Computational Design Process in Bioclimatic Architecture.

Optimization of comfort and energy performance.

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Architecture

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Abstract

The climate change and the worsening of environmental conditions on the planet are major challenges that need to be addressed by architects worldwide. The building industry, being one of the biggest sectors in global economy, has significant impact on the natural environment. It is responsible for the depletion of around 50% of all non-renewable resources on the planet, and 50% of total greenhouse gas emissions. The current economic model is focused mostly on minimizing the production cost with no regards to environmental consequences. The resulting architecture is highly standardized and disconnected from the local climate and its cultural context. To tackle the negative consequences of the current architectural practice, designers and city planners are trying to rethink existing paradigms and methods. The research proposes a holistic model of sustainability based on a bioclimatic approach. By evaluating and testing existing computational design methods, it is trying to improve the creative process of architecture at early design stages. The study presents a new design framework which incorporates recently developed computational tools, building performance simulation, and optimization algorithms. The integration of the design workflow and performance evaluation in one software (Grasshopper plugin) makes the process more efficient and easier to follow.

The study evaluates the effectiveness of the methodology in comparison with standard design practices. The obtained results show significant improvement of building comfort and energy performance.

Key words: Bioclimatic design, Computational design, Building performance simulation, Multi-objective optimization, Sustainability

Resumo

As alterações climáticas e o agravamento das condições ambientais no planeta são grandes desafios que precisam de ser enfrentados por arquitectos de todo o mundo. A indústria da construção, sendo um dos maiores sectores da economia global, tem um impacto significativo sobre o ambiente natural. É responsável pelo esgotamento de cerca de 50% de todos os recursos não renováveis do planeta, e 50% das emissões totais de gases com efeito de estufa. O modelo económico actual centra-se principalmente na minimização do custo de produção, sem quaisquer consequências ambientais. A arquitectura resultante é altamente padronizada e desligada do clima local e do seu contexto cultural. Para enfrentar as consequências negativas da actual prática arquitectónica, designers e urbanistas estão a tentar repensar os paradigmas e métodos existentes. A investigação propõe um modelo holístico de sustentabilidade baseado numa abordagem bioclimática. Ao avaliar e testar os métodos de design computacional existentes, está a tentar melhorar o processo criativo da arquitectura nas fases iniciais do design. O estudo apresenta uma nova estrutura de design que incorpora ferramentas computacionais recentemente desenvolvidas, simulação de desempenho de construção e algoritmos de optimização. A integração do fluxo de trabalho de concepção e avaliação do desempenho num único software (plugin Grasshopper) torna o processo mais eficiente e mais fácil de seguir.

O estudo avalia a eficácia da metodologia em comparação com as práticas de desenho padrão. Os resultados obtidos mostram uma melhoria significativa do conforto do edifício e do desempenho energético.

Palavras chave: Design bioclimático, Design computacional, Simulação de desempenho do edifício, Otimização multi-objectiva, Sustentabilidade

Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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List of acronyms

AD – Algorithmic Design
BPS – Building Performance Simulation
CD – Computational Design
CPZ – Control Potential Zones
CSET – Center for Sustainable and Environmental Technology
EE – Embodied Energy
EPW – Energy Plus Weather
EU – European Union

GD – Generative Design
GHG – Green House Gas
HVAC – Heating Ventilation Air Conditioning
IPCC – Intergovernmental Panel on Climate Change
MIT – Massachussets Institute of Technology
MoMA – Museum of Modern Art
nZEB – nearly Zero Energy Building
OE – Operational Energy
PD – Parametric Design
PMV – Predicted Mean Vote
PPU – Predicted Percentage of Dissatisfied
UN – United Nations
USA – United States of America
UTCI – Universal Thermal Climate Index
WWR – Window-Wall Ratio

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INTRODUCTION

"We are searching for some kind of harmony between two intangibles: a form which we have not yet designed, and a context which we cannot properly describe." – Christopher Alexander in *Notes on the Synthesis of Form* (1964)

The evolution of architecture throughout the human history can be described as an interplay between technological development and environmental adaptation. From the first primitive shelters created by our ancestors, architecture served as a tool of redefining our relationship with the natural environment. The understanding of the reciprocal relation between built and natural world was intuitively understood by the traditional societies. Vernacular architecture is the best living evidence of their knowledge about material and form. The big part of that knowledge has been lost or forgotten in the process of industrialization of the western civilization. Industrial revolution, which started more than two hundred years ago, redefined our idea of society and progress but also let us think that humanity can exploit and expand its environment indefinitely with the help of modern technology and science. Last two centuries of economic and technological development were possible thanks to the cheap and accessible energy sources based on the extraction of fossil fuels. In architecture the adoption of the new economical paradigm was parallel to development of highly processed and industrialized materials (steel and concrete) which dominated the building industry worldwide. (Finocchiaro & Lobaccaro, 2017; Chiesa, 2021) Standardization of construction methods in the 20th century allowed architects to develop new "universal" language of modern architecture that started to be apply all over the world.

The 21st century global economy model has only strengthened the underlying patterns of building production. Contemporary architecture is usually a by-product of industrialized building technology and globalized material supply chain. It can be completely detached from the local resources and social context. Because of its globalized structure, building industry is generating a massive environmental impact in terms of energy use and CO2 emissions. Building materials are very often sourced, manufactured, and transported between different countries before they reach the destination. As a result of global economy dynamics, the need for adaptation of architecture to the local climate and resources is often neglected.

The current environmental crisis we are facing, requires from us to rethink how we approach our habitat. At the beginning of 21st century we are aware that the current model of the economic growth is unsustainable in the longer perspective. The amount of energy and resources needed to accommodate the current levels of human welfare is greater than the capacity of our planet. The possibility of the collapse of global economic system was already presented in the report" Limits to Growth" published in 1972. (Wikipedia, 2022b) The main objective of that report was to "warn of the likely outcome of contemporary economic and industrial policies, with a view to influencing changes to a sustainable life-style." (Meadows et at., 1972) To conclusion made by scientists was alarming. They predicted that if the present growth trends (considering population, industrialization, pollution, food production, and resource exploitation) remain unchanged we can expect "sudden and uncontrollable decline in both population and industrial capacity" in the next century.

After 50 years from the time of publishing the report, these predictions were validated with the new statistical data. (Herrington, 2021) According to the two most probable scenarios, if the current trajectory of CO_2 emissions and non-renewable resources extraction remains the same, we can expect worldwide decline in the human welfare around the year 2040 (Figure 1).

Climate crisis has already become a part of our reality. It is estimated that around 85% of the earth population is already affected by the human induced climate changes that includes raising temperature and changes in precipitation. (The Washington post, 2021) This worsening of the living conditions on the planet is one of the greatest challenges for the future generations to overcome. As the young generation of architects is becoming more aware of the environmental impact of the building industry, it is our obligation to embrace sustainability as one of the primary goals.

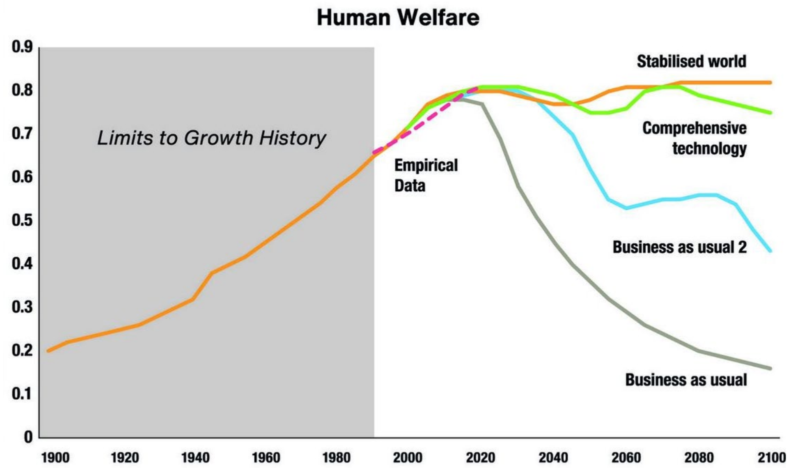


Figure 1 – Human Welfare scenarios (source: earth4all, 2022)

As a response to environmental crisis, architects need to develop holistic model of sustainable design. In the recent years we can observe significant development of passive and low-tech architectural solutions. Some of these models have its origin in the vernacular architecture. It is remarkable that in many cases environmental performance of ancient buildings is much better than in the case of modern constructions. The traditional architecture shows how to adapt the buildings to specific climate and use resources in efficient way. Beyond that is also an expression of local identity manifested through building techniques and relation to the landscape.

In contrast to that, contemporary architecture is usually devoid of any cultural or social influence. (Koolhaas, 2002). Although it globally embraced high performing materials and building techniques it is often unable to create meaningful spaces. Paradoxically, to generate emotional response, contemporary architecture is very often evoking historical references while at the same time ignores the fundamental aspects of material and building process. This lack of integrity in architectural thinking results in the negative impact of our built environment. To embrace the holistic vision of sustainable architecture we need to learn again how to relate our design to the issues of climate, material, and energy.

Objectives of study

In general terms, the presented research aims at integrating the theory and practice of bioclimatic design in the context of recently developed software and plugins. It is trying to demonstrate the potential of computational tools in the field of sustainable architecture. The main objective of the dissertation is to propose an innovative design framework for optimization of building performance and comfort. The focus of the work is to examine if the current computational tools can be useful in the evaluation of the passive and bioclimatic strategies in architectural design. By involving building simulation and optimization software at the early stage of design, the author is hoping to improve building performance parameters without compromising the quality of the architectural solution.

The work is also trying to investigate the limitations of computational tools while being applied to passive building strategies. The final objective of the thesis is to investigate if the proposed design framework can be successfully used for an actual architectural project. By comparing the thermal and visual comfort of different architectural solutions, it is trying to assess the feasibility of bioclimatic architecture in the Portuguese context.

Methodology

To achieve the previously defined objectives, the method of scientific research has been applied.

The methodology of the presented work is divided into five distinct parts:

(1) Literature review – provides the overview about the most crucial topics of the dissertation. It aims at describing the history as well as the current theories and approaches in bioclimatic architecture and computational design. It is also comparing some of the state-of-art software used in architectural design process.

(2) Framework proposal – presents the bioclimatic design optimization method based on the previous studies by other authors and information from literature review. It describes the consecutive steps of proposed design framework and the digital tools used along the process.

(3) Application of the framework – describes how the above-mentioned method has been applied to the specific case study. By analyzing two distinctive design methods it allows to compare the efficiency of conventional and computational workflows.

(4) Results evaluation – describes the performative results of the different design solutions obtained by applying optimization framework and conventional design workflow. It presents the quantitative data about the performance of different bioclimatic strategies used in the case study simulation.

(5) Conclusions – summarizes the main findings of the presented work. In the last part, the potential improvements to the presented framework are considered. Finally, few ideas for the future studies are proposed.

Structure

The structure of the dissertation can be divided into three functional parts: background, framework, and conclusions.

BACKGROUND – divided into two chapters:

Chapter 1 | Bioclimatic architecture and sustainability

| The chapter describes the history and evolution of bioclimatic architecture. It introduces the main principles of bioclimatic approach and position it in the context of current environmental challenges.

Chapter 2 | Computational design process

| The chapter describes the relation between architecture and computer sciences. It summarizes the use of computational tools in the current design practice and introduces the concept of performance-based design. In the later parts, the current state-of-art computational software is being presented.

FRAMEWORK - divided into two chapters:

Chapter 3 | Bioclimatic optimization framework

| This chapter introduces the framework applied in the research. It is proposing new workflow that allows for the integration of bioclimatic strategies and current computational tools.

Chapter 4 | Case study – House in Montemor-o-Novo

The chapter of the case study is divided into three main parts:

I. Study 1 – Analysis of the reference project

| Analyses the existing reference project design, and evaluates its comfort and energy performance

II. Study 2 – Application of bioclimatic optimization framework

| Describes the application of previously developed framework to same design task. It is showing the underlying computational process and use of specific tools. At the end the chapter, performative results of the optimization are being presented and analyzed.

III. Results comparison

| Compares the results of both studies to draw conclusion about the strategies and workflows applied.

CONCLUSIONS – containing one chapter:

Chapter 5 | Conclusions

| This chapter describes general evaluation of the obtained research methodology, as well as the applicability of the optimization framework. It synthesizes dissertation findings and proposes the future research directions.

CHAPTER 1

Bioclimatic architecture and sustainability

"Architecture, in other words, is a form of understanding of the given environment. As such, it consists in explanation of the unity of life and place, in order that we may understand where we are, how we are, what we are." – Christian Norberg-Schulz

The rapid expansion of the urban centers around the world is arguably one of the defining characteristics of our times. Year 2007 marked the definitive point in human history, as more than half of the world population started to live in urban areas. (Our World in Data, 2019)

Although it seems that the migration of global population to big urban centers is inevitable, it does not necessarily mean to improve people's living conditions. In his book "Radical Cities" Justin McGuirk described how the pressure of urbanization in Latin America cities, led to a failure of modernistic (and later neo-liberal) urban planning methods. (McGuirk, 2014). Nowadays, most of the metropolitan cities around the world must deal with the expansion of slums and suburban areas known for extremely poor living conditions. Unconstrained growth of the cities caused imbalance and disconnection between our ways of living and the needs of the natural environment. The root of this disconnection can be associated with the worldview that our western civilization inherited from the period of the industrial revolution. In the beginning of 19^{th} century, new technological inventions such as the combustible engine unlocked the energetic potential of fossil-fuels. The industrial technology was understood as a tool of dominating and transforming the natural environment. Urbanization models developed at the end of that century (for ex. Cerda's plan of Barcelona) assumed the unconstrained expansion of urban areas.

The exponential growth of cities requires a continuous supply of energy and building materials. As a result, about half of the non-renewable resources depleted across the planet are used in the construction industry (Doan et al., 2017) The globalized building industry is also contributing to the homogenization of the city landscape. As noticed by Droege, "fossil-architecture" is mostly driven by low-cost and standardized solutions that depreciate within a brief period. Habitation is usually reduced to "ordinary consumer products fueled at low cost". (Droege, 2006)

The negative social and environmental consequences of the city growth need to be addressed by architects and building industry professionals. New architectural approaches take inspiration from nature and recognize the need for an adaptation to the local environment. (Chiesa, 2021). Among different practices, "Bioclimatic design" is particularly interesting as it embodies the holistic vision of sustainable architecture.

The following paragraphs aim at describing the history and evolution of Bioclimatic architecture. The historical and contextual part is followed by a description of bioclimatic principles and strategies. By analyzing the different building components, it is possible to categorize them as bioclimatic parameters that can be integrated into the design process.

1.1. History and evolution

Long time before the idea of bioclimatic design was “invented” by the western civilization, it has been intuitively understood by the traditional societies all over the world. One of the first authors that brought this fact to public attention was Bernard Rudofsky, architect and curator of controversial exhibition (presented in MoMA in 1964) entitled “Architecture without Architects”

His exhibition was displaying the high artistic and functional value of the so called “vernacular” architecture. (Rudofsky, 1987). Besides recognizing the ingenious adaptative capacity of traditional buildings, the exposition was also criticizing contemporary modernistic approach to architecture. As stated in his book published for the exhibition:

“There is much to learn from architecture before it became an expert's art. The untutored builders in space and time, the protagonists of this show, demonstrate an admirable talent for fitting their buildings into the natural surroundings. Instead of trying to "conquer" nature, as we do, they welcome the vagaries of climate and the challenge of topography.” (Rudofsky, 1987).

Another author who positioned the climate, as a key factor in the development of pre-industrial architecture was Victor Olgyay. In his book “Design with Climate: Bioclimatic Approach to Architectural Regionalism” he analyzed the geographical context of indigenous dwellings all over the globe and observed that depending on the climatic conditions, specific architectural forms has been developed. (Olgyay, 2015) (Figure 2)

Figure 2 – Map of Bioclimatic architecture (source: Finocchiaro & Lobaccaro, 2017)

1.1.1. Pre-modern times

In the context of European civilization, good examples of climatic adaptation can be found in traditional Mediterranean houses. Whenever possible, they were oriented towards the south to take advantage of the passive heating of the building during the winter. (Markus & Morris, 1980)

The importance of orientating the buildings and cities according to the sun was already highlighted by Vitruvius in his Ten Books on Architecture. (Morgan & Warren, 1960) The distribution of rooms inside the building was adapted according to the available natural light during the day. He also suggested avoiding the negative impact of the prevailing winds and the high humidity. In Book VI of his treaty, the need for the adaptation of the building style to a specific geographic area is mentioned.

The wide variety of climatic strategies to mitigate excessive heat has been developed by the Arab culture. In the regions with hot and arid climate, the typology of courtyard houses was prevailing. The vernacular architecture in Morocco consisted of thick walls constructed from raw earth using techniques such as rammed earth or adobe bricks (Figure 3). Due to the high thermal inertia of the walls made of this material, the conduction of heat to the inside of the building was delayed during the day and could be released during the night, improving the indoor thermal comfort. Ventilation in the dwellings was enhanced by a vertical structure of the building that contributed to the chimney effect and improved airflow.

Figure 3 - Ksar Ait Ben Haddou (source: photo of the author)

Another ingenious example of traditional passive solutions are the windcatchers popular in the regions of Egypt and historic Persia. (Grosso, 2021) The architecture of windcatchers differs significantly depending on the region and environmental conditions (Figure 4). In some case they consist of isolated towers with distribution shafts while in others they are directly attached to the top of the building. The main principle of this devices is to take advantage of the natural occurrence of the prevailing winds. By redirecting the flow of colder wind inside the building, this strategy can help to ventilate the building and improve the thermal sensation of the occupants. (Wikipedia, 2022c)

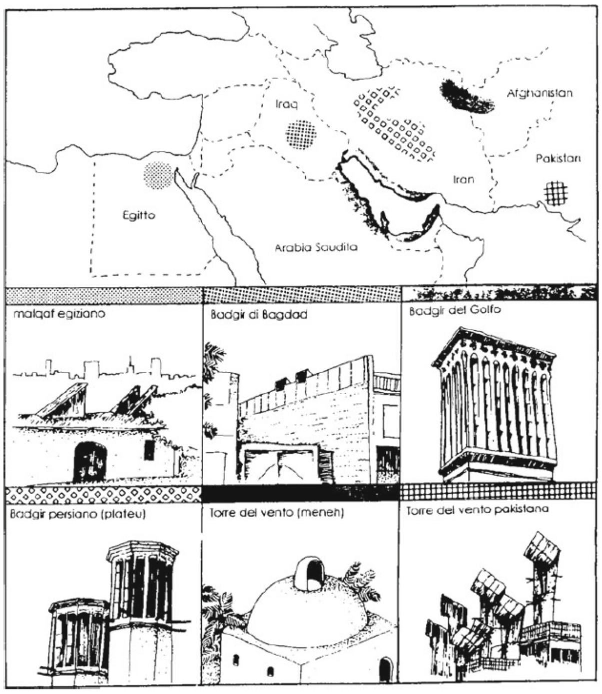


Figure 4 – Windcatcher types in the middle east region (source: Grosso, 1997)

The bioclimatic characteristics of vernacular architecture in North America was studied by Knowles (1974). He investigated the archeological remains of ancient Native American population in the south-western part of USA. The traditional dwellings of the Anasazi culture were often located in between canyons for a defensive purpose. As in the case of "Longhouse pueblo" (Figure 5) the settlement was built by the entrance of a cave that protected the houses from the elements but also limited their solar exposure.

