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Bioshading System Design Methodology (BSDM)

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Bioshading System Design Method (BSDM) is an architectural problem-based method that uses Nature events as inspirational sources to develop and create performative and design solutions for responsive shading systems. The design method is supported by a circular relationship between three main domains: Architecture, Nature, and Artifact. The "Architecture" domain corresponds to 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.

Keywords: Design method; Research methods; Architectural design; Environmental design; Biomimetics.

Introduction

In the context of rapid urbanization, a significant part of the actual sustainability-related challenges is related to urban and architectural design. In fact, the built environment plays a critical role in setting the conditions for the well-being of people within the limits of life-supporting ecosystems. Therefore, improved, as well as new strategies for the design of environmentally responsible, and socially meaningful buildings shall be envisaged considering a framework of scarce material and financial resources (European Commission, 2015). As part of a building's external envelope, facades mediate two conflicting environments in a process that exchanges material and energy

flows. Facades are therefore a crucial target in the quest for reducing resource consumption and better use available natural renewable resources as solar radiation.

In the last 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 (Candy & Edmonds, 1994) (Oxman, 2006) (Tokuç, Özkaban, & Çakır, 2018). Mimicking Nature in developing new architectural design proposals through the use of powerful computational models is now a reality, pushing a wide-spread movement of a more conscious and sustainable design (Helms, Vattam, & Goel, 2009) (Deniz & Keskin-Gundogdu, 2018).

Biomimetics may be considered as the programmatic link between science and technology, working as 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) (Vandevenne, Duflou, & Duflou, 2016).

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 different levels such as material, structure, and mechanisms (Vincent, 2009).

Through the last two 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 useful and anticipatory to many natural and societal challenges such as natural disasters or diseases (Bar-Cohen, 2006) (Aziz & El Sherif, 2016). It may be argued that all the means and the know-how needed to solve current major challenges already exist, although some links still must be established between domains that usually act separately.

Biomimetics is a field that already constructs some common lexicon among areas such as engineering and medicine. Integrating its know-how and lexicon in the teaching and practice of architecture would improve buildings responsiveness to existing and forthcoming performance requirements through enhanced responsiveness and interaction with humans and the environment.

Putting together facade design and biomimetics, the main question addressed in this research is: How to develop architectural shading systems mimicking the adaptation strategies of terrestrial plants?

1 Related Work

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.

In 2005, the industrial designer Carl Hastrich developed the Biomimicry Design Spiral (Figure 1). 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.

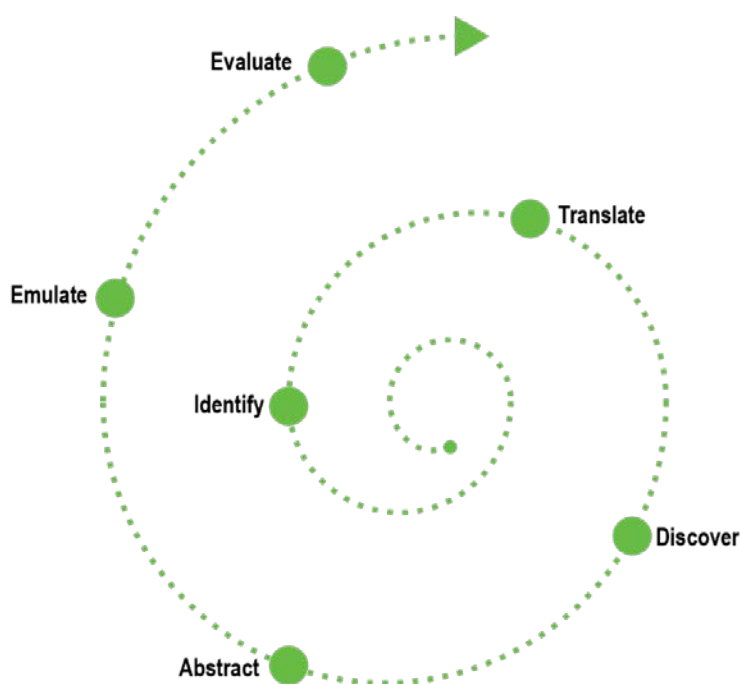


Figure 1. Biomimicry Design Spiral (adapted from Deluca, 2016).

Three years later, 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. (Bogatyrev & Bogatyreva, 2014). Gruber (Gruber, 2011) stated 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).

Based on Badarnah's Ph.D. dissertation, Badarnah and Kadri presented BioGen in 2014 (Badarnah & Kadri, 2015), a methodology for biomimetic design concept generation. 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: exploration model; pinnacles analysis; 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.

In the same year, Garcia-Holguera develops the Ecomimetic design method - a conceptual approach based on the previously presented methods. 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.

In 2017 López et al (López, Rubio, Martín, & Corxford, 2017) presented the Biomimetic principles for the development of adaptive envelopes. 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 2). In order to understand how plants' principles can be used to create adaptive architecture, this phase is divided into two subphases: the first works inside the Nature domain identifying adaptive strategies and mechanisms present in biological organisms; the second subphase works inside the Architecture domain encouraging 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).

