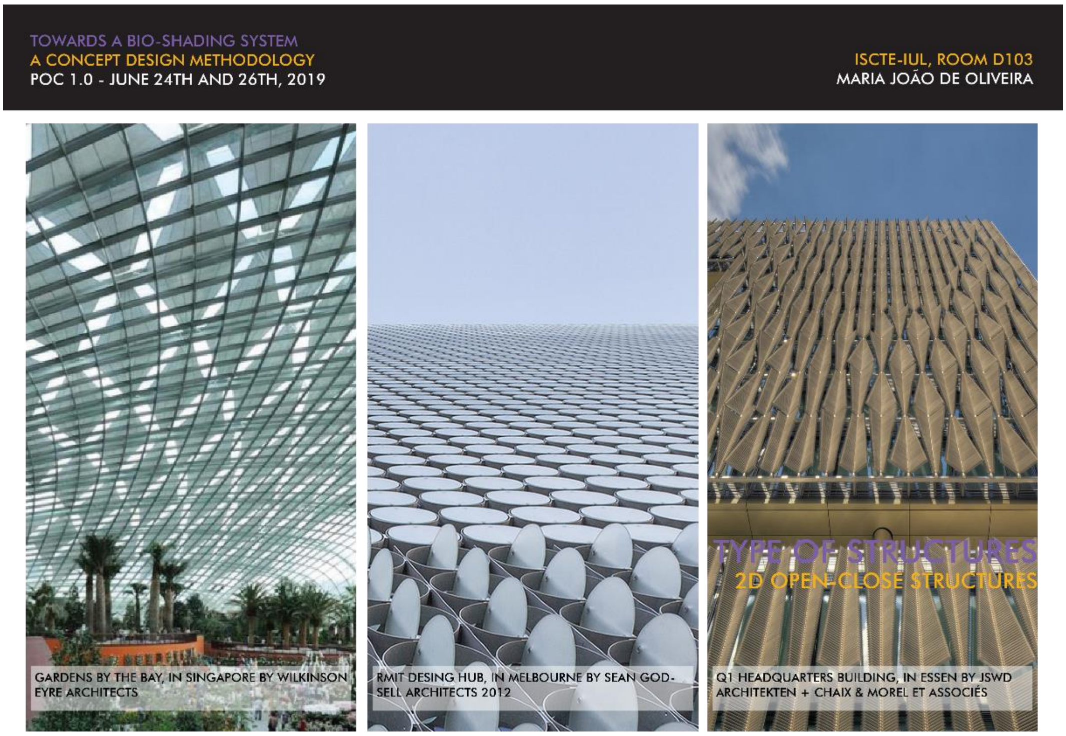
BIOMIMETIC *MEME*

Slide 11.0:46. Biomimetic Meme.

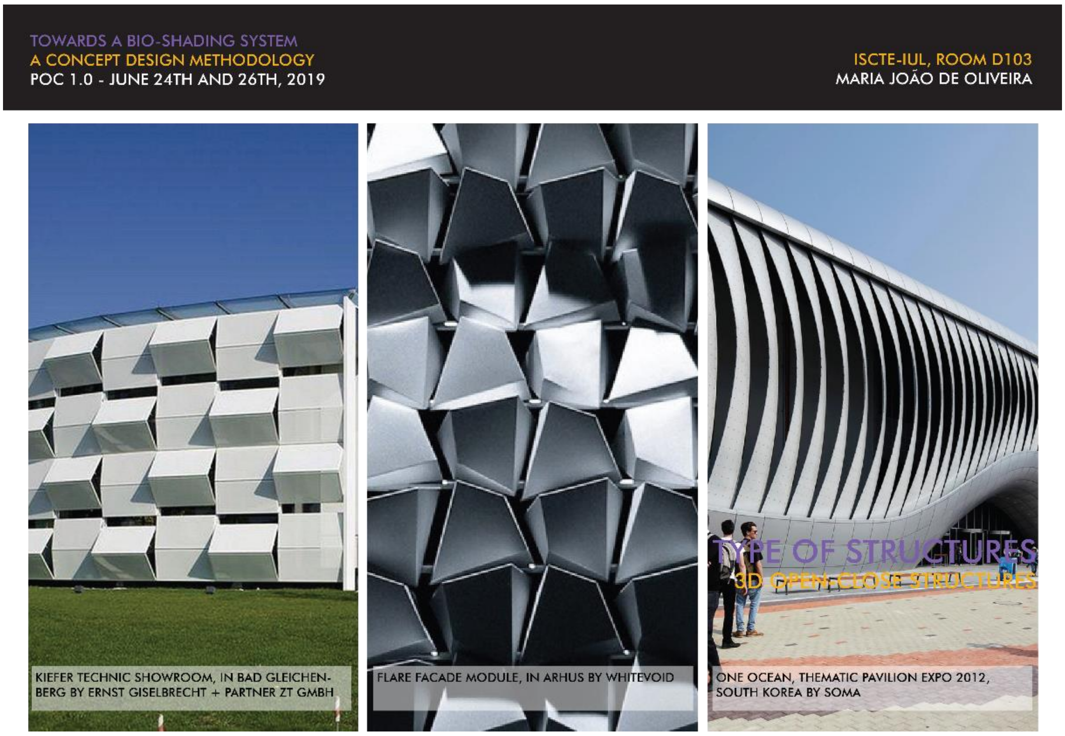
11.1.2 PoC 1.0 presentation (2nd Session) – projection support



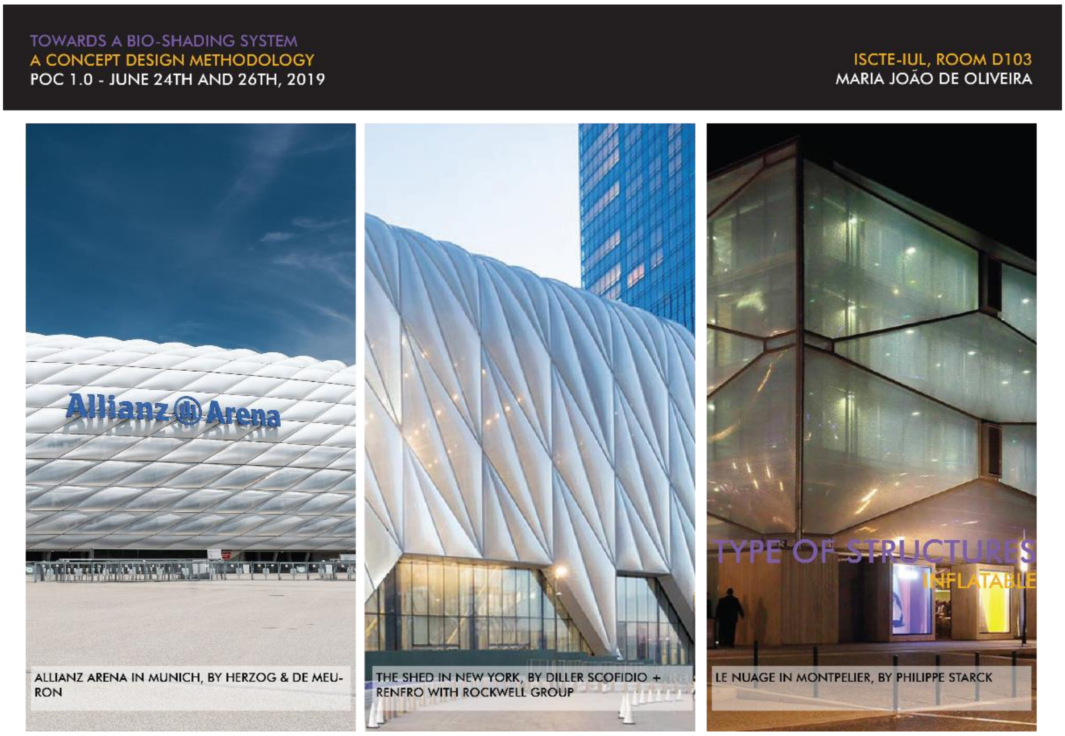
Slide 11.0:47.Type of Structures and Actuation.



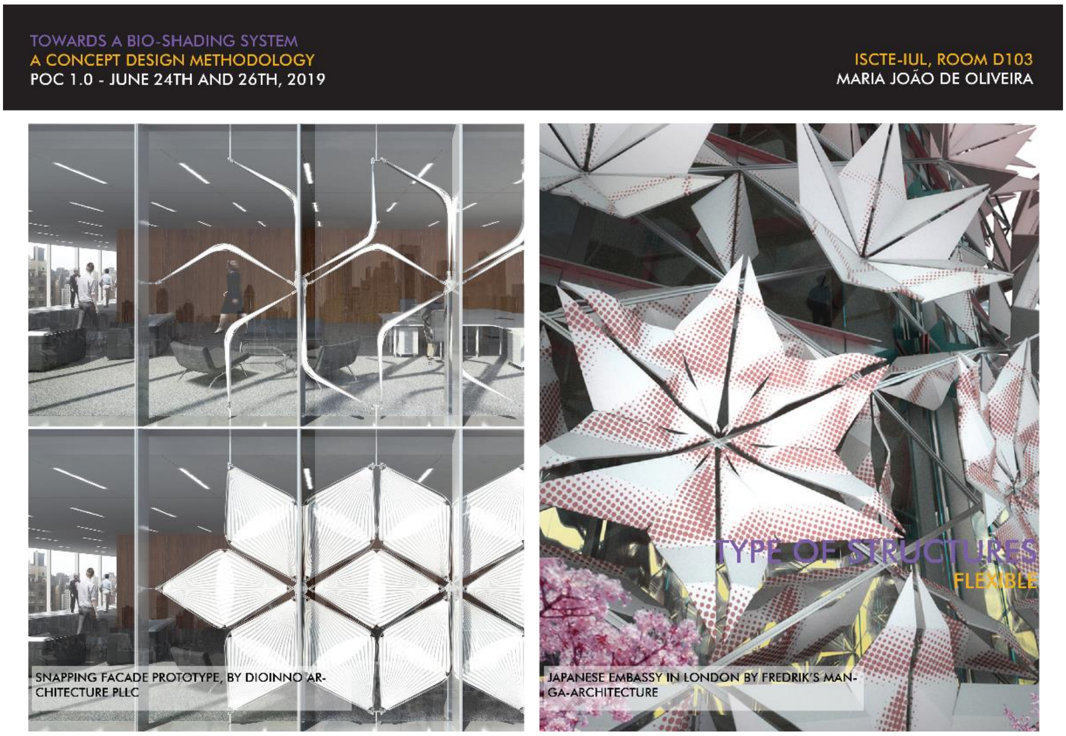
Slide 11.0:48. 2D Open-Close Structures.



Slide 11.0:49. 3D Open-Close Structures. .

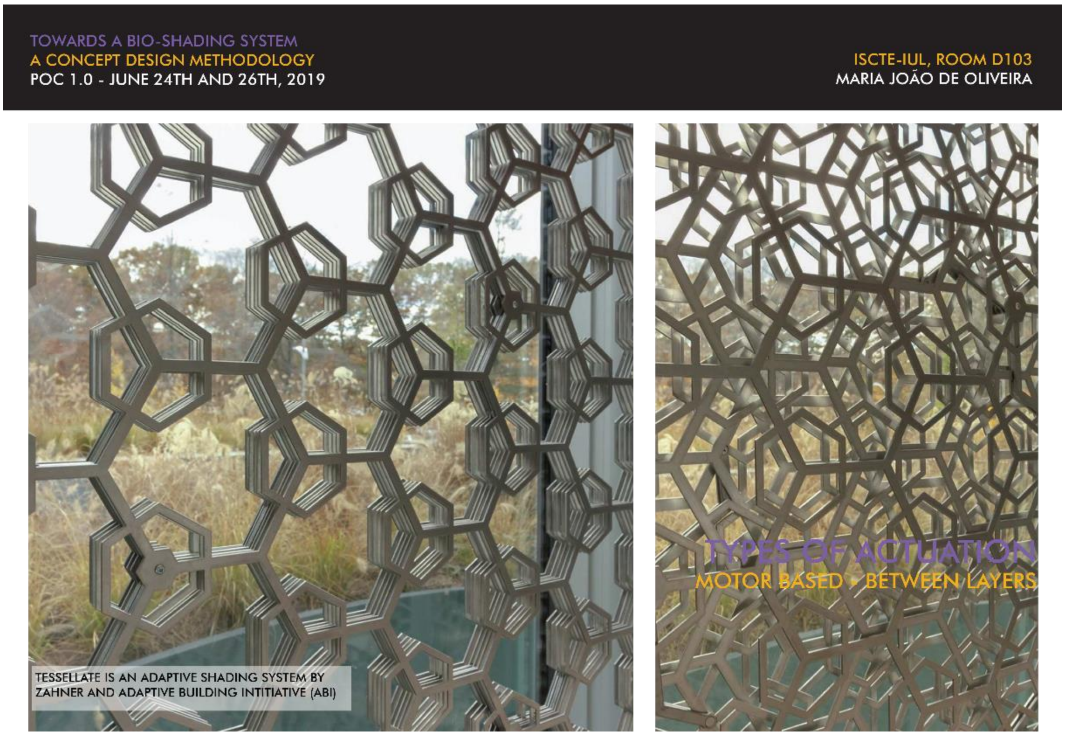


Slide 11.0:50. Type of Structure – Inflatable.



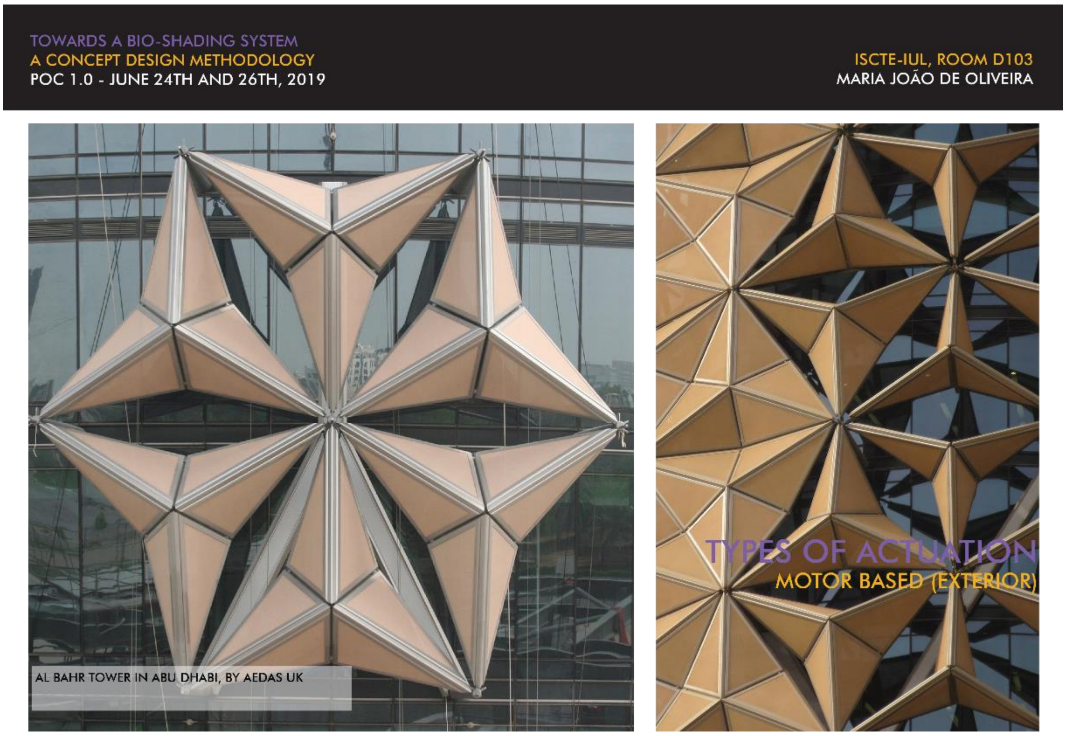
Slide 11.0:51. Type of Structure – Flexible.

Slide 11.0:52. Type of Strucuture - Tensigrity.

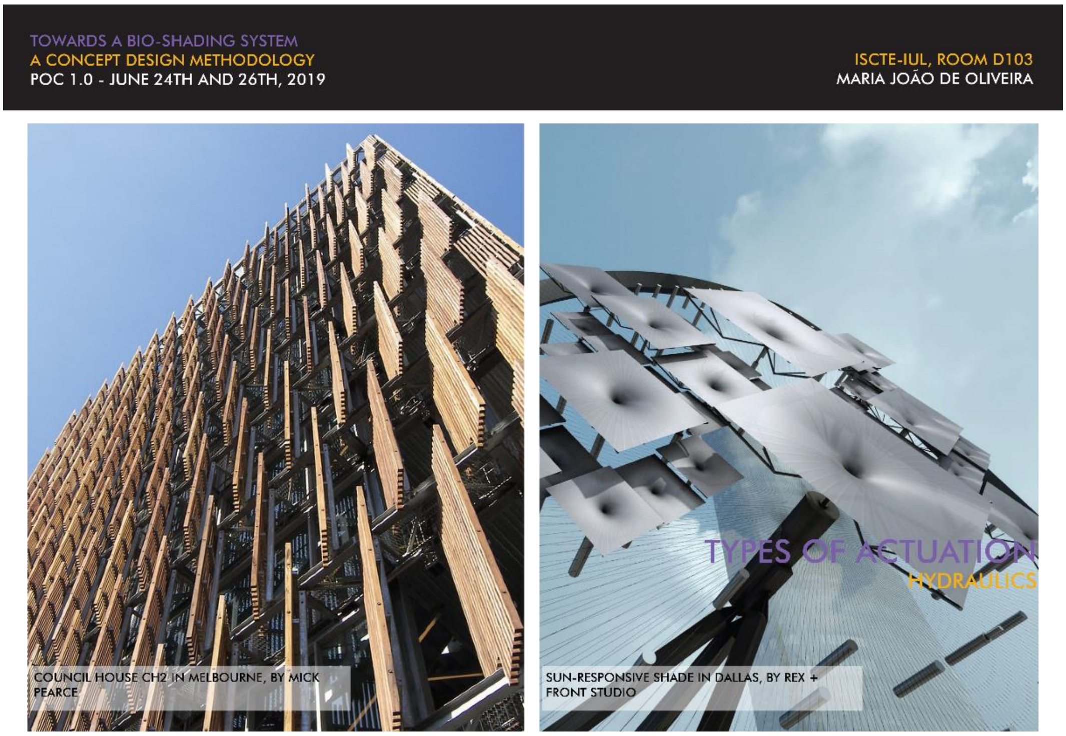


Slide 11.0:53. Types of actuation - Motor based between layers.

Slide 11.0:54. Types of actuation - Motor based between layers.

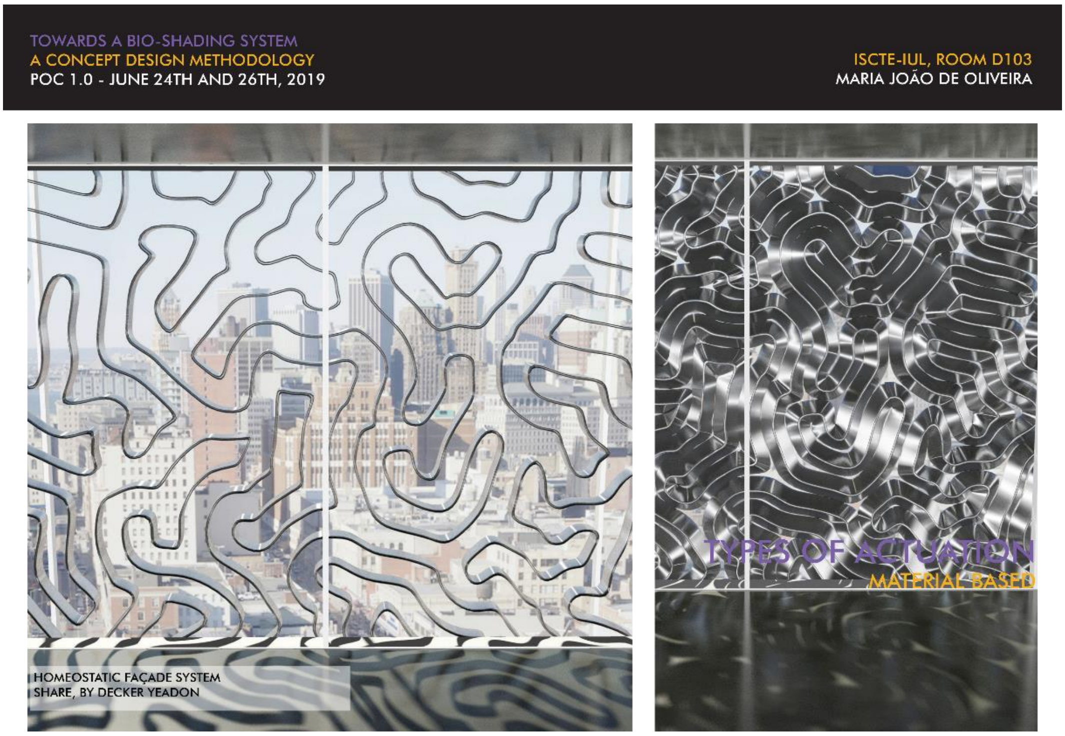


Slide 11.0:55. Types of actuation - Motor based exterior.



Slide 11.0:56. Types of actuation - Hydraulics.

Slide 11.0:57. Types of actuation - Pneumatics.



Slide 11.0:58. Types of actuation – Material-based.

Slide 11.0:59. Types of actuation – Material-based.

11.2 Climate Consultant 6.0 Analysis

Graph 11.0:1. Climate Consultant 6.0: Weather Data Summary.

WEATHER DATA SUMMARY

LOCATION: Lisboa, null, PRT
Latitude/Longitude: 38.73° North, 9.15° West, **Time Zone from Greenwich** 0
Data Source: INETI 085360 WMO Station Number, **Elevation** 71 m

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	212	274	322	397	450	470	510	501	402	316	245	208	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	324	332	331	354	402	409	472	494	415	373	354	366	Wh/sq.m
Diffuse Radiation (Avg Hourly)	95	125	135	162	164	165	167	161	146	132	106	93	Wh/sq.m
Global Horiz Radiation (Max Hourly)	553	688	858	959	990	1008	1005	974	881	754	583	478	Wh/sq.m
Direct Normal Radiation (Max Hourly)	830	888	920	945	978	982	952	976	901	875	811	798	Wh/sq.m
Diffuse Radiation (Max Hourly)	233	267	317	374	353	403	394	386	335	301	216	182	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	2040	2882	3821	5192	6367	6893	7348	6769	4924	3465	2423	1946	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	3110	3476	3916	4621	5680	6001	6806	6671	5069	4077	3494	3416	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	921	1316	1604	2122	2327	2420	2405	2170	1796	1449	1049	868	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	23900	31718	36837	45819	51207	53258	57160	55611	45126	35888	27619	23245	lux
Direct Normal Illumination (Avg Hourly)	28201	30604	31801	35095	40505	41684	47840	49364	40735	34877	31883	30006	lux
Dry Bulb Temperature (Avg Monthly)	10	11	12	14	17	20	22	22	21	17	13	11	degrees C
Dew Point Temperature (Avg Monthly)	7	7	8	9	11	13	14	14	14	13	10	7	degrees C
Relative Humidity (Avg Monthly)	81	79	76	72	71	70	66	64	69	74	80	80	percent
Wind Direction (Monthly Mode)	20	300	10	0	350	310	350	340	340	340	20	350	degrees
Wind Speed (Avg Monthly)	4	4	4	5	5	5	5	5	4	4	4	4	m/s
Ground Temperature (Avg Monthly of 3 Depths)	12	11	12	13	15	17	19	19	19	18	16	14	degrees C

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Graph 11.0:2. Climate Consultant 6.0: Comfort Model.

COMFORT MODEL

LOCATION: Lisboa, null, PRT
Latitude/Longitude: 38.73° North, 9.15° West, **Time Zone from Greenwich** 0
Data Source: INETI 085360 WMO Station Number, **Elevation** 71 m

COMFORT MODELS:

Human Thermal comfort can be defined primarily by dry bulb temperature and humidity, although different sources have slightly different definitions. Select the model you wish to use:

○ **California Energy Code Comfort Model, 2013 (DEFAULT)**

For the purpose of sizing residential heating and cooling systems the indoor Dry Bulb Design Conditions should be between 68°F (20°C) to 75°F (23.9°C). No Humidity limits are specified in the Code, so 80% Relative Humidity and 66°F (18.9°C) Wet Bulb is used for the upper limit and 27°F (-2.8°C) Dew Point is used for the lower limit (but these can be changed on the Criteria screen).

◉ **ASHRAE Standard 55 and Current Handbook of Fundamentals Model**

Thermal comfort is based on dry bulb temperature, clothing level (clo), metabolic activity (met), air velocity, humidity, and mean radiant temperature. Indoors it is assumed that mean radiant temperature is close to dry bulb temperature. The zone in which most people are comfortable is calculated using the PMV (Predicted Mean Vote) model. In residential settings people adapt clothing to match the season and feel comfortable in higher air velocities and so have wider comfort range than in buildings with centralized HVAC systems.

○ **ASHRAE Handbook of Fundamentals Comfort Model up through 2005**

For people dressed in normal winter clothes, Effective Temperatures of 68°F (20°C) to 74°F (23.3°C) (measured at 50% relative humidity), which means the temperatures decrease slightly as humidity rises. The upper humidity limit is 64°F (17.8°C) Wet Bulb and a lower Dew Point of 36F (2.2°C). If people are dressed in light weight summer clothes then this comfort zone shifts 5°F (2.8°C) warmer.

○ **Adaptive Comfort Model in ASHRAE Standard 55-2010**

In naturally ventilated spaces where occupants can open and close windows, their thermal response will depend in part on the outdoor climate, and may have a wider comfort range than in buildings with centralized HVAC systems. This model assumes occupants adapt their clothing to thermal conditions, and are sedentary (1.0 to 1.3 met). There must be no mechanical Cooling System, but this method does not apply if a Mechanical Heating System is in operation.