"Still more careful observations show that buildings were placed inside the cave in such a way that their vertical stonewalls, and horizontal terraces received great benefit from the low winter sun, while being protected during the summer by shadows cast from the upper edge of the cave opening and by the high summer altitude of the sun." (Knowles, 1974)

The high efficiency of this solar heating strategy was confirmed later through the solar studies of the site model. (Knowles, 1974)

Figure 5– Longhouse Pueblo in Mesa Verde National Park, USA (source: National Park Service, 2022)

The examples of buildings mentioned above represent only a small fraction of the existing strategies and forms of vernacular architecture from around the world. The main reason of highlighting them is to give a notion of the great scientific value brought, by those structures, to the future debate about environmental adaptation. As Markus & Morris (1980) put it:

"Historical studies of vernacular buildings are helping in the development of a new kind of planning and architectural theory — concerned not with monumental planning and design, but with the pattern of cities, settlements, and buildings as expressive of the structural relationship between technological, social, symbolic and natural forces — that is, a cultural theory of form." (Markus & Morris, 1980)

1.1.2. 20th century

The vision of architecture at the beginning of the 20th century was influenced by rapid industrialization and the idea of technological development. The automated production of new construction materials such as steel, concrete and glass unlocked the potential for new architectural forms. In a way, technological advancement changed the way in which architects approached the design process.

Before the industrial revolution: "*vernacular builders instinctively followed the limitations imposed by nature on the materials that could be accessed and the strategies which could be drawn upon to preserve thermal stability. But by the middle of the twentieth century, it was no longer self-evident. Fossil-fueled feats of engineering had allowed a universalist ethic to take hold, telling us that anything could be built anywhere*" (Chiesa, 2021).

Modernistic architecture that has been developed at the beginning of the 20th century was deliberately rejecting traditional building practice. This new approach was manifested by the frequent use of industrialized materials and the rationalization of building forms (i.e., the reduction of ornamental or symbolic elements). The introduction of mechanical equipment inside the buildings was a way of achieving a total environmental control of the interior spaces. The preferred method for resolving the problems of thermal comfort was to apply artificial systems for cooling and heating. (Olgyay, 2015) The adaptation of architecture to specific environmental conditions was against the international and universalistic vision of modern architecture. *"As Le Corbusier described in one of his early books, titled the Radiant city, the variety of climates that "had forged races, cultures, customs, dress, and work methods" was also responsible for the "confusion, disorder, and the martyrdom of man" that had characterized architectures of the past."* (Finocchiaro & Lobaccaro, 2017)

Although the general tendency of Modern Architecture was in contradiction to bioclimatic approach, some of the architects applied bioclimatic elements in their works. The following examples feature the works of Alvaar Aalto, Buckminster Fuller and Frank Lloyd Wright.

<u>Alvaar Alto</u>

The Sanatorium building in Paimio design by Alvaar Aalto in 1929 was carefully oriented towards the sun. To take maximum advantage of the sunlight, all the hospital rooms faced the South and South-East direction. The southern wing included the solarium terraces covered by a continuous glass facade which allowed plenty of natural light inside the building. The frequent exposure to the natural sunlight was essential for the treatment of patients with tuberculosis. During the hot periods, the windows could have been covered with retractable venetian blinds to avoid the overheating of the interior spaces. (Grosso, 2021) (Figure 6).

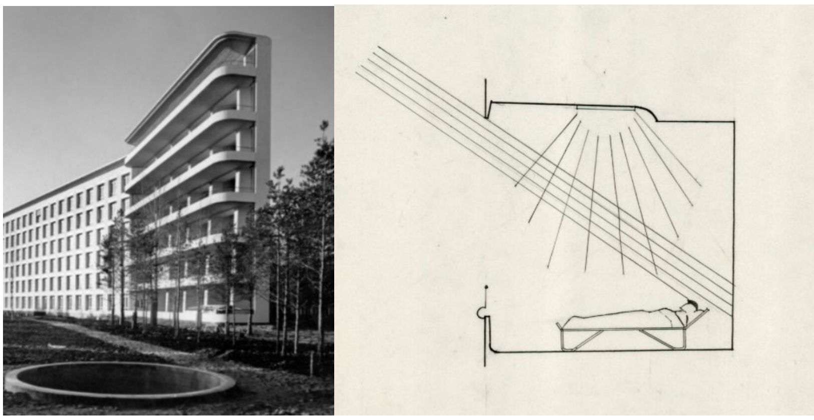


Figure 6 – Sanatorium in Paimio, photo, and architect's design of the solarium (source: Paimio Sanatorium Foundation, 2022)

<u>Buckminster Fuller</u>

The Dymaxion house was designed by Buckminster Fuller in 1930 (redesigned later in 1945) as a response to the high demand of new houses after the World War II. It was one of the first prototypes of self-sufficient housing units developed in the 20th century (Figure 7). The concept of the house was highly technological and "had the merit of exploring the environmental potential of innovative construction systems, often on the basis of empirical analyses and scientific experiments observations.” (Finocchiaro & Lobaccaro, 2017). The project was conceived as a prefabricated, lightweight construction that could be easily assembled and placed in different climatic conditions. The hexagonal (and in the later version round) shape of the building was supposed to optimize the solar exposure and provide natural light from any direction. The core of the building comprised of a passive stack ventilation system letting the air out through the chimney while supplying the air through multiple ducts hidden in the envelope. The Dymaxion concept also included rainwater collection and filtration systems. (Finocchiaro & Lobaccaro, 2017) Although the project was never fully realized and only half-finished prototypes were constructed, it is an important example of an early environmental approach in architecture.

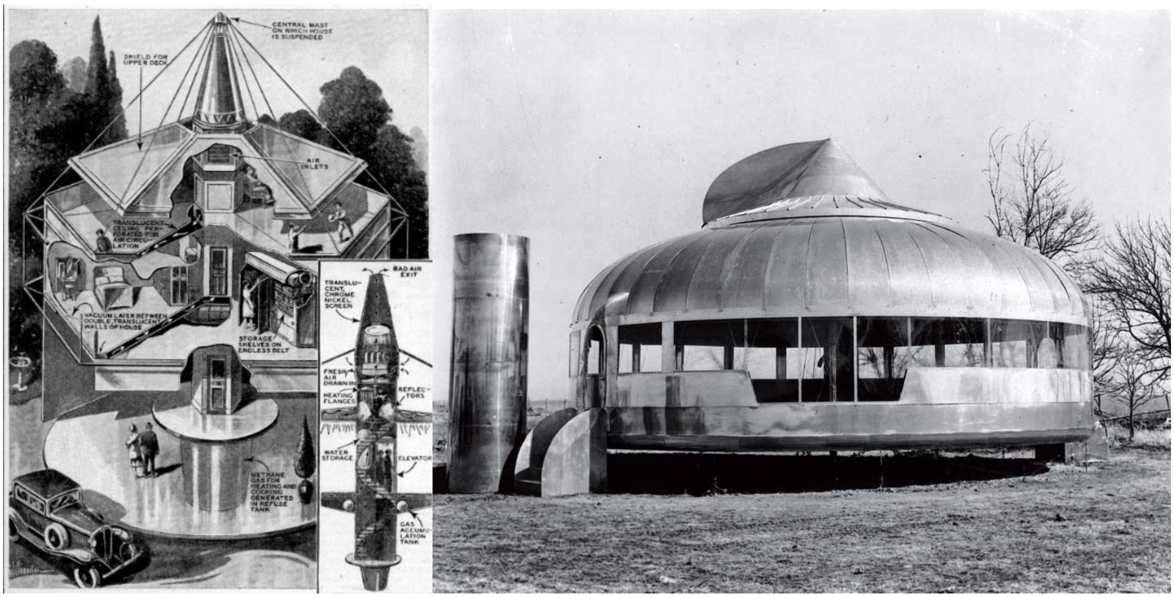


Figure 7 - Buckminster Fuller’s project of the dymaxion house (source: Archdaily, 2013)

<u>Frank Lloyd Wright</u>

The “Solar Hemicycle” house was designed in 1944 by Frank Lloyd Wright for clients Herbert and Katherine Jacob (Figure 8). Although the project was already the second commission from the same clients, it was significantly different from the previous designs. In contrast to the architect’s famous prairie style houses, this project was meant to be explicitly ‘bioclimatic’ by optimizing solar gains and other passive strategies. “Solar Hemicycle” is semicircular in plan with the internal part of the arc facing south. The building is two-story high, and its southern façade is glazed with over 4-meter-tall windows. On the northern side the whole structure is partially buried in the ground till the height of the second-floor windows. Closing the building from the north was essential in order to protect it from the prevailing northern winds. This spatial configuration was intended to minimize heat losses through the building envelope by reducing the exposed area of the walls. Large openings on the south side allowed for the heating of the common spaces through direct radiation but also by absorbing and storing the heat in the exposed concrete floor. The interior walls and finishing details, made in limestone, could also absorb the heat and increase the thermal inertia of the building. In the summer, to avoid overheating, the façade was protected by an overhung roof. It was estimated that due to the passive solar strategies applied in the building, the heating energy needs during winter were reduced by 53%. (Feldman architecture, 2022)

Figure 8 – Solar hemicycle house by Frank Lloyd Wright (source: Wikiarquitectura, 2022)

“Solar Hemicycle” is one of the emblematic modern constructions where the form of the building is imposed by climatic and comfort factors. Although Frank Lloyd Wright couldn’t yet apply scientific tools to predict the environmental behavior of his proposal, he intuitively understood how to optimize the building form.

Scientific foundations of bioclimatic design

Underscoring the scientific aspects of building design was necessary for establishing the “bioclimatic” approach as we know it today. New discoveries in climatology and building sciences allowed for better understanding the relations between the architecture and natural environment.

One of the most important authors who led the foundation of bioclimatic design was Victor Olgyay.
In his book :“Design with Climate: Bioclimatic Approach to Architectural Regionalism” he proposed an integrated vision of design practice embracing both natural sciences and architecture. His publication combined scientific background from different scientific disciplines (biology, climatology and technical sciences) with the practical recommendations for passive architectural design. The last part of the book offered theoretical examples of urban layouts designed according to his method. Olgyay’s studies were inspired by the work of Köppen and Geiger who developed a classification of the world’s climates considering not only the temperatures but also the occurrence of different types of vegetation. (Köppen & Geiger, 1961). The climatic zones scheme was useful for Olgyay to establish different climatic adaptation strategies. In his chapter about “Environment and building forms” he draws a parallel between the climatic adaptation of building forms and the morphological evolution of living organisms, hence his proposition to call this approach “bioclimatic”. (Olgyay, 2015) (Figure 9)
The works of Olgyay bridged the gap between the traditional building knowledge and the scientific understanding of thermophysical properties.

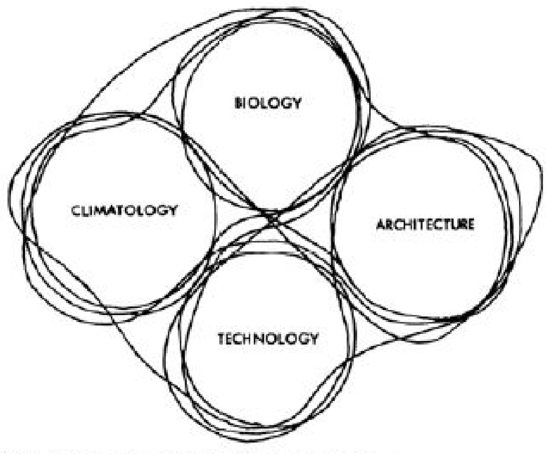


Figure 9 – Interlocking fields of climate balance (source: Olgyay, 2015)

In the following years, the bioclimatic approach was investigated by many other researchers. Bruno Givoni is known for introducing the psychometric chart used for evaluating the potential of different passive strategies. He was also researching, cooling strategies that could be applied in hot climates. (Grosso, 2021)

After the oil crisis in 1973, the question of energy use and preservation became very important as the economy of many western countries was dependent on cheap fossil-fuel. In that period, passive buildings appeared as a viable alternative to energy intensive buildings. Architects started to advocate the integration of passive systems at the early stage of the design process. In one of the design handbooks from 1982, Brown et al. (1982) wrote "*that most decisions that affect a building's energy use occur during the schematic design stage of the project. Furthermore, the effort required to implement those decisions at the beginning of the design process is small compared to the effort that would be necessary later on*." Bioclimatic principles have also been applied in city design with a hope of resolving the problems of urban sprawl (Knowles, 1974). In the 70s and 80s most of the research on bioclimatic architecture in Europe and US was focused on the methods of passive heating. However, the potential of passive architecture started to be explored also in the context of hot climate zones, mostly in of the developing countries. (Cook, 1989)

In his book about passive cooling, Jeffrey Cook (1989) tried to summarize the condition of international design practices in the context of passive strategies after 1974. He observed that in most countries, building approach could be characterized in one of three ways:

I. Continuation of indigenous traditions – occurred mostly in the context of less developed or less globalized regions of the world where local climate, tradition and native materials still played decisive role in the architectural expression and thermal comfort of the buildings.

II. Modernism – with highly industrialized construction materials and methods, which independently from the geographic location could be associated with the International Style. Environmental comfort was delivered mainly through mechanical systems depended on external sources of energy.

III. Bioclimatic design – following the principles of passive design developed internationally from 1950s onwards. These practices included both the use of local and industrialized materials and methods. In many cases, they meant to integrate heating and cooling systems as well as lightning and ventilation needs by providing passive solutions. (Cook, 1989)

By the end of the 20th century, bioclimatic approach to architecture was already internationally recognized, although the accumulated technical knowledge was still largely overlooked in the global building practice. (Grosso, 2021)

1.1.3. Present and Future

The development of computer technology and data science in the second half of the 19th century stimulated new discoveries in environmental sciences. A significant improvement in computational power allowed for a faster and more accurate analysis of climatic data and the construction of predicative model.

At the same time, new findings about the climate change brought serious concerns about the stability of the global ecosystem. The growing social awareness about global warming led to several political action such as the establishing of the Intergovernmental Panel on Climate Change (IPCC) in 1988 and the adoption of the Kyoto Protocol in 1997 in order to reduce global GHG emissions.
Around the year 2000, the Nobel prize laureate, Paul J. Crutzen popularized the term "Anthropocene" used to describe the current condition of our globe. He argued that the human influence on the planet is so significant that it can be identified as a separate geological era.

As a result of the growing environmental awareness, Sustainability and Ecology become a central topic in contemporary architecture. Computational methods developed in recent years allows for an effective implementation of passive strategies. Building performance simulation tools give and opportunity to test different applications of bioclimatic design and quickly evaluate their efficiency.

Finocchiaro and Lobaccaro (2017) described how the current computational tools expanded the perception of bioclimatic design: *"Bioclimatic design is now transitioning into a new era where passive strategies, once intimately connected to a specific climatic context, are now extending their geographical boundaries of applicability. Potential of passive strategies for improving comfortable conditions can moreover be further enhanced recurring to hybrid systems where the small amount of energy required for their use can be provided by building integrated renewable energy systems."*

In their publication they presented an example of the contemporary state-of-art bioclimatic design. Eberle 2226 was designed in Austria in 2013 by Baumschlager Eberle Architekten with the idea of optimizing comfort and energy consumption of the building. (Figure 10).

Figure 10 – Eberle 2226 office building by Baumschlager Eberle Architekten (source: Archdaily, 2015)

The main passive strategies applied in the building concept included the use of natural ventilation and thermal inertia. To regulate the temperature and air exchange inside the building, the architects used a digital control system that was responding to environmental conditions. In the winter, the thick and airtight envelope of the building kept a warm temperature inside. Digitally controlled windows were used as a natural ventilation system to minimize heat losses. The internal heat gains from occupants and the electric equipment could generate enough heat to preserve thermal comfort. In the summer, natural ventilation has also been used to cool the building and let the hot air out. The use of high thermal inertia walls (almost 80 cm thick ceramic bricks) was a passive way of stabilizing the temperature inside the building for the entire year. A narrow range of comfortable temperature between 22-26ºC was achieved without any mechanical heating, cooling, or ventilation systems (Eberle and Aicher 2015).

"This building decreed the transition from traditional HVAC systems into a new era made of digital building components for environmental control, where digital data loggers are connected to physical building components (…), in order to optimize environmental performance of buildings towards maximum energy efficiency." (Finocchiaro & Lobaccaro 2017)

Another interesting example of contemporary bioclimatic architecture is the project of the Centre for Sustainable Energy Technology (CSET) in Ningbo, China, designed by Mario Cucinella Architects.
The university building is a showcase of different passive and hybrid solutions. It also completely self-sufficient in terms of energy as it uses different types of renewable sources such as photovoltaic panels, geothermal heat pumps and wind turbines. Similarly, to the previous example, various devices for controlling the ventilation and openings of the building are integrated into the Building Management System. The system evaluates in real time the internal and external conditions and automatically decides on applying different cooling and heating modes. By hybridizing both passive and active

strategies, the building is quickly reacting to changing weather condition and can use resources in a more efficient way. (Widera, 2016) The form of the building is also adjusted to promote passive strategies. The northern side is mostly opaque to provide better insulation for the envelope. From the south, a double skin glass façade is inclined in a way to reflect the excessive solar heat in summer but also to allow the sun to penetrate the building in the winter. Natural ventilation in the building occurs due to the opening in the double skin façade that allows the air to enter from the bottom and the top of the tower. In the winter, cold air is being collected and pre-heated through the passive and active means like earth coupling, geothermal energy or radiative coils embedded in the floors. In the summer the air can be collected from the top of the tower (analogically to the ancient windcatchers) and passed through air handling units to be cooled down and dehumidified. As the air becomes heavier after the process, it goes down the light well and can be distributed throughout the lower levels. (Widera, 2016)

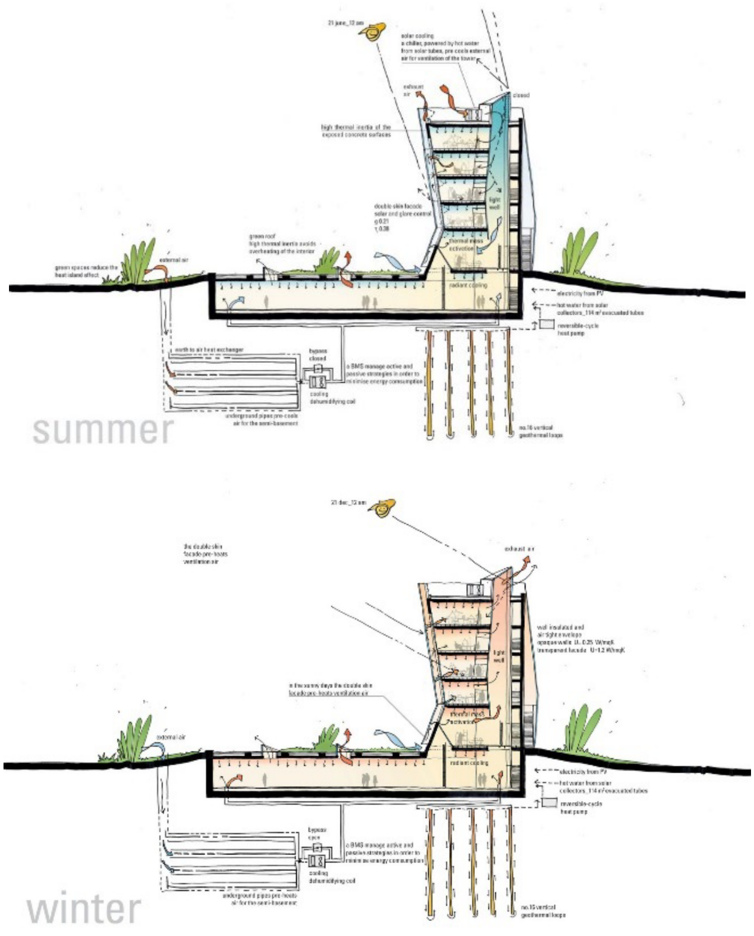


Figure 11 – Environmental strategies diagrams, Centre for Sustainable Energy Technologies / Mario Cucinella Architects (source: Archdaily, 2016)

The examples of sustainable buildings mentioned above show that bioclimatic approach can be successfully combined with the most recent technological systems. The effective application of these hybrid systems relies on a good understanding of the climatic potential of a given location. In this sense bioclimatic approach can be applied universally around the globe.