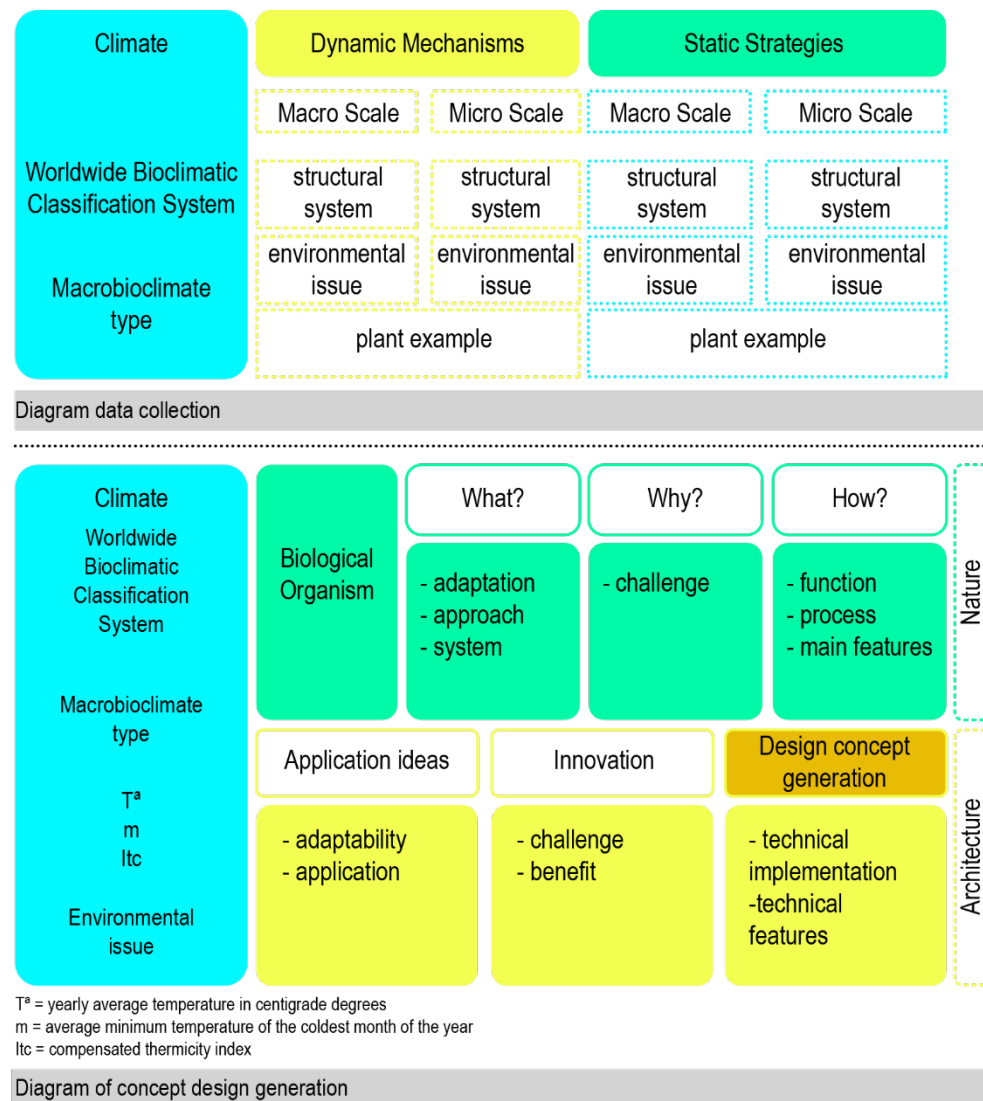


Figure 2. Diagram of data collection and design concept generation proposed by López et al, 2017.

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

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.

This paper presents a façade shading system design method leading architects through biomimetic concepts and processes and building a fluid and deductive process leading designers to physical model prototyping.

2 Bioshading System Design Method

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

The design method is supported by a circular relationship between three main domains: Architecture, Nature, and Artifact (Figure 3). Each domain corresponds to a progressive formation step of the design process. The "Architecture" domain corresponds to the "Definition" of the architectural challenge that the user aims to 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. 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, that guide the user through the different processes of design.