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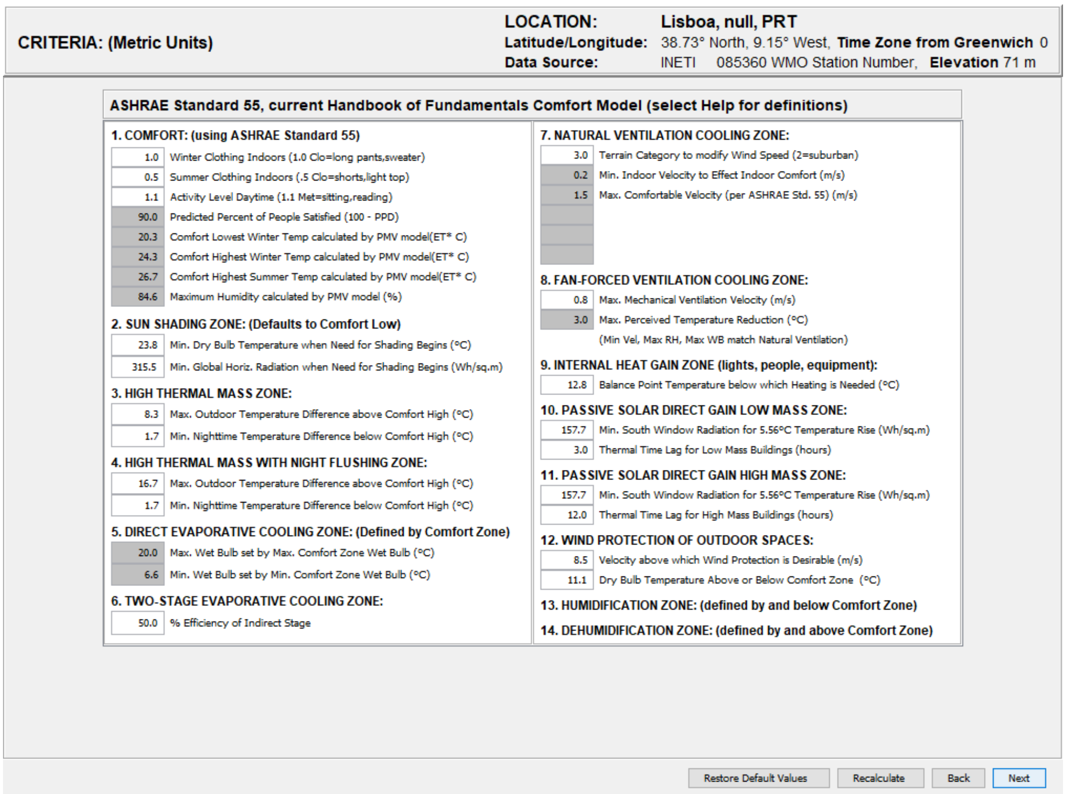
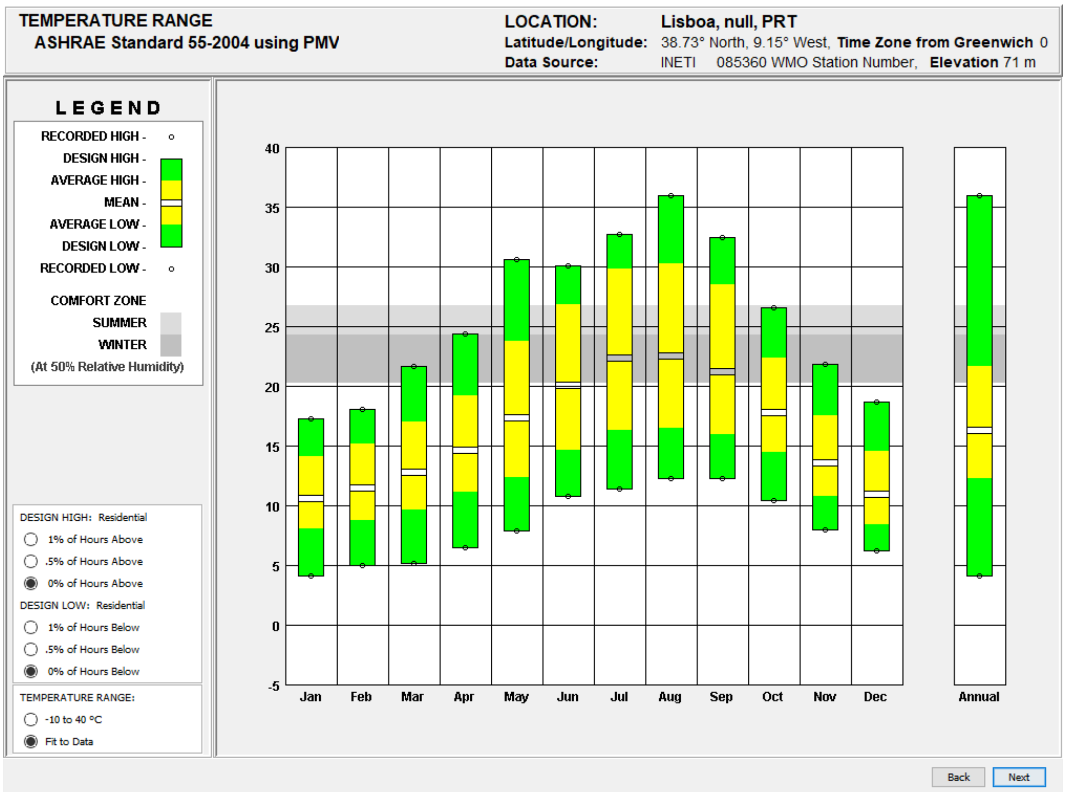
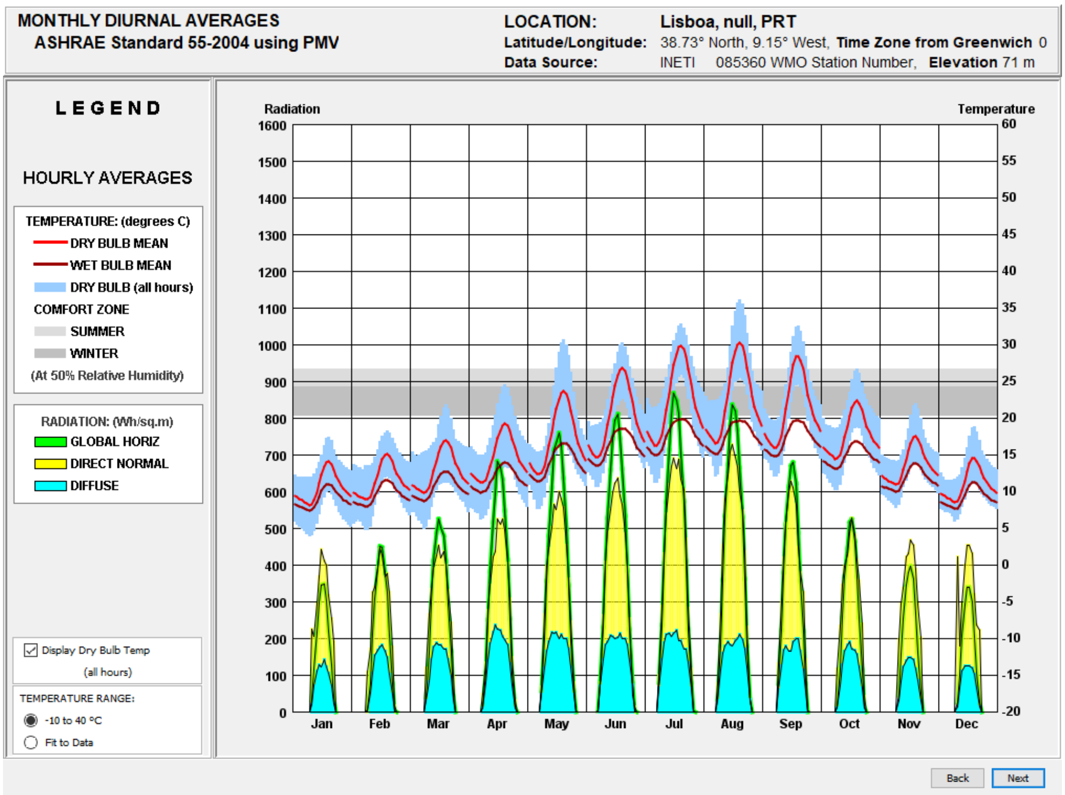
Graph 11.0:3. Climate Consultant 6.0: Criteria board.



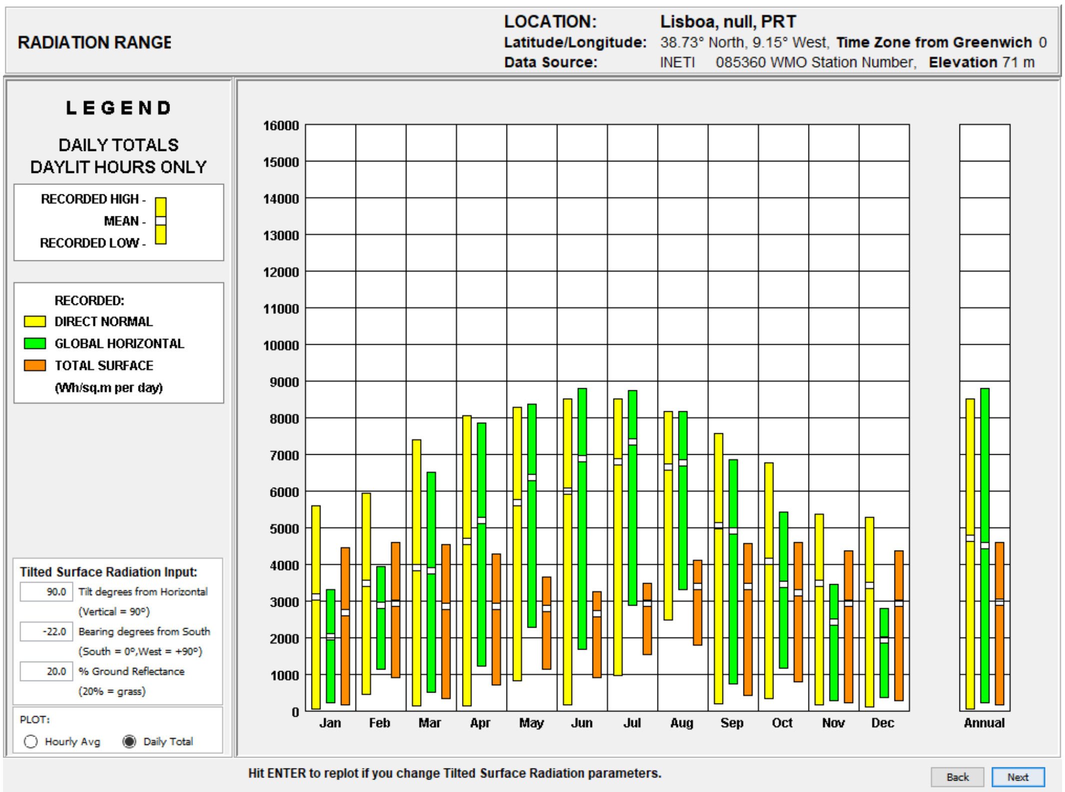
Graph 11.0:4. Climate Consultant 6.0: Temperature Range.



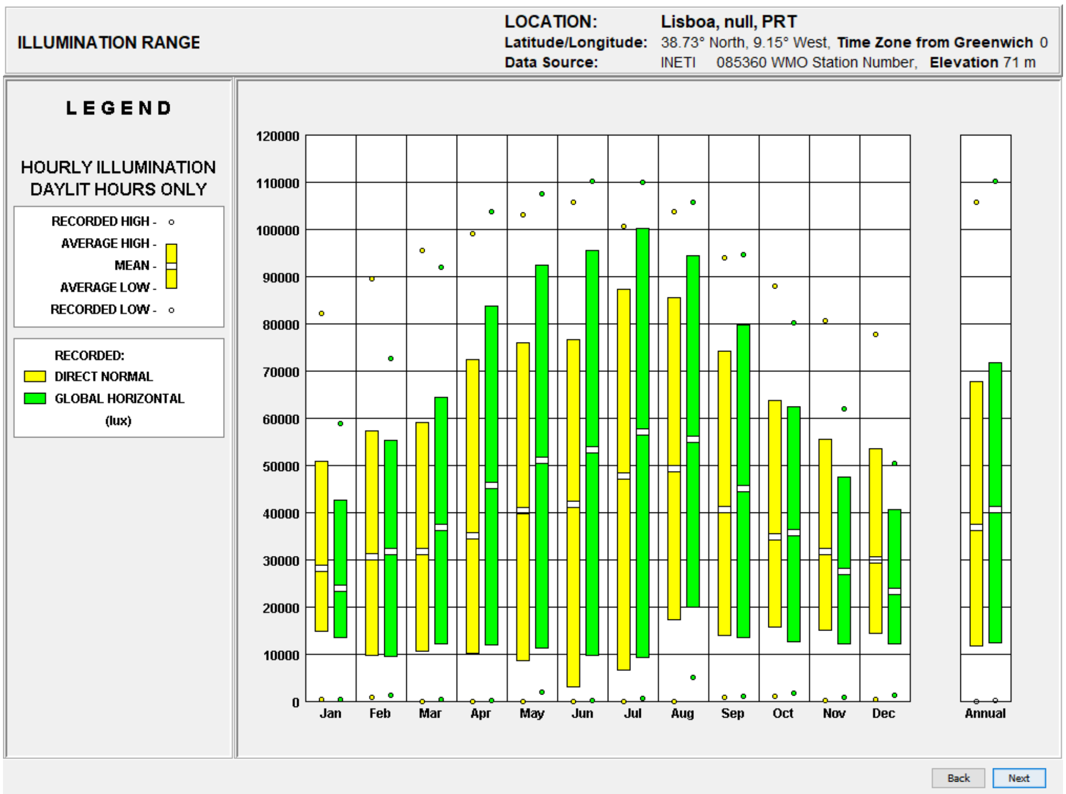
Graph 11.0:5. Climate Consultant 6.0: Monthly Diurnal Averages.



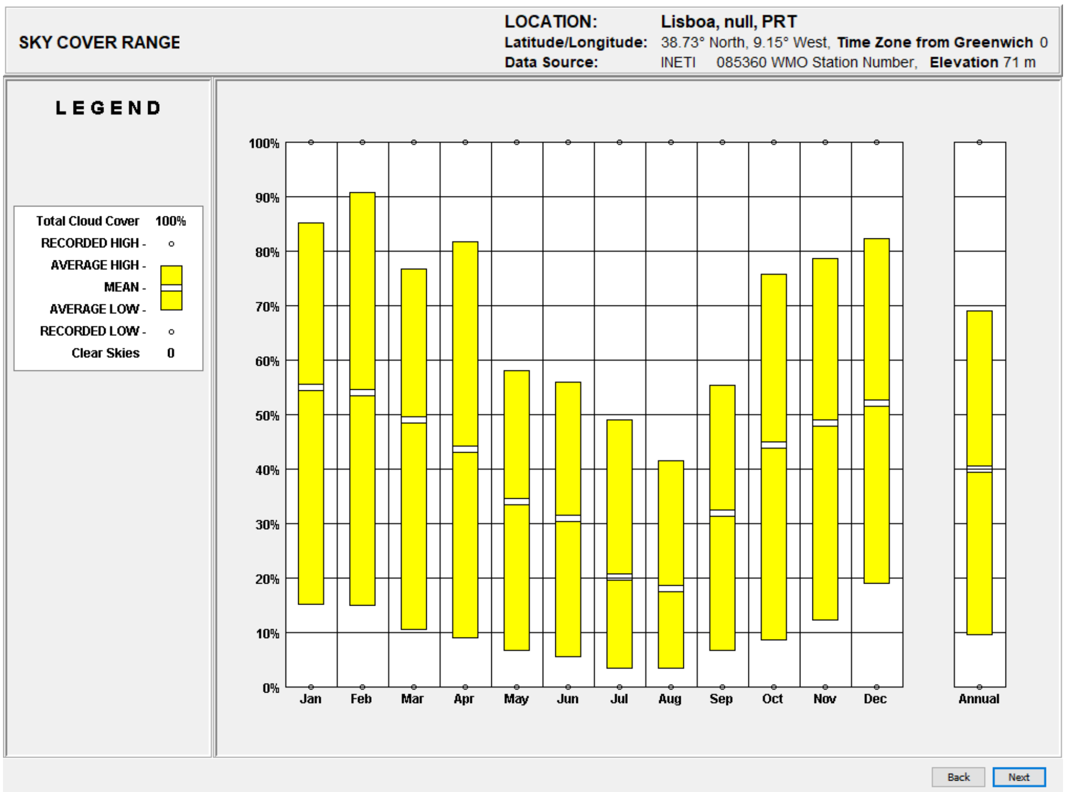
Graph 11.0:6. Climate Consultant 6.0: Radiation Range.



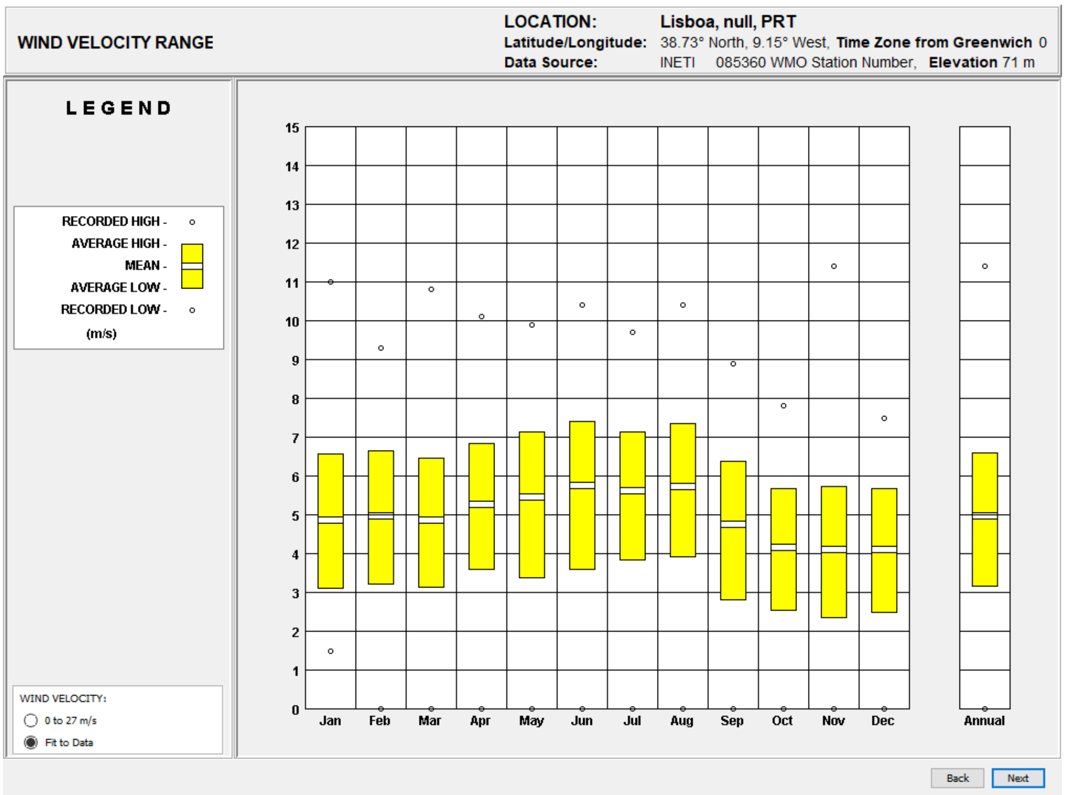
Graph 11.0:7. Climate Consultant 6.0: Illumination range.



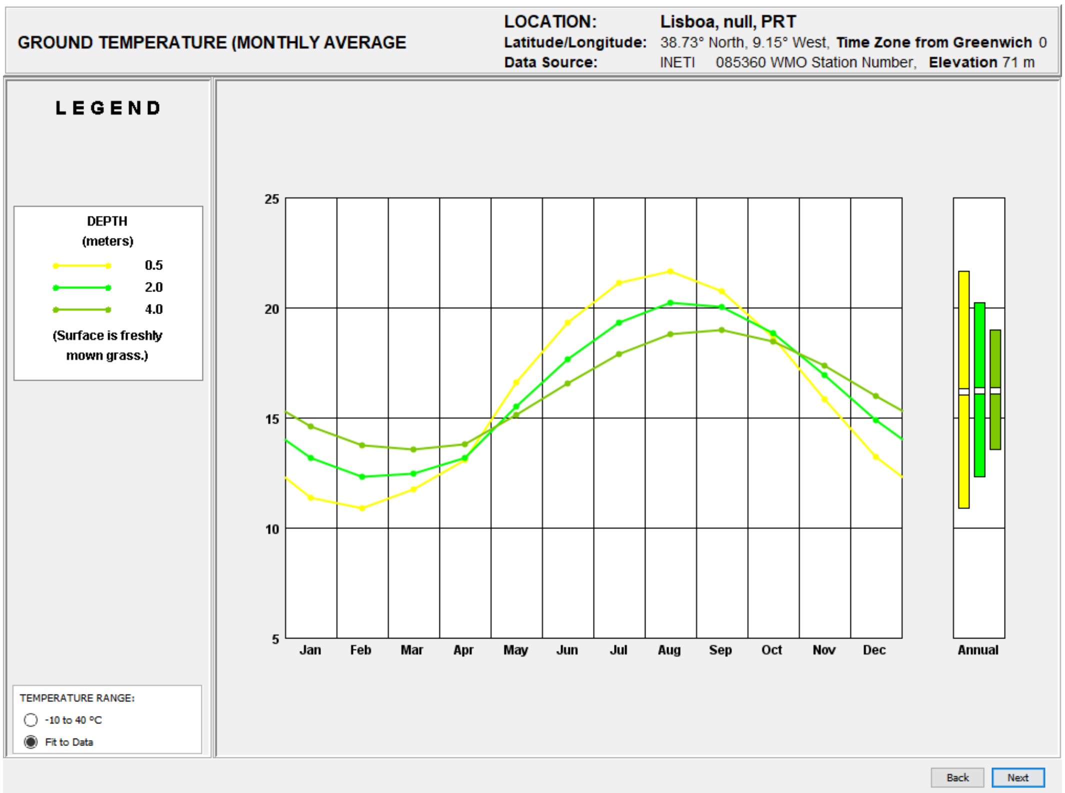
Graph 11.0:8. Climate Consultant 6.0: Sky Cover Range.



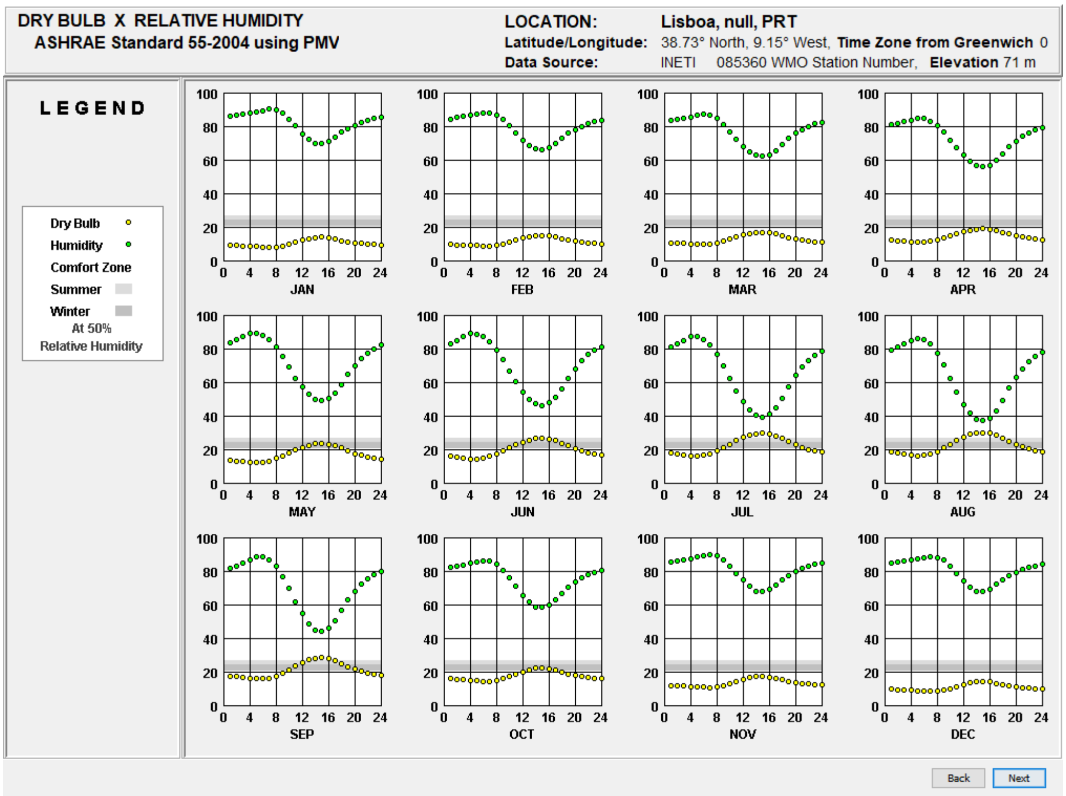
Graph 11.0:9. Climate Consultant 6.0: Wind Velocity Range.