Architecture in the future is likely to evolve toward a more adaptive and nature-inspired model. Architects start to understand the build environment as a dynamic system that needs to evolve in time to avoid becoming obsolete. Concepts like biomimetics brings the idea of applying the knowledge about natural systems to concrete engineering problems. As Christopher Alexander pointed out: *"People used to say that just as the 20th century had been the century of physics, the 21stcentury would be the century of biology... We would gradually move into a world whose prevailing paradigm was one of complexity, and whose techniques sought the co- adapted harmony of hundreds or thousands of variables. This would, inevitably, involve new technique, new vision, new models of thought, and new models of action."* (Alexander, 2002)

1.1.4. Bioclimatic Architecture in Portugal

The presented research is focused on the application of bioclimatic strategies in the hot zones with the emphasis on the climate of South Portugal. Therefore, a brief review of the most common bioclimatic strategies has been undertaken.

Similarly, to the other countries, bioclimatic architecture in Portugal has its roots in local building practices. *"The Portuguese context is rich in vernacular architectural manifestations and in the range of passive strategies used in different regions to favor the beneficial effects of the climate and to mitigate its harmful effects."* (Fernandes et al., 2014)

One of the most comprehensive inquires on vernacular architecture in Portugal was undertaken by the Portuguese Architects Association (AAP) and published in 1961. (Simões et al., 2019)

The book was divided into chapter describing different zones of the country depending on the prevailing building forms and material. The architecture of northern Portugal was described as adopted to more mountainous terrain and relying mostly on stone, while the south as "*located on flatlands and plateau areas of the meridional region where natural light is plentiful, and which is bonded to soft materials transformed by fire and painted with lime, as a response to a life more open to the outdoors, more grounded on earth, and settled in dense villages which are interlinked*" (Simões et al., 2019)

Analysis of building materials and typologies popular in Alentejo region shows different methods of adaptation to the hot climate of the region.

Until mid of 20th century, the dominant building technique was rammed earth which in some cases was complemented by adobe, fired brick or stone masonry elements. (Correia, 2007) (Simões et al., 2019) The massive earthen walls were usually supported by buttresses and relieving arches. The roof construction was slightly inclined and made of circular wooden beams and planks supporting traditional ceramic tiled roofs. The floors of the houses were often covered with thin square mosaic bricks. The use of materials with high thermal inertia was one of the main passive techniques regulating temperatures in the interiors. Because of the walls thermal time lag, during the day the building was absorbing the heat slowly, allowing comfortable temperature during the day. At the end of the day when the outdoors temperature started to drop the building was releasing the heat, reducing the needs for heating in the night. In the hottest months, the interior was also cooled in the night by opening the windows for cross-ventilation. (Fernandes et al., 2007). The bioclimatic strategies included also the covering of the earth walls with lime. This solution wall fundamental for the protection of the rammed earth walls from natural erosion but also to minimize the solar gains of the façade. (Simões et al., 2019). White color of the walls was an "important element against extreme solar radiation, (…) allowing for a reflectance of about 90% of all the radiation received" (Koch-Nielsen, 2002; Fernandes et al., 2007)

The typology of the rural houses usually consisted of single volume with a low and horizontal expression. (Figure 12). The front façade was exposed to north-east to avoid the most aggressive sun exposure. (Simões et al., 2019). The walls oriented to the west and south had very little or no openings to protect the interior from heat. To create a comfortable condition for the outdoor spaces several different solutions could be introduced. In cases when several building volumes created a single complex, they often resulted in the closed courtyard space (patio) providing the shade for outdoor activities. Another popular shading element consisted of balconies, roofed terraces and porches which created pleasant microclimate and transitional space for the houses.

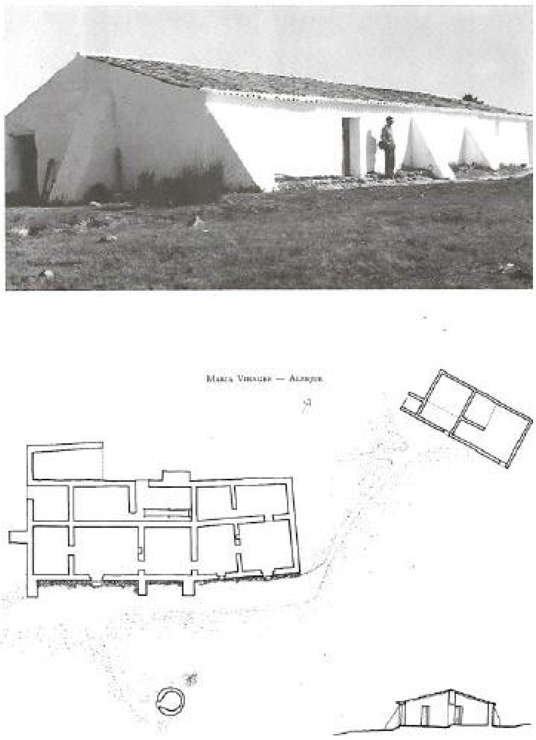


Figure 12 – Vernacular architecture of Alentejo, Alcacer do Sal (source: Simões et al., 2019)

The landscape and vegetation were also essential elements for climatic adaptation of the building. As have been observed in one the buildings located in Evora, climbing plants were used as a thermal protector of the façades. "When they possess thick leafy branches an immovable air layer is created

between the foliage and the wall, factor that substantially reduces the exterior superficial thermal conductance coefficient" (Fernandes and Correia da Silva, 2017).
The analysed elements of bioclimatic architecture in Alantejo region can serve as an inspiration for the future sustainable practice. As noticed by Fernandes et al: *"The strategies of adaptation to the environment present in these constructions, characterized by simplicity, passive operation and reduced environmental impact, are particularly relevant to the challenges that contemporary construction faces, allowing the reduction of dependence on energy from non-renewable sources."* (Fernandes et al., 2014)

1.2. Bioclimatic principles and strategies

As described by Grosso: *"Bioclimatic design focuses on maximizing comfort levels by optimizing the suitability and exploitation of the full potential of passive solutions connected to local climate, due to the correct design of building envelopes, considering climate and site, and the control of the natural heat gain balance, including dissipation, mitigation, and prevention of heat gains".* (Grosso, 2021)
Following paragraphs intend to describe the main bioclimatic principles and strategies and categorize them as parameters associated with architectural design.
In terms of architectural process, some of the most important project conditions like building location and its climate are defined before the start of the conceptual design process. They precede the architectural project and can be understood as the external design parameters. In most of the cases, architects do not have any control over these parameters, therefore they should adapt the project accordingly.

1.2.1 Location

Geographic location is an important parameter that defines the general characteristics of a place.
By checking the geographic coordinates, it is possible to identify the summer and winter period which depends on the location on either the northern or the southern hemispheres of the globe. It is important to notice that the locations with similar geographic latitude doesn't necessarily share the same climate as there are more factors influencing local conditions. The occurrence of local building resources (like wood, stone, or earth) also differs depending on the geographic location.
Another important aspect of a place is its topography. Topography defines how the terrain of the plot influences a project. Adaptation strategies in the mountains should be different than the ones applied in flat or coastal areas. As an example, sun in the valleys can be blocked by the mountain peaks and consequently limit the amount of radiation reaching the building throughout the year. Topography can also significantly change the speed and direction of the wind that influences the heat losses from the envelope. Regarding the coastal areas, the light can be reflected from big water surfaces and cause inconvenient glare. (Guedes et al., 2019)

Different topographic conditions can also encourage the use of specific passive strategies. For instance, on sites with greater inclination, the buildings can be embedded into the ground for better wind protection and insulation.

1.2.2 Climate

Climate is the "the average course or condition of the weather at a place usually over a period of years as exhibited by temperature, wind velocity, and precipitation". (Merriam-Webster, 2022b)
As the climate change is rapidly progressing, the stable definition of climate is debated by some authors (Chiesa & von Hardenberg in Chiesa, 2021) Nevertheless, it is considered as a crucial parameter in bioclimatic design. Different climatic zones can be identified according to the Köppen - Geiger climate classification systems (Figure 13).

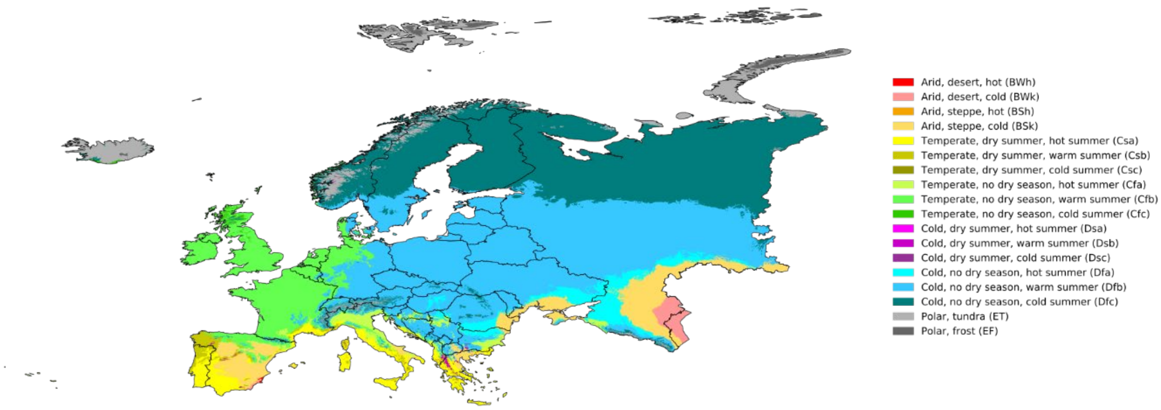


Figure 13 – Köppen-Geiger climate classification map for Europe (1980-2016) (source: Wikipedia, 2022d)

The recognition of climatic zones brings a general understanding of possible adaptation strategies. The climatic conditions of a place can be analyzed through the following quantitative parameters:

a) Air temperature - Usually understood as a dry bulb temperature which indicates the temperature measured by a thermometer not being exposed to the sun and moisture. The air temperature is one of the most important indicators as it is defining the comfort conditions for humans.
b) Relative humidity - Describes how much the air is saturated with water vapor. It is a relation between current absolute humidity and the maximum possible value of humidity for a given temperature (described in %). Humidity is an important factor influencing the perception of thermal comfort. It is linked to the human capacity of releasing heat necessary for achieving the thermal balance. High values of relative humidity can result in a higher perceived temperature of the environment.
c) Wind Speed and Direction - Wind speed can be defined by its speed (in m/s) and direction.

It is important to assess the prevailing wind direction to evaluate if it can be used for natural ventilation of the building. Cold winds blowing in the winter can increase the heat losses from the envelope, therefore it is recommended to protect the building from their negative impact. In the summer, winds can be advantageous for natural ventilation and for improving thermal comfort inside the building.

d) Solar Radiation – The solar radiation received by the building comes from the sun in different forms. Short wave direct radiation describes the amount of energy that heats the building after passing through the atmosphere. During cloudy days, direct radiation is reflected and diffused by the sky, therefore the energy arriving to the building surface is reduced. Nevertheless, some percentage of that energy arrives to the ground in the form of short wave diffused radiation. Some part of the short-wave radiation can be also reflected towards the building by surrounding surfaces. (Olgyay, 2015) This effect can be a significant factor in city centers where the glass façades of the buildings can reflect the heat towards the street. Another important source of energy come from the short-wave radiation of the ground surfaces. When the thermal absorption of the ground is high, the accumulated energy is gradually released and results in increased temperature of the air close to the surface. This phenomenon occurs often in cities and causes the urban heat island effect. As described previously, the solar energy transfer has a complex nature and depends on the changing weather conditions. Good bioclimatic design should account for different radiation effects to minimize overheating and glare.

e) Precipitation - The amount of rainfall is an important factor to consider in the building design. Some architectural solutions can be more practical in regions with higher amount of rain (sloped roofs, water drainage, elevated ground floor). In climates with scarce water sources, strategies for rainwater collection can be applied.

Another useful indicator of the climatic condition can be expressed through heating and cooling degree days. “It provides an indication of severity of the climate in different locations by documenting when during a given year the external air temperature falls below or rises above a specified temperature, requiring thus heating or cooling. The specific temperature is called base temperature and represents the temperature at which no heating nor cooling loads are required in buildings for that climate.” (European Commission, 2016) Heating degree days are measure as the total amount of hours during which heating, and cooling was necessary to maintain thermal comfort. This measure can be useful for a designer to understand if the applied passive strategies should address mostly heating or cooling issues.

1.2.3 Bioclimatic strategies

Bioclimatic strategies can be applied to the form and internal organization of the project. Different building components can be defined as the design parameters determining the final form of the building. They can be manipulated by architect to achieve comfortable and sustainable environment.

1.2.3.1 Building form and orientation

The shape of the building is one of the principal design parameters. It defines the overall proportions and dimensions of different spaces. The design of building volumetry should be dependent on the climatic conditions of its location. In the general terms the form should minimize the negative effects of the environmental conditions. In the cold climates the main challenge is to minimize the heat losses from the envelope. For that reason, the form of the building should be as compact as possible to minimize external surface area. (Olgyay, 2015)

In the temperate climates the temperature differences allow for more diverse and elongated forms.
Thermal stresses imposed on the envelope are not extreme, although it might be favorable to maximize the sun exposure to benefit from passive heating. An East-west elongation is usually preferable. (Olgyay, 2015)

In the hot-arid regions winter conditions favors an elongated shape (for optimization of heat gains), however because of high temperatures in summer the forms should be more squarish to avoid overheating. In result one of the common adaptation strategies is to close the building from the outside and create internal openings, for example courtyards or light wells. The openings should provide enough shade and offer some cooling elements like vegetation or water surfaces. (Olgyay, 2015)

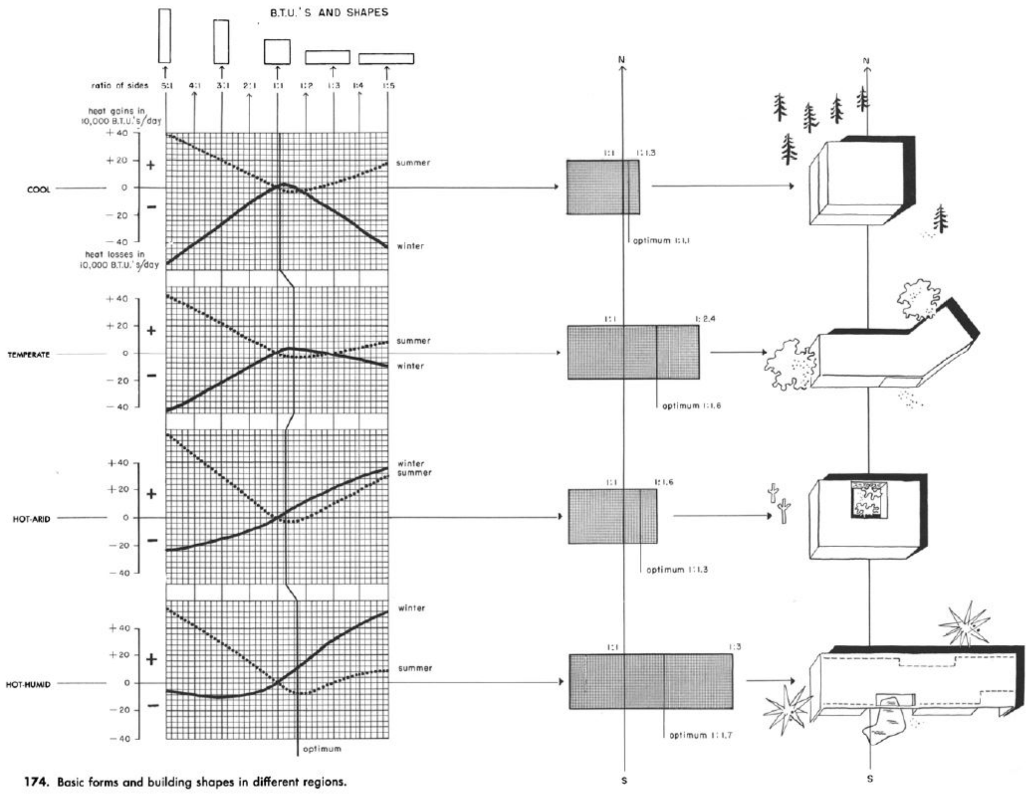


Figure 14 - Recommended building forms in different climates (source: Olgyay, 2015)

Another important aspect of the building shape (especially in hot climates) is the volume depth. The proportions of the building should allow for cross ventilation and natural daylight inside the building, in other words, provide the passive areas which support the occupants comfort without the use of mechanical devices. The depth of these areas (measured from the exterior wall) is related to the building floor height (usually two times the height). “The proportion of passive area of a building in relation to its total area provides an indication of the potential of the building for the use of bioclimatic strategies. The concept of passive zone should be considered from the first stages of the project when one defines the shape and orientation of the building”, (Correia, 2002)

Regarding the orientation of the buildings in hot climates, they should avoid the low angle sun from eastern and western directions what can be achieved by orienting the buildings parallelly to east-west axis.

1.2.3.2. Building envelope

Building envelope defines the elements that separates the external and internal environmental conditions. Facade design is the most fundamental parameter regulating the performance and comfort of the building.