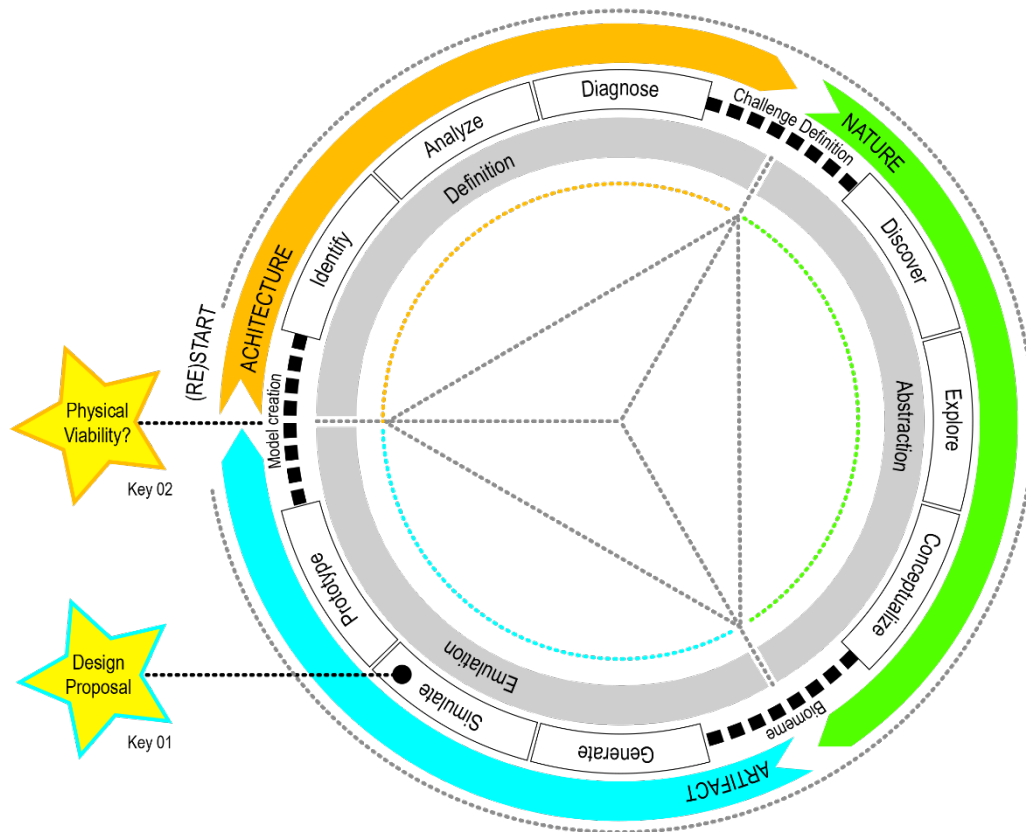


Figure 3. Bioshading system design method - workflow.

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, and features. At the final phase of this Abstraction process - Conceptualization - BSDM users create their Biomeme – a nature-based human-made 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 are designing and evaluating their shading system solutions through digital tools, supported by a set of type of structures and actuators, materials and CAM resources, 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.

BSDM establishes a general investigation strategy that outlines how research should be carried out, providing a method for a contextual inquiry and a usability study. In relation to its predecessors, BSDM advances the design process by including specific tools to reach a prototype stage. Without conditioning the digital tools of representation, analysis and evaluation, it allows the generation of the project and its creative process to proceed in a singular and individual way, guaranteeing originality in all the solutions generated.

3 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 4).

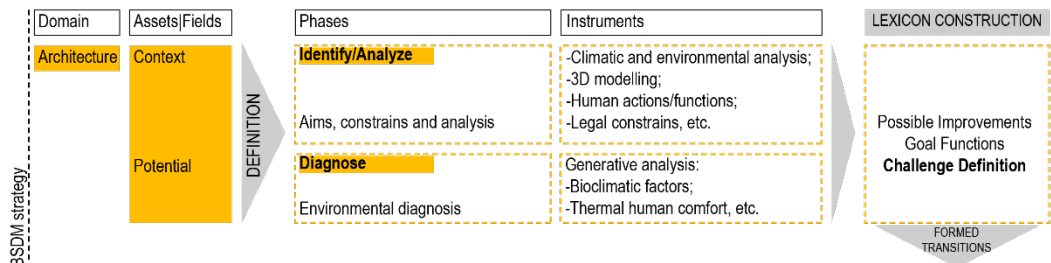


Figure 4. Bioshading System Design Method Strategy - Architecture Domain.

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 5), 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.