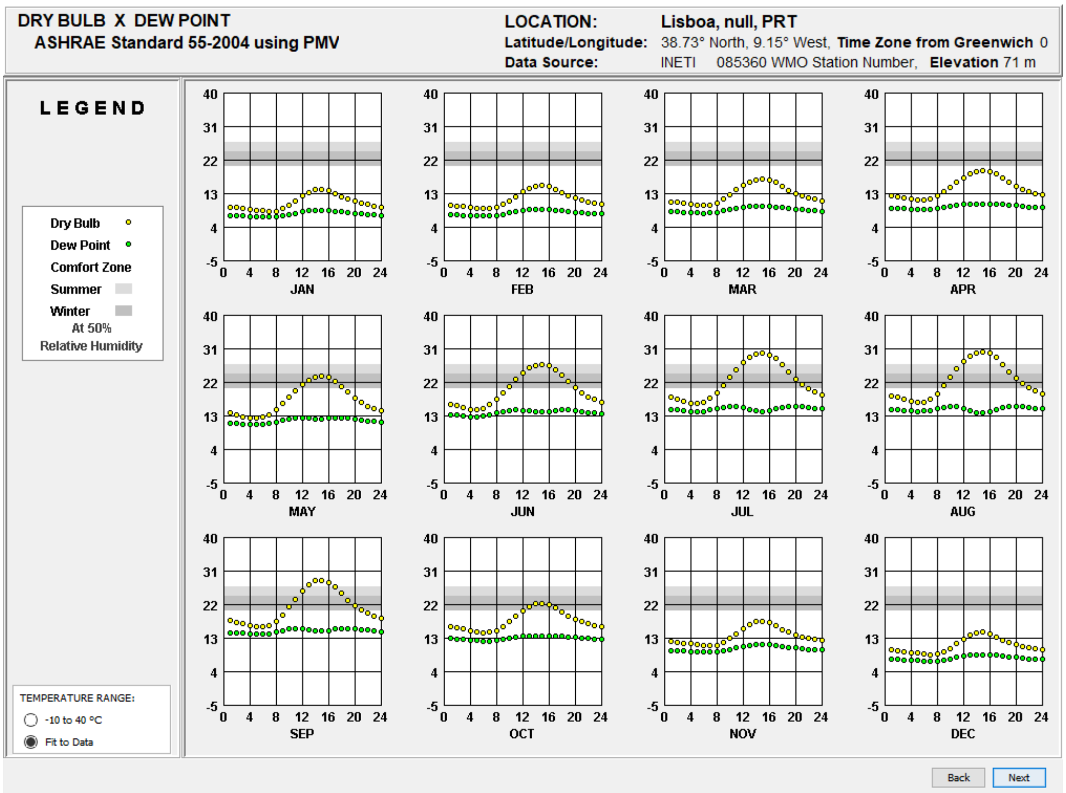
Graph 11.0:10. Climate Consultant 6.0: Ground Temperature (Monthly Average).



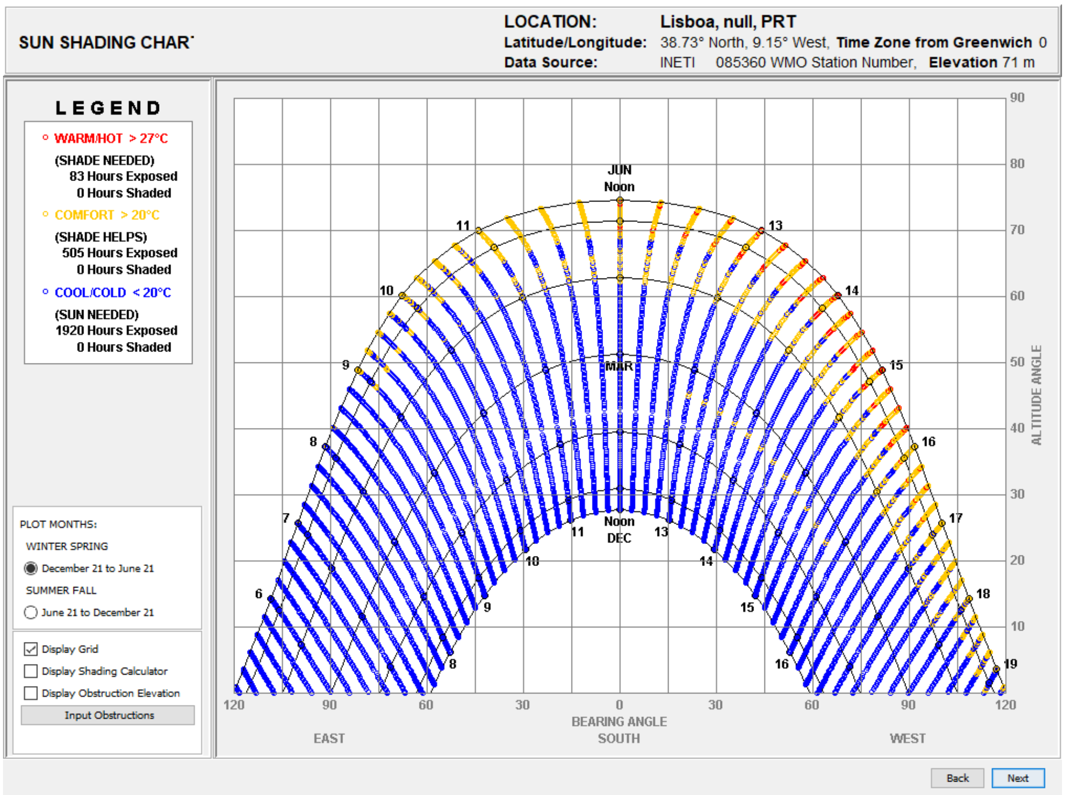
Graph 11.0:11. Climate Consultant 6.0: Dry Bulb X Relative Humidity.



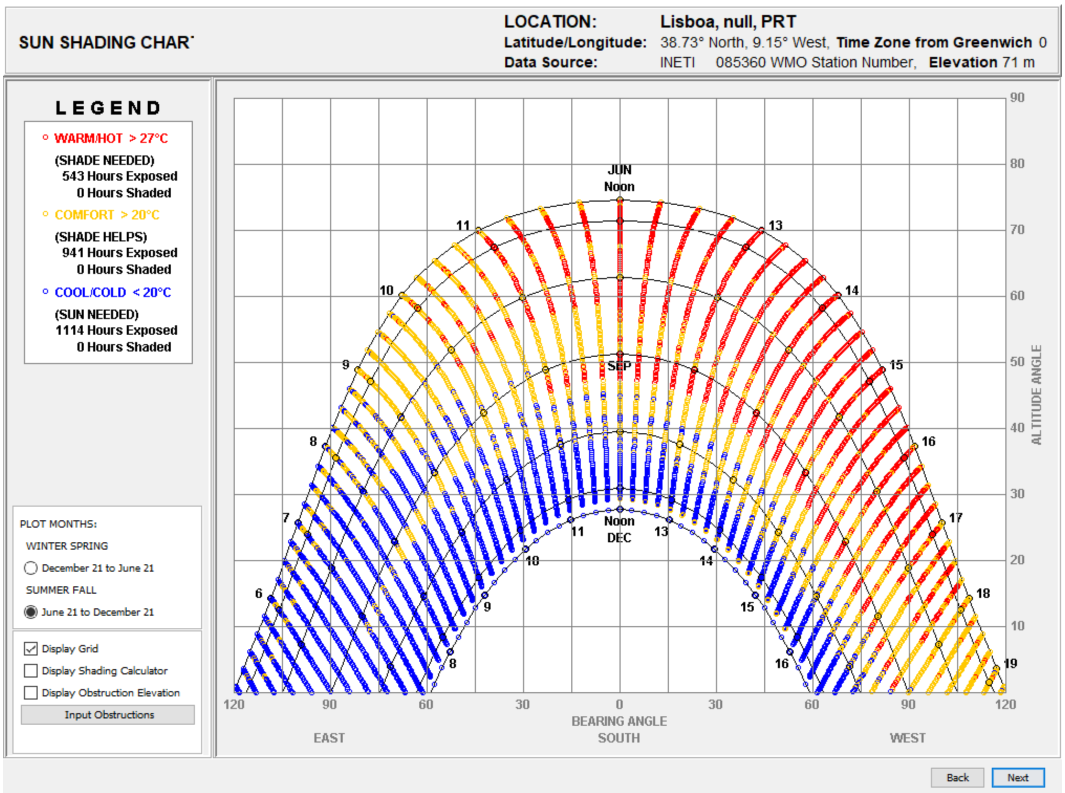
Graph 11.0:12. Climate Consultant 6.0: Dry bulb X Dew Point.



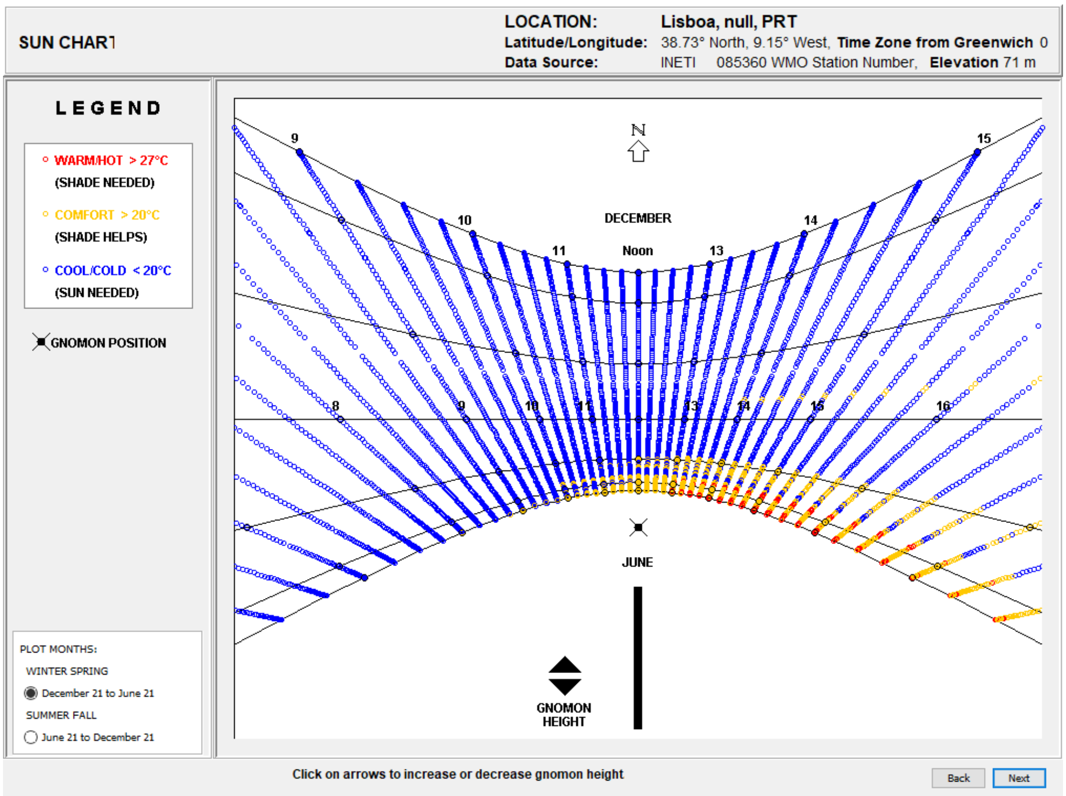
Graph 11.0:13. Climate Consultant 6.0: Sun Shading Chart December/June.



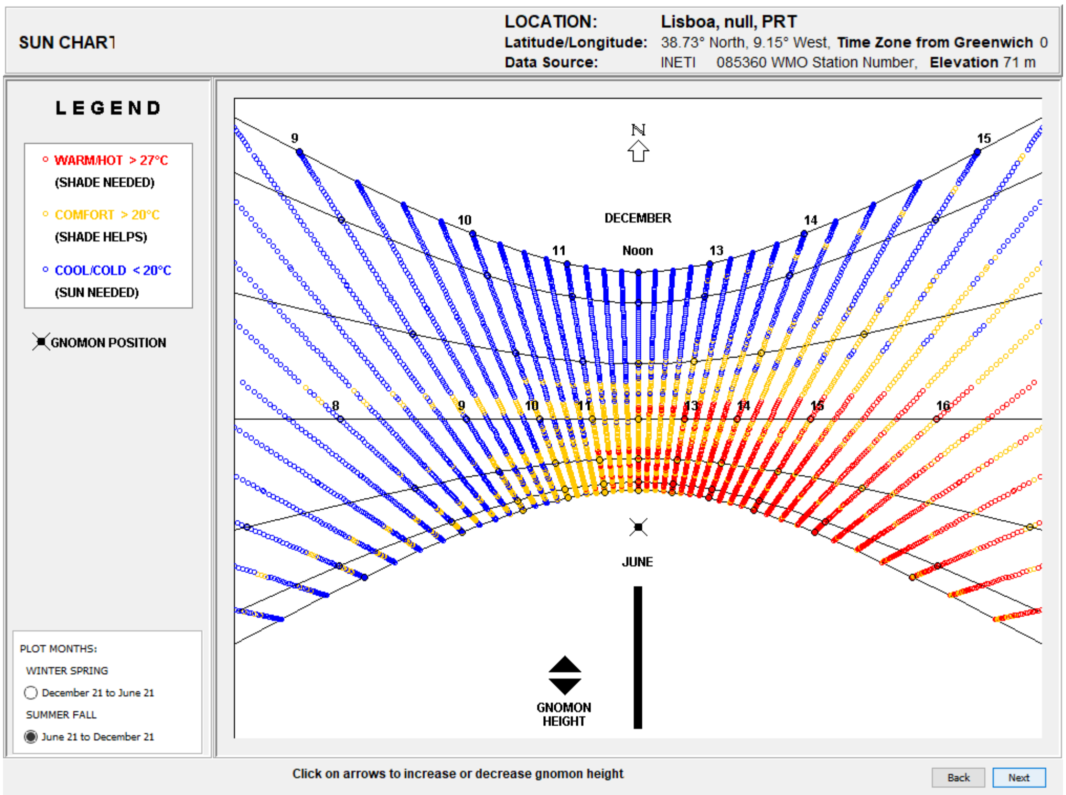
Graph 11.0:14. Climate Consultant 6.0: Sun Shading Chart June/December.



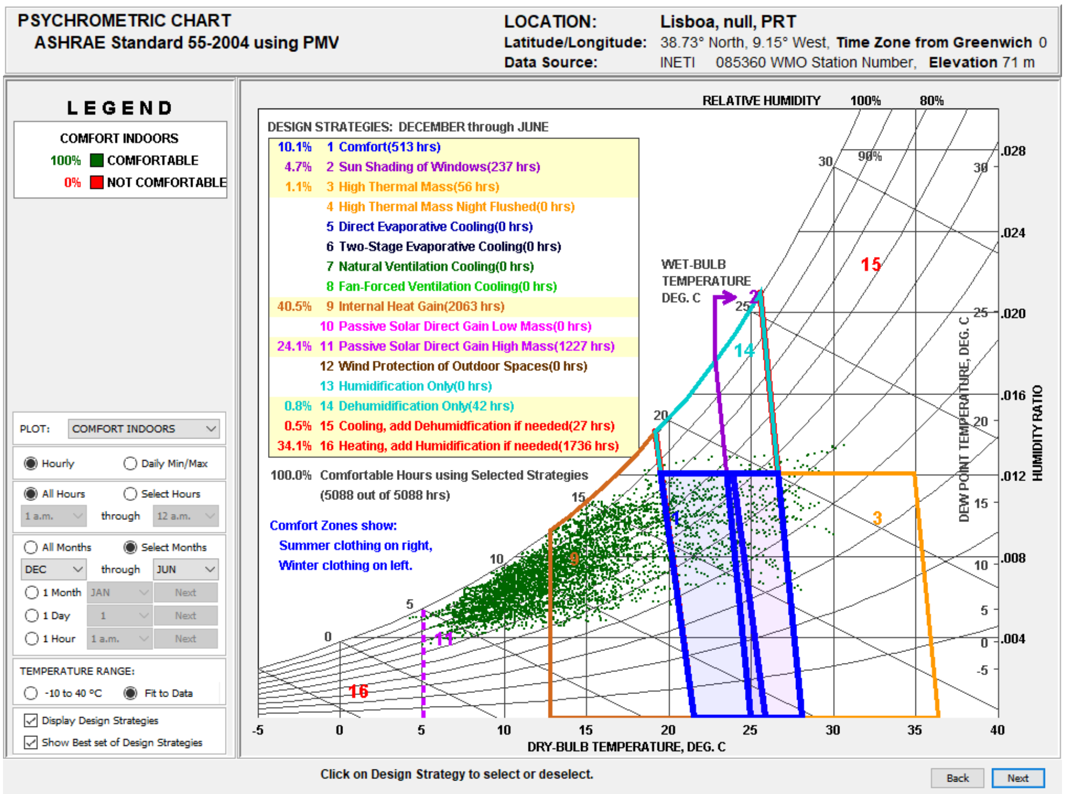
Graph 11.0:15. Climate Consultant 6.0: Sun Chart December/June.



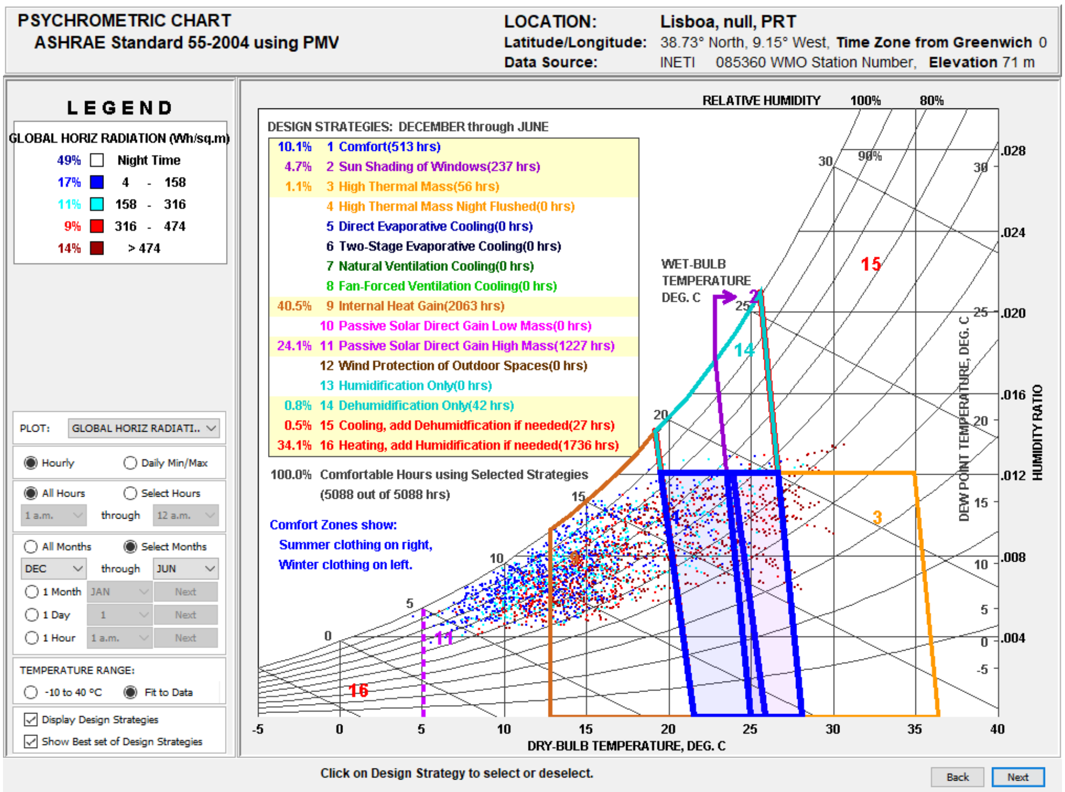
Graph 11.0:16. Climate Consultant 6.0: Sun Chart June/December.



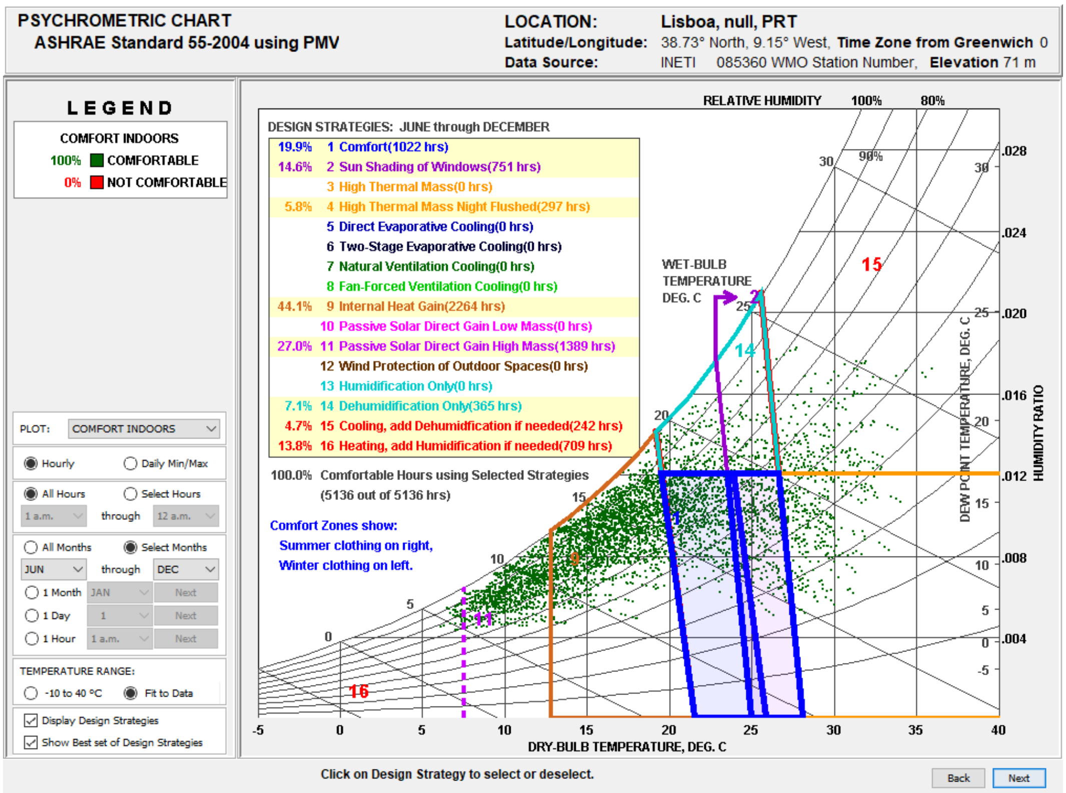
Graph 11.0:17. Climate Consultant 6.0: Psychrometric Chart (Comfort Indoors) December/June.



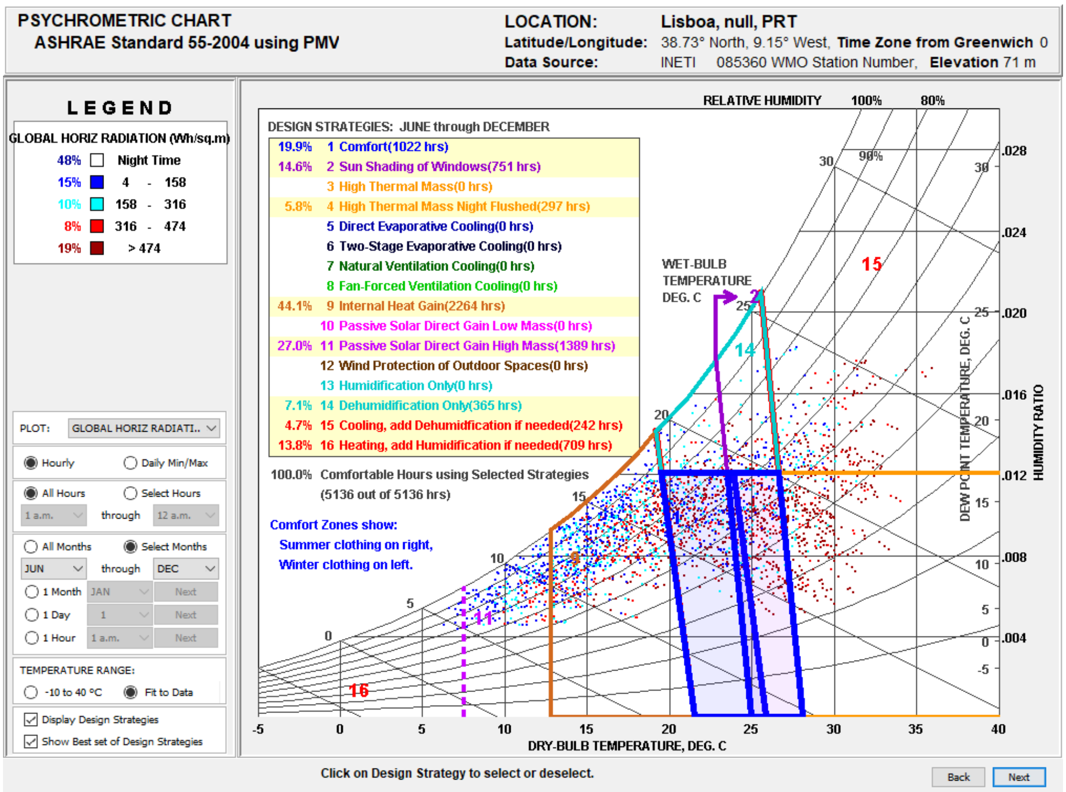
Graph 11.0:18. Climate Consultant 6.0: Psychrometric Chart (Global Horizontal Radiation) December/June.