1.2.3.2.1. Opaque elements

Opaque elements of the building envelope consist of walls, roofs, and floors. In the building design they usually serve both the structural and environmental function. During the design process the architect should account both for the static and thermal performance of the opaque elements to provide safe and comfortable space. Regarding the thermal comfort, the most fundamental property of the opaque elements is their thermal resistance. The value of thermal resistance is equal to material thickness divided by its conductivity. Thicker and less conductive materials are better insulators and can protect the building from exchanging the heat. From the bioclimatic perspective, good insulation of the buildings is important to keep the internal heat gains inside the house when the external temperature drops below the comfort levels. Good insulation is equally important in the hot climates, as it might prevent the conduction of the heat from the outside to the inside of the building. To prevent the convection of the cold or warm air to the inside, building envelope should be also relatively airtight.

Another important strategy, effective in the hot climates includes the use of wall thermal inertia for regulation of the interior temperature. Thermal inertia is the property describing how quickly a given materials can accumulate heat. It is related to specific heat capacity and density of the given material. Materials with high thermal inertia require more energy to raise their temperature but also remain warmer for the longer periods of time. As they accumulate and release heat more slowly, they can stabilize diurnal temperature differences. In the hot climates, use of high thermal inertia materials (for example earth or stone) prevents the building from accumulating too much heat in the peak hours.
In the night, the accumulated heat can be flushed out of the building through natural ventilation.
This strategy in only effective when the amplitude of temperatures between the day and night is more than 10°C (Guedes et. al., 2019).

Another relevant factor for the opaque elements is their solar reflectance. Depending on their color and texture, wall finish materials can reflect significant amount of solar radiation. The light-colored coatings help to reduce the temperature of the building envelope and avoid the heat conduction into the building. “The best project solutions combine different passive cooling strategies, to achieve greater efficiency – such as cooling by night ventilation with thermal mass and external insulation.” (Guedes et. al., 2019).

1.2.3.2.2. Glazing

Glazing parameters have a significant impact on the thermal balance in the building.
"The orientation and sizing of the glazed areas, as well as the choice of glass, determine to a large extent the penetration of solar radiation in the building" (Guedes et. al., 2019). Thermal transmittance of the windows is generally higher than that of the opaque elements, therefore the amount of heat gains and heat losses can be greater. As the windows contribute not only to the thermal but also visual comfort of the building it is important to balance these factors. Building with a smaller percentage of glazing can provide significant energy savings, however the requirements for natural lightning should not be compromised. (Hee et al., 2015). Appropriate use of glazing can be also beneficial for reducing the heating needs when used as a passive solar heating system. As the windows allow significant amounts of solar radiation to the inside of the building the energy can be accumulated by internal surfaces and increase the indoor air temperature. Previously presented Solar Hemicycle building (by Frank Lloyd Wright) is an early example of such a system.
Nevertheless, in the context of hot climates the Wall-window ratio (WWR) of the facades should be limited. As written by the author of "Bioclimatic Architecture in Warm Climates": "the area of glazing should not exceed 30% of the North and South facades' areas, considering that windows have adequate shading. In the East façade, this value should be reduced to a maximum of 20% in any situation. In the West façade, openings should be, if possible, avoided" (Guedes et. al., 2019).
To increase the windows efficiency double-glazing and low-emissivity glass can be applied. Low-e glass can efficiently block infrared radiation, reducing the overall solar transmission by more than 50%. The use of shading elements can significantly improve the window performance. Therefore, the design of both elements should be considered simultaneously.

1.2.3.2.3 Shading

Different bioclimatic strategies for shading allow to reduce the heat stress of the buildings.
Architectural elements like balconies, terraces and patios are often used in hot climates.
Special attention should be taken for shading of the windows as they allow big part of radiation inside of the building. The most popular shading elements for windows include blinds and shutters.
The distance between the shading element and the glazing area should be big enough to prevent the interior from thermal radiation captured by the shading device. (Guedes et. al., 2019).
External shading is more efficient in preserving the thermal comfort as it blocks the solar radiation outside of the building, while internal shading is only useful for regulating the amount of natural light.
One of the popular bioclimatic strategies is the use of fixed horizontal overhangs. They can provide protection of the windows in the summer months (when the sun angles are higher) and allow radiation to penetrate in the colder months, resulting in passive solar heating of the buildings. They should be used mainly in the southern façade of the building. "In the East and West façades, a horizontal fixed device is better than vertical, but the facade is never completely shaded. Vertical fins can protect the North façade from the rising sun and sunset." (Guedes et. al., 2019).

Adjustable shading devices are usually more effective in regulating the thermal comfort then the fixed ones. As they are operated by the occupants or intelligent control systems, they can adjust the position of the shades to allow exact amount of sun radiation according to environmental conditions and program needs (Guedes et. al., 2019).
Bioclimatic shading strategies also include use of vegetation. Planting deciduous trees next to the building is a natural way of regulating sun radiation throughout the year. In the summer leaves cover is filtering the sun while in the winter, when the trees are bear, sun can heat up the building envelope. (Guedes et. al., 2019).

1.2.2.3. Natural ventilation

Natural ventilation is a sustainable alternative to mechanical ventilation of the buildings.
It does serve several functions in providing the occupants comfort like:

- Provision of fresh air
- Heat removal from the envelope
- Convective and evaporative cooling of human body.

One of the studies estimated that cooling requirements in Europe are expected to overtake those for heating as we approach 2050. (Isaac and van Vuuren, 2009 in Chiesa, 2021). For that reason, passive ventilation strategies should be developed as an alternative to energy-intensive mechanical systems. Natural ventilation strategies can be divided into separate types (Guedes et. al, 2019): Wind driven strategies (using the natural occurrence of wind) and Stack-effect strategies (inducing the air flow by the air temperature difference).

Wind driven strategies include:

- Single-sided ventilation - with useful wind penetration from 3 to 6 m or two times of the building floor height.
- Cross ventilation - with useful penetration up until 9 m or three times of the building floor height.

Stack-effect strategies include:

- Single sided double openings – it utilizes the difference in window positions. The lower window brings the colder air inside while the warmer air is let out through the higher opening.
- Atria
- Solar and thermal chimneys
- Vent-skin walls – they can help in cooling down the walls by allowing the ventilation gap between the layers.

Other types of ventilation related to specific bioclimatic strategies are:

- Nighttime ventilation – used together with the high thermal inertia strategy described earlier to flush the heat accumulated in the wall structure during the day.
- Wind towers – the strategy used in case of strong prevailing winds that can be used for cooling of the interior. The wind towers are channeling the air flow to the interior through the network of ducts.

1.2.4. Psychometric chart

Psychometric chart designed by Baruch Givoni is a useful tool relating the specific environmental conditions (external parameters) with the potential of several bioclimatic and conventional strategies for achieving the thermal comfort. Its showing how the thermal comfort of the interior space can be expanded by applying different heating and cooling methods. “The perimeter of each zone defined the conditions under which a specific passive strategy could be considered as an effective solution. The boundaries of such areas, later named by Steven Szokolay as control potential zones – CPZ – depended both on the technology adopted and on the environmental conditions under which a specific strategy was applied.” (Finocchiaro & Lobaccaro 2017). As can be seen in figure 15, psychometric charts suggest the use of several bioclimatic strategies like: Capture of internal gains,
Passive solar heating, Active solar heating, Solar protection, High thermal mass with night cooling and Natural ventilation. By plotting the weather data from the given location on the psychometric chart it is possible to predict which passive strategies can be effectively applied to provide thermal comfort in the building.

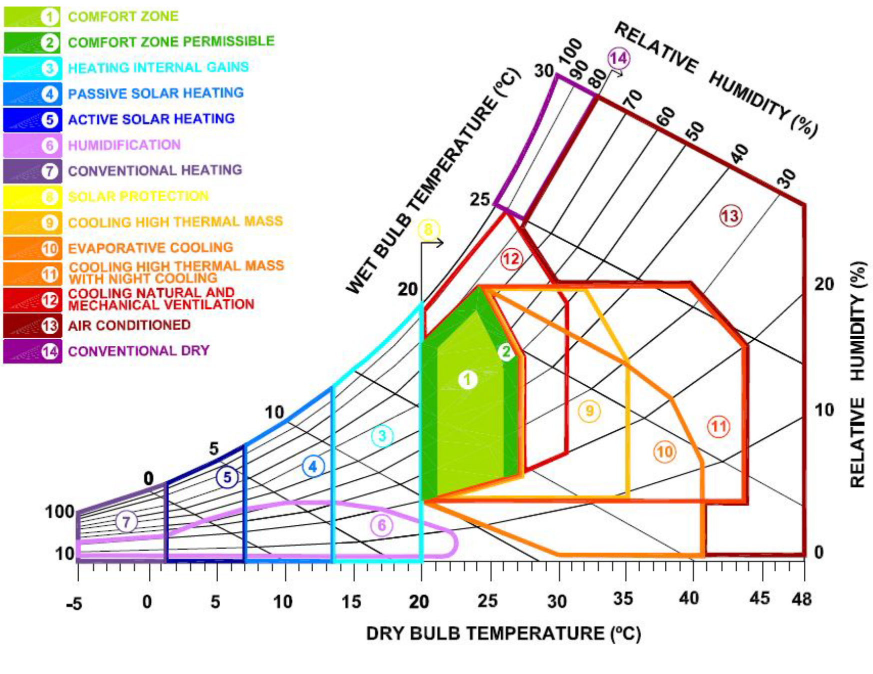


Figure 15 - Psychometric chart by Givoni (source: Givoni, 1992)

CHAPTER 2

Computational Design Process

"Technology is the answer, but what was the question?" – Cedrick Price

The question asked by Cedric Price back in 1966 is gaining great relevance at the beginning of the 21st century. In the present times, technology becomes an inseparable part of our reality and ever-present force changing our society. Great development in computer sciences has opened new possibilities for understanding and solving complex problems in almost all fields and disciplines.
Growing concern about sustainability is adding another layer of complexity to the architectural design. To deal with these complex problems more and more architects start to incorporate digital tools into their design process. Some of the advanced software used previously only by the computer specialists have become much more accessible to designers. As noticed by Phil Bernstein "Where the architectural design process in the pre-digital age was one of careful contemplation, limited calculation, experienced intuition and, ultimately judgement, today's designer can rely on an array of analytical, simulative and visualization tools that enhance understanding of an emergent design and predict its ultimate performance." (Peters and Peters 2018) As Computational tools are becoming increasingly popular among architects; it is necessary to understand how to use them in an efficient and considerate way.

However, there is a certain danger underlying the application of algorithms in architecture design. As Cristopher Alexander wrote already in 1964:

"The effort to state a problem in such a way that a computer can be used to solve it will distort your view of the problem. It will allow you to consider only those aspects of the problem which can be encoded and in many cases these are the most trivial and the least relevant aspects." - (Alexander, 1964*).*

For the last 60 years, computing power have been growing exponentially, yet the main issue with applying computers to architectural design has remained the same. In recent years, there has also been a growing concern about the impact of artificial intelligence on decision making processes. As many jobs are being digitalized and automatized, the sense of human agency becomes vaguer than ever. The potentials and pitfalls of the human-machine interaction in architectural design have been discussed by Paola Sturla in an interview entitled The Thinking Machine:

"*We need to question what we do in order to understand what AI can do for us. We don't want to be blown away by the tool. We want to control the tool, make choices, and be accountable, while being surprised by its generative output."* - (Paola Sturla in Harvard University Graduate School of Design, 2019)

Computational tools can help architects to rationalize and optimize their design decisions on the early stage of design. However, to use these tools responsibly we need to understand how they can influence our design process without compromising our goals. It is time to reflect on how the current technology should be used to respond to climate crisis of the 21st century.

The first part of this chapter introduces some concepts of general design theory. The second part reviews latest design approaches that emerged from the computational practice. In the following parts the fundamental aspects of parametric design process and performance-based approach are described as they constitute the conceptual framework for the case study. The last part presents a brief overview of the most popular computational tools, through comparison of different simulation and optimization software used by architects.

2.1. Design problems as wicked problems

In the article "Dilemmas in a General Theory of Planning, Rittel & Webber (1973) suggest that every planning activity (including architecture) is open and inconclusive by its very nature.

They point out that when the designer needs to deal with interacting open systems, there is no possibility of finding the optimal solution: "the problems that planners must deal with are wicked and incorrigible ones, for they defy efforts to delineate their boundaries and to identify their causes, and thus to expose their problematic nature." (Rittel and Webber, 1973).

This particular aspect highlights the significant difference between architectural design and other kinds of engineering problems. As the optimal solution for any design is essentially unattainable there is no straightforward way of approaching the problem. For that reason, one of the first and most important parts of the design process is the definition of goals that are expected to be reached with a solution. Besides clearly understanding the design goals, it is also necessary to know their evaluation criteria. According to Hitch: “We must learn to look at our objectives as critically and as professionally as we look at our models and our other inputs." (Hitch, 1960) Clear formulation of design objectives, helps designer to avoid arbitrary decisions and to evaluate the results of their design. It allows architect to choose between several design options depending on their alignment with the objectives. The process of arriving to the best option becomes an optimization process and can be described in mathematical terms. As Rittel and Webber stated in their article, the whole difficulty of “solving” the design problem lays not in the optimization of the design but setting up the objectives and constrains that defines the optimization problem (Rittel and Webber, 1973). Therefore, the architect’s decision about the project priorities is the most difficult part of the design process.

2.2. Computational design: Evolution and definition

Computational design is a general term describing various methods which utilize computational tools during the design process. The history of the computational design started around 1960s when the series of conferences and scientific projects led to the first application of computers to design process. Famous “Sketchpad” designed by Ivan Sutherland in 1963 was the earliest program using graphical user interface. It was an early prototype of Computer-Aided-Design (CAD) software. Another important event discussing advances in architectural field was the Boston Architectural Center Conference, “Architecture and the Computer” organized in 1964. The idea of applying the computer in creative architectural process was initially rejected by many prominent architects (like Walter Gropius or Christopher Alexander), although the use of computational tools was steadily increasing due to the need for automation of repetitive tasks (like drafting). (Terzidis, 2004 in Cateano et. al, 2020).
In 1972, the 1st International Congress on Performance was dedicated to newly emerged possibilities of building performance simulation. (Cateano et. al, 2020). Till 1990s application of computational tools among professionals was mostly limited to simple drafting tasks and did not involve conceptual stages. In the last two decades, thanks to the improved accessibility and integration of design software, digital tools started to be applied on various stages of the design process, improving both the creation and execution of architectural projects. Along with the growing popularity of computational design methods, different sub-categories started to emerge. The study conducted by Cateano (2020) proposes a comprehensive definition of computational design methods dividing it into three categories:

- Generative design – defines as an approach that uses algorithms to generate designs. The basic generative rules encoded in the design can lead to complex geometries and unexpected results.
- Algorithmic design – also uses algorithms but in this case the basic rules encoded in the script can be directly linked to described design result.
- Parametric design – defines an approach which uses the variable parameters to describe multiple sets of designs.

As the definitions are not mutually exclusive in many cases the design process can be described by each of the above. For each of these approaches, form-finding represent a core element of the process as it defines the geometry of the projects and other related aspects like materials, energy performance or fabrication possibilities. Computational design methods “enabled architects to enhance the design process, either by making it more efficient or by expanding its conceptual boundaries”. (Cateano et. al, 2020).

2.3 Parametric design process

In general terms "design process" can be described as a continuous series of decision-making activities that collectively shape the outcome. (Lee & Ostwald, 2020) In case of parametric design, the underlaying assumption is that the building form can be defined by establishing geometric relations between the elements which can be defined as numerical parameters. By attributing different values to different geometrical parameters, the building form (and other attributes) can be manipulated resulting in several alternative version of the project. This design method requires from the designer different cognitive approach then in case of traditional methods based on sketching or manual 3D modeling.
Instead of trying to visualize and capture the final building form, architect defines the rules of the geometry generation. The results of algorithmic definition can be then visualized and evaluated in 3D environment of the modeling program. The advantage of parametric design process is that designers can change and modify their design at any stage without the need of readjusting all the elements of the model (the geometrical relations between the elements remains the same). Another asset is that different design alternatives can be develop in parallel using the same definition. (Oxman 2017)
Thus, the exploration of big amount of design alternatives becomes much easier and faster.
Although it might seem that parametric design process might be restricting the creative freedom (associated usually with traditional sketching methods), the study lead by Lee and Ostwald (2020) showed that computational methods support the creative decision making and lead to original and unexpected results. "Computational design has emerged because it has the capacity to resolve multiple constraints and deal with extreme complexity of variables." (Castellano, 2011). For that reason, it offers a design methodology that fits better the complex nature of environmental problems.

2.4. Performance based approach

According to different sources people spend around 85% of their time in the indoor spaces (Finocchiaro & Lobaccaro, 2017). Considering the fact that most of our activities happens in the closed spaces, it is extremely important to provide the comfortable environment in our buildings. Performance based design is a contemporary architectural approach focused on satisfying certain comfort and efficiency requirements. The process of architectural design is driven by several performative objectives that the project is meant to deliver. Greg Foliente describes the performance-based design as "the practice of thinking and working in terms of ends rather than means, where designers are concerned with what a building or building product is required to do, rather than prescribing how it is to be constructed" (Peters and Peters 2018). Although the definition of the building performance can be understood in broader social and cultural categories, in most of the cases, it is related to measurable physical conditions occurring in the building system. The applicability of performance-based approach has been developing parallelly to advances in computational methods. Parametric design tools are particularly convenient in translating the architectural elements into empirically comprehensible systems. As the form of the building is defined by several numerical parameters it can be easily manipulated and optimize to reach the performative objective of the project. The use of computational tools in performance driven design brought several advantages for the architects. Environmental aspects of building design that were previously very difficult to evaluate, like comfort, material or energetic impact could be now incorporated into the design process. As highlighted by Finocchiaro and Lobaccaro (2017): “With the advent of parametric modeling tools, numerical equations developed for climate analysis and modeling buildings’ environmental performance could be used as generative algorithms for the architectural design of high performative buildings.” In the scope of bioclimatic approach parametric tools allows to simulate the effectiveness of several passive solutions. Integration of the design process and energetic optimization can reveal the potential of passive and energetically self-sufficient buildings. What is also interesting, this new design approach is challenging the existing aesthetic paradigms. As noticed by Oxman: “concepts such as parametric and performance-based design can be considered ‘form without formalism’ and promote ‘new ways of thinking about form and its generation’’.(Oxman 2010 in Peters and Peters 2018).

2.5. Building performance simulation tools

Energy consumption required for heating and cooling of the spaces is responsible for approximately 35% of the total operational emissions of CO2. The building construction phase adds another 11% of carbon emissions. (UN Environmental and International Energy Agency, 2017) (Pérez-Lombard et al., 2008). To minimize the impact of building industry on natural environment architects should understand and control energy needs of their project. In the recent year, the growing accessibility and speed of building performance simulation (BPS) tools allows professionals to estimate the building performance at the early stages of the design process. According to Szokolay (2012) the exchange of energy flows between the building and the environment can be calculated using different mathematical equations. Therefore, the concept of building simulation assumes that the knowledge about the real behavior of the building can be obtained by reproducing the physical conditions in digital model generated by computer. To describe the time-evolution of the building system the mathematical model is constructed from different theoretical principles based on mathematical equations and physical observations. “The model is transformed into a computable algorithm, and the computation of the equations over time is said to simulate the system under study.” (Peters and Peters 2018). In this way, by providing the data input to the simulation model designer can predict the behavior of the proposed project. By changing the parameters related to building material and geometry they can test multiple design options and get almost immediate feedback about the simulated performance. (Finocchiaro & Lobaccaro, 2017).