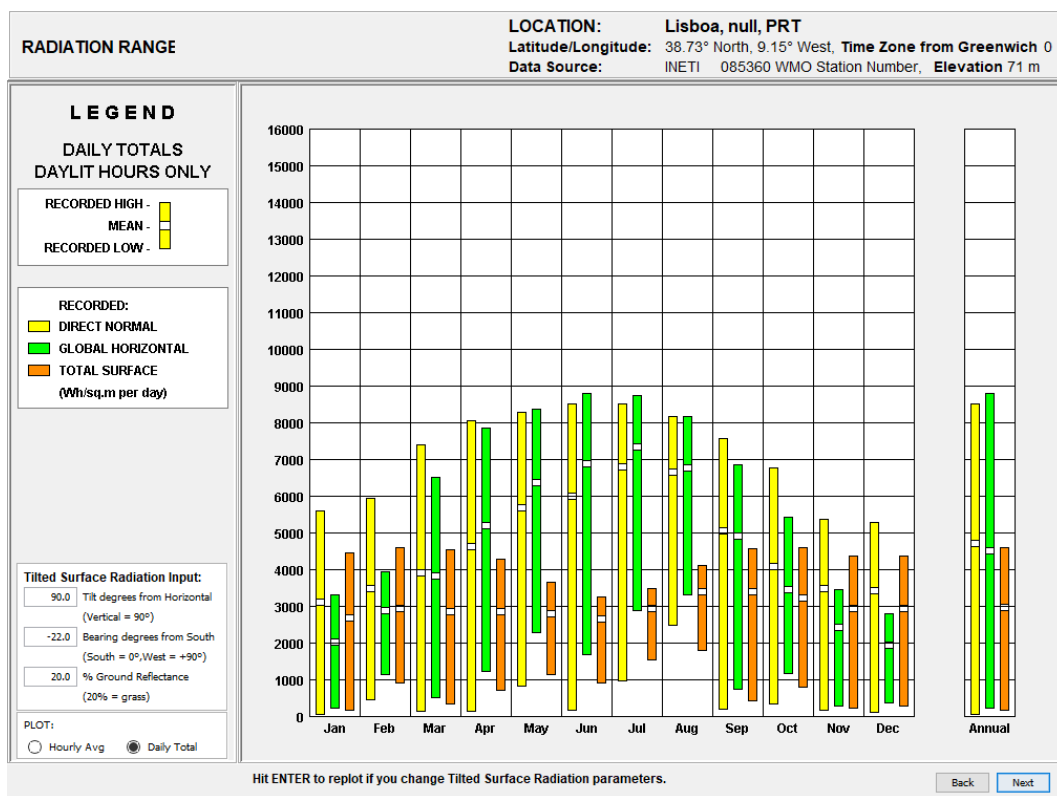


Figure 5. Climate Consultant 6.0 – Lisbon radiation range for vertical surface facing South/Southeast.

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 6); radiation rose (Figure 7); 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. 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 (Oliveira, 2019, pp. 184-186).

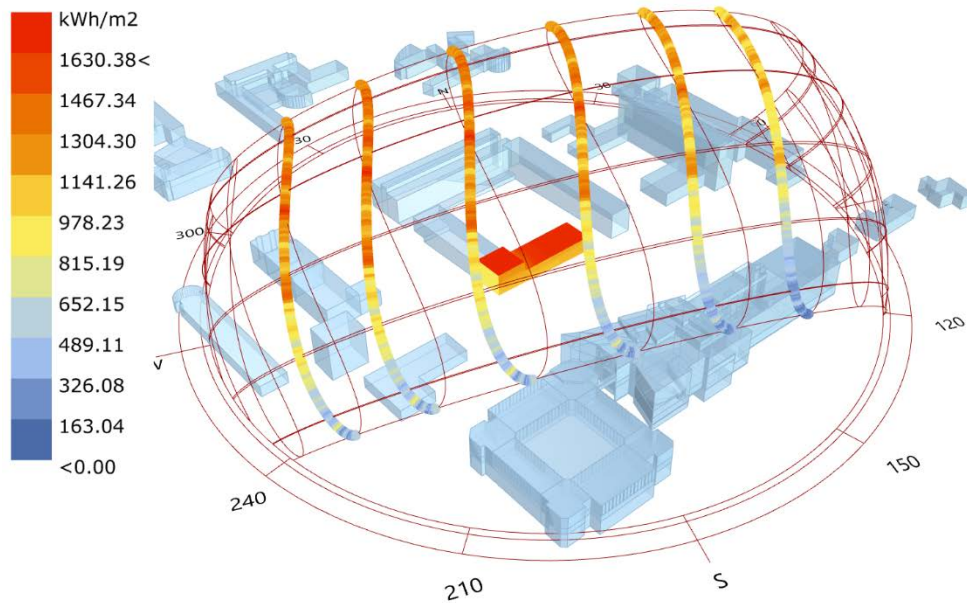


Figure 6. Ladybug: Radiation analysis (June to December period).

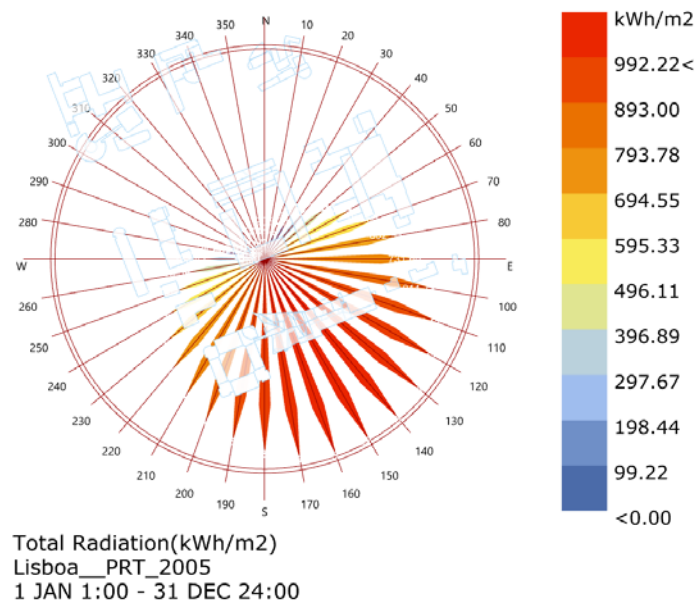


Figure 7. Ladybug Annual Radiation Rose.