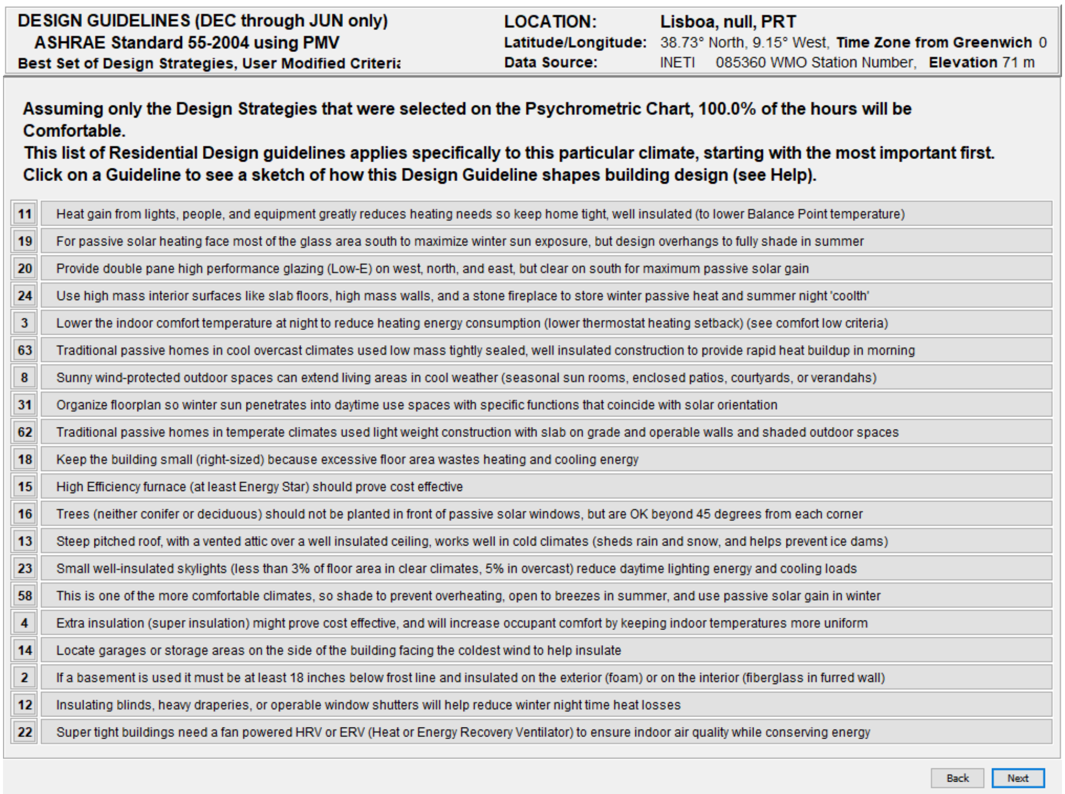
Graph 11.0:19. Climate Consultant 6.0: Psychrometric Chart (Comfort Indoors) June/December.



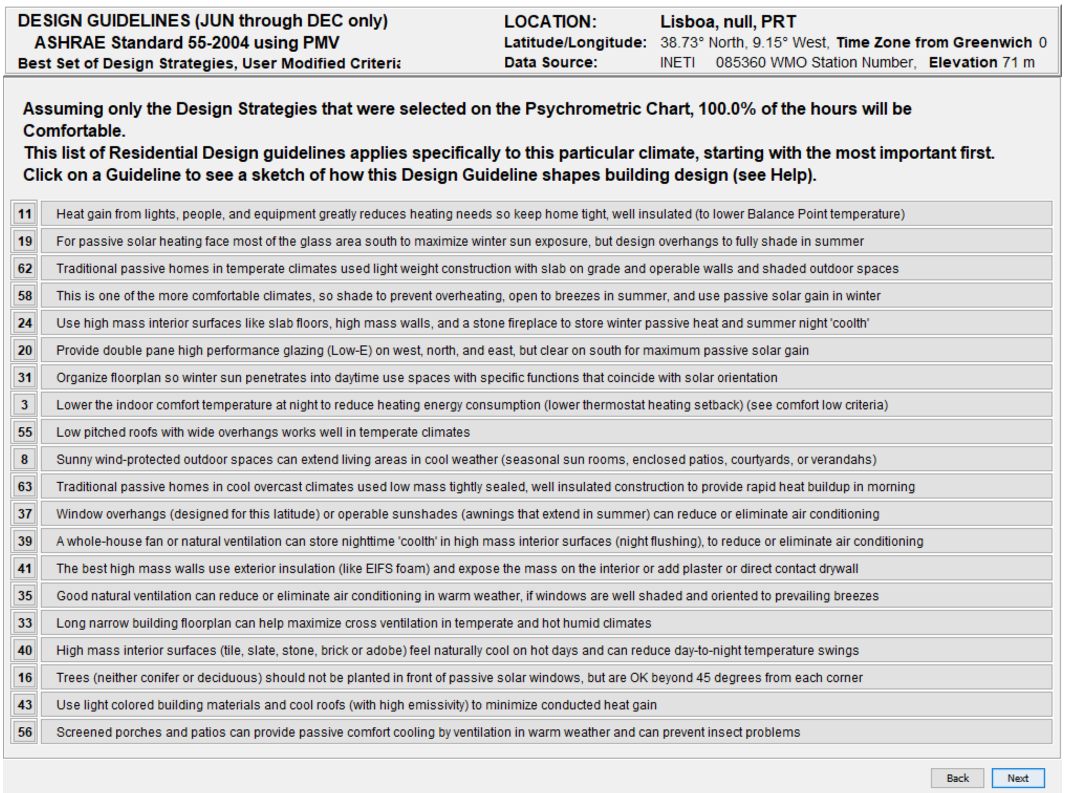
Graph 11.0:20. Climate Consultant 6.0: Psychrometric Chart (Global Horizontal Radiation) June/December.



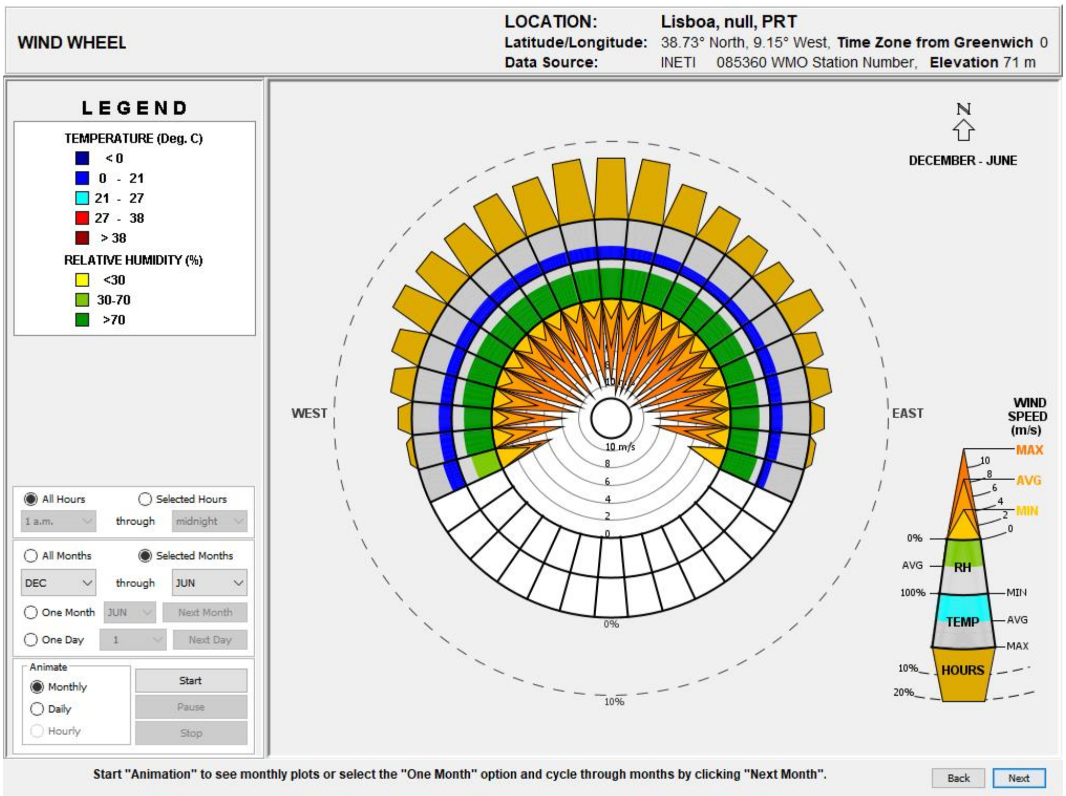
Graph 11.0:21. Climate Consultant 6.0: Design Guidelines (December through June).



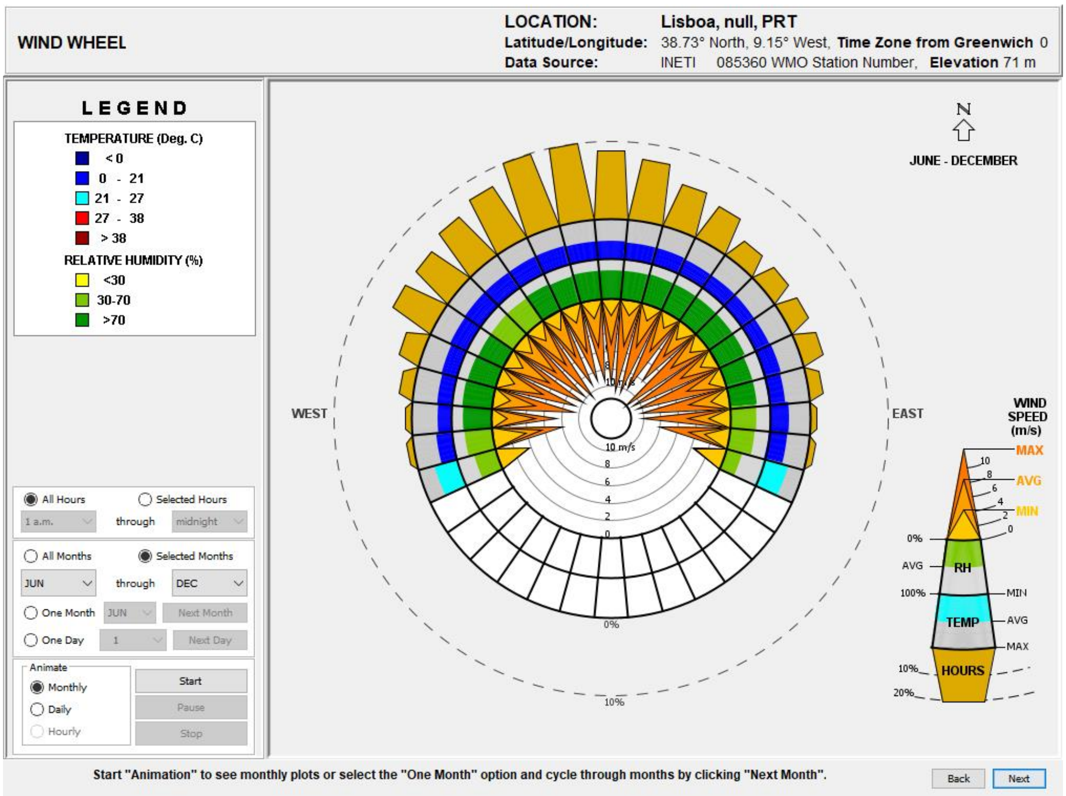
Graph 11.0:22. Climate Consultant 6.0: Design Guidelines (June through December).



Graph 11.0:23. Wind Wheel (December/June).



Graph 11.0:24. Wind Wheel (June/December).



11.3 Ladybug Analysis

11.3.1 Dry Bulb Temperature

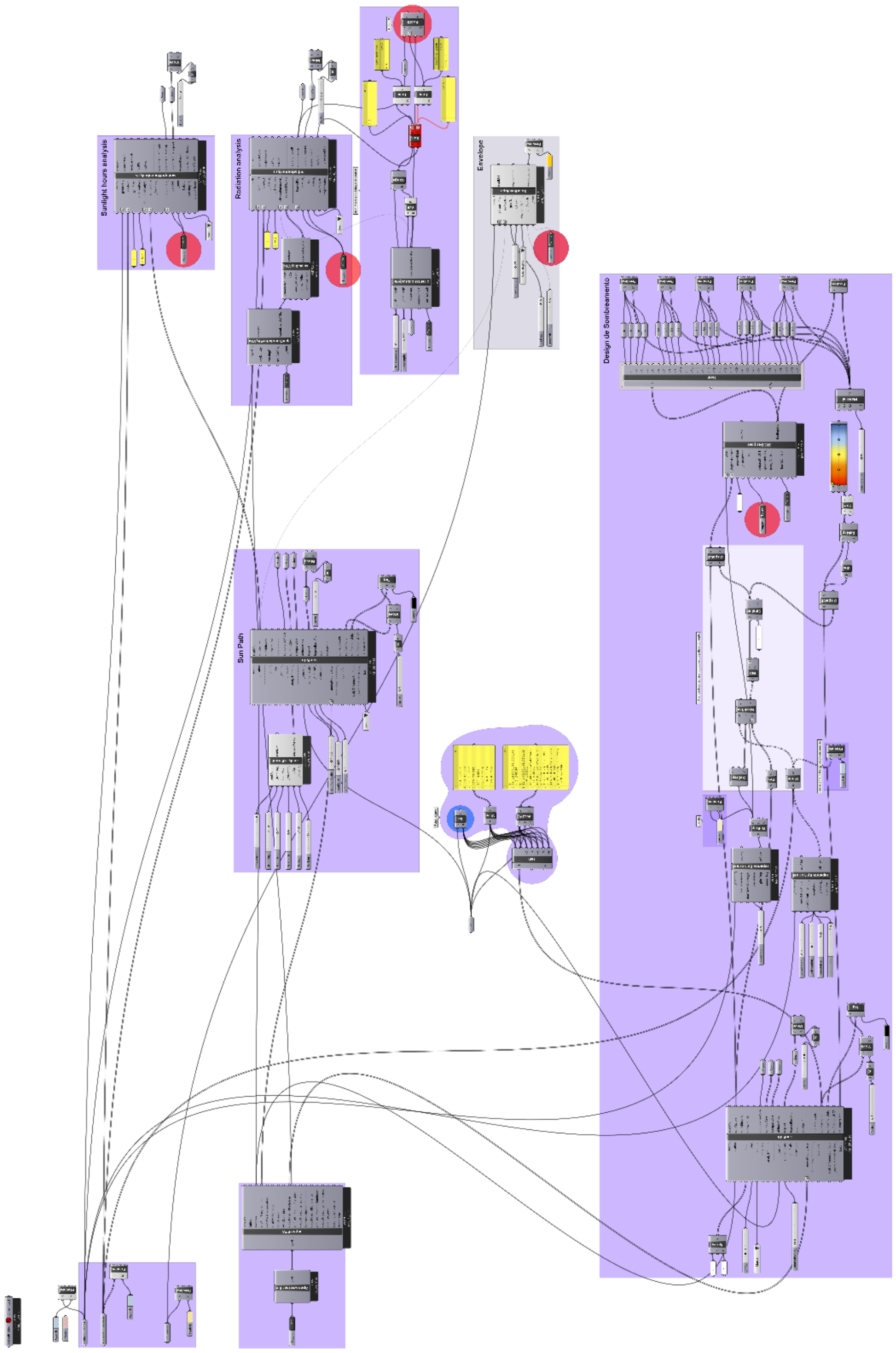
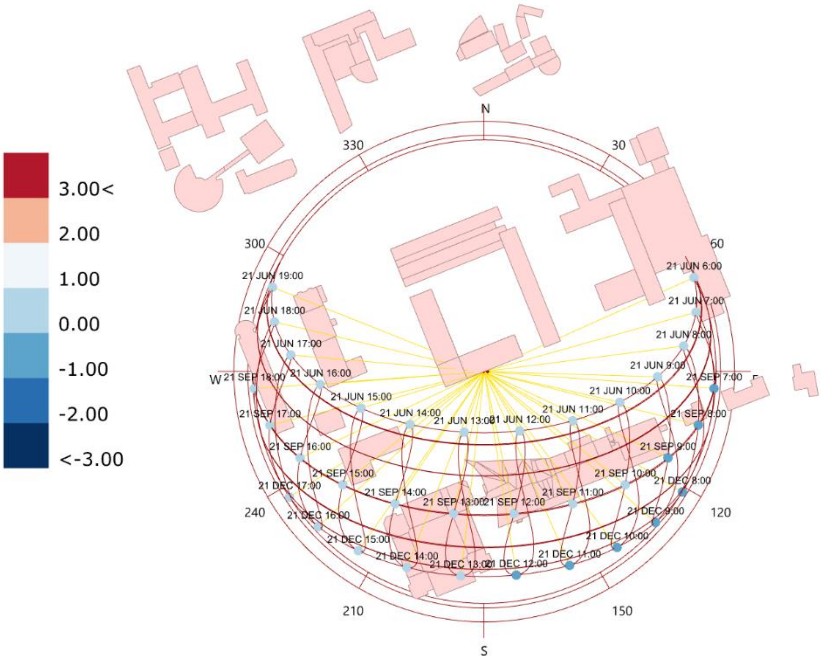


Figure 11.0:1. Ladybug Analysis: Comfort Sun Path, Sun Shading and Radiation Grasshopper + Ladybug parametric definition.



-3 = Extreme Cold | -2 = Cold | -1 = Cool | 0 = Comfort | 1 = Warm | 2 = Hot | 3 = Extreme Heat

Figure 11.0:2. Ladybug Analysis: Comfort Sun Path.

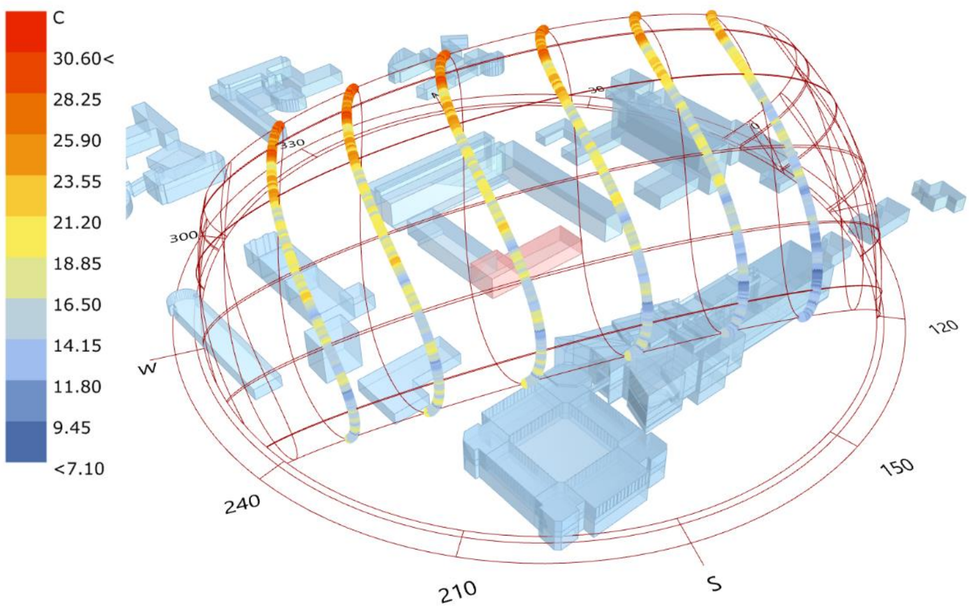


Figure 11.0:3. Ladybug Analysis: Sun Path December/June.

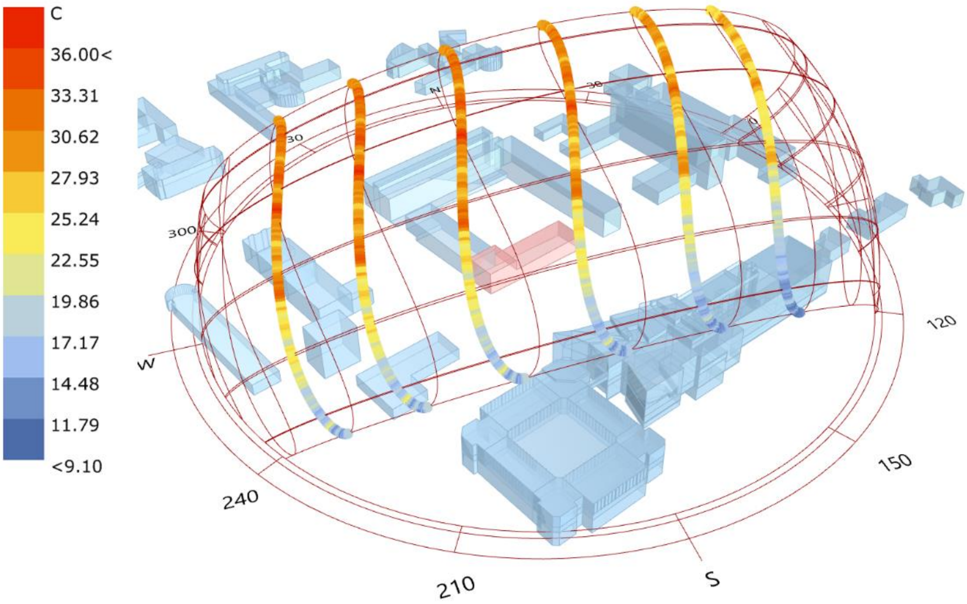


Figure 11.0:4. Ladybug Analysis: Sun Path June/December.

11.3.2 Radiation

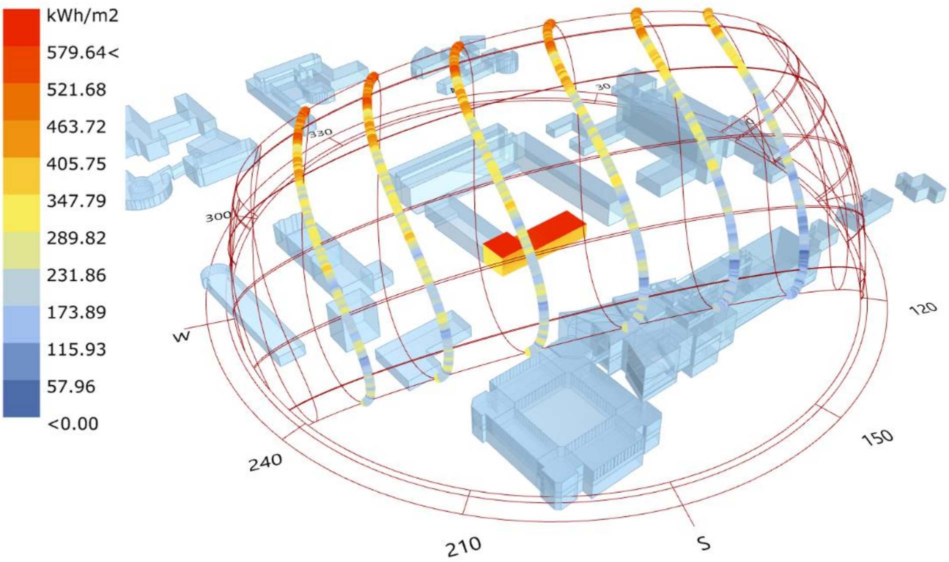


Figure 11.0:5. Ladybug Analysis: Radiation December/June.

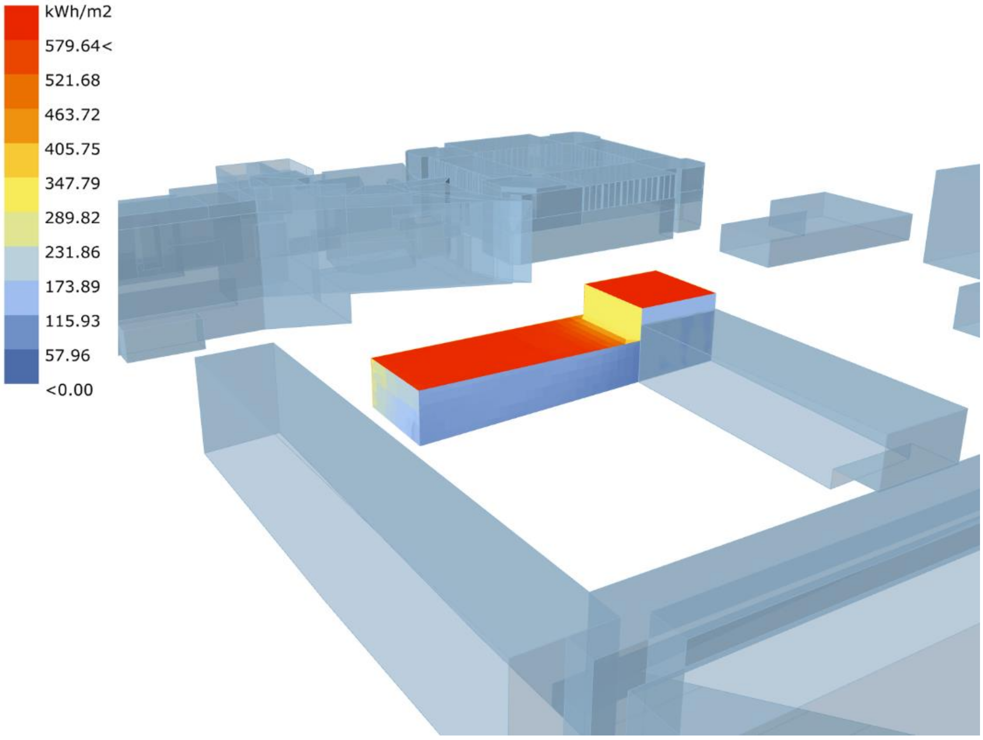


Figure 11.0:6. Ladybug Analysis: Radiation December/June - Northeast façade.

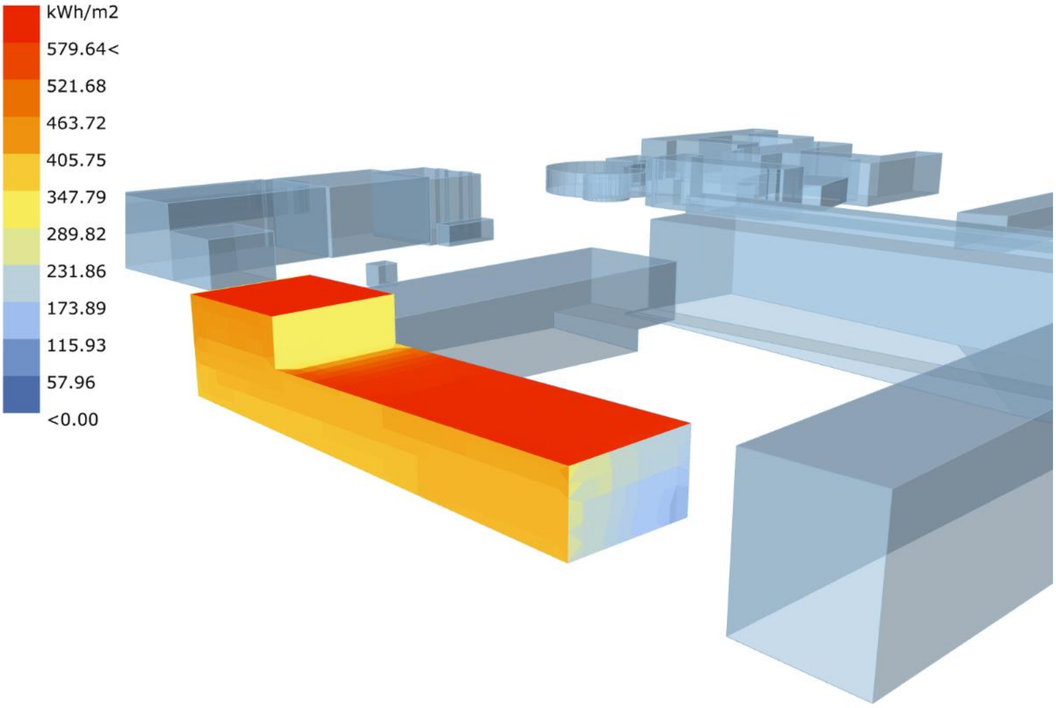


Figure 11.0:7. Ladybug Analysis: Radiation December/June - Southeast façade.