Application of BPS can lead to significant improvements in the architectural design process. As observed by Patrick MacLeamy, changes in project at the early stage of design are less costly and more impactful then on the later stages of the project. (Figure 16) Therefore, shifting the energy optimization efforts to the conceptual phase of design, can lead to much better results and minimize the costs associated with environmental improvements in construction phase.

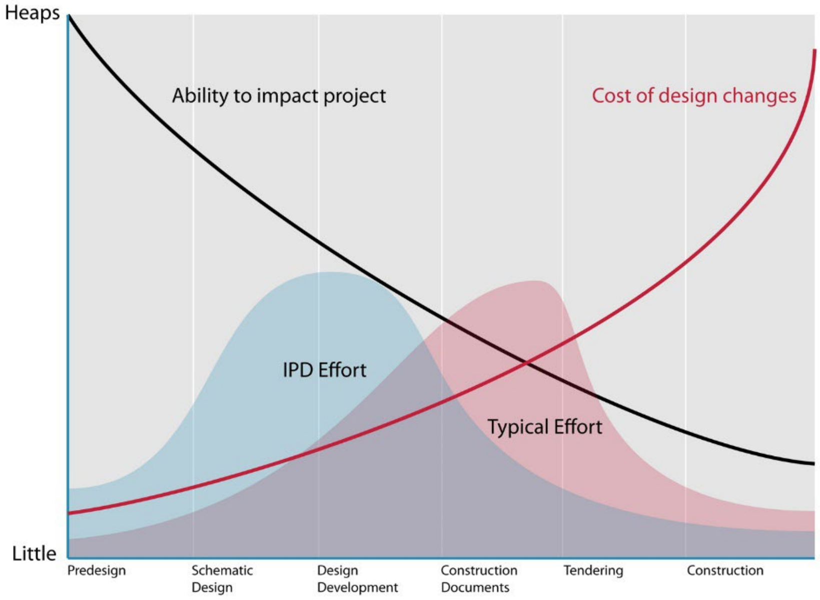


Figure 16 – MacLeamy curve. Relation of project phase to cost and impact of the design changes.

According to Jan Hensen, the main issue in application of BPS tools is that they are generally used in the final stage of building design and mostly for optimization of single design option instead of several alternatives. (Hensel 2013 in Peters and Peters 2018). Another obstacle to the usability of the simulation software in architecture is the fact that the engineering tools were often developed to perform only one specific type of analysis. While this specialized approach might be useful for solving concrete engineering problems, in case of the architectural design, multiple different factors needs to be evaluate at the same time. Several aspects of the project, like structural stability, energetic performance, thermal and visual comfort, or cost should be considered together. Instead of one specialized tools architects need a flexible toolset that could be adapted to different building scales and contexts. In the recent years, several tools allowing for the straightforward integration of building design and performance simulation have been developed. Some of the most popular tools have been presented below.

2.5.1. Ladybug tools

"Ladybug tools" consist of several plugins used for environmental analysis and energy simulation. The first plugin was developed by Mostapha Sadeghipour Roudsari in 2013 as an open-source plugin for Grashopper visual programming language. The software is compatible with Rhinoceros3D modelling software. The newest generation of the ladybug tools is divided into three plugins:

- Ladybug plugin provides the tools for analysis and visualization of climatic data.
- Honeybee plugin allows the construction of energy models that can be used for simulation of thermal (Honeybee-Energy) and daylight (Honeybee-Radiance) performance. The plugin runs the model data in separate simulation software (Energyplus or Radiance) and import the simulation results back to the Grasshopper environment. It allows for modelling of multiple thermal zones and customized geometries.
- Dragonfly plugin can be used for urban scale energy simulation. It also delivers the tools for renewable energy optimization and modeling of the urban heat island.
- Butterfly plugin runs the advanced computational fluid dynamic (CFD) simulations. It is used to perform precise analysis of the wind speeds and directions using OpenFOAM simulation engine.

The big advantage of the software is that all design components can be parametrize and customize using Grasshopper native components and several other plugins. "They ease the process of extracting an analysis model from the design model and are designed to support iterative processes. Users can set up fairly advance analysis models and iterate between dozens of possible combinations of input parameters without recreating the entire model. This is not only changing the approach to conventional building simulation but introducing new opportunities for integrated design analysis workflows." (Mostapha Sadeghipour Roudsari in Peters and Peters, 2018)

2.5.2. Climate Studio

Climate Studio is a commercial software for integrated energy and daylight simulation. The program is compatible with Rhinoceros3D and can be also connected with Grashopper plugin to perform parametric studies. Similarly, to Ladybug Tools, it uses the EnergyPlus and Radiance simulation engines for energy and daylight evaluation. The functionality of the software includes several simulations, e.g., energy efficiency, dynamic shading, electric lightning, spatial thermal comfort, natural ventilation and renewable energy. (Climate Studio 2022)

2.5.3. Insight 360

Insight 360 is a plugin for Autodesk Revit modeling software used for energy and daylight simulations. One of the main advantages of the program is that it allows to set up a simulation directly from the BIM model without a need to export or reconstruct the model. The tool can perform multiple types of simulations including energy, daylight, and solar potential. The program interface provides straightforward comparison of different design options that can be used for optimization of building design. The values of the physical parameters can be obtained from the Revit's library or assigned directly to BIM model. The tool can be used for concept massing studies as well as detailed building models. (Autodesk 2022)

2.6. Black box optimization tools

When the computational methods are used for architectural design, very often a vast amount of design solutions is generated. The simulated performance of different design options can vary significantly therefore, to find the best performing solutions, several optimization methods can be used. The goal of optimization is to find the architectural solutions which achieve the best results in terms of given evaluation criteria. In case of architectural optimization problems, the explicit formulation of the objective function is often unavailable, because of the unknown correlation between different buildings parameters (like geometry, physical properties of materials, climate, or other time-related variables). According to Wortman and Nannicini: "Architectural designers generate and evaluate design candidates employing simulations and other quantitative measures derived from a parametric model without specifying a closed-form mathematical expression that relates the model parameters to the fitness criterion." (Wortmann and Nannicini, 2016). To optimize these unknown functions architect can used the black box optimization methods. They allow the user to search for the best solutions without the prior knowledge about the relations between different parameters of the function. We can distinguish three different classes of black box optimization methods: metaheuristics, direct search, and model-based methods. (Wortmann and Nannicini, 2016)
Depending on the optimization problem and the number of design evaluations, the effectiveness of optimization method (and its specific algorithm) can vary significantly. Therefore, it is important for the designers to understand the strengths and deficiencies of different optimization methods.

The results of the survey published in the article "Simulation-based Optimization in Architecture and Building Engineering" showed that Rhino/Grasshopper is the most popular platform for computational design and optimization. (Wortmann et, al. 2022). In the following paragraphs three different plugins for Grasshopper has been described to give a brief overview about the optimization possibilities in architectural practise.

Galapagos

The plugin is one of the first optimization plugins developed by David Rutten in 2010.
It is available as a default component in Grasshopper plugin and according to the research it is still the most frequently used software for architectural optimization. (Wortmann et, al. 2022)
The plugin offers two metaheuristic optimization methods for single objective optimization: simulated annealing algorithm and genetic algorithm. The interface of the optimization solver is simple and easy to learn. Most of the optimization parameters (so called hyperparameters) are predefined and allows for quick set up of the optimization process which can be beneficial for unexperienced users. (Rutten 2013)

Opposum

Opposum plugin supports the single objective and multiobjective optimizations including different metaheuristic as well as model-based methods. The advantage of the plugin is that it offers multiple algorithms which can be used for solving varied optimization problems. It also allows for customization of many hyperparameters, therefore it is useful for more advanced users.

Wallacei X

Wallacei X allows to perform mutiobjective optimization with the popular genetic algorithm NSGA-II. (Deb, et al. 2002). Besides running the optimization process, the plugin includes several tools for the output data analysis. It also provides the tools for quick data visualization including the graphic representation of Pareto fronts, diamond charts and fitness value graphs. The advantage of the plugin is the user-friendly interface and the integration of different data analysis and visualization components into one software.

Digital tools presented in this chapter reinforce the integration between different engineering fields and design phases. The conceptual design, energy analysis and optimization process influence each other and through continuous feedback loop, lead to the data driven architecture. According to Roudsari the future developments in BPS will be focused on improving the usability of the software. As he says: “It is now much easier to set up analysis models, which in turn makes it easier to generate more results, and subsequently move from data scarcity to data overload. As a result of this shift, there is a critical need for supporting tools for data analysis and visualisation in order to help designers and engineers with making design decisions”. (Mostapha Sadeghipour Roudsari in Peters and Peters 2018)

CHAPTER 3

Framework

3.1. Literature review: Previous studies

A big part of the research involving the energy and comfort simulation analysis is focused on office and large-scale buildings. The formal expression of this type of buildings is often driven by economic factors, optimization of building costs or compliance with certain building standards. As these parameters are easily quantifiable the optimization tools can be successfully applied to improve the design solution. Other types of buildings like public facilities or private houses often requires from the architect to consider other “soft” parameters which are more difficult to define in mathematical terms. Therefore, it is often less clear why the architects should apply computational processes to design of these buildings. The following case studies shows different ways of applying computational workflows to various types of design problems.

In the study featuring an existing building of architecture school in Oporto (Caldas et al., 2001) tested a generative system for the optimization of the energy consumption. The generation of the façade was constrained by the rules respecting the initial composition of the windows. The system allowed for the exploration of different window sizes without losing the characteristics of the architect’s original design. The objective of the optimization was to minimize the annual energy consumption through the manipulation of the window and shade parameters. The model was tested in 3 different climatic zone to check the differences in façade behavior. The most efficient configuration achieved 10% lower annual energy consumption.

In their study of the office building, (Konis et al., 2016) proposed and tested the application of a Passive Performance Optimization Framework. The building geometry was generated by defining the building footprint correlated with the total floor area of the building. The final volumetry of the building was achieved by extruding the footprint to reach the desired number of floors. After the main volumetry was formed, the script created different sizes of window openings depending on defined WWR. Other control parameters defined the building’s orientation (by rotating it) and the envelope construction materials. The resulting model could be described by 19 different parameters defining the final geometry. This comprehensive amount of geometry variations allowed for the exploration of many different building options. The optimization of the building performance included two conflicting objectives, namely energy use intensity and useful daylight illuminance. A multi-objective optimization software (Octopus) was used to find Pareto optimal solution. It is worth noticing that the improved performance was achieved mostly by the application of passive strategies related to the geometry of the building such as correct proportions and orientation of volumetry, distribution of the openings and shading.

On the contrary, a study conducted by Toutou et al. (2018) focused mainly on the optimization of building materials and window shading. Their study was conducted on a multifamily housing unit located in the hot arid zone of Cairo. The optimization parameter included different glass and wall materials as well as sizing and orientation of the windows and the dimension of shading devices. The workflow introduced in the study is an easy-to-follow example of multizone building optimization. It highlights the importance of exploring different material solutions as a way of improving the thermal performance.

Research led by Giuffrida et al. (2021) focused on the optimization of rammed earth building performance. The authors studied how the application of different passive strategies such as night-time cross ventilation and shading can improve the thermal comfort inside the building. In the second part of the study, the authors optimized the thermal performance of the building model by exploring different types of insulation. The study proved that the application of rammed earth combined with passive strategies and organic insulation materials can significantly improve the thermal comfort and reduce the energy loads of the building.

The summary of the case studies analysis is presented in Table 1 in the Annex. It shows that building performance optimization can be useful in a variety of scales and contexts. As it can be seen, different design problems require different formulation. The role of the architect is to discover the nature of a specific problem and a way of solving it. In the context of computational design, it means that the definition of the parameters and constraints is a crucial part of the creative process. The main difficulty is to find a balance between the amount and the relevance of possible design alternatives. Also, the developed design framework needs to be flexible enough to accommodate different use cases

3.1. Bioclimatic Optimization Framework proposal

The objective of the proposed framework is to integrate the use of computational tools into the bioclimatic design process.

The developed scheme is intended to be flexible enough to accommodate different use cases, but also to be easy-to-follow and easy-to-implement. It brings the main principles and parameters of bioclimatic architecture and situates them as part of a computational design workflow. The main computational tool used in the framework was Grasshopper plugin for Rhinoceros 7, as it integrates different simulation and optimization tools into one integrated process. The graphic visible in Figure 17 (see also in the Annex) represents the relations between the different stages and the elements of the developed framework and indicates the tools used for streamlining the design process.

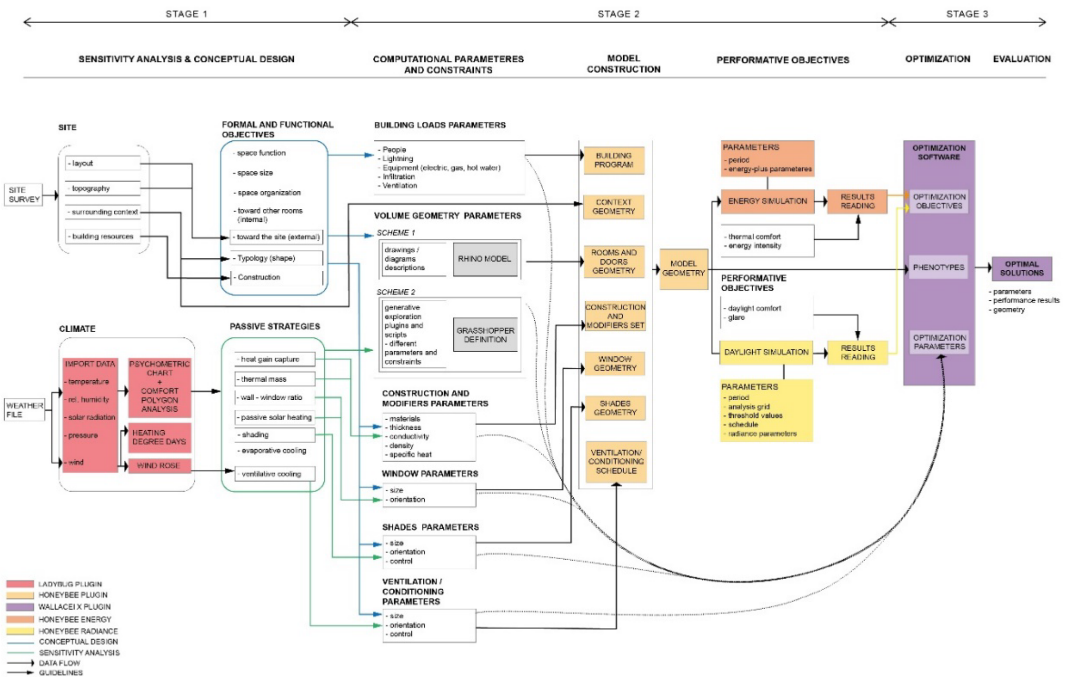


Figure 17 – Bioclimatic optimization framework graph (source: work of the author)

3.1.1. Stage 1: Sensitivity analysis and Conceptual design

The first part of this stage is the analysis of the building site and its climatic context. The sensitivity analysis should be performed to recognize the main conditions underlaying the design process. The following aspects should be analyzed:

I. Potentials and limitations of the site:

- site layout (size, orientation, regulations)
- topography (flat, inclined)
- surrounding context (characteristic elements of landscape, local building traditions, common building typologies)
- building resources (local or industrialized materials)

II. Climate analysis

- analysis of psychometric chart (climatic conditions in relation to comfort)
- analysis of passive strategies and comfort polygons (potential of passive strategies in relation to the thermal comfort)
- analysis of wind speeds and directions
- heating/cooling degree days (requirements for heating and cooling)

Information about the site should be collected from surveys and on-site visits. It is also important to conduct research on the traditional local (vernacular) architecture of the place to understand the potentially different material and adaptation strategies. Climate data can be downloaded from the online database of the nearest weather station point. Ladybug plugin allows for importing the weather files in EPW format through one of its native components. They can be also download through a dedicated software such as Meteonorm (Meteonorm, 2022). It is important to verify the year of data collection to make sure they represent the current climatic conditions of the place.

The second part of this stage is related to conceptual design. It consists of defining the formal and functional objectives of the project. Conceptual design should naturally consider the potentials and limitations of the site analyzed in the previous paragraph. The following elements should be considered:

I. Formal and functional objectives

- room function
- room size
- room organization
  - internal (towards other rooms)
  - external (towards the site)
- typology (shape)
- construction (system)

Conceptual design is a fundamental part of the design process defining the main direction of the project. The definition of very precise objectives might restrict the exploratory potential of iterative processes. For example, by allowing only one specific configuration of the building layout, we exclude all other possible layouts from being evaluated and optimized. At the same time, by defining objectives in a more rigorous way, architects can achieve greater control over the design process. Constraining design objectives can make the project more intentional. It prevents generating many irrelevant design options.

3.1.2 Stage 2A: Defining computational parameters and constrains

The second stage of the framework focuses on translating the conceptual design objectives to computational design parameters. The general idea is to use the information about useful bioclimatic strategies for the definition of the parametric domain. Model parameters should be set in way that represents the use of a given passive strategy or construction type. This includes both geometric and physical parameters. It is crucial to limit the problem search space by constraining parameter values. As mentioned by Konis et al. (2016), a "significant number of unrealistic outcomes can be avoided in the optimization process through making appropriate assumptions when initializing the optimization parameters".

The definition of computational parameters and constraints includes:

- Volume geometry parameters
    - Scheme 1
      -definition of geometry through drawings, diagrams or other conventional methods which can be later translated into Rhino 3D model.
    - Scheme 2
      -definition of geometry through different parameters and constrains encoded in generative plugins and scripts which later can be translated into Grasshopper definition.
- Window geometry parameters
  -Dimensions
  -Orientation
  -Control type and schedule
- Shade geometry parameters
  -Dimensions
  -Orientation
  -Control type and schedule
- Construction and modifiers parameters
  - Material
  - Layer order
  - Thickness
  - Conductivity
  - Density
  - Specific heat capacity
  - Transmittance
  - Reflectance

- Ventilation and Air conditioning parameters
  - Mode (natural, mechanical, mixed)
  - Heating/cooling setpoints
  - Window schedules

- Building loads parameters
  - People
  - Lightning
  - Equipment (Electric, Gas Hot water)
  - Infiltration
  - Ventilation

All these parameters have an influence on the form or comfort performance of the building. At this stage the designer should synthesize previously defined objectives and bioclimatic strategies evaluated with psychometric chart. It is up to the architect's decision which of the parameters should be set as variables in the generative process and which should remain constant. This stage of the design process can be called divergent as it produces various design options that can be later evaluated by the model. In Grasshopper environment, the variable parameters are represented by sliders or value lists.

The second part of this stage consist of translating the geometry into a simulation model.

The parameters and the properties described previously can be assigned to a simulation model thanks to the Honeybee plugin. After connecting different elements together, the final model can be exported to EnergyPlus and Radiance engines to evaluate its performance. It is important to notice that the more complex the geometry is, the longer the simulation time will be. In some cases, the geometry needs to be simplified to minimize the simulation time.