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 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 2). In Table 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 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.

	<i>Functions</i>
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 1. Shading System's main functions.

	<i>Building types of use</i>					
<i>season+period</i>	<i>residential</i>	<i>services</i>	<i>residential</i>	<i>services</i>	<i>residential</i>	<i>services</i>
winter – day period						
winter – night period						
summer – day period						
summer – night period						
	<i>east</i>		<i>south</i>		<i>west</i>	

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

An example of the use of Table 2 is provided in Table 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 km² 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 °C 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 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 4).

	<i>Building types of use</i>			
<i>season+period</i>	<i>residential</i>	<i>services</i>	<i>residential</i>	<i>services</i>
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
	<i>east</i>		<i>south</i>	

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

	<i>Building types of use</i>											
<i>season+period</i>	<i>east – resid/serv</i>						<i>south – resid/serv</i>					
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 4. Shading System functions example – Crossing table.

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

	<i>Functions</i>
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 5. *Functions selection.*

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 1), six actions can be related: i) permeability; ii) reflection; iii) refraction; iv) intersection; v) material, and vi) scale. One or more Actions 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 (Table 6).

	<i>Functions</i>					<i>Functions</i>	<i>Actions</i>
1	Direct radiation – entry					3	A+D
2	Direct radiation – blockage					4	B+C
3	Diffuse radiation					5	A+C+D
4	Glare control					6	A+D+E+F
5	External views						
6	Natural ventilation						
7	Architectural integration						
8	Others						

 $\cap$

	<i>Actions</i>
A	Permeability
B	Reflection
C	Refraction
D	Intersection
E	Material
F	Scale
G	...
H	...

 $=$

	<i>Functions</i>	<i>Actions</i>
3		A+D
4		B+C
5		A+C+D
6		A+D+E+F

Table 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 (Table 7).

	<i>Actions</i>
A	Permeability
C	Refraction
D	Intersection

$$\cap$$

	<i>Agents</i>
a	Translucency
b	Opacity
c	Morphology
d	Strcuture
e	Density
f	Pigment
g	Pattern
h	Orientation
i	Roughness
j	Air flow
k	...

$$=$$

		<i>Actions + Agents</i>									
<i>Actions</i>	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
		<i>Agents</i>									

Table 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.

4 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 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, that support the idea of similarity between buildings and terrestrial plants.

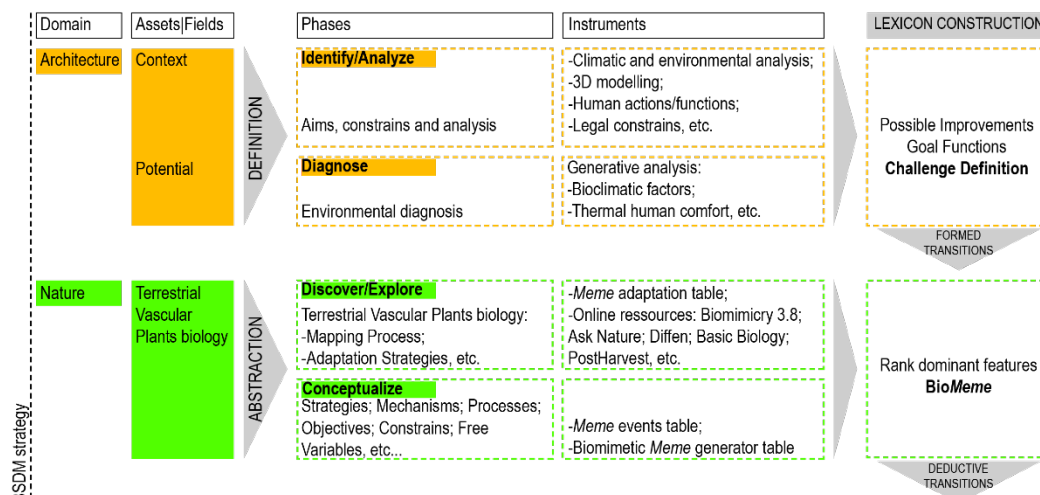


Figure 8. Bioshading System Design Method Strategy – Architecture and Nature Domain.

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 (Oliveira, 2019, pp. 162-170), 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 (Table 8). 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). 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.