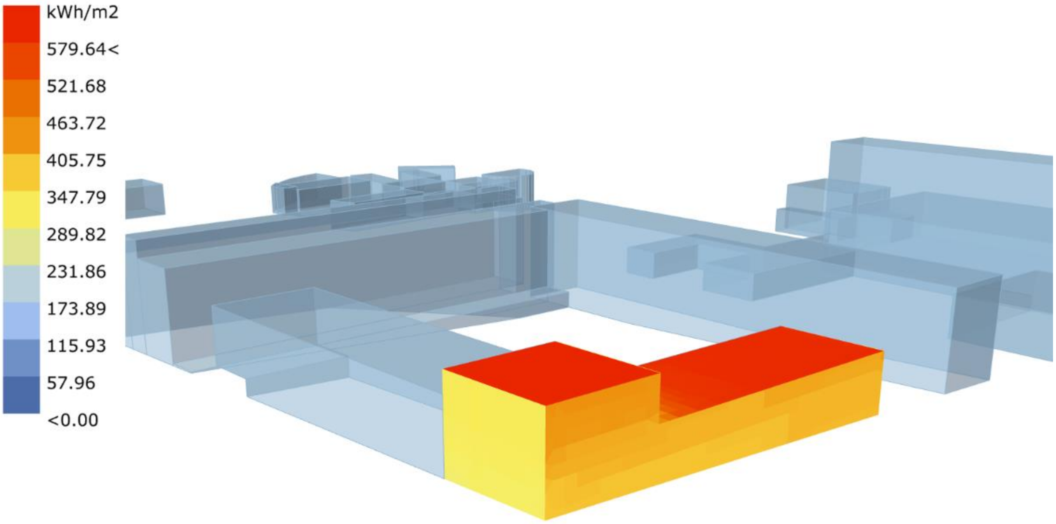


Figure 11.0:8. Ladybug Analysis: Radiation December/June - Southwest façade.

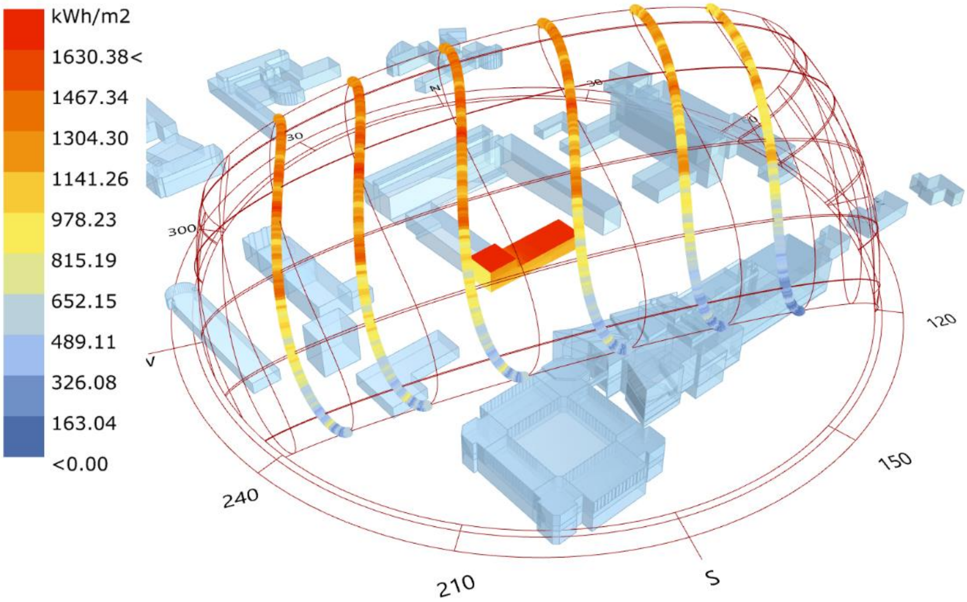


Figure 11.0:9. Ladybug Analysis: Radiation June/December.

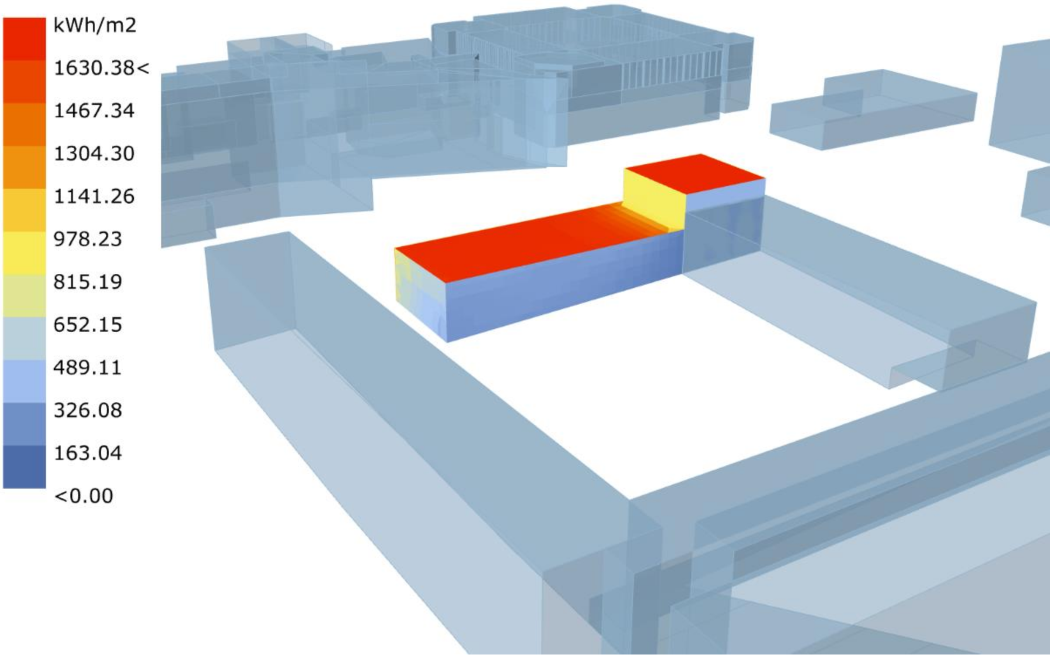


Figure 11.0:10. Ladybug Analysis: Radiation June/December – Northeast façade.

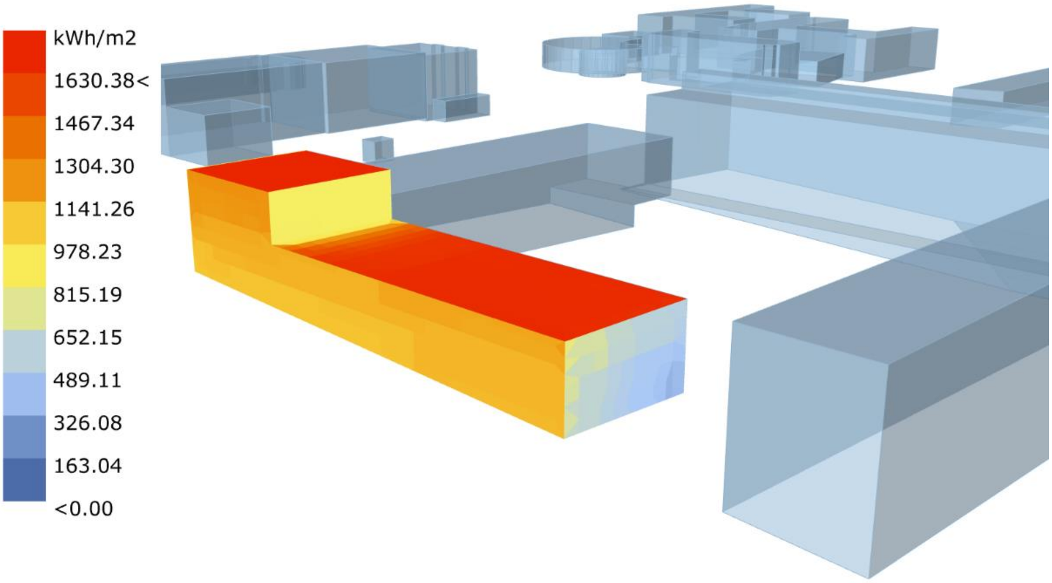


Figure 11.0:11. Ladybug Analysis: Radiation June/December – Southeast façade.

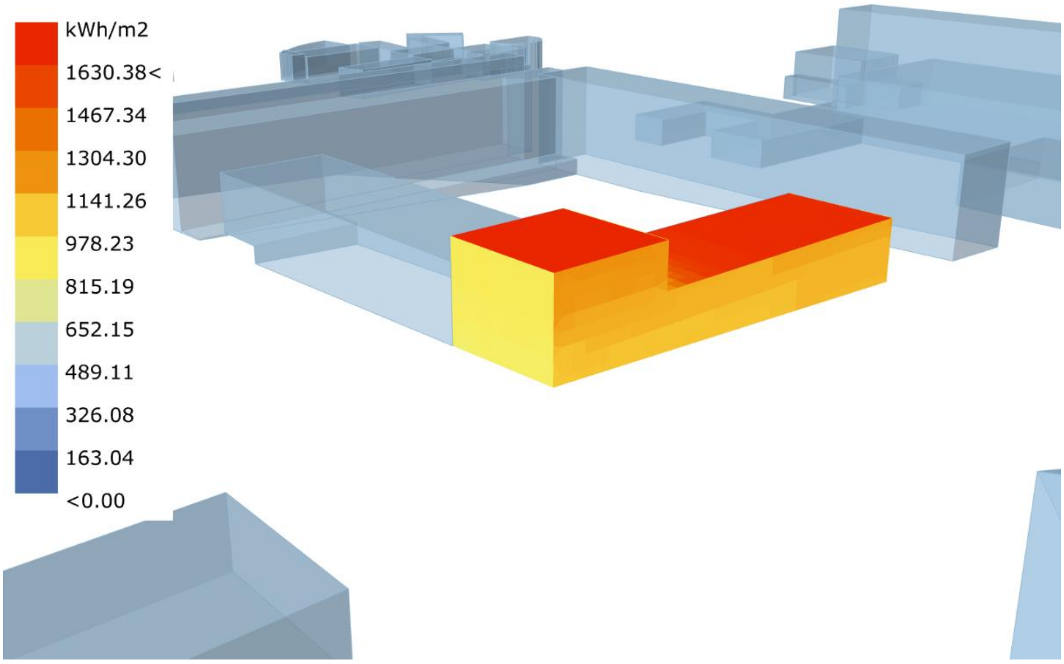


Figure 11.0:12. Ladybug Analysis: Radiation June/December – Southwest façade.

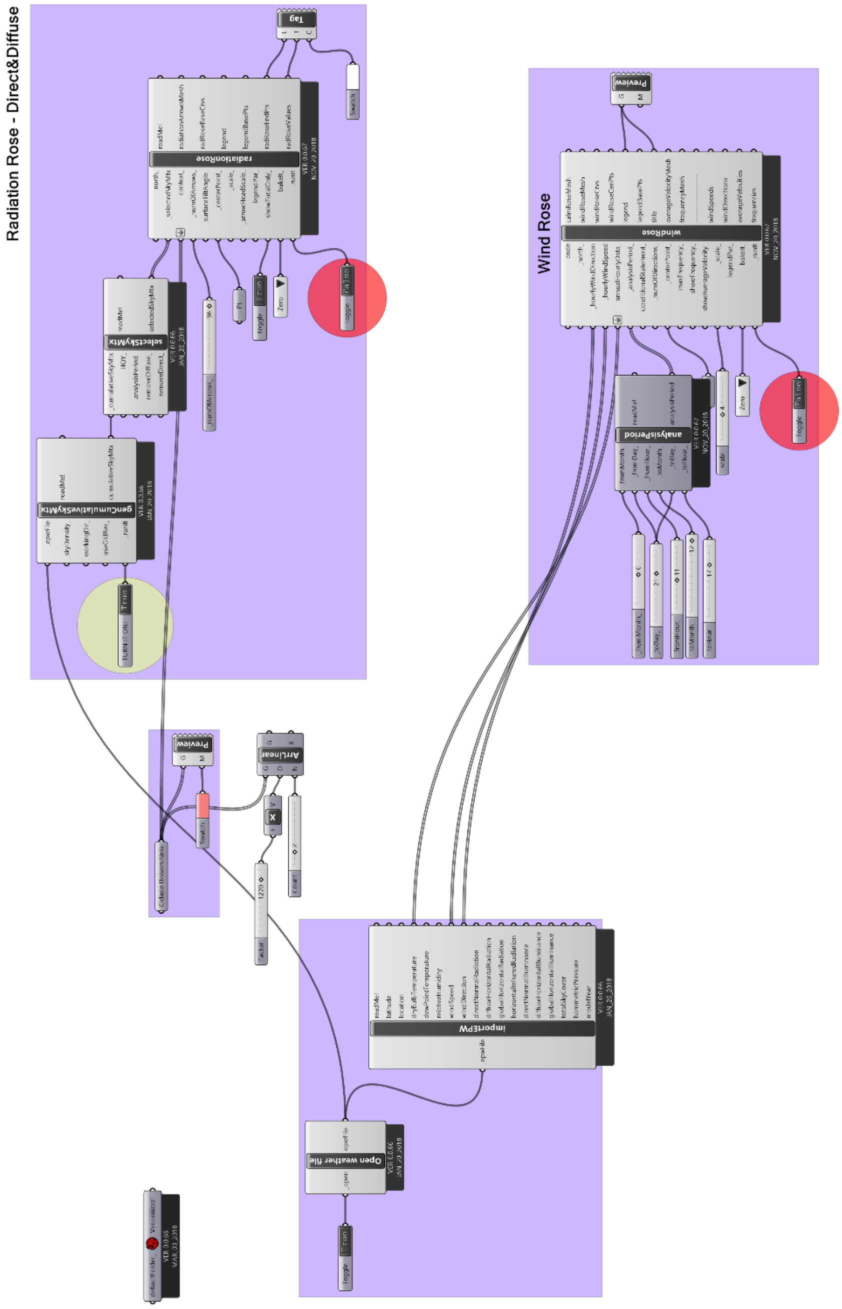


Figure 11.0:13. Ladybug Analysis: Radiation Wind-Roses Grasshopper + Ladybug parametric definition.

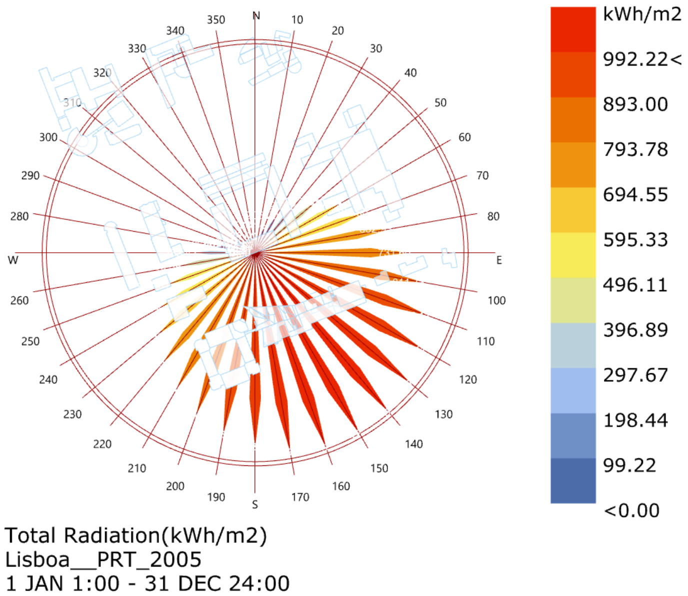


Figure 11.0:14. Ladybug Analysis: Radiation Rose.

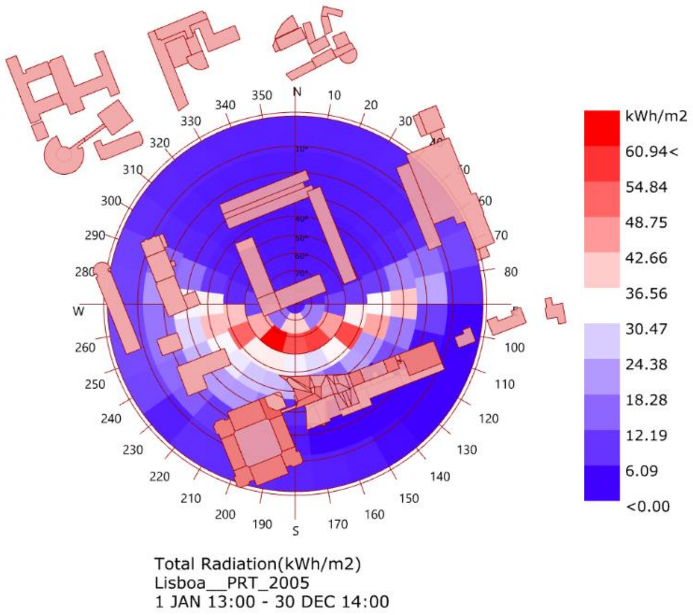


Figure 11.0:15. Ladybug Analysis: Total Radiation.

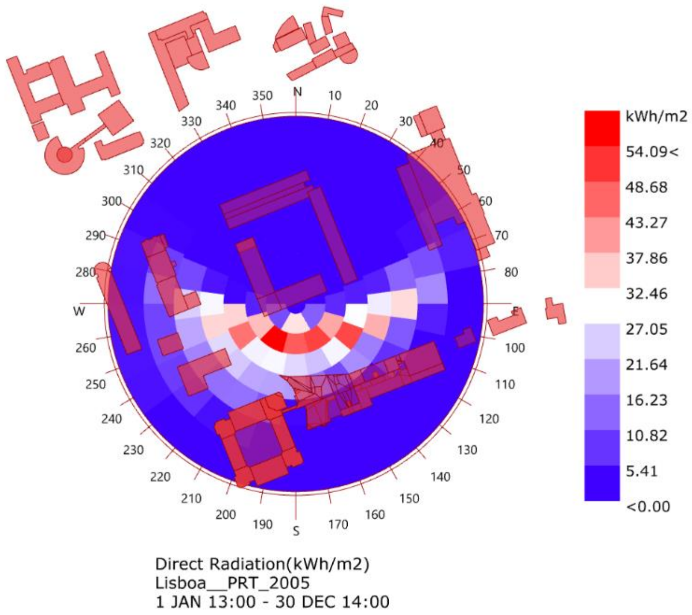


Figure 11.0:16. Ladybug Analysis: Direct Radiation.

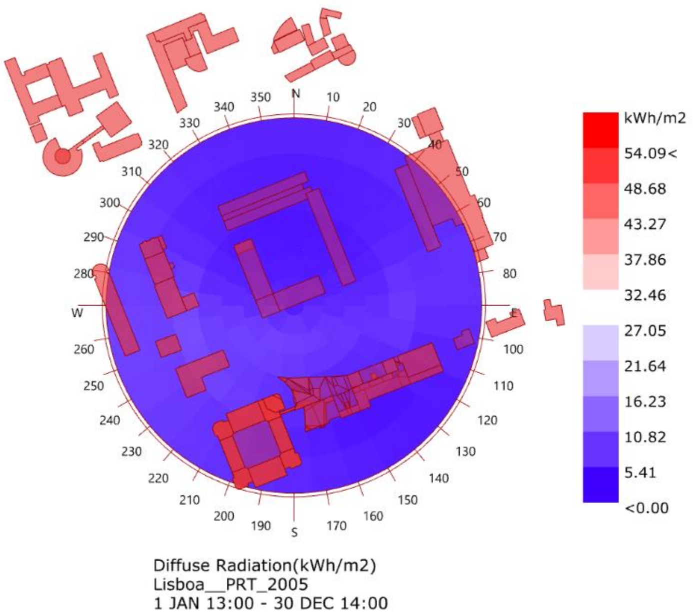


Figure 11.0:17. Ladybug Analysis: Diffuse Radiation.

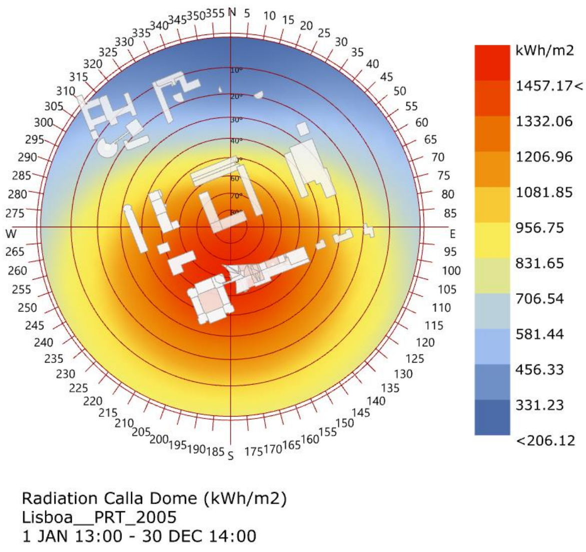


Figure 11.0:18. Ladybug Analysis: Radiation Calla Dome/Stereographic.

11.3.3 Irradiation

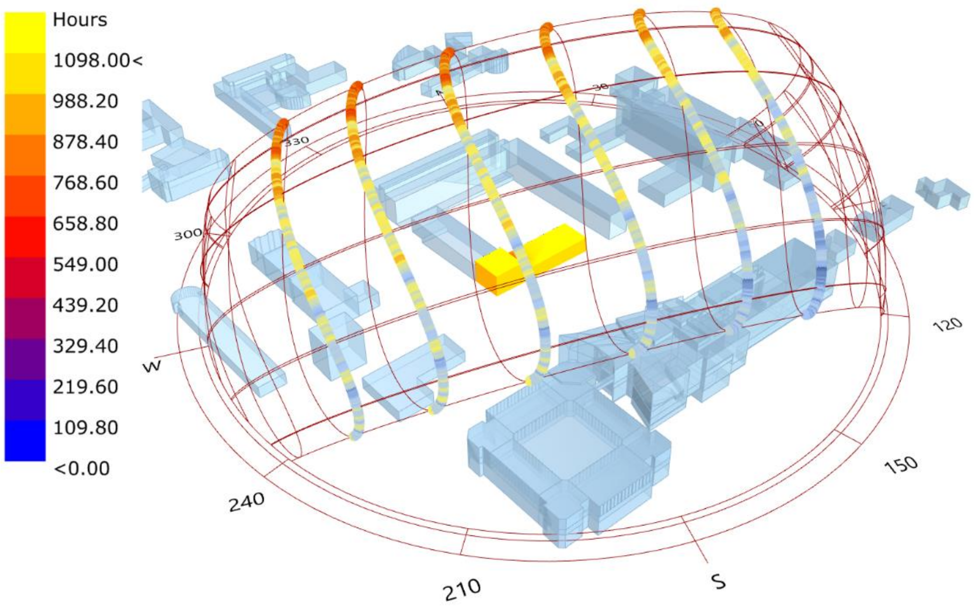


Figure 11.0:19. Ladybug Analysis: Irradiation December/June.

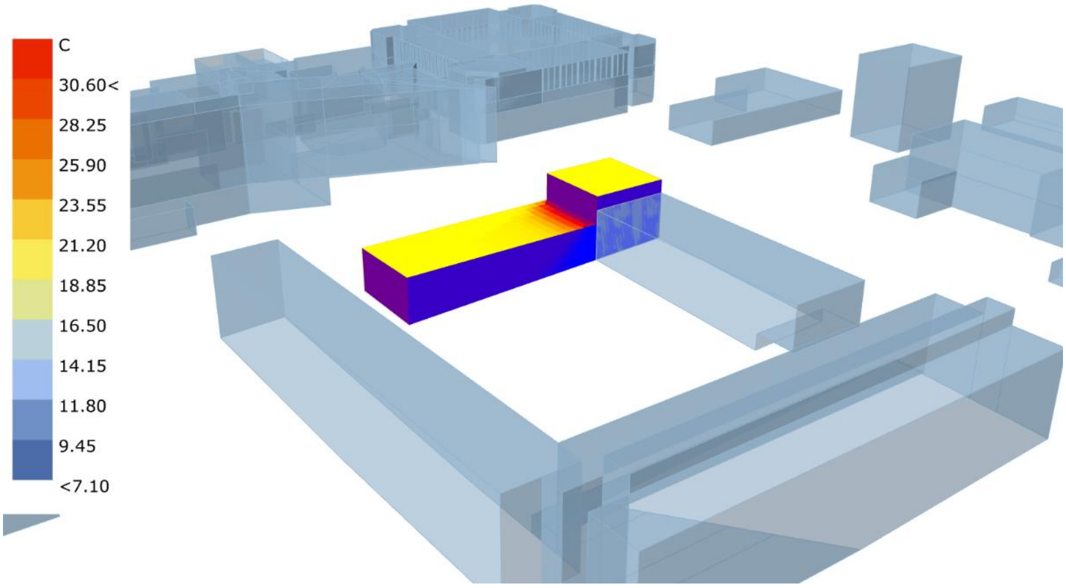


Figure 11.0:20. Ladybug Analysis: Irradiation December/June - Northeast façade.