The passive building simulation model should include following elements:

- Rooms and doors geometry
- Windows geometry
- Shades geometry
- Context geometry
- Ventilation/Conditioning Schedule
- Construction and Modifiers Set
- Building program

It is worth noting that the program allows for assigning different parameters to separate rooms or even single geometries which offers broad customization possibilities.

3.1.3. Stage 2B: Defining performative objectives

This stage of the framework defines what will be the goal of optimization process. In the presented research the focus is put on two fundamental aspects of architecture: comfort and sustainability. Two main aspects of comfort are considered:

Thermal comfort – can be defined as the environmental conditions perceived by subjective human mind as satisfactory (in terms of bodily sensation). (ASHREA, 2022)

Visual comfort – can be defined as the light conditions perceived by subjective human mind as satisfactory for specific type of activity, in specific place and time.

Although there are different definitions of thermal and visual comfort, and none of them can fully describe the diversity of conditions, comfort standards are useful tool for establishing the evaluation criteria for architectural design.

In terms of sustainability, the focus is put on the operative energy consumption as it has significant impact on climate change and natural resources depletion. Among different ways of assessing energy consumption one of the most useful measures is the energy use intensity.

In the specific case of comfort and energy performance optimization, the following objectives can be defined:

I. Energy simulation
   - minimization of EUI (energy use intensity)
   - minimization of heating/cooling loads
   - maximization of thermal comfort
     - PMV (predicted mean vote)
     - UTCI (universal thermal climate index)
     - Adaptive comfort

II. Daylight simulation
   - maximization of DA (daylight autonomy)
   - maximization of UDI (useful daylight illuminance)
   - maximization of GA (glare autonomy)

The definition of the performative objectives is necessary to set the criteria upon which building performance is evaluated. The designer should have some notion of what kind of the optimization will be performed (thermal comfort, daylight, energy etc.) to set up relevant parameters in the previous stage. In this sense, the development of computational parameters and performative objectives should be simultaneous. To give an example, if the optimization is considering only daylight performance, the thermal properties of materials do not need to be accounted for. Another important aspect worth consideration before setting our performative objectives is to understand if our objective functions are conflicting with each other or not. In case they are correlated (for ex. daylight and energy consumption) there might be no need to set them as separate objectives because the results are going to show similar behavior. In case of conflicting objectives (for ex. daylight and energy consumption) the optimization process shows the performance trade-offs between different design solutions, which can be useful information for choosing the right option. Besides defining the performative objectives, it is also important to define simulation parameters. They serve as an instruction for simulation engines, prescribing the level of details and computational resources. In result, they determine the accuracy and time of the simulation. Depending on the simulation type the main parameters include:

I. Energy simulation parameters
   - Period
   - Openstudio/EnergyPlus parameters

II. Daylight simulation parameters

- Period
- Analysis grid
- Threshold values
- Schedule
- Radiance Parameters

Setting up the simulation parameters is done through Honeybee-Energy and Honeybee-Radiance plugins.

After the definition of the performative objectives and simulation parameters, simulation model can be evaluated, and the results can be red through dedicated component.

3.1.4. Stage 3A Optimization

During the optimization stage various iterations of the parametric model can be compared, with a goal of finding the one which performs the best. To evaluate various design solutions with different objective functions the method of multi-objective evolutionary optimization is used. This stage of the design process can be described as convergent, as it allows to identify some of the best performing design solutions from the total search space defined in the previous stage. The optimization is being performed with the Wallacei X plugin. The functionality of the plugin has been already described in the previous chapter. Before running the optimization, the following parameters need to be defined:

- Population size:
- number of generations
- number of individuals per generation
- Crossover probability
  (percentage of solutions in the generation that will reproduce for the next generation) (Makki et al., 2019)
- Mutation probability
  (percentage of mutations taking place in the generation (Makki et al., 2019)
- Crossover and Mutation Distribution index
  (large distribution index value gives a higher probability for creating offspring near parent solutions and a small distribution index value allows distant solutions to be selected as children solutions.) (Makki et al., 2019)
- Random seed

Depending on the type of optimization problems, different parameter values should be set to achieve a fast and efficient convergence of design options.
The successful optimization of the multi-criteria problems should result in establishing the Pareto front with the optimal solutions.

3.1.5. Stage 3B Evaluation of the results

The last stage of the framework is dedicated to the evaluation of the optimization results.

The data results from the Wallacei X plugin can be red with the dedicated Wallacei Analytics component or exported to other software. The selected best solutions can be exported and associated with the input model geometry. By comparing the geometry parameters with the resulting phenotype, it is possible to draw conclusions about the influence of certain solutions on the energy and comfort performance of the building. The optimization process is not only a method of selecting the best design option but also a research tool allowing to understand interdependencies between the form and the performance. A great advantage of this approach is that it re-establishes the position of the architectural practice. Architectural design becomes not only one of the steps of building production but also scientific research with a potential of generating knowledge and technological innovation.

CHAPTER 4

Case study – House in Montemor-o-Novo

The presented analysis of the case study is divided into two parts. The first one describes the existing project of the house and focuses on understanding the main decisions undertaken during the design process. The main characteristics of the reference project are identified to used them later as the conceptual design guidelines in the second study. After that, the comfort and energy parameters of the building are evaluated to verify its performance.

In the second study, the same design problem (single family house project) is being optimized by applying the bioclimatic optimization framework described in the previous chapter.

By applying the proposed methodology to a real-life use case, it is possible to illustrate its practical value. The aim of the study is to verify the building performance achieved through a "conventional" design process and compare it with the results of a computational one. However, the underlying goal is that the generative design process does not compromise the architectural value of the project nor the original intention of the architect.

4.1. Study 1 – Analysis of the reference project

The case study analyzed in the scope of the research is a project of a single-family house located in Montemor-o-Novo in Portugal. The preliminary design of the house was developed by architectural studio Atelier dos Remedios, led by prof. Francisco Teixeira Bastos and Madalena Cardoso De Menezes. The project was developed for a private client at the beginning of the year 2021. It was chosen as a case study because it represents a contemporary housing project inspired by local building tradition and rural context. The architects apply several bioclimatic strategies to improve the comfort of the house. The project shows the preliminary design of the building; therefore, it can be compared with the proposed framework, focusing on the initial design phase. It was also possible to interview the author of the project to understand the main design decisions and site constrains. A personal insight into the design process was necessary to understand not only the result but also the different alternatives considered along the way.

4.1.1. Site and Climate

The project is located on the outskirts of Montemor-o-Novo in the Central Alentejo region. It is surrounded mostly by a rural landscape with a few detached houses scattered along the road. The terrain of the plot has a slight inclination toward the middle part. The hill in the middle offers a good view towards Montemor's castle. On the site, there are two pre-existing ruined buildings from which the bigger is meant to be demolished to free the space for the new house. The smaller preexisting agricultural unit needs to be preserved to not exceed the maximum building footprint for the new construction. The area for the new building is also constrained by the offset limit of the plot (25m into the plot). The site plan of the project with the summary of the footprint areas can be found in Figure 18.

Figure 18 – Site plan survey (source: Atelier dos Remedios)

The climate of the location can be described as Mediterranean temperate (Csa in the Köppen classification - Figure 19), hot and dry during the summer. Maximum temperatures in the summer are very high. During the months of July and August they can reach between 35ºC and 40ºC. In the inland part of Alentejo, the average rainfall is around 500 mm and varies greatly from year to year.

Figure 19 - Climate zones in Portugal (source: Wikipedia, 2022e)

4.1.2. Form and Function

The building was designed as a single-family house with a total footprint area of 162 m2. The typology of the building can be described as a courtyard house. The main building consists of 3 connected longitudinal wings oriented towards east, north, and west. A preexisting agricultural unit encloses the space from the south, creating an irregularly shaped courtyard. The layout of the building was developed in a way to allow clear separation of functions. The eastern and northern wing consist of the main living spaces (living room and kitchen) connected by the entrance corridor to the dormitory wing. The western wing features the master bedroom with a private bathroom and two guest rooms sharing another bathroom located between them. The functional layout of the project can be consulted in Figure 20.

Figure 20 – Functional layout of the project (source: Atelier dos Remedios)

During the design process, several objectives influenced the resulting configuration of the spaces. They will be analyzed in detail in the further part of the case study. In general terms, it seems that the two most important decisions which defined the design were:

1) introducing the central enclosed space (the patio)
2) orienting the living space to the east to capture the panoramic view on the castle

Besides that, the architect intended to harmonize the building volumes with the landscape by referring to traditional slopped roof structures popular in the Alentejo region. In terms of materials and constructive solutions, the architect proposed two alternative systems. The first one consists of the lightweight insulated wooden frame construction put on the reinforced concrete foundation. The second one represents a typical masonry system made with thermal ceramic bricks and an external insulation layer. Both solutions have the same exterior finishing made from white coating mortar for the wall and ceramic tile for the roof. By selecting these materials, the architect links the project's aesthetics with the building tradition of Alentejo. Figure 20 shows the Revit model axonometry and the resulting simulation model exported to Rhino 7 viewport.

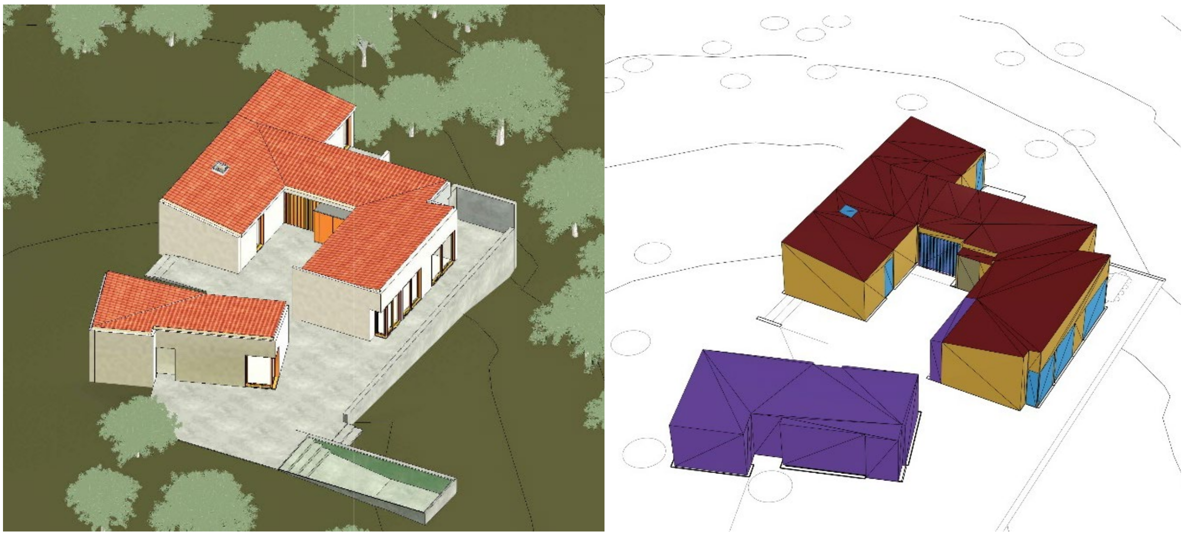


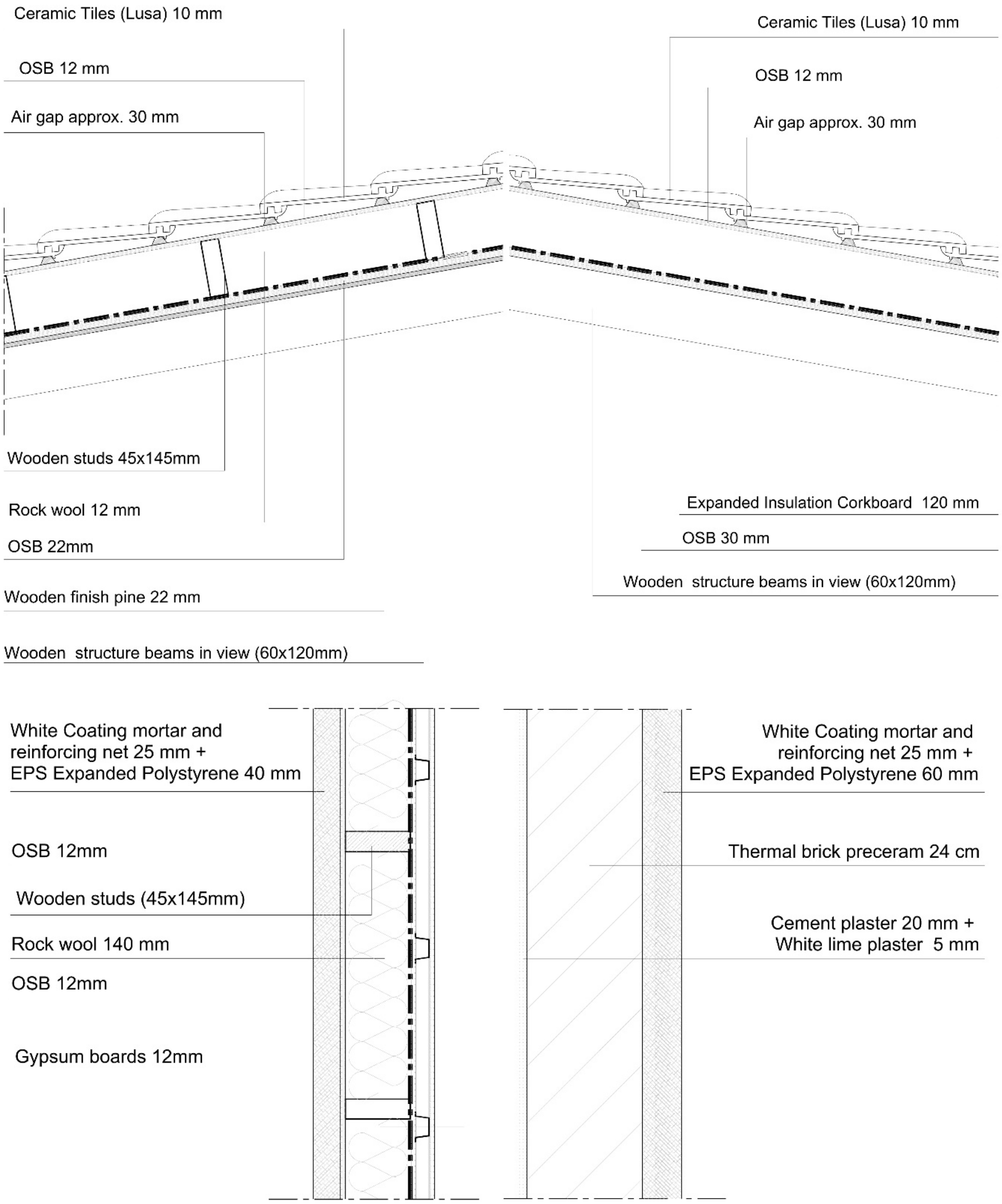
Figure 21 – Axonometric view of the project in Revit viewport and exported Honeybee model in Rhino 7 (adapted from: Atelier dos Remedios)

It is worth mentioning that several solutions applied in the project are explicitly bioclimatic. The organization of the building as elongated wings increases the potential for the cross-ventilation of the rooms. The internal courtyard is also a typical vernacular strategy to create a comfortable microclimate in front of the building. The general proportions of the windows are roughly respecting the recommended ratios for west and northern direction in the hot climates. The glazing of the west side of the dormitory volume covers 15% of the wall surface which is a good strategy to avoid overheating. The larger windows in the western side of the living room are recessed from the wall and are protected by an overhang. The potential disadvantage for the thermal performance of the building is the large, glazed area (WWR around 50%) of the eastern wall of the living room. To protect it from glare and overheating, shading strategies should be applied.

In the next chapter, the comfort and energy performance of the project is tested to define the reference comfort values and the energy consumption of the building.

4.1.3. Performance analysis

The performance analysis of the project was executed using a similar workflow as the one described in the second stage of the bioclimatic optimization framework. The building geometry, programs and physical properties were assigned to the simulation model with the use of the Honeybee plugin. The original project geometry was first exported from the Revit model to Rhino 7 software using the Pollination plugin for Revit. The geometry was then assigned to the Grasshopper script as separate categories of room volumes, doors, windows, shades, and context. These elements were later connected to the respective categories of the Honeybee simulation model. In terms of construction, two alternative options established by the architect were evaluated. The first one represents a lightweight wooden frame constructive system and the second one shows a thermal brick masonry construction. The detailed drawings of the construction layers can be found in the figure 22.



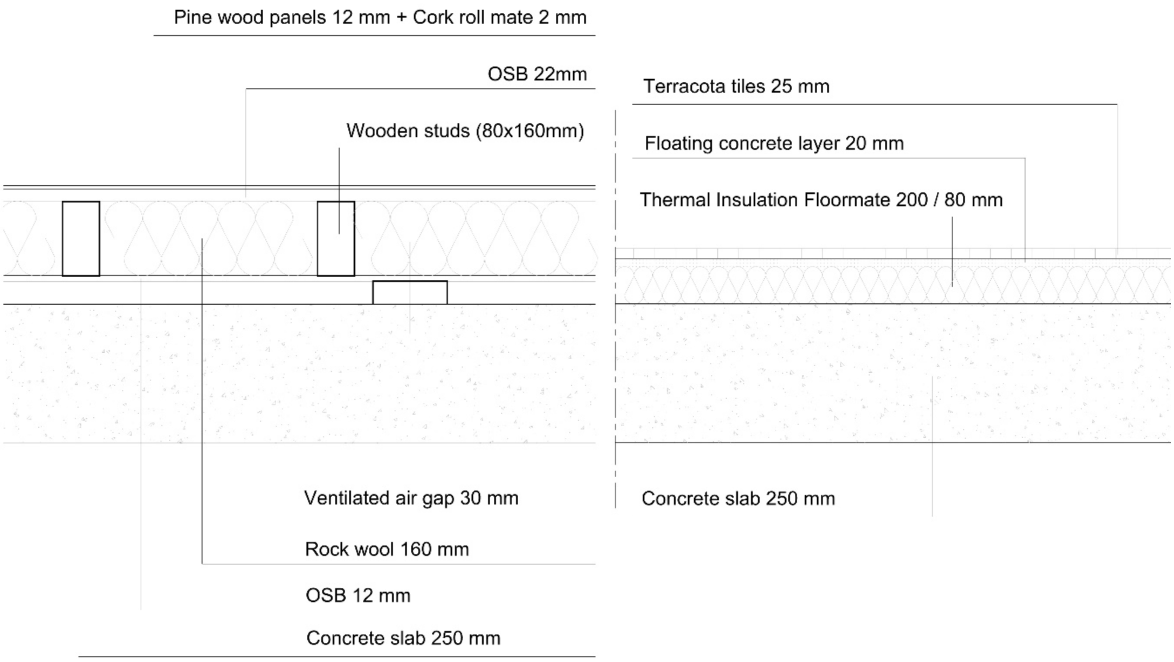


Figure 22 – Details of constructive solutions 1 and 2 (adapted from: Atelier dos Remedios)

To represent them in the simulation model following solutions have been attributed to the model geometry:

I. Wooden frame construction
   - Roof - Wooden beams with rock wool insulation (14 cm thick) between the beams, ceramic tiles on the exterior and wooden finish in the interior.
   - External walls - Wooden posts with rock wool insulation (14 cm thick) between the posts, external insulation made of 4 cm expanded polystyrene, white coating mortar finish on the exterior, gypsum board finish in the interior.
   - Internal walls - Hollow metal frame system (10 cm thick) covered with gypsum board
   - Floor - Concrete foundation slab (25 cm thick), wooden frame floor with 160 mm rock wool insulation (elevated 3 cm above the concrete slab), cork roll mate insulation 2 mm, pine wooden panels for flooring

II. Thermal brick masonry construction
   - Roof - Supported on wooden beams, expanded corkboard insulation (12 cm thick) above the beams, ceramic tiles on the exterior
   - External walls - Thermal brick (24 cm thick), external insulation made of 6 cm expanded polystyrene, white coating mortar finish on the exterior, white lime plaster finish in the interior.
   - Internal walls - Made of lightweight aerated blocks 120 cm with white lime plaster finish
   - Floor - Concrete foundation slab (25 cm thick), thermal insulation layer (8 cm thick), leveling concrete layer, terracotta tiles for flooring

The exact list of the material layers and their physical properties assigned to the simulation model can be found in Table 3 in the Annex. Besides the thermal characteristics, light reflectance values have been assigned by applying modifiers to the rooms in the Honeybee model. The reflectance values can be consulted in Table 4 in the Annex. After attributing the material properties to the model, the building program was defined to account for the typical house energy usage and internal loads generated throughout the year. The midrise apartment program available in the default honeybee library was assumed as the most adequate for the purpose of the analysis. The only parameter of the building program that was adjusted considers the infiltration values. As the building is a new construction it is expected that the high airtightness standards will be obtained, therefore the infiltration value was lowered to represent a highly airtight building.