<i>Actions</i>	<i>Actions</i>	=	<i>Designation</i>	<i>Description</i>	<i>Cause/Intentions</i>
<i>A</i>	<i>a+e</i>		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 shorter and easier distribution of nutrients.
<i>C</i>	<i>a+e+h</i>		<i>(Permeability $\cap$ density + Refraction $\cap$ density)</i>		
<i>D</i>	<i>e+h</i>		Stoma	Tiny opening or pore that is used for gas exchange.	Found in the epidermis of leaves, stems and other organs, stoma is a pore bordered by a pair of guard cells that are responsible for regulating the size of the stomatal opening.
			<i>(Permeability $\cap$ Translucency)</i>		

Succulent (Intersection $\cap$ density)	Reduce exposure by reduce projected area for radiation.	Succulents increae their volume, usually to retain water in arid climates or soil conditions.
Epidermis (Permeability $\cap$ density + Permeability $\cap$ Translucency)	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, regulate gas exchange, secretes metabolic compounds and absorbs water and mineral nutrients (fundamentally roots).
Heliotropism (Refraction $\cap$ Orientation + Intersection $\cap$ Orientation)	Heliotropism is a diurnal or seasonal movement in plants that is induced by sunlight (Evert & Eichhorn, 2012)	Heliotropic plants tracks sunlight during day period in order to maximize its exposure.

Table 8. Connection example between shading Actions and Agents with Plants Adaptation Events.



Figure 9. 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 and Table 10). 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.

<i>Meme Event</i>	<i>Adaptation</i>	<i>Strategy</i>	<i>Main Principles</i>	<i>Main Features</i>
XXX	XXX	XXX	XXX	XXX

Table 9. Meme Events Table.

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

<i>Meme Event</i>	<i>Adaptation</i>	<i>Strategy</i>	<i>Main Principles</i>	<i>Main Features</i>
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; Tracking
Packing structures	Morphological	Dynamic	Packing structures, 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 whtn inflated, resultin in opening (Badarnah, 2012)	Circular/Ellipse; Permeable; Expandable; Open/close
Succulent	Morphological	Static	Pleated body morphology with surfaces almost parallel to radiation prevent excess of heat loads.	Fractal; Expandable; Opaque; Intersection; Storage.

Table 10. Meme Events Table – Example.

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 11). 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.

<i>Selected actions</i>	A meme	B meme	C meme	... meme	Biomeme
K1					
K2					
K3					
<i>Meme Strategies</i>					
Dynamic					
Static					
<i>Meme Adaptation</i>					
Morphological					
Physiological					
behavioral					
<i>Meme Pattern features</i>					
XXX					
XXX					
<i>Meme Material features</i>					
XXX					
XXX					
<i>Meme Performative Features</i>					
XXX					
XXX					

Table 11. Biomimetic Meme Path Matrix – provided to the BSDM users during the Conceptualization phase.

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 12). 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.

<i>selected actions</i>	Epidermis	Heliotropism	Pack.Struct.	Stoma	Succulent	Biomeme
Permeability	X		X			
Refraction		X	X		X	X
Intersection	X		X		X	X
<i>Meme Strategies</i>						
Dynamic	X	X		X		X
Static			X		X	
<i>Meme Adaptation</i>						
Morphological			X	X	X	X
Physiological	X					
behavioral		X				
<i>Meme Pattern features</i>						
Parallel divisions	X					
Hexagonal			X			
Circular/ellipse		X		X		X
Fractal					X	
<i>Meme Material features</i>						
Permeability	X			X		X
Flexible		X		X		X
Expandable	X				X	X
Lightweight		X	X			X
<i>Meme Performative Features</i>						
Intersection	X		X			X

Tracking		X			X	X
Storage					X	
Open/close				X		

Table 12. Biomimetic path matrix - Example.

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.

5 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 (Figure 10).