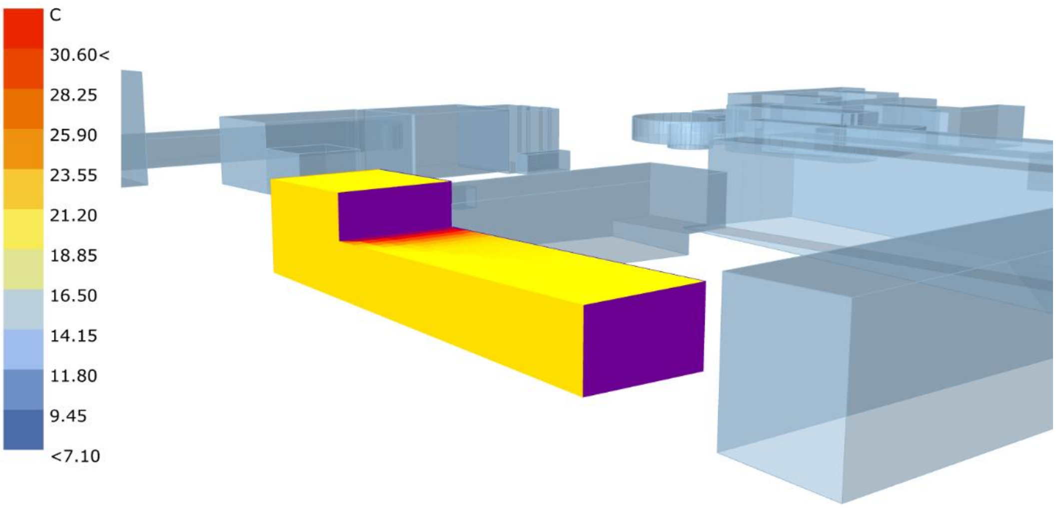


Figure 11.0:21. Ladybug Analysis: Irradiation December/June - Southeast façade.

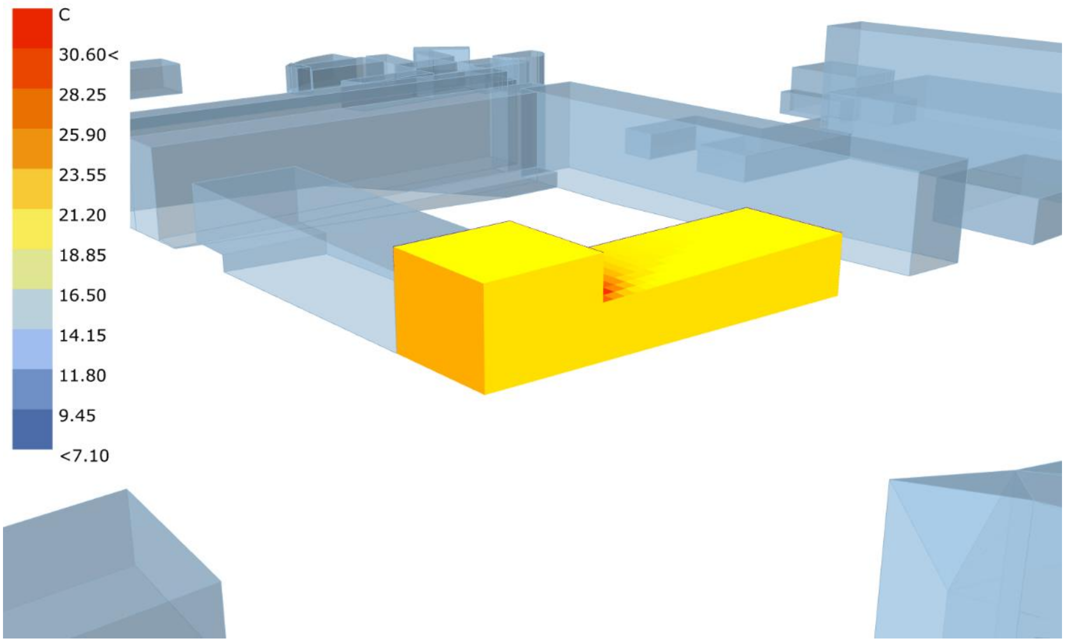


Figure 11.0:22. Ladybug Analysis: Irradiation December/June - Southwest façade.

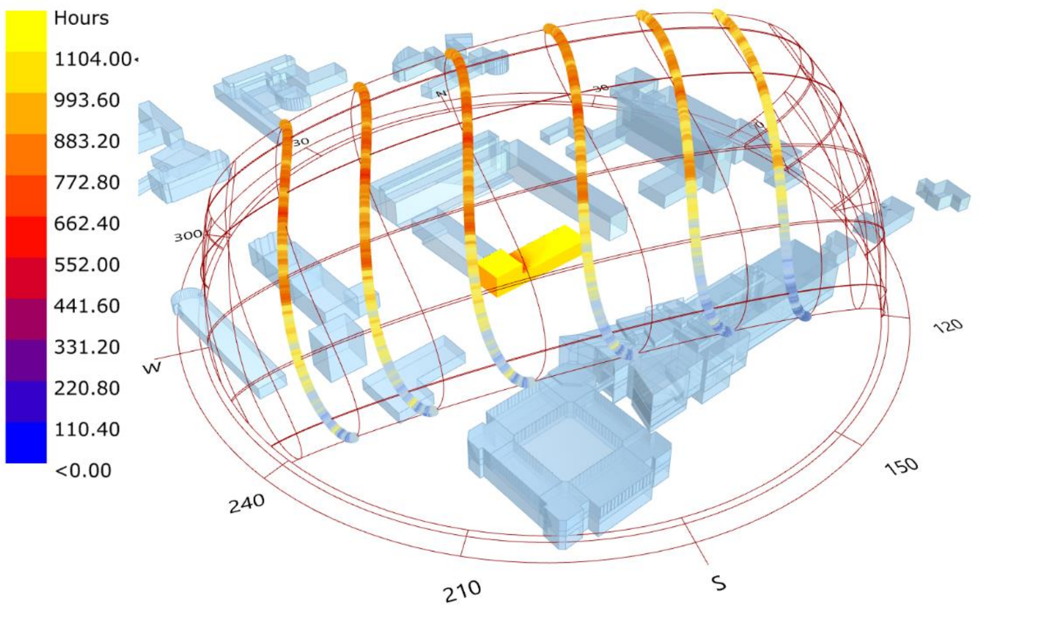


Figure 11.0:23. Ladybug Analysis: Irradiation June/December.

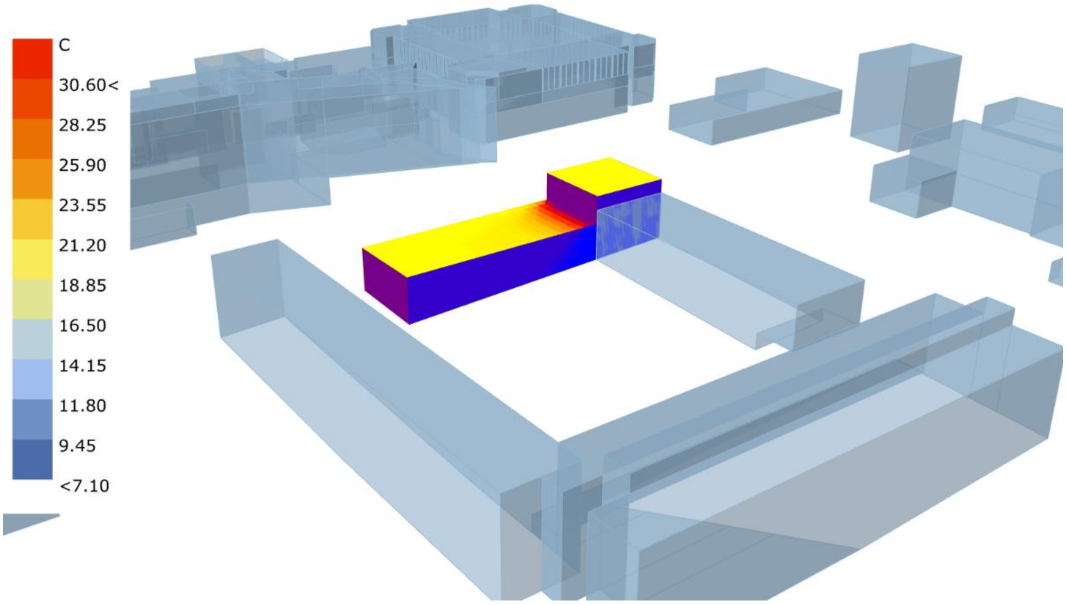


Figure 11.0:24. Ladybug Analysis: Irradiation June/December - Northeast façade.

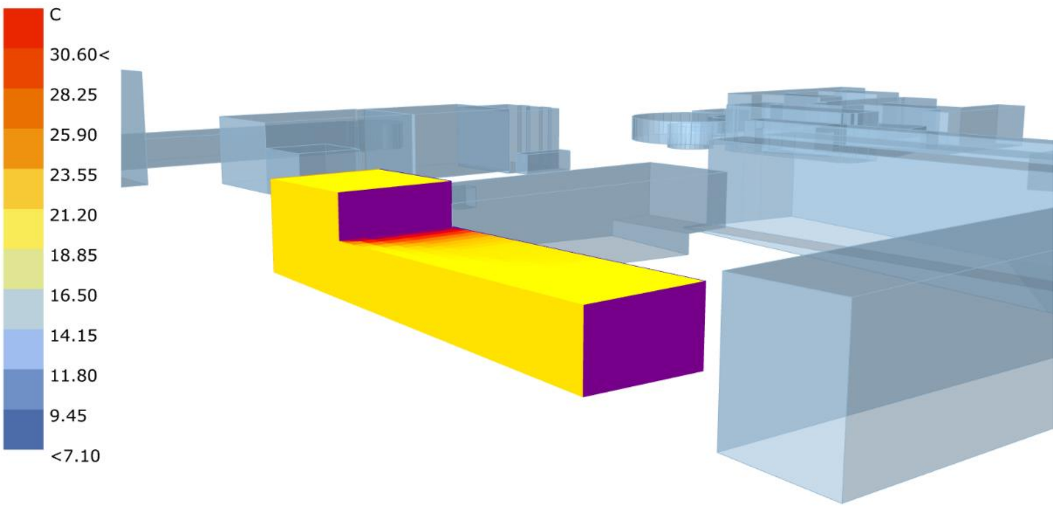


Figure 11.0:25. Ladybug Analysis: Irradiation June/December - Southeast façade.

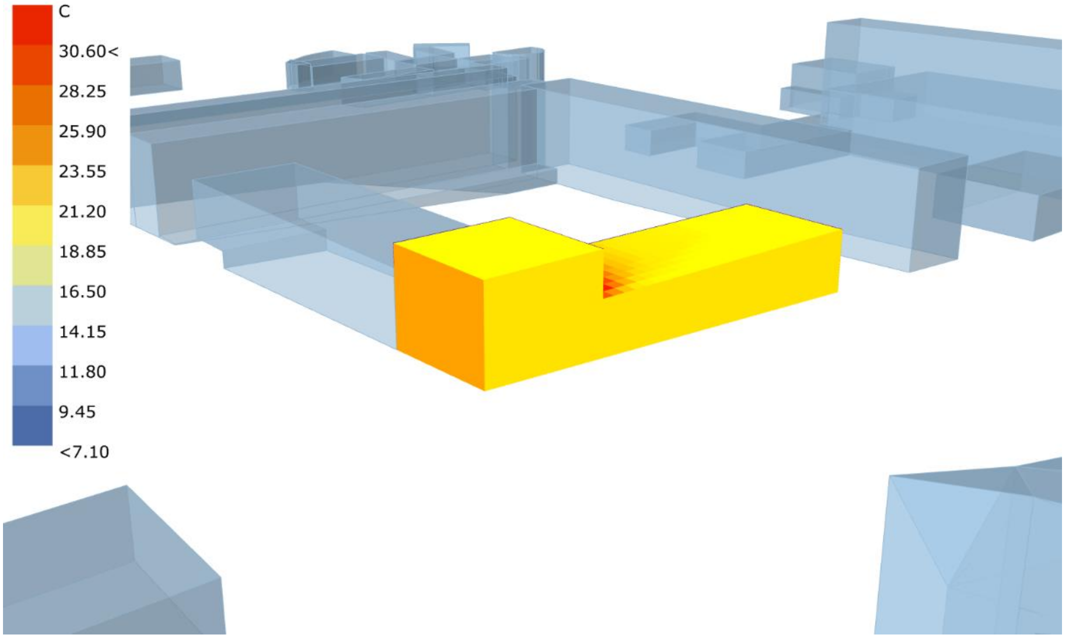


Figure 11.0:26. Ladybug Analysis: Irradiation June/December - Southwest façade.

11.3.4 Shading Design

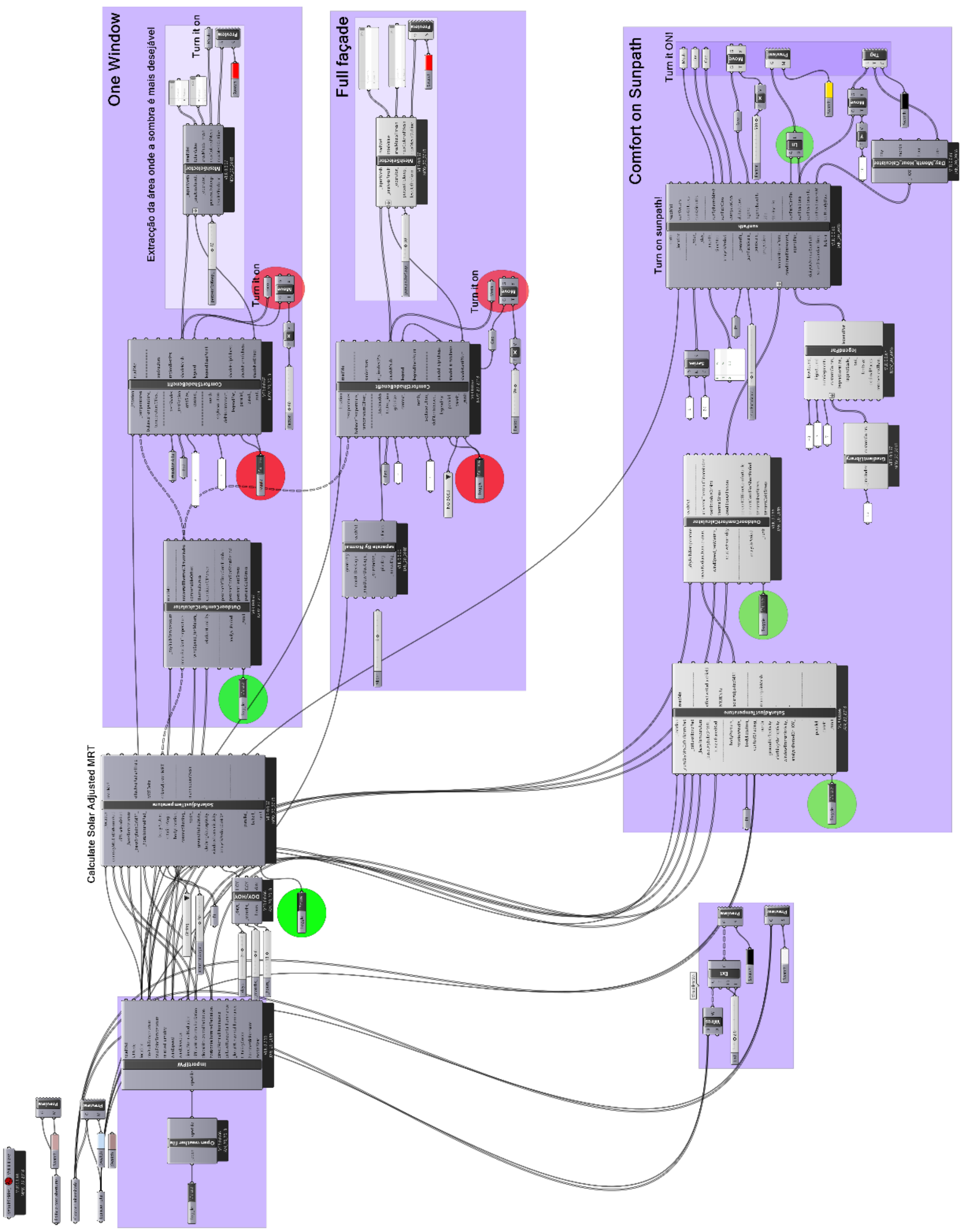


Figure 11.0:27. Ladybug Analysis: Façade+Window shade Design, Grasshopper + Ladybug parametric definition.

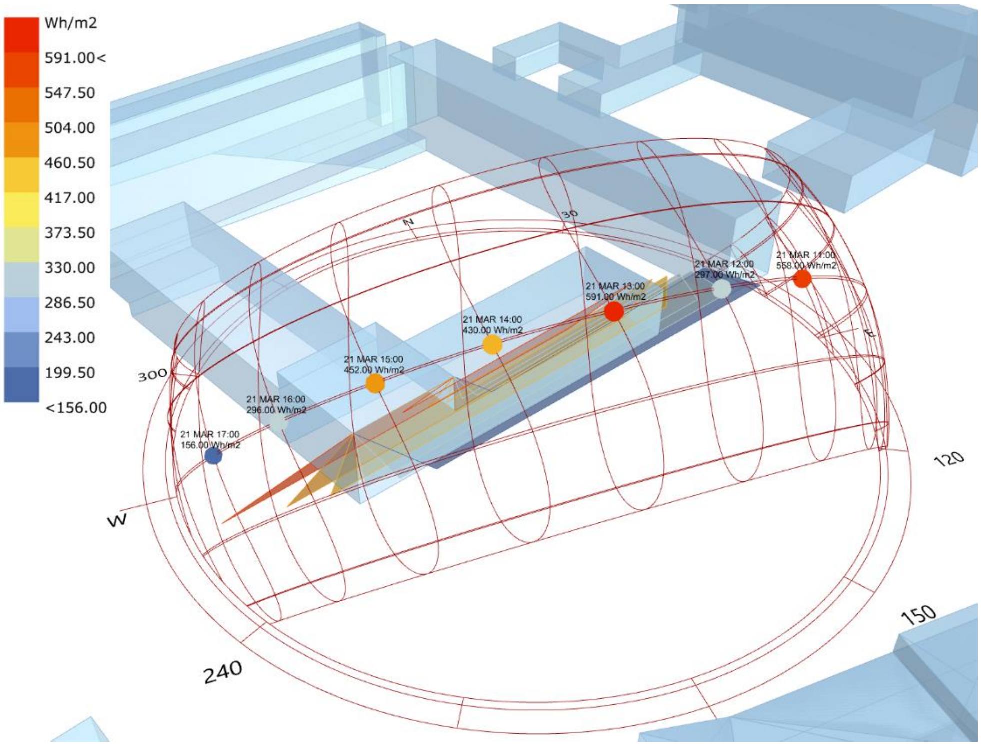


Figure 11.0:28. Ladybug Analysis: One Shade at 21st March.

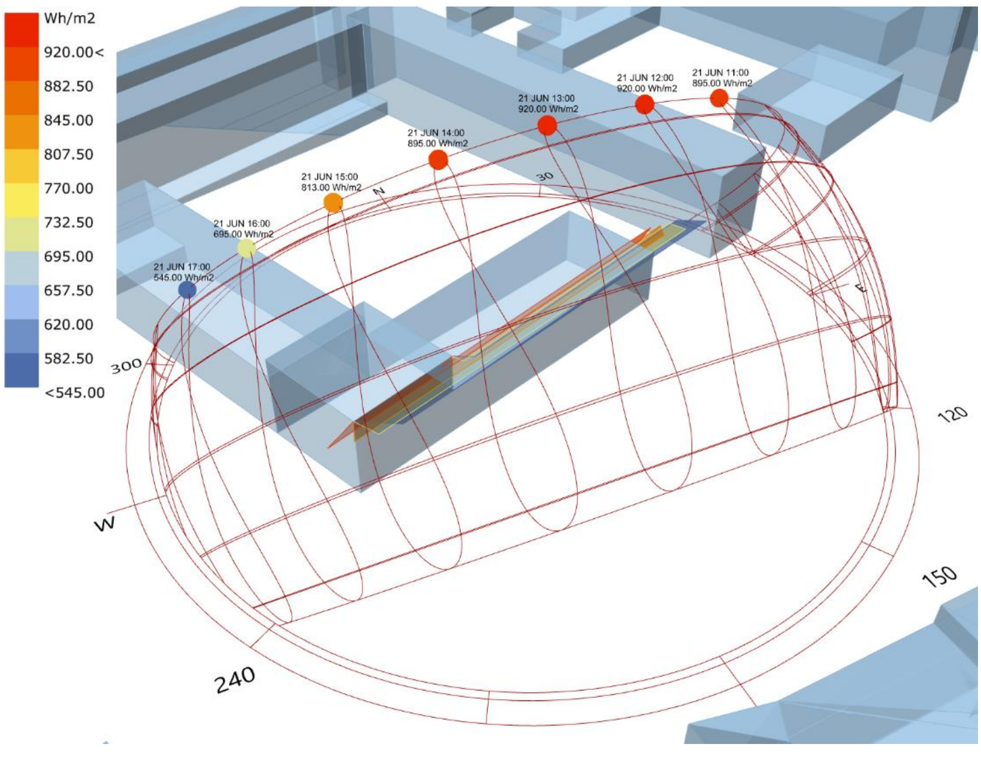


Figure 11.0:29. Ladybug Analysis: One Shade at 21st June.

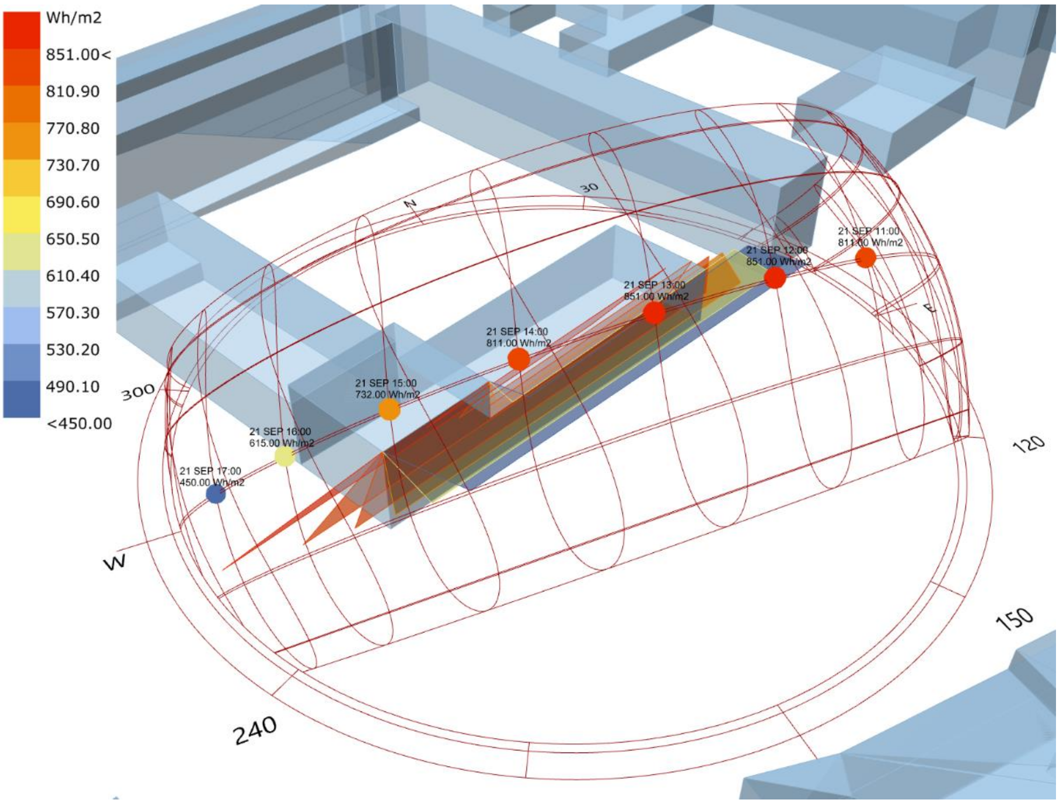


Figure 11.0:30. Ladybug Analysis: One Shade at 21st September.

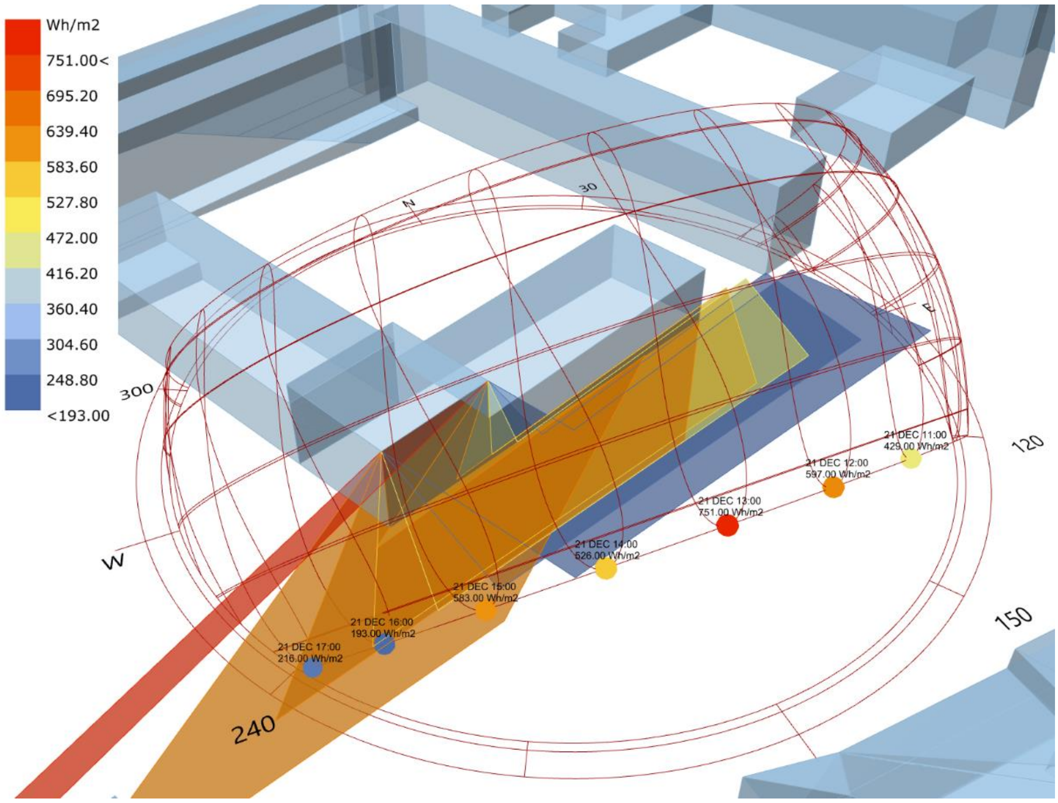


Figure 11.0:31. Ladybug Analysis: One Shade at 21st December.