Two alternative construction types were evaluated considering different ventilation and air conditioning scenarios. The first scenario assumes, that the building doesn't use any air conditioning or heating system. It represents a completely passive behavior of the building, where the temperature is regulated only through the opening and closing of the windows. With this assumption, the model simulates the opening and closing of the windows under certain temperature conditions. The other scenarios include a mixed mode conditioning of the building. They assume that under certain conditions the building is ventilated by operable windows and when the outdoor temperature is too hot or too cold the mechanical air conditioning system is turned on. In these scenarios, an Ideal Air system for cooling and heating was used to simplify the procedure. As the definition of the setpoints values has a considerable influence on the comfort and energy consumption results, several different options of heating and cooling setpoints have been tested. Table 5 shows all the evaluated combination of construction types and conditioning scenarios.

Table 5 – Matrix of simulated scenarios

	Scenario 1 Unconditioned natural ventilation	**Scenario 2 Mix Conditioned**	**Scenario 3 Mix Conditioned**	**Scenario 4 Mix Conditioned**
Construction 1	window setpoints: min indoor 18 max. indoor 27 min outdoor 16 max outdoor 28 **x** wooden frame	setpoints: heating 18 cooling 25 window setpoints: min indoor 20 max indoor 24 min outdoor 18 max outdoor 25 **x** wooden frame	setpoints: heating 20 cooling 25 window setpoints: min indoor 22 max indoor 24 min outdoor 20 max outdoor 25 **x** wooden frame	setpoints: heating 20 cooling 28 window setpoints: min indoor 22 max indoor 27 min outdoor 20 max outdoor 28 **x** wooden frame
Construction 2	window setpoints: min indoor 18 max. indoor 27 min outdoor 16 max outdoor 28 **x** thermal brick	setpoints: heating 18 cooling 25 window setpoints: min indoor 20 max indoor 24 min outdoor 18 max outdoor 25 **x** thermal brick	setpoints: heating 20 cooling 25 window setpoints: min indoor 22 max indoor 24 min outdoor 20 max outdoor 25 **x** thermal brick	setpoints: heating 20 cooling 28 window setpoints: min indoor 22 max indoor 27 min outdoor 20 max outdoor 28 **x** thermal brick

To evaluate the comfort and energy efficiency of the building, three different criteria were evaluated: Useful daylight illuminance (UDI), Adaptive comfort and Energy use intensity (EUI).

UDI was used as a measure of visual comfort in the living room and bedrooms as they constitute the most frequently used areas. Adaptive comfort was chosen as the measure of thermal comfort as it considers the gradual human adaptation to the climatic conditions. In comparison with the other comfort measures like PMV or PPD, it is more realistic in accounting for occupant-controlled and naturally ventilated buildings. (Guedes, 2009; Fernandes et al., 2019) EUI was chosen as the energy efficiency parameter, as it relates the total energy consumption (in KWh) to the building floor area, which is useful for the comparison of different buildings.

Simulations of the daylight and energy performance were run for the period of the full year evaluating every hour of the year (1 timestep per hour). The daylight simulation schedule was set as default (considering the hours between 8am and 5pm on weekdays). Although there is no scientific consensus about the standard values of the UDI parameters, Velux recommends a minimum value of 200 lux for residential rooms. (Velux, 2022)

Considering the upper limit, illuminance levels higher than 2000 lx are likely to produce visual or thermal discomfort. (Nabil & Mardaljevic, 2006) Therefore, the threshold parameters of the UDI considered as comfortable were set between 200-2000 lux. The Adaptive comfort parameters were defined according to the ASHRAE 55 standards for unconditioned buildings. Although the adaptive comfort measure shouldn't be applied to fully conditioned buildings, for the purpose of this study it was used to compare an unconditioned and mix-mode conditioned building. The Adaptive comfort performance criteria was defined as the percentage of time during the year when the thermal status of the subject is neutral (according to the adaptive criteria parameters). A detailed list of the simulation parameters can be consulted in Table 6 below.

Table 6 – Simulation parameters

Parameters	Energy simulation	Parameters	Daylight simulation
Period	Whole year	Period	Whole year
Timestep	1 per hour	Timestep	1 per hour
Terrain	Country	Analysis grid size	1 m
Shadow calculation	1-Full Exterior	Analysis grid floor distance	0.7 m
Calculation method	Polygon Clipping	UDI Threshold	200-2000 lux
Update method	Periodic	Schedule	08:00 – 17:00 weekdays (generic)
Frequency	-30	Radiance detail level	1 - medium
Max figures	-15000	Radiance additional parameters	(generic)
Sizing	DDY form EPW		

4.1.3. Results Evaluation

After performing the simulations for different conditioning scenarios (according to Table 5), two different construction types can be compared. Table 7 presents the simulation results for three analyzed objectives.

Table 7 – Performance results for Study 1

	Scenario 1 Unconditioned natural ventilation	Scenario 2 Mix Conditioned	Scenario 3 Mix Conditioned	Scenario 4 Mix Conditioned
	Adaptive comfort % / UDI % / EUI kWh/m2	Adaptive comfort % / UDI % / EUI kwh/m2	Adaptive comfort % / UDI % / EUI kWh/m2	Adaptive comfort % / UDI % / EUI kWh/m2
Building Construction 1	50.6 / 81.2 / 74.2	83 / 81.2 / 144.7	94 / 81.2 / 150.2	59.8 / 81.2 / 128.2
Building Construction 2	52.9 / 81.2 / 74.2	79.2 / 81.2 / 140.2	97.4 / 81.2 / 152.3	64.9 / 81.2 /125.8

Regarding the daylight, the reference building achieved the result of 81% comfort throughout the year (UDI threshold defined as 200-2000 lux). As it can be seen on the UDI map presented in Figure 22, most of the rooms are compliant with the UDI range for most part of the year.

Figure 23 – UDI map of the results (source: work of the author)

The lowest percentage of the useful illuminance can be found in the living room close to the window areas. This effect occurs as the big eastern windows are not protected by any kind of shading device resulting in too high level of illuminance (above 2000 lux). The overall visual comfort could be improved by adding internal or external shading protection to large window areas.

Regarding the thermal performance of the building, the different conditioning scenarios resulted in different comfort and energy intensity values. In case of the unconditioned building, both types of constructions meet the thermal comfort criteria for around 50% of time. Construction Set 1 was performing slightly better than Construction Set 2, nevertheless the obtained values are not enough to consider a fully passive functioning of the building. The hourly comfort charts for the living room space for both constructions can be seen in the figure 24. The results show that during the summer period the building is largely overheated. Wooden frame construction performs slightly better in the winter period due to the lower heat losses, however in the summer, the low thermal transmittance of the insulated walls results in the higher temperatures of the interior.

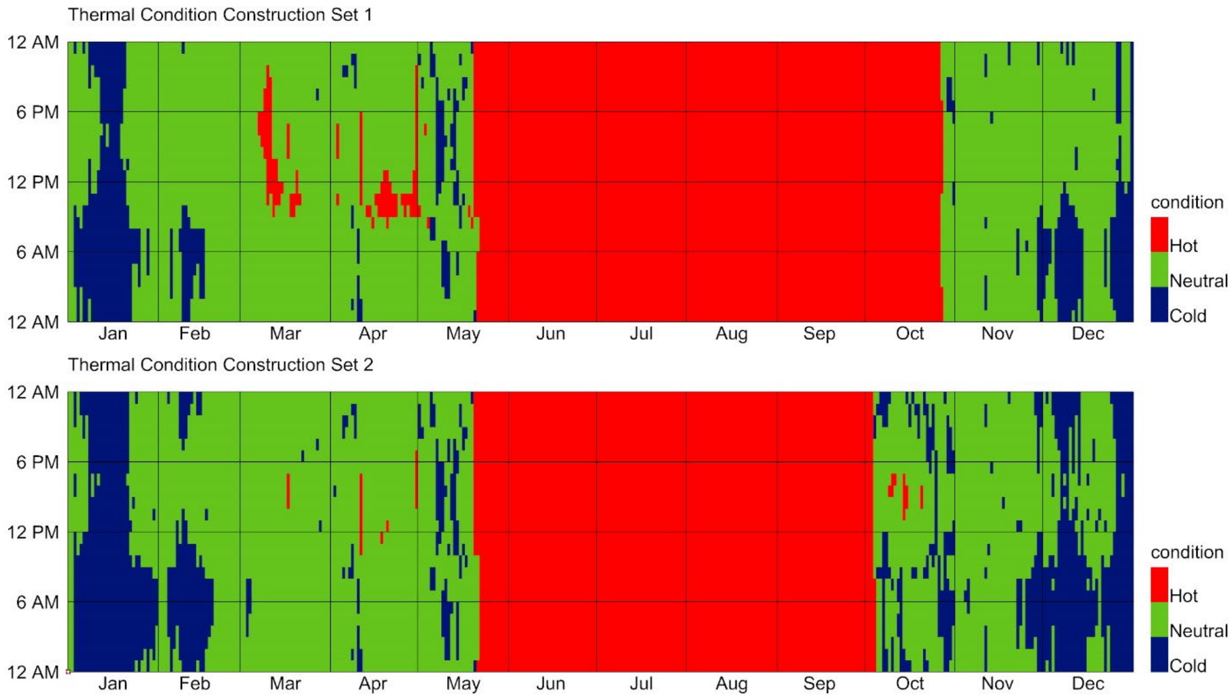


Figure 24 – Adaptive comfort results of the living room, Construction set 1 and 2 (Unconditioned) (source: work of the author)

The energy consumption for these scenarios was accounting only for lightning and equipment loads, as there were no heating or cooling systems turned on. The energy intensity value was equal to 74.2 KWh/m2.

The three remaining conditioning scenarios achieved higher values of thermal comfort. In the second scenario, comfort standards were met around 80% of time and the EUI was around 140 kWh/m2. The further analysis of the scenario showed that thermal discomfort was perceived mainly due to the too cold conditions during the winter months (13% of the time for Construction set 1 and 19 % of the time for Construction set 2). Therefore, in the next scenarios the heating setpoints were raised from 18 ºC to 20 ºC to provide more comfortable conditions in the colder period.

The third scenario with the standard setpoint values (20ºC for heating and 25 ºC for cooling) achieved a high percentage of comfortable time. Construction Set 1 was comfortable for 97.4 % of time and Construction Set 2 performed only slightly worse. This heating scenario was the only one that could be realistically considered for the building operation as it didn't compromise the occupants' thermal comfort. The EUI of the building was estimated for around 150 KWh/m2. To analyze the most significant energy loads for this scenario, an energy balance chart was constructed using the Honeybee-Energy plugin. It is showing the monthly distribution of the respective energy loads in the building. As it can be seen in Figure 25, both construction types exhibit a similar behavior.

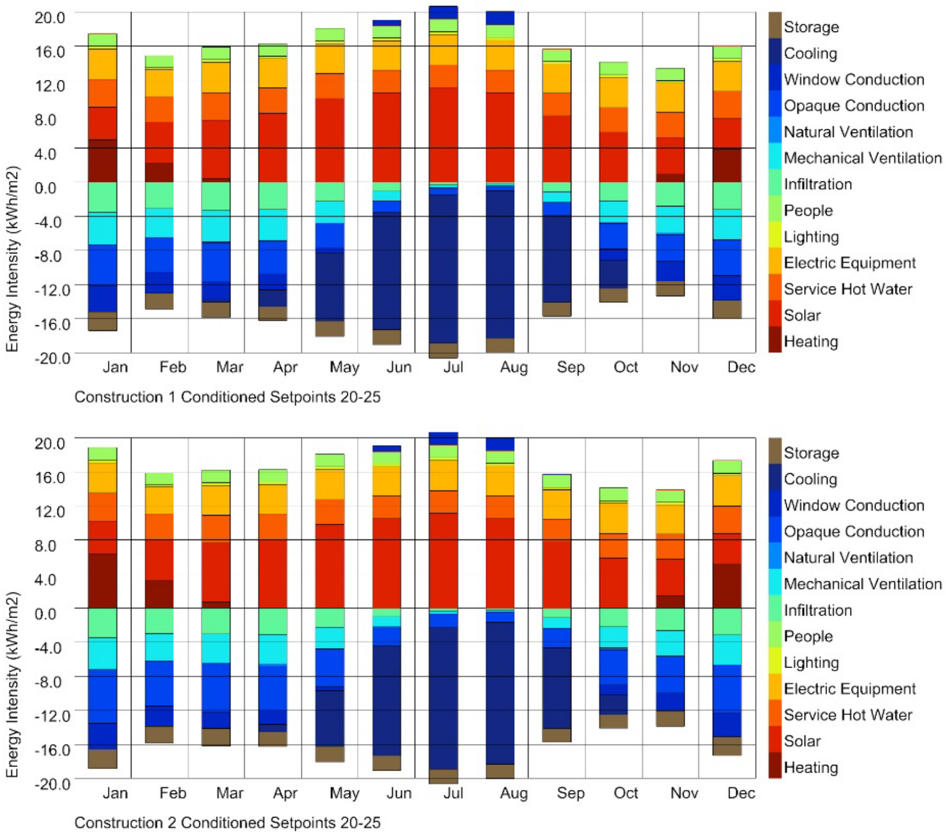


Figure 25 - Energy balance for standard recommended setpoints (20-25) (source: work of the author)

A big part of the EUI comes from the cooling component in the period from May till September. Heating loads are relatively small and occur mainly from December till February.

The fourth scenario was developed to test if it is possible to reduce the energy consumption by permitting more flexible cooling requirements. The cooling setpoint was set for 28 ºC to check if natural ventilation can provide thermal comfort in warmer conditions. The simulation results showed that although the EUI of the building decreased in comparison to the previous scenario (from 150 KWh/m2 to 125 KWh/m2), the thermal comfort of the building was much lower (59% and 64% for respective constructions). In conclusion, the fourth scenario cannot be considered as an adequate conditioning scheme for this type of construction.

The analysis of the different conditioning scenarios showed that the initial project proposal doesn't meet thermal comfort standards by applying only passive measures. Although the building envelope has relatively low transmittance values, the heat gains resulting from solar radiation and window conduction cause overheating. Therefore, to achieve comfortable conditions in the house, a significant amount of cooling is required which, in return, increases the EUI of the building. To reduce the heat gains inside the building the percentage of glazing area could be reduced. Different shading strategies can be considered to limit the amount of sun radiation. Another possibility of improving the building performance during the summer includes the application of constructive systems with high thermal inertia to delay the heat conduction through the opaque envelope. On the other hand, the potential of passive solar heating was not fully explored. It could potentially reduce the heating needs in the winter.

4.2. Study 2 – Application of the bioclimatic optimization framework

The objective of the second study is to evaluate the applicability of the proposed bioclimatic optimization framework. To compare the effectiveness of the adopted methodology, the same case study problem was chosen for the analysis. The design and evaluation process has been performed using various software including Rhino 7, Grasshopper and Ladybug Tools plugins. It is important to highlight the significant difference between the use of the BPS tools in the first and the second study. In the first one, simulation was used only at the last stage of the design process to verify the performance of the building. In the second study, building simulation plays an active role in the generative process of form-finding.

4.2.1. Sensitivity Analysis

In accordance with the adapted framework, the first step of the analysis covers the potentials and limitations of the site. The main constrain of the site is the previously mentioned limit for the buildable area (Figure 26). As the building can be placed only on the top of the hill, the prevailing winds should be studied. The previously mentioned view of the Montemor castle is also an important asset. The surrounding rural context of the place gives an opportunity to apply strategies and materials found in local vernacular architecture. The popular housing typologies and building materials of Alentejo region were described in I chapter of the presented research.

Figure 26 – Site potentials and constraints (adapted from: Atelier dos Remedios)

A climate analysis was conducted to identify the most effective bioclimatic strategies. The weather data for the nearest available location, the city of Evora, was downloaded from Meteonorm software database. The Ladybug plugin was used to generate a psychometric chart for the specific climatic condition (Figure 27).

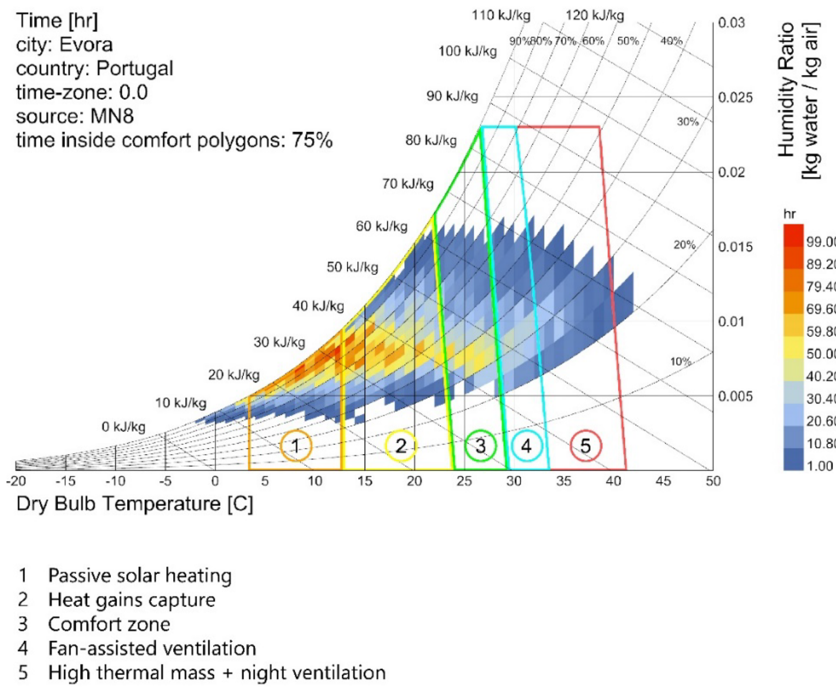


Figure 27 - Psychometric chart with potential of passive strategies (source: work of the author)

As it can be seen on the diagram, the temperature is ranging from around 0 till 40 degrees. Although for most of the time, temperature is between 5 and 30 degrees with the relative humidity above 30 %. The default comfortable conditions occurred for 12% of the time. The analysis of the comfort polygons evaluated the potential of the following passive strategies for enhancing thermal comfort: passive solar heating (12% of the time), heat gains capture (42% of the time), use of fan-assisted ventilation (5% of the time), high thermal mass and night ventilation (6% of the time). Combining the use of several passive strategies could potentially provide comfort for 75% of the year. Two of the most significant strategies (capture of heat gains and passive solar heating) provides comfort conditions in the colder periods. The high thermal mass of the building combined with night ventilation can help to mitigate the effects of heat in the summer.