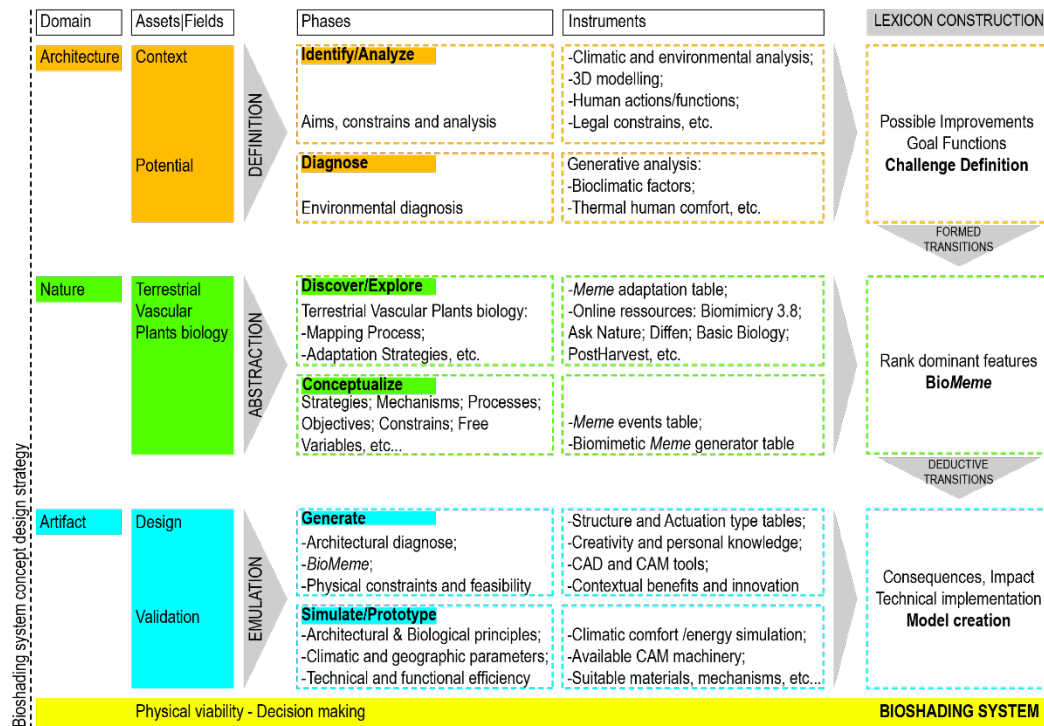


Figure 10. Bioshading System Design Method Strategy.

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 13 and Table 14) Shading Systems Structures, Table 13, describes the five principle shading systems types of structures: open/close deployable and rotational structures, inflatable, flexible, and tensegrity. Shading systems actuation types, Table 14, 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 and cons of application. In the type of structures (Table 13), possible actuation clues are also listed, while in the actuation table (Table 14), 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.

Type of structures	Short description	Pros	Cons	Possible actuation
<u>Open/Close structures</u> <i>Deployable sequences 2D – cylindrical scissor joint</i>	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> <i>Rotation</i>	Actuation happens in the tridimensional space – usually, rotation occurs on the Z-axis, and the pattern elements/units could rotate between 0° to 360°; 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	This type of shading requires to be 24/7 updated - as the elements can rotate 360°, 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	

Type of structures	Short description	Pros	Cons	Possible actuation
		could still perform.	environment elements; Needs its own structure.	
<i>Inflated</i>	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.
<i>Flexible</i>	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.

Type of structures	Short description	Pros	Cons	Possible actuation
<i>Tensegrity</i>	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 13. Shading Systems Structures.

Actuation type	description	pros	cons	required resources, knowledge
<i>Motor-based Between layers</i>	- 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
<i>Motor-based Exterior</i>		- 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	

Actuation type	description	pros	cons	required resources, knowledge
			- High energy consumption demand	
<i>Hydraulic</i>	- 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.
<i>Pneumatic</i>	- 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.
<i>Material-based</i>	- 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

Table 14. Shading systems actuation types.

As soon as the design model is mature, digital simulation is required (Figure 11). 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 systems implementation as well as the building energy cost at medium/long-term.