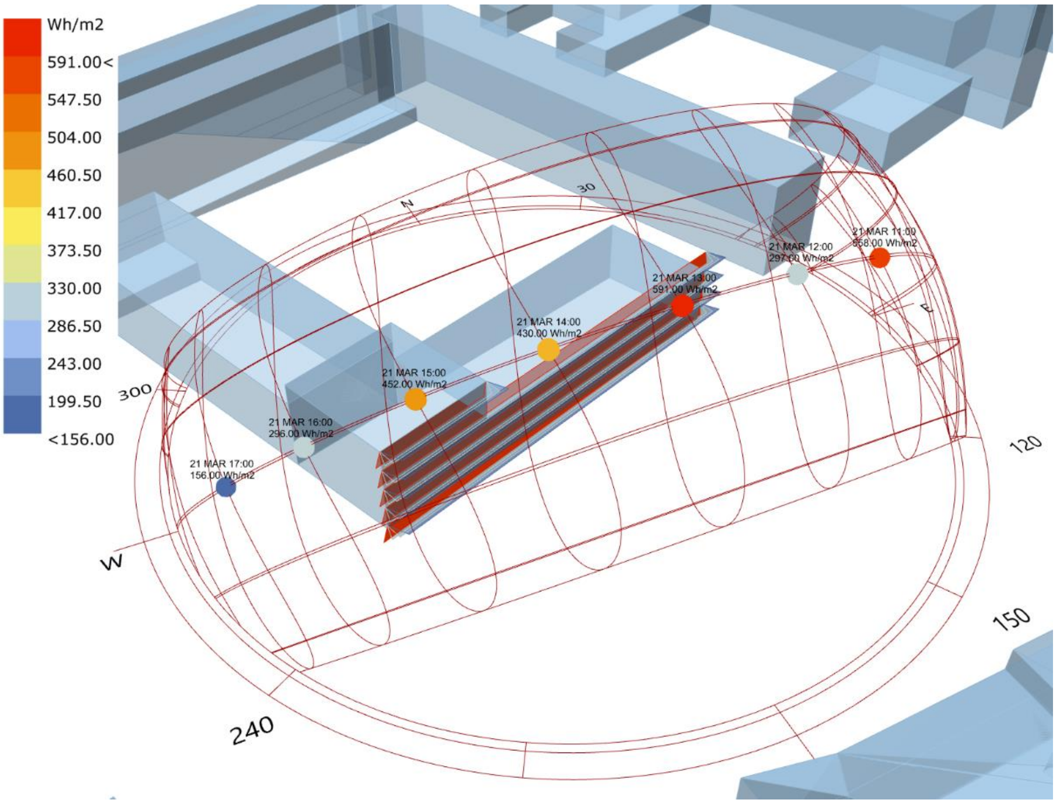


Figure 11.0:32. Ladybug Analysis: Five Shades at 21st March.

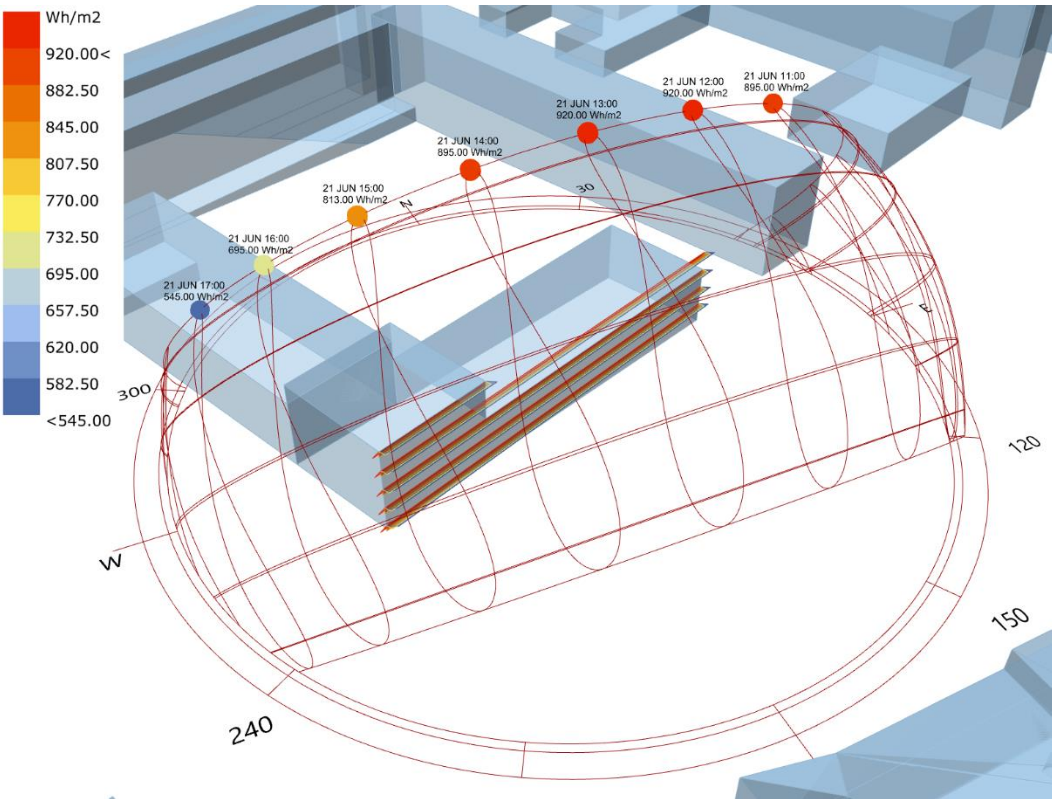


Figure 11.0:33. Ladybug Analysis: Five Shades at 21st June.

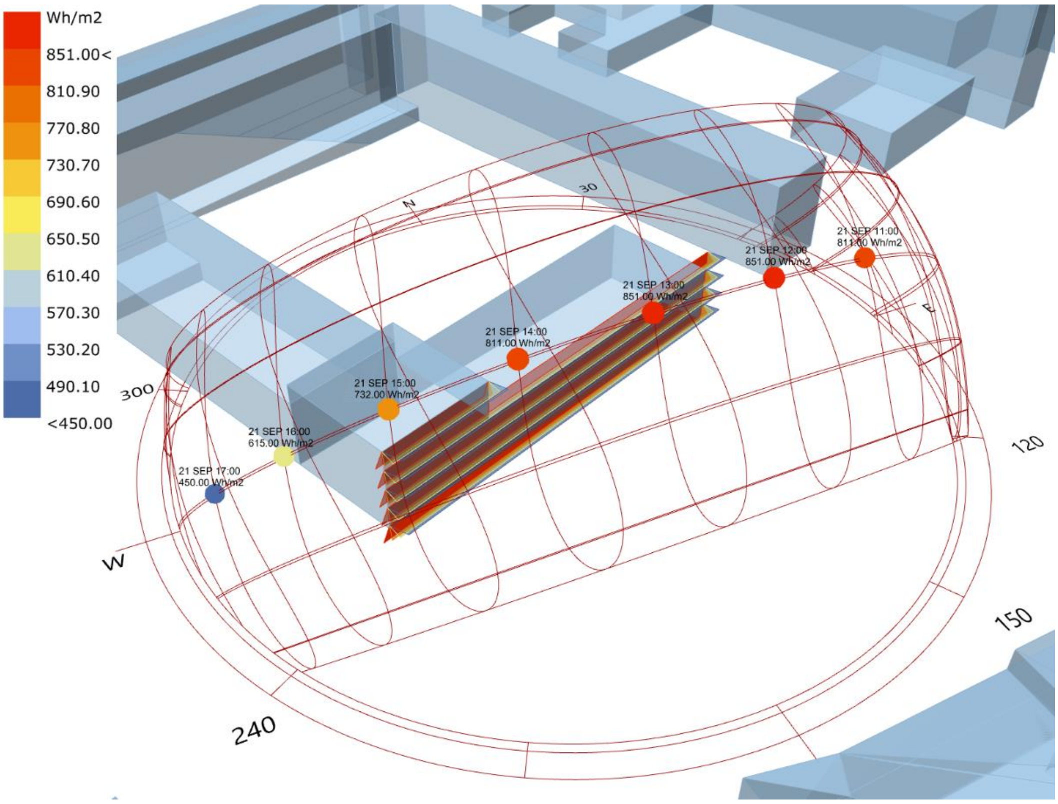


Figure 11.0:34. Ladybug Analysis: Five Shades at 21st September.

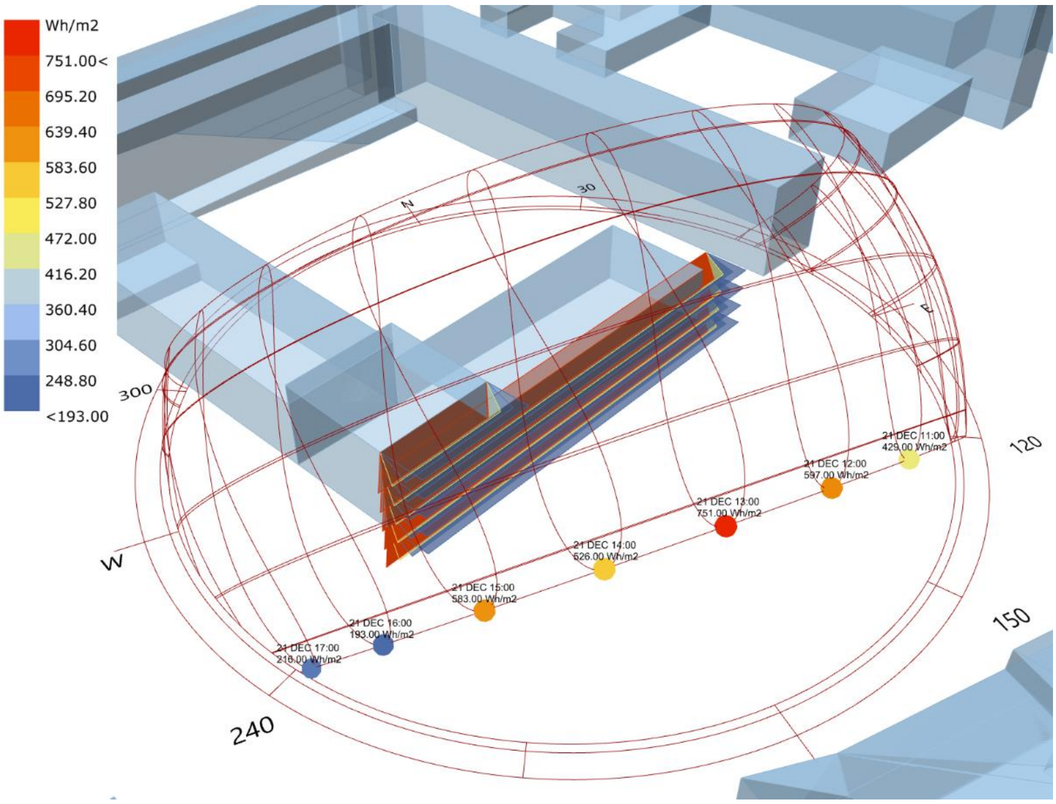


Figure 11.0:35. Ladybug Analysis: Five Shades at 21st December.

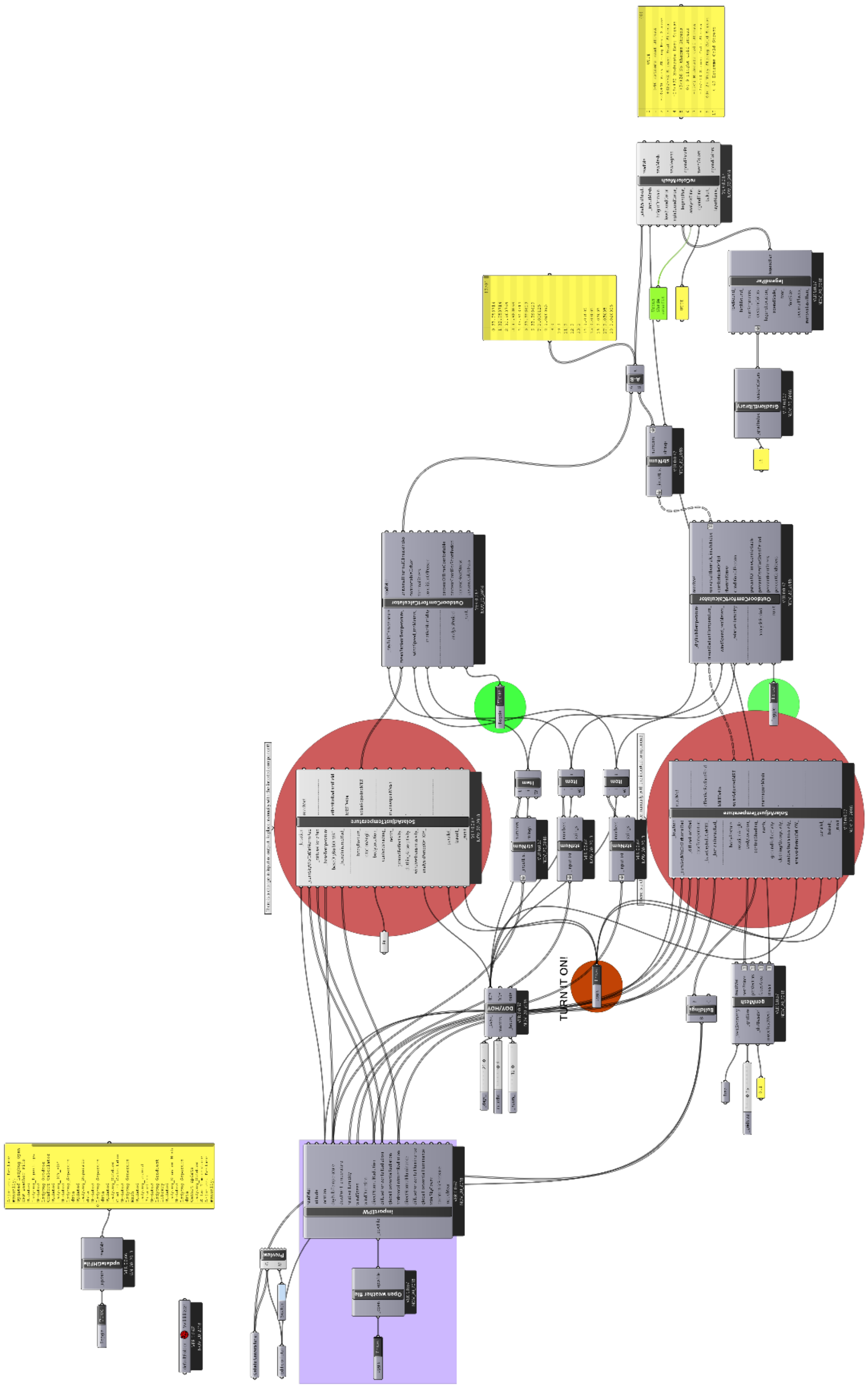


Figure 11.0:36. Ladybug Analysis: Urban shade benefit Grasshopper + Ladybug parametric definition.

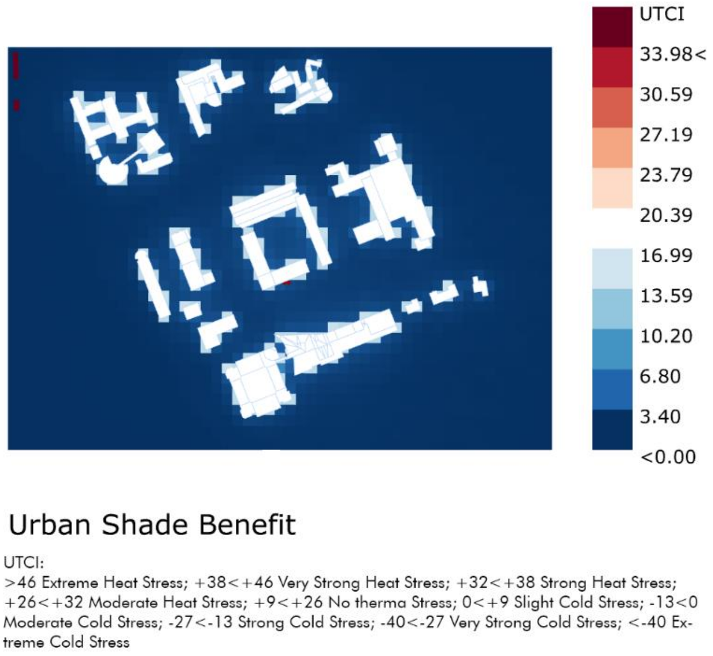


Figure 11.0:37. Ladybug Analysis: Urban Shade Benefit.

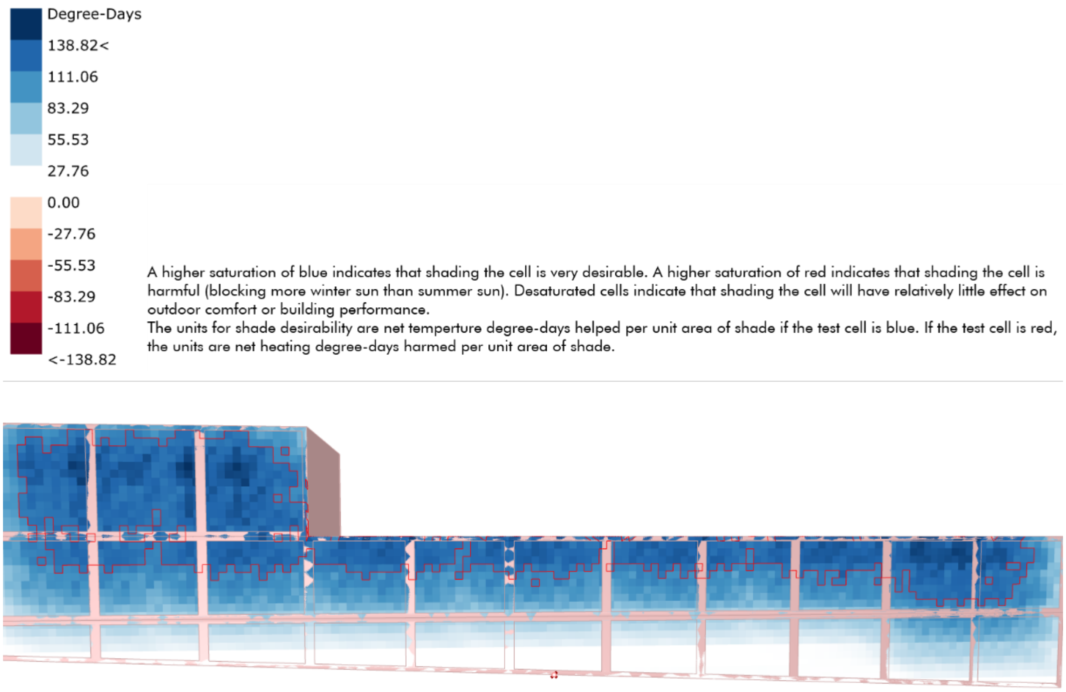


Figure 11.0:38. Ladybug Analysis: Shading Comfort Façade.

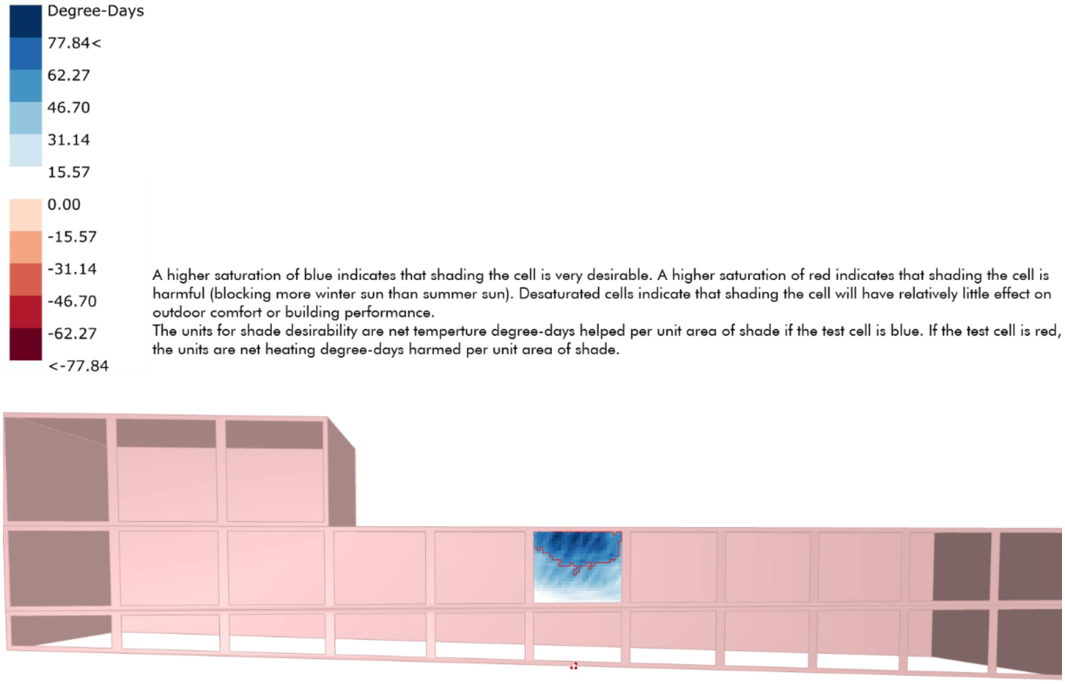


Figure 11.0:39. Ladybug Analysis: Shading Comfort Window.

11.3.5 Wind

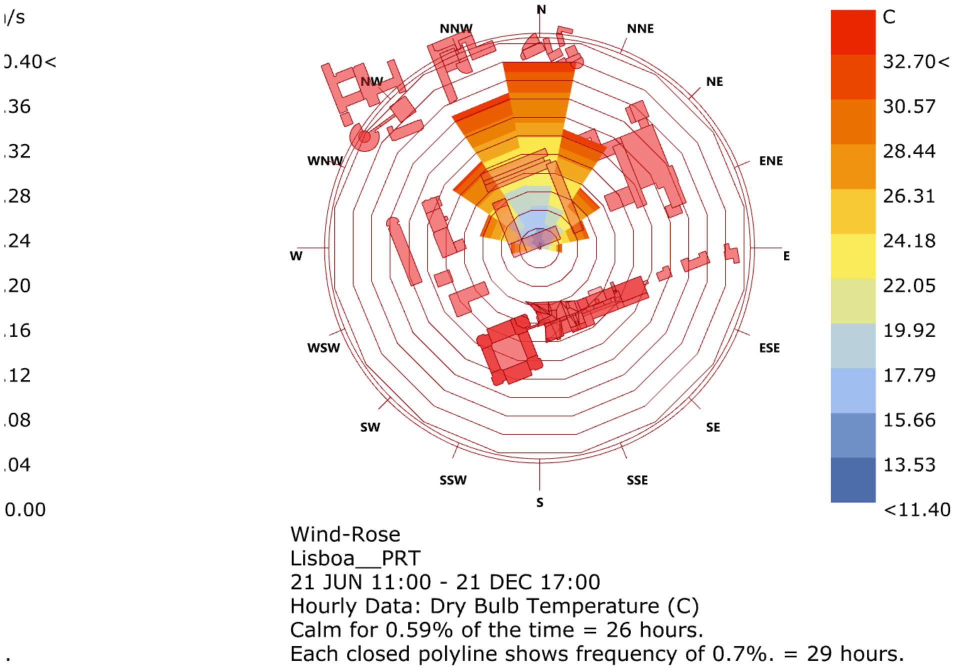


Figure 11.0:40. Ladybug Analysis: Air Temperature Wind Rose.

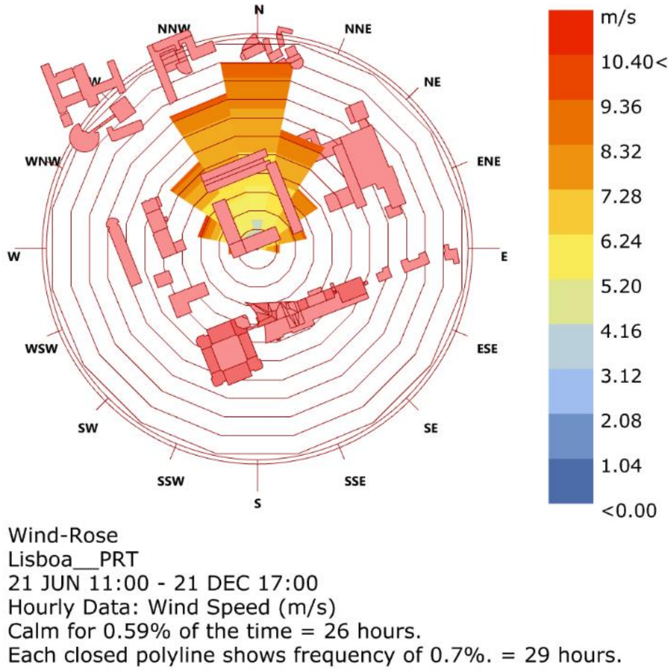


Figure 11.0:41. Ladybug Analysis: Wind Speed Wind Rose.