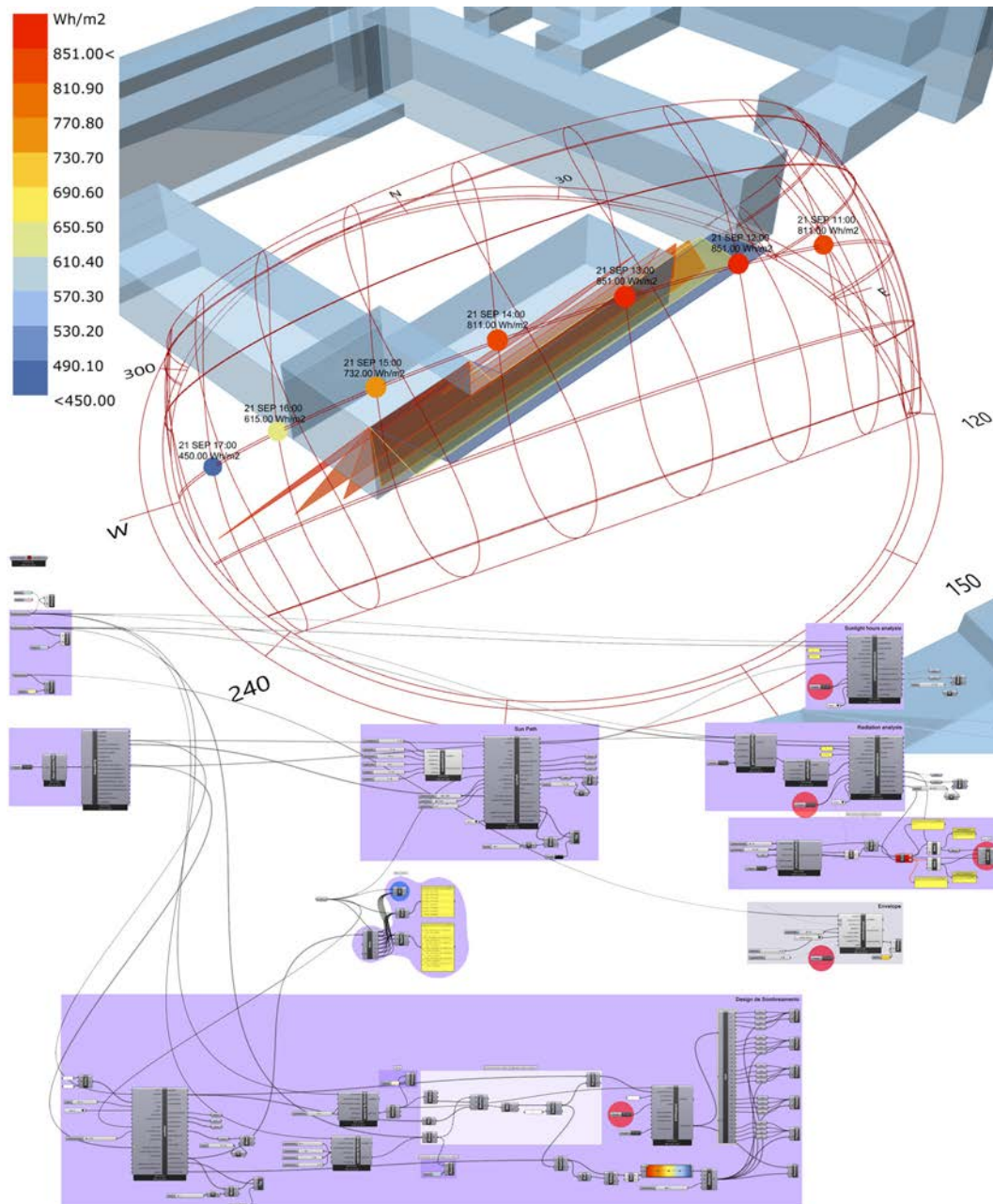


Figure 11. Shading system example: Ladybug analysis proposal.

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. To many, this may be a common statement, but it is important to emphasize it.

In the initial phase of Prototype, the designer has to consider the shading systems 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 method. 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 method 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.

6 Discussion

BSDM is not a closed method and, at this initial stage of its proposal and implementation, an objective and critical perspective is crucial for its further development. From the reader point of view some questions could arise: Was there any conditioning by the context premises, considering the shading systems architectural motto? Yes. It is a fact that the method starts from an initial diagnosis over the shading systems functions, actions and agents, which is a conditioning factor of the method application. However, the exploratory work as well as its structure launch solid basis of the extraction of functions, actions and agents of any other architectural motto. How is this method conditioned by software knowledge and plants biological knowledge? The method refers to, and is tested with, a specific set of software, but it is not restrictive at this point, meaning that the user can choose the tools that better suits his/her skills or the project needs. Design conceptualization with BSDM is rooted on terrestrial vascular plants' biological knowledge. This conceptualization enables the BSDM user to import biological technical terms, concepts and facts to the architectural lexicon, being this the major addition in relation to other methodologies. BSDM's major weakness lies on the fact that, for its efficient implementation, it is necessary that its user receives a brief training in biology, in order to understand the standard natural phenomena, preparing him/her for the conceptualization of adaptation events of terrestrial vascular plants. Major strenghts are: The division of the method into three domains facilitates its application to other scopes of architecture and design besides shading, applying the same extraction and conceptualization methods to different functions, actions and agents; The database of nature offers an infinite source of examples of adaptation that occur in nature and, as the method implicit process does not copy them, rather conceptualizes them, the user has total creative freedom; BSDM is a method that includes the fabrication of the artifact, driving the user to the physical creation of the product, what is a distinguishing factor from all other methodologies and an added value for the user in the proof of concept of his/her project, allowing adjustments before final production.

7 Conclusions

The built environment plays a critical role in creating the conditions for the well-being of people in circular and inclusive societies and communities. Environmentally responsible and socially meaningful architecture requires new design methods that support all actors involved in finding, assessing and producing novel solutions. Nature is a well-established, proven source of inspiration in many fields as well as in the building industry.

In the quest for new, optimized solutions for a circular architecture, solar control is one crucial design expertise because it contributes to reduce energy consumption, improve comfort and better use a natural renewable resource.

This research presents a new design method for biomimetic shading systems for façades, developed on a problem-based approach, termed Bioshading Systems Design Method (BSDM). BSDM is built upon existing knowledge related to biomimetic processes and supplies a theoretical and methodological support to its users, based on the combination of three complementary fields of study: Architecture, Biology and Computation, using terrestrial plants as the natural source of inspiration. The way the method relates and combines those three fields was designed to provide an effective support to designers. From defining the architectural challenge to prototyping a nature-based proposal, the user is guided through a biomimetic database about terrestrial plants. A set of pre-defined, solar control-related functions is transformed into a set of actions that lead to the accomplishment of those functions. Then, the biomimetic database is scanned for similar actions performed by terrestrial plants. The plant property that assures the respective action is identified as the agent that needs to be replicated in the realm of architecture and construction. This is possible due to the main innovation of BSDM: a bridging lexicon connecting architecture, nature and physical prototyping, and allowing the creation of a Biomeme – the tailored inspirational set of agents that provides the fundamental characteristics of the future shading system, and also an easier and more efficient link to fabrication.

With its open boundary condition, based on a transdisciplinary lexicon, BSDM can potentially integrate other fields of study or adapt its initial architectural premises in order to create different types of tailored biomimetic design outputs.

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