11.4 Shading Systems Functions + Actions + Agents.

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	Functions
1	Direct radiation - entry
2	Direct radiation - blockage
3	Diffuse radiation
4	Glare control
5	External views
6	Natural ventilation
7	Architectural integration
8	Others

Functions are relations or expressions involving one or more variables. The considered functions are vital for the shading system performance and efficiency, improving and maintaining building its homeostasis.
Functions define a goal, a precise objective for the shading system.

	Actions
A	Permeability
B	Reflection
C	Refraction
D	Intersection
E	Material
F	Scale
G	...
H	...
I	...
J	...

Actions collaborate to perform a higher level function. They are shading system characteristics, linked to its physical properties.
Actions are determinant to develop strategies for the shading system physical conception.

	Agents
a	Translucency
b	Opacity
c	Morphology
d	Structure
e	Density
f	Pigment
g	Pattern
h	Orientation
i	Roughness
j	Air flow
k	...
l	...
m	...

Agents compose the action strategy.
Also called bio-agent, they represent any principle or substance capable of producing an effect, whether physical, chemical or biological.
Agents represent the means of action to perform a predetermine function.

Figure 11.0:42. Shading Systems Functions+Actions+Agents Definitions.

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	east		south		west	
season+period	housing	services	housing	services	housing	services
winter - day period	1;3;4;5	3;5;6	1;3;5	1;3;5;6	1;3;4;5	2;3;4;5;6
winter - night period	2;6	2	2;6	2	2;6	2
summer - day period	2;3;4;5	2;3;5	2;3;5	2;3;5	2;3;4;5	2;3;4;5
summer - night period	1;6	1;6	1;6	1;6	1;6	1;6
Considers 7 and 8 always relevant and present						

Functions + Actions	
1	A
2	A
3	A+D
4	B+C
5	A+C+D
6	A+D+E+F
7	E+F
8	all

Actions + Agents		a	b	c	d	e	f	g	h	i	j	
Actions	**A**	X	X			X		X			X	4
	B					X	X	X	X			4
	C	X				X			X	X		4
	D			X	X	X			X			4
	E				X		X			X	X	4
	F			X	X	X		X			X	5
		Agents										
		2	1	2	3	5	2	3	3	2	3	

Figure 11.0:43. Shadinng Systems: Orientation, Functions and Actions + Agents tables.

11.5 Terrestrial Vascular Plants Global System

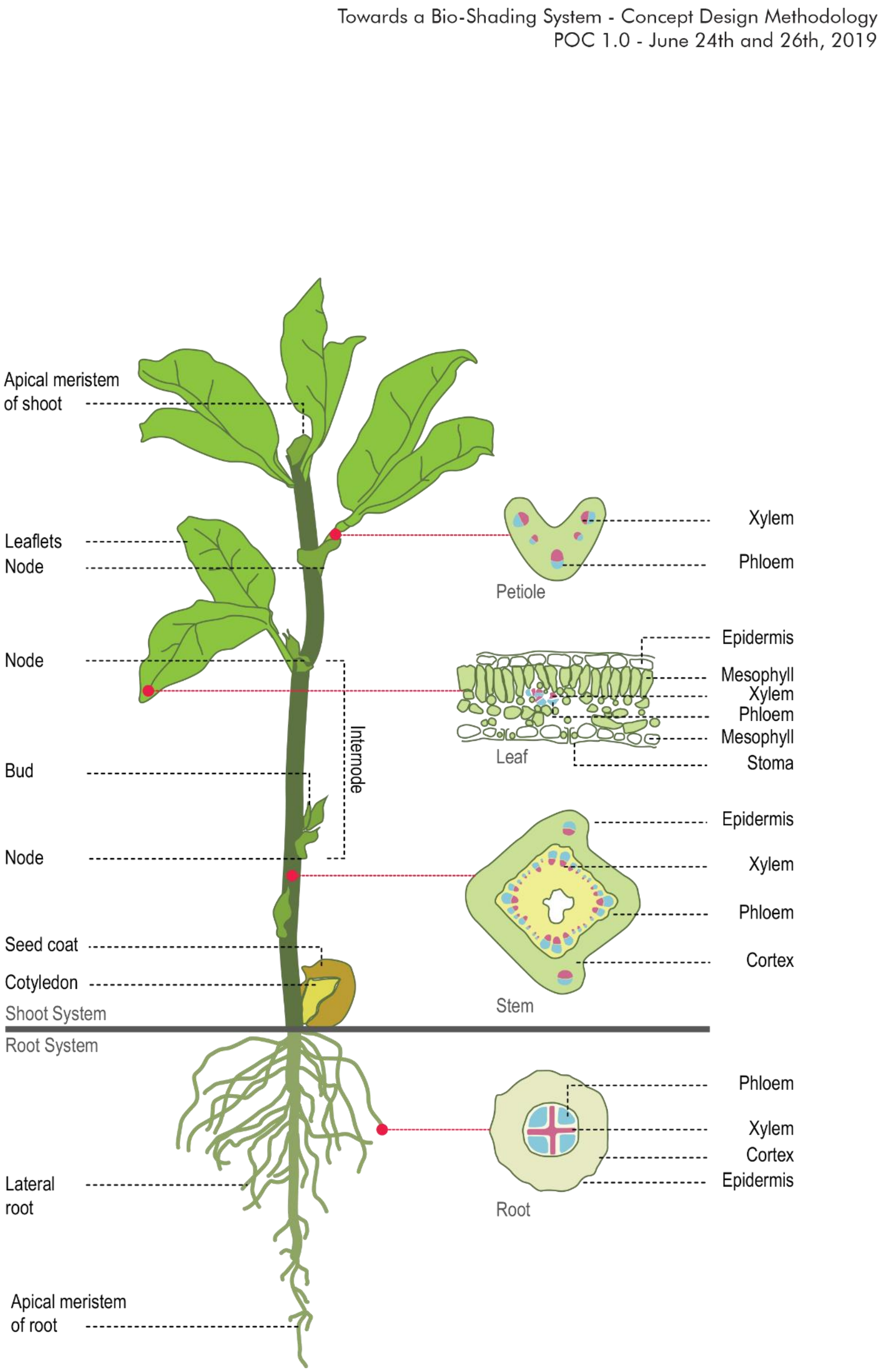

Figure 11.0:44. Terrestrial Vascular Plant Global System.

11.5.1 Plants Adaptation Events Tables

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MORPHOLOGICAL	
Asymmetry	Zero planes of mirror image, on leaves, petals, sepals or stems).
Canopy Plants	Increase radiation by multilayer arrangements of leaves with loose distribution.
Carnivorous Plants	Adapted to grow in soils poor in nutrients, these plants get their nutrients from trapping and consuming animals or protozoans.
Climbing plants	Long stemmed rooted in soil at ground level and use trees or other vertical supports to climb up to get access to light.
Deciduos plants	Those who lose all their leaves for part of the year "the drop of a part that is no longer needed" – plants lose their leaves to conserve water or to better survive winter weather conditions.
Fractal	Plants that are composed by similar parts – self familiar.
Hydrotropism	Hydrotropism is a plant's direction of growth, determined by a stimulus in water concentration.
Inflorescence	This name is given in the arrangement that the flowers take on the stem of a plant.
Packing structures	Maximizing strength while reducing materials by incorporating tetrahedral elements that can be stacked in hexagonal containers.
Phyllotaxis	Phyllotaxis is the arrangement of leaves on a plant stem.
Spermatophytes	Also known as "seed plants", are composed by Gymnosperms and Angiosperms:
	Gymnosperm – Have naked seeds. Seed develops either on the surface scale, or leaf-like appendages of cones, or at the end of short stalks;
	Angiosperm – Have seed or ovules enclosed during pollination. Their seeds have three parts: (1) an embryo, (2) a supply of nutrients for the embryo and (3) a seed coat – they are flowering plants.
Stoma	Tiny opening or pore that is used for gas exchange.
Succulent	Reduce exposure by reduce projected area for radiation.
Symmetry	Proportional and harmonious characteristic present on leaves, petals, sepals and stems.
Tracheid	Long cell in the Xylem system of vascular plants. Tracheid hold water against gravity when transpiration is not occurring.
Under-storey Plants	Increase radiation exposure by monolayer arrangements of leaves with dense distribution.
Vessels	Are one of the cell types found in xylem.
Whorl	Whorl is an arrangement of sepals, petals, leaves, stipules or branches that radiate from a single point and surrounds or wrap around the stem.

Figure 11.0:45. Plants Morphological Adaptation Events.

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PHYSIOLOGICAL	
Anthocyanins	Water soluble vacuolar pigments that depending on their PH may appear – red, blue or purple in leaves. Anthocyanins results as a camouflage protecting the plants from insects, making they more vulnerable to predators by inhibiting the reflecting of green wavelengths (Evert & Eichhorn, 2012, p. 490).
CAM Plants (Crassulacean Acid Metabolism)	CAM plants uses a method of carbon fixation in dry conditions.
Chloroplasts	Are small organelles inside the cells of plants and algae. Chloroplasts is responsible for the conduction of photosynthesis (Evert & Eichhorn, 2012, p. 102).
Endothermic	A process or reaction in which the system absorbs energy from its surroundings in the form of heat (Evert & Eichhorn, 2012, p. 97).
Epidermis	Epidermis is a layer of cells that covers the leaves, flowers, roots and stems of plants, forming a boundary between the plant and the external environment.
Exothermic	A process or reaction that releases energy from the system, usually in the form of heat (Evert & Eichhorn, 2012, p. 97).
Meiosis	A type of sexual reproduction in which the number of chromosomes is reduced by half through the evaporation of homologous chromosomes producing two haploid cells – number of division 2; Daughter cells 4 haploid cells (Mixing chromosomes).
Mitosis	A process of asexual reproduction in which the cell divides in two, producing a replica, with an equal number of chromosomes in each resulting diploid cell number of division 1; Daughter cells 2 diploid cells (crossing over cannot occur).
Osmosis	Refer to a spontaneous movement of water cross a membrane from a region of low salute concentration to a more concentrate solution. This equalize concentrations on both sides of a membrane.
Pholem	Transportation of food and nutrients such as sugar and amino acids, from leaves to storage organs and growing parts of plants. This bidirectional movement (moves up and down the plant system from 'sauce to skin' of substances in called translocation).
Superhydrophilic	It's a surface layer that attracts water.
Superhydrophobic (coating)	Is a surface layer that repels water.
Thermogenic Plants	Plants that can raise their temperature above that of the surrounding air.
Trichomes	Described as outgrows on plants, trichomes have variable shapes, cytology and functions. These elements could appear on different surfaces of most of the angiosperms, contributing to light piping, protecting the plant against temperature stress by increasing the water loss reduction.

Figure 11.0:46. Plants Physiological Adaptation Events.

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BEHAVIORAL	
Bark trees	Keeps surface cool by minimizing absorption of solar light and maximizing thermal emission.
Bioluminescence	A fraction of the stored energy its (re)converted to light energy. Bioluminescence is an accidental product of energy exchanges in most luminescent organisms.
Cactus (Cacti)	Have thickened, fleshy parts adapted to store water – Spines. Spines help prevent waterless by reducing air flow close to the Cactus, providing some shade.
Diaheliotropic	Plants that orient their leaves to receive maximum sunlight.
Gravitropism (geotropism)	Is a growth movement by a plant or fungus in response to gravity (Evert & Eichhorn, 2012, p. 662).
Heliotropism	Heliotropism is a growth movement in plants that is induced by sunlight (Evert & Eichhorn, 2012, p. 680).
Nyctinastic movements	The leaves of plants respond to daily alternation between light and darkness by moving up and down.
Paraheliotropic	Plants that move their leaves to avoid sunlight (reducing dehydration).
Phototropism	Phototropism is a growth movement induced by any light stimulus.
Roots	In vascular plants, root is the organ of a plant that typically lies below the surface of the soil. They can also be aerial or aerating. Plant roots is their way of collecting water and nutrients essential for growth and survival.
Skototropism	Growth away from the light (movement towards darkness).
Thigmotropism	A response to contact with a solid object.
Vernation	How the leaves are arranged on the buds, folding or curling.
Xylem	Vascular system that transports water and minerals from roots to aerial parts of the plant.

Figure 11.0:47. Plants Behavioral Adaptation Events.

11.5.2 Online Resources

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Online ressources

https://asknature.org/

https://basicbiology.net/biology-101/introduction-to-biology

https://bio-sis.net/life-principles/

https://biomimicry.net/

https://www.diffen.com/

https://eol.org/

https://www.postharvest.net.au/

https://www.biology-online.org/

Figure 11.0:48. Plants Events Online Research Resources.

11.5.3 Biomimetic *Meme* Path Matrix.

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selected actions	A meme	B meme	C meme	... meme	Biomimetic meme
A	X				X
B		X			X
C			X		X
D				X	X
Meme Strategies					
Dynamic	X	X		X	X
Static			X		
Meme Adaptation					
Morphological	X		X		X
Physiological				X	
behavioral		X			
Meme Pattern features					
Loose	X				
Multilayer			X	X	X
Hexagonal		X			
etc...					
Meme Material features					
Flexible	X	X			X
Translucent			X	X	X
Hard					
etc...					
Meme Performative Features					
Tracking	X				
Bending		X		X	X
Unidirectional movement				X	
etc...					

Figure 11.0:49. Biomimetic Meme path matrix.

11.6 Shading Systems type of structures and Actuations.

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POC 1.0 - June 24th and 26th, 2019

Structure type	**Short description**	**Pros**	**Cons**	**Possible actuation**
Open/Close structures *Deployable sequences 2D – cylindrical scissor joint*	The structure is a double layer of identical but inverted flat discs made of curved plates that open in sequence reminiscent.	This type of structures has no gaps when closed and forms a perfect circle when open; Could function in a sandwich system.	The structure needs additional space, to expand - this expansion will trigger a structural overlap over the façade, inducing a sub sequential shading; Each cell of the system is composed by several units, if one fails, the entire cell will block; Friction of elements Highly maintenance; Needs its own structure.	These types of structures are usually performed by motor-based actuation; Hydraulic it's also a possibility.
Open/Close structures *Rotation*	Actuation happens in the tridimensional space – usually rotation occur in Z axis, and the pattern elements/units could rotate between 0º to 360º; Rotation could also perform freely through autonomous units – eyes.	Usually, translated in monolayer structures, these elements could assume different shapes; These systems could be applied outside or inside the façade system; Patterns could close without gaps or could overlap; These systems are a synchronization of the unitary movement of its units, if one fails, the system could still perform.	This type of shading requires to be 24/7 updated - as the elements can rotate 360º, and are flat, they need to monitor the solar rotation daily, in order to minimize the entrance of heat / light in the summer and to facilitate the gains of heat / light in the winter; These systems are usually vulnerable to the external or internal environment elements; Needs its own structure.	
Inflated	Inflated, also called pneumatic structures, could fulfill large areas with volumetric cushions.	Very versatile and highly durable; Fast erection and lightweight; Could achieve large areas and volumes; Although PVC is still one of the most used materials in this type of system, other more sustainable, such as ETFE, with properties at the level of solar gains have been developed;	Requires its own structure; The manipulation of the air could be done through numerous techniques; After being inflated, super-pressure structures require a constant flow of air in order to maintain the shape of the envelope in its deployed state; The air intake duct creates a permanent background noise.	Pneumatic Actuation; Inflatable structures could also result from the combination between pneumatics and tensegrity; Material-Based - recent material advances have developed 'smart-materials' with the same capacities, but still scale limited.

Figure 11.0:50. Shading Systems Types of Structure 01.

Flexible	Due to its semi rigid components these structures may flex in defined directions; Is a deformable typology, that undergo deformation in a fluid and controlled manner.	This type of systems could cover large areas, using retractable structures; Multilayer compactable structures; Could accommodate rotation, translation and linear movements;	Needs independent structures, and accurate mechanisms; These systems are usually vulnerable to the external or internal environment elements; Depending of its mechanisms, generally these are heavy structures; Flexibility level its provided by the elastic materials.	Motor-based are the most common and explored actuation in these structures; Hydraulic; Pneumatic are less common in these type of structures, however combined with motor-based actuation some retractable air inflated experiences have been conducted; Material-based.
Tensegrity	Is a structural principle based on a set of discontinuous components in compression that interacts with a set of continuous tensile elements which are prestressed, thus generating stiff ness in the structure and creating a stable volume in space.	Free-form expression, versatile and lightweight; Since the compressive elements are disjointed, this provides the possibility to fold these members and hence the structure can be compactly stowed; These structures follow the principle of movability.	Tensegrity systems are limited due to the difficulty of controlling them at every stage of deployment; Usually exhibit complex structural structures – mechanics and lots of joineries; These systems are usually vulnerable to the external or internal environment elements;	Motor-based; Hydraulic; Man-hand!

Figure 11.0:51. Shading Systems Types of Structure 02.

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Actuation type	**description**	**pros**	**cons**	**required resources and knowledge**
Motor-based Between layers	- Motor-based actuation system, usually automated can reduce glare and solar heat significantly, by a BMS (building management system) that tracks the sun position and monitors light conditions.	- One-layer provides protection from the outside elements, the other protects from potential damage or interference with its operation	- Maintenance of the different units/elements could be conditioned by the space and type of seal between layers - High energy consumption demand	- Common mechanical knowledge
Motor-based Exterior		- Easier to procced maintenance over the different units/elements	- Exposed to the external elements - Matter could get into mechanisms, causing malfunction - Shorter lifespan of the system - High energy consumption demand	
Hydraulic	- Confined pressurized systems that use moving liquids	- Liquids are not very compressible there is no delay in the movement - Could be applied to most different actuations such rotation, linear movement, compression, etc.	- Uses several non-sustainable or recyclable liquids, like mineral oil, ethylene glycol, synthetic types or high temperature fire-resistant fluids to make power transmission possible.	- Physics, mechanical and electronic advanced knowledge.
Pneumatic	- Confined pressurized systems that use moving air and other gases - Currently, most sustainable solution to reduce heat gain by using lightweight ETFE air cushions	- Easily-compressible gas like air or pure gas - Only need a compressor - Power: pneumatics uses pressures ranging from 36–45 Kg per each 6cm^2	- Because gases can be compressed there is a delay in the movement/force - Require periodical maintenance - Requires a separate support system	- Physics, mechanical and electronic medium knowledge.
Material-based	- Smart materials – crossing different material properties, by adding features and characteristics from other materials and/or organisms	- Usually, this type of actuation generates low-energy systems - Capacities are built into the material, eliminating the need for complex mechatronic assemblies	- So far, unknown.	- Large research team: material, physics and chemical knowledge. - Laboratorial resources.

Figure 11.0:52. Shading Systems Types of Actuation.

11.7 PoC 1.0 Participants Declaration of Authorization/Consent

Declaration of Authorization/Consent

Name	**Ana Castanho**
Email	[redacted]
Profession	**PhD Student**
Nationality	**Portuguese**
Date of birthday	**25/01/1985**
Id card number	[redacted]

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Lisbon, June 26th 2019

(Signature) Ana Lídia Vargas Castanho

Figure 11.0:53. Ana Castanho Declaration of Authorizations/Consent.

Declaration of Authorization/Consent

Name	**Carlos Alberto Lemos Claro de Sequeira**
Email	[redacted]
Profession	**Architect**
Nationality	**Portugal**
Date of birthday	**10 July 1980**
Id card number	[redacted]

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(Signature) ____________________

Figure 11.0:54. Carlos Sequeira Declaration of Authorizations/Consent.

Declaration of Authorization/Consent

Name	DIANA BORGES GABÃO
Email	[redacted]
Profession	ARCHITECT
Nationality	PORTUGUESE
Date of birthday	21 / 04 / 88
Id card number	[redacted]

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(Signature) ____________________

Figure 11.0:55. Diana Gabão Declaration of Authorizations/Consent.

Declaration of Authorization/Consent

Name	**Filipa P. F. Crespo Osório**
Email	[redacted]
Profession	**Architect – PhD Student**
Nationality	**Portuguese**
Date of birthday	**29-04-1981**
Id card number	[redacted]

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(Signature) ______________________

Figure 11.0:56. Filipa Osório Declaration of Authorizations/Consent.

Declaration of Authorization/Consent

Name	**João Duarte Batalha Parcelas**
Email	[redacted]
Profession	**student**
Nationality	**Portuguese**
Date of birthday	**03-10-1997**
Id card number	[redacted]

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Figure 11.0:57. João Parcelas Declaration of Authorizations/Consent.

Declaration of Authorization/Consent

Name	**João Pedro Teles de Macedo Mendonça Sousa**
Email	[redacted]
Profession	**Architect**
Nationality	**Portuguese**
Date of birthday	**06-10-1989**
Id card number	[redacted]

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(Signature) ____________________

Figure 11.0:58. João Sousa Declaration of Authorizations/Consent.

Declaration of Authorization/Consent

Name	**Luisa Maria Macedo de Almeida Pinheiro Barreiros**
Email	[redacted]
Profession	**architecture student**
Nationality	**Portuguese**
Date of birthday	**22-10-1995**
Id card number	[redacted]

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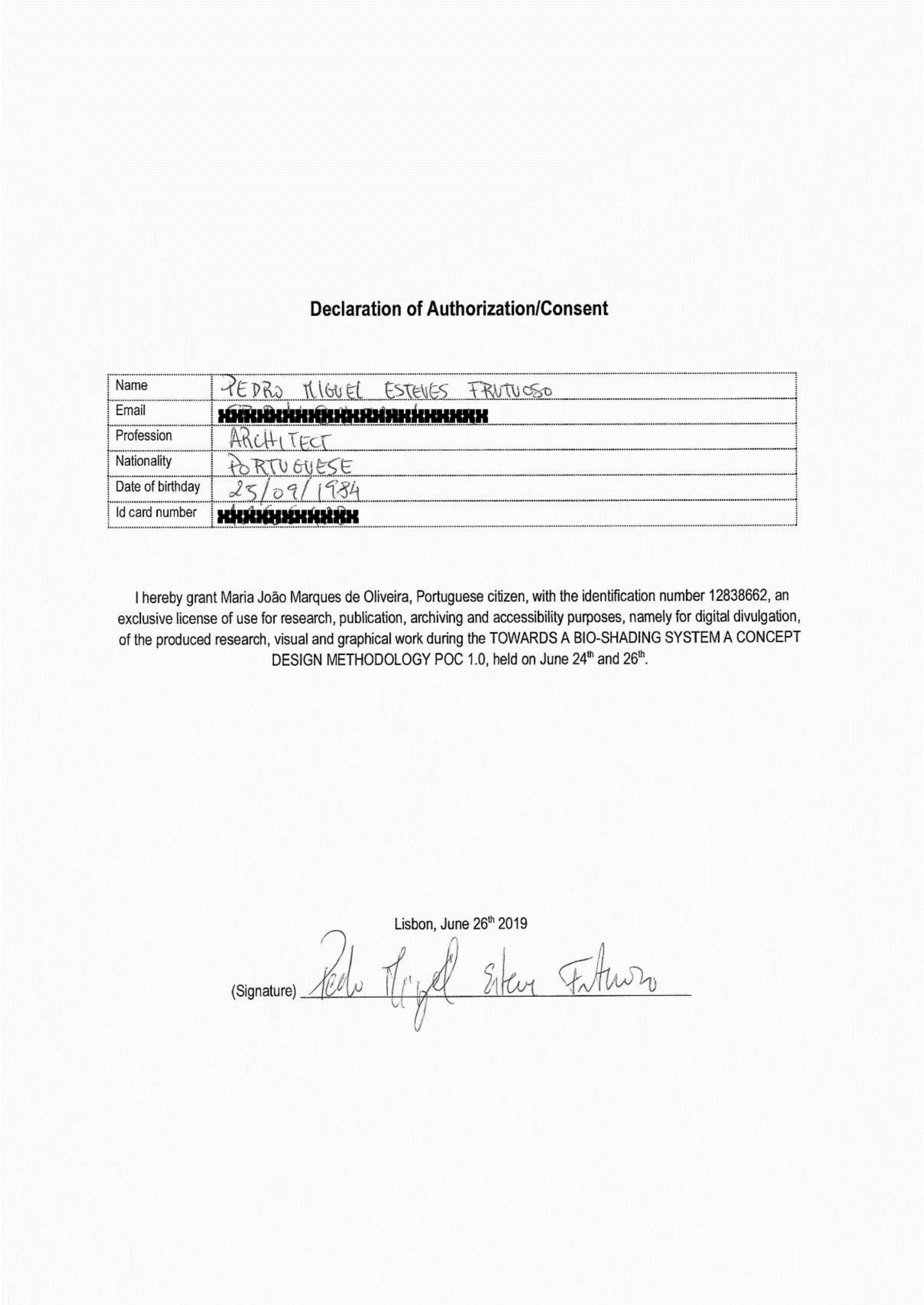
(Signature) ______________________

Figure 11.0:59. Luísa Almeida Declaration of Authorizations/Consent.



Declaration of Authorization/Consent

Name	PEDRO MIGUEL ESTEVES FRUTUOSO
Email	[redacted]
Profession	ARCHITECT
Nationality	PORTUGUESE
Date of birthday	25/09/1984
Id card number	[redacted]

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(Signature) ____________________

Figure 11.0:60. Pedro Frutuoso Declaration of Authorizations/Consent.

Declaration of Authorization/Consent

Name	**Raquel Sales Martins**
Email	[redacted]
Profession	**Architect**
Nationality	**Portuguese**
Date of birthday	**1992-07-13**
Id card number	[redacted]

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Lisbon, June 26th 2019

(Signature) 

Figure 11.0:61. Raquel Martins Declaration of Authorizations/Consent.

Declaration of Authorization/Consent

Name	**Susana Aires Fonseca Neves**
Email	[redacted]
Profession	**Architect**
Nationality	**Portuguese**
Date of birthday	**1988/09/15**
Id card number	[redacted]

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Lisbon, June 26th 2019

(Signature) Assinado por : **SUSANA AIRES FONSECA NEVES**
Num. de Identificação: BI133805859
Data: 2020.07.02 00:35:27+01'00'

CARTÃO DE CIDADÃO

Figure 11.0:62. Susana Neves Declaration of Authorizations/Consent.