The analysis of the prevailing winds was performed with the Ladybug plugin to study the potential of natural ventilation strategies. Wind patterns in the summer and winter period were studied separately.
As it can be seen in Figure 28, winds in the winter period are mostly calm (below 5m/s) and do not follow any specific direction. Having that in mind, the architect can assume that there is no need for any special protection against the wind, as it does not cause significant heat losses. In the summer, the winds are a bit more frequent but still moderate in speed and without a prevailing direction. The temperature stays below 26 for most of the time.

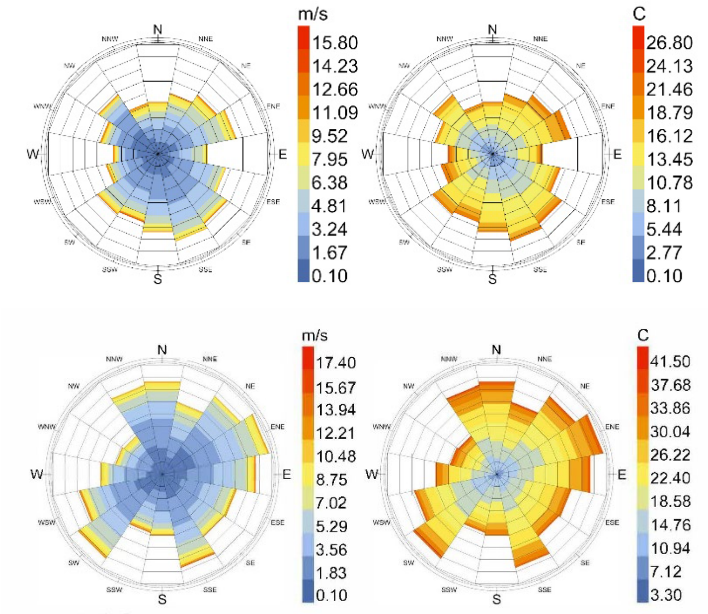


Figure 28 - Wind speeds and directions for winter and summer period (source: work of the author)

The obtained information indicates a moderate potential for the natural ventilation of the building. Moreover, it is important to notice that the actual wind conditions on the site can be significantly different from the ones obtained in nearby locations. Therefore, the results of the wind analysis are only indicative. The last part of the climate analysis considers heating and cooling degree days at the give location. The values were obtained for the default building balance points (18 and 25), resulting in 1549 heating hours and 229 cooling hours throughout the year.

4.2.2. Conceptual design

The formal and functional objectives in the second study are aligned with the ones defined for the first study. The room functions and sizes should respect the functional organization of the original project. The separation between the living and dormitory space must be preserved. The external organization of the building volume should also generate an enclosed space in front of the building. The building typology and formal expression should be harmonized with the local rural context, therefore the use of elongated volumes and pitched roofs is preferred. The design should also consider the privileged orientation of the living room and master bedroom which guarantees a view of the Montemor castle. For that reason, the façade facing that direction should incorporate larger openings.

In terms of construction, the design should utilize locally available materials and constructive techniques. In the next sub-chapter, the previously defined objectives and passive strategies are translated to computational parameters and constraints.

4.2.3. Computational parameters and constraints

The definition of computational parameters and constraints follows the bioclimatic optimization framework. The following project parameters were considered:

<u>Volume geometry parameters</u>

In the first attempt, the research considered the use of the Grasshopper plugin for generative building layouts that could be used to explore different floor plan options. (DeCodingSpaceToolbox, 2019). The plugin was tested with the aim of generating relevant floor plan configurations. The plugin allowed for a strict definition of room areas as well as internal relationships between the floor plan elements. Its main disadvantage was the inability of controlling the orientation of the rooms towards the site. The rooms could not be associated with a certain geographic direction; therefore, the generative output did not consider most of the conceptual requirements of the project. As the mentioned tool seemed to be unsuitable for the specific design problem, in the second attempt, the author used “conventional” design methods. Three alternative floor plans were developed to meet the conceptual and bioclimatic criteria defined in the previous sub-chapters. The simplified floors plan schemes can be consulted in the figure 29.

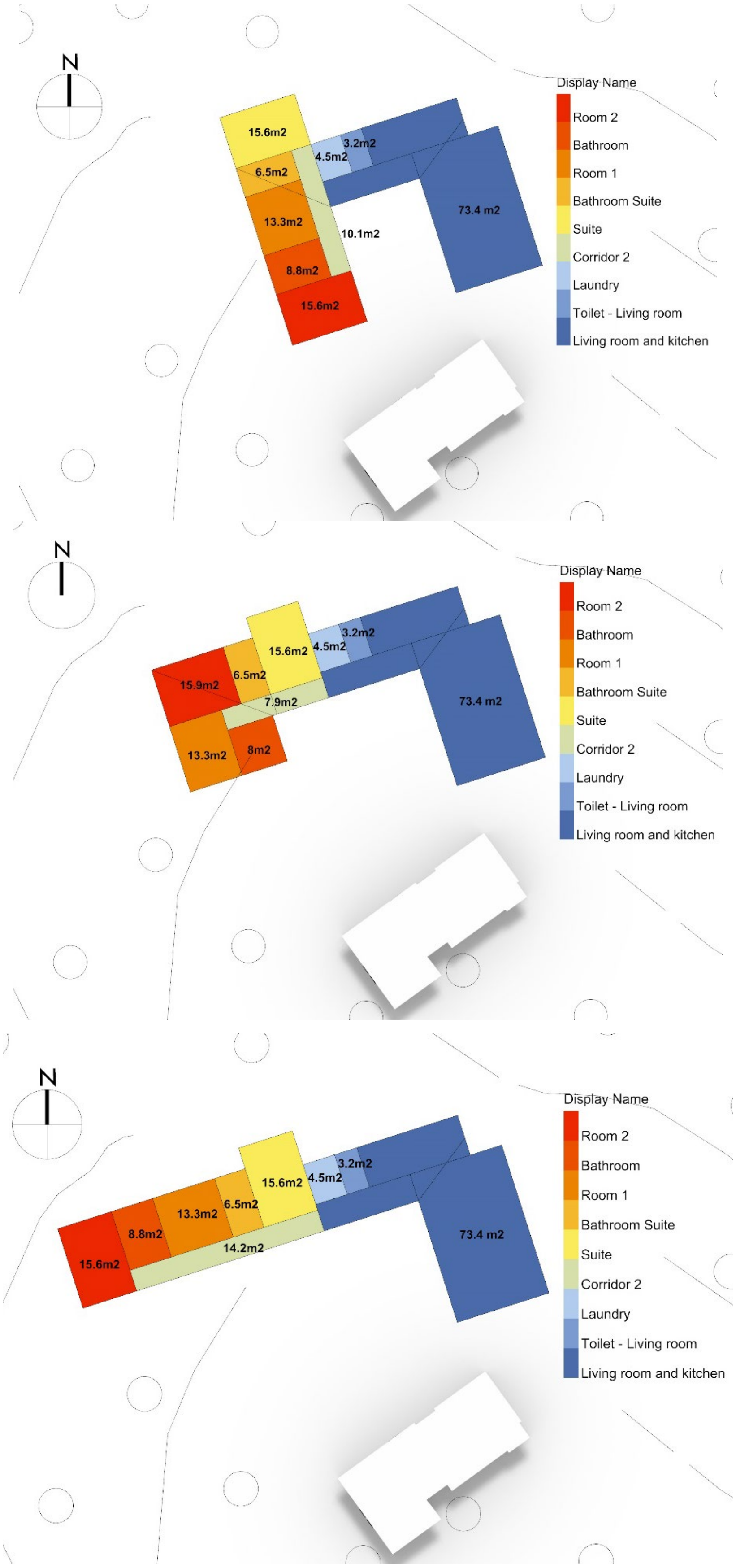


Figure 29 – Schematic floor plan configurations of the three options (work of the author)

The first volumetry is based on the same floor plan layout as in the referenced case study. The exact shape was slightly simplified to avoid problems with assigning it to the simulation model. The second volumetry was created by changing the semi-closed courtyard typology towards a more elongated form. The examples of vernacular architecture from the region show that reducing the surface area on the western side prevents excessive heat gain in the afternoon. Rural houses are often elongated, with the main façade facing north-east (Simões et al., 2019). The third proposed volumetry was following the same local bioclimatic pattern and represents the most elongated layout. In all geometry configurations, the living room and the master bedroom have a view towards Montemor castle. The parameter of the layout orientation was added to the model to explore the optimal position of the building. Figure 30 presents the three geometry alternatives assigned to the Honeybee model.

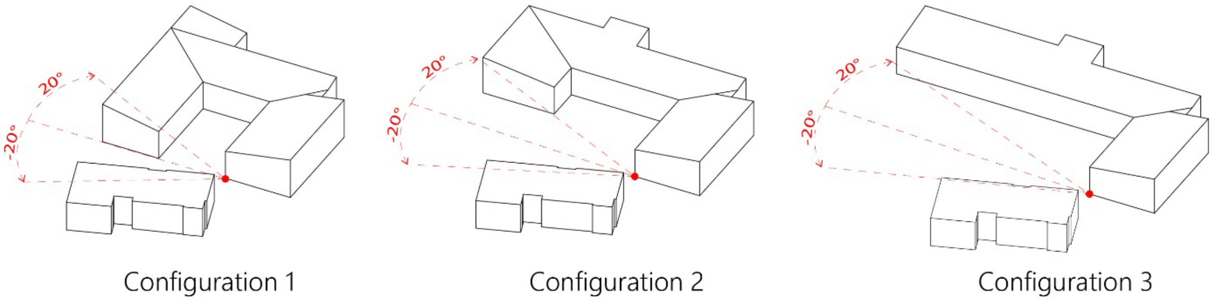


Figure 30 - Geometry alternatives and orientations (work of the author)

Window geometry parameters

Window parameters have a fundamental influence on the energy consumption and comfort of a building. Smaller windows can prevent radiation heat gains in the summer and conduction losses in the winter. On the other hand, they are limiting the amount of natural light in the building. (Hee et al., 2015) As the WWR has an impact on two conflicting performance parameters (daylight and thermal comfort), architects need to find a balance that allows to achieve reasonable results in both categories. Appropriate parameters for the glazing ratios and orientation in hot climates were described in the previous chapter. (Guedes et al., 2019) To allow for the broad exploration of the optimal solution, each window's orientation was assigned as a separate optimization parameter. Another variable assigned to the model was the window height. A change in this parameter value allows to test both the vertical and horizontal proportion of the windows. A few exceptions regarding the parameters of the eastern windows were made, to meet the view requirement. These were defined as balcony windows with higher range of possible WWR ratios. As a result, the total number of possible glazing combinations was equal to 12500. All windows were defined as operable to allow the cross-ventilation of the rooms.

Shade geometry parameters

Three different shading strategies were defined to explore the greatest potential in improving the comfort and energy balance of the project. (Figure 31)

The first one considers the use of horizontal shading (pergola). This bioclimatic strategy can be used to limit the heat gains in the summer while allowing for passive solar heating in the winter (when the sun angle is low). This solution is frequently used in southern Portugal as it improves the thermal comfort inside the house and provides a sun-protected space around the building. (Simões et al., 2019) The length of the pergola was chosen as an optimization parameter and was customized depending on the wall orientation.

The second strategy involves the use of recessed windows. Different recess depths were accounted as optimization parameters depending on the geographic orientation. It should be noted that the recessed window geometry was simplified in the Honeybee model and was represented as an extrusion of the window contour. The reason for this workaround is that the simulation model is constructed from theoretical surfaces (with no thickness) and cannot represent the thickness of the wall.

The third shading strategy includes the use of mechanically controlled blinds. Several studies confirmed the effectiveness of this strategy in regulating thermal and visual comfort. (Grobman et. al., 2020). Movable blinds are also more flexible than the fixed shading as they can be adjusted according to environmental conditions and do not obstruct the view. The optimization parameters defined for this strategy accounted for different blind widths and angles. Two different options were considered regarding the internal and external position of the blinds. The control parameter for turning on the shades was related to the interior temperature of the respective rooms. When the temperature in the zone was above 26°C, the blinds were considered closed.

The presented shading strategy should be applied separately, therefore the Grasshopper script shouldn't allow for the simultaneous evaluation of all the parameters. A detailed list of all geometry parameters can be consulted in Table 2 in the Annex.

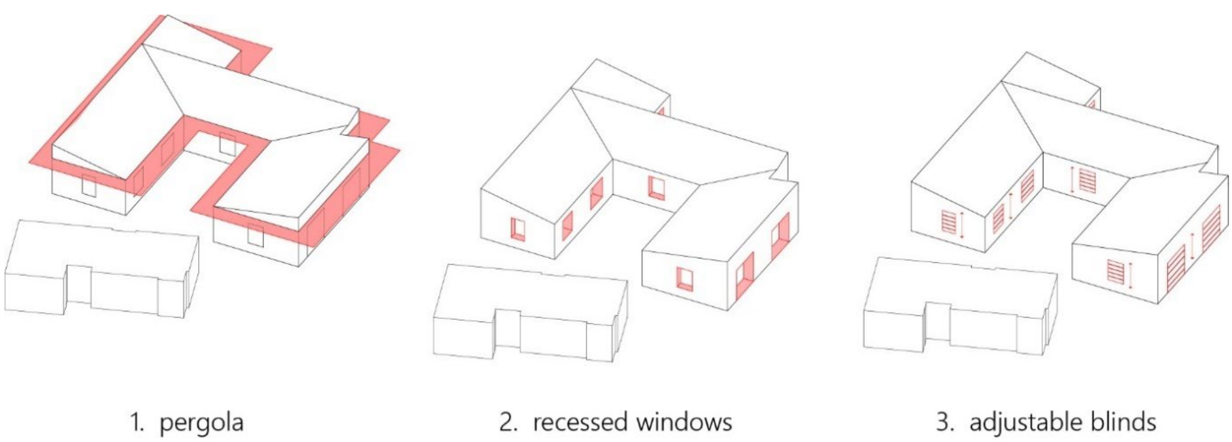


Figure 31 - Shading strategies (source: work of the author)

Construction and modifiers parameters

For the optimization, four different material assemblies are considered, including lightweight wooden frame (Construction Set 1) and thermal brick masonry (Construction Set 2) which were used in the previous study. Two other construction alternatives use rammed earth as the primary structural solution. The bioclimatic potential of high thermal inertia materials like earth was described in the chapter 1. The building simulation study led by Gupta proved that in the hot arid climates rammed earth solutions can outperform conventional constructions (like cavity brick or insulated timber frame) in terms of thermal comfort and energy consumption. (Gupta et. al, 2020). Therefore, the use of earth walls was considered as a potentially relevant construction parameter. For Construction Set 3 the thickness of the rammed earth wall was set to 50 cm. As an exterior finish, white lime plaster was chosen as a traditional strategy to reflect the sunlight. In case of Construction Set 4, the thickness of the wall was reduced to 40 cm, while an EPS insulation layer was added to the exterior of the building. Prefabricated earth blocks were used for the interior walls as they also increase the thermal inertia of the building. The roof and floor layers for Construction Set 3 and 4 are the same as those of the thermal brick masonry building (Construction Set 2). The complete list of the assigned construction parameters can be found in Table 3. The modifiers values for daylight simulation are visible in Table 4.

Ventilation and air conditioning parameters

To optimize the passive functioning, the building is considered unconditioned (there are no heating and cooling systems). Natural ventilation control works with the setpoints described already in the previous study (scenario 1).

Building loads parameters

The building loads parameters are fixed and have the same values as in Study 1. They were obtained from the Honeybee library as the default values for the “2019::Midrise Apartment::Apartment” program. The only program value that has been change is considering the building infiltration rate that has been modified to represent newly constructed airtight building (0.0001 m3/s per m2 of facade).

4.2.3. Performative objectives

The goal of the optimization process was to find the best performing passive solution. Two performative objectives were defined: the maximization of UDI and the maximization of Adaptive Comfort. As it was mentioned before, these objectives are usually conflicting with each other and depend mainly on the WWR and shading design of the building.

To facilitate the comparison of the building performance results in Study 1 and Study 2, the same simulation parameters were defined for both studies. (Table 6)

4.2.4. Optimization Parameters

The optimization parameters were defined in the Wallacei X plugin according to the default recommendations. The total search space of the optimization problem, considering all possible parameter values for three different strategies, accounted for 164 100 000 possible model configurations. To narrow the search domain, the optimization process was divided into three separate runs determined by the use of a particular shading strategy. The first optimization run considered the use of pergolas. The second one optimized the use of recessed windows and the third one improved the use of movable blinds. The Population parameter was determined according to the time needed for a single optimization run. The processor on which the simulation was run, required around 1min 25 sec to evaluate the daylight and energy performance of a single model. To achieve a realistic optimization time, the population size was set to 1000 which resulted in 23 hours for a single optimization. For every generation, 25 different design options were evaluated. The detailed list of optimization parameters can be found in Table 9.

Table 9 – Optimization parameters

	Strategy 1	Strategy 2	Strategy 3
No. genes	13	13	12
No. values	55	51	47
Search space	120.000.000	36.000.000	8.100.000
Population	1000 (25x40)	1000 (25x40)	1000 (25x40)
Crossover Probability	0.9	0.9	0.9
Mutation Probability	1/13	1/13	1/12
Crossover Distribution Index	20	20	20
Mutation Distribution Index	20	20	20

4.2.5. Evaluation of the results

The optimization results were analyzed using the Wallacei X plugin and customized diagrams from Grasshopper. The pareto-optimal solutions were selected from all three optimization runs.

The first and the third strategy optimization resulted in 25 solutions describing the Pareto front. The second strategy optimization found 20 optimal solutions.

The parameters defining the best solutions were exported to an Excel file and can be compared in Table 10 in the Annex. The performative results of the entire population were plotted on the graph showing the fitness of each solution. The best solutions and resulted Pareto fronts can be found in Figure 32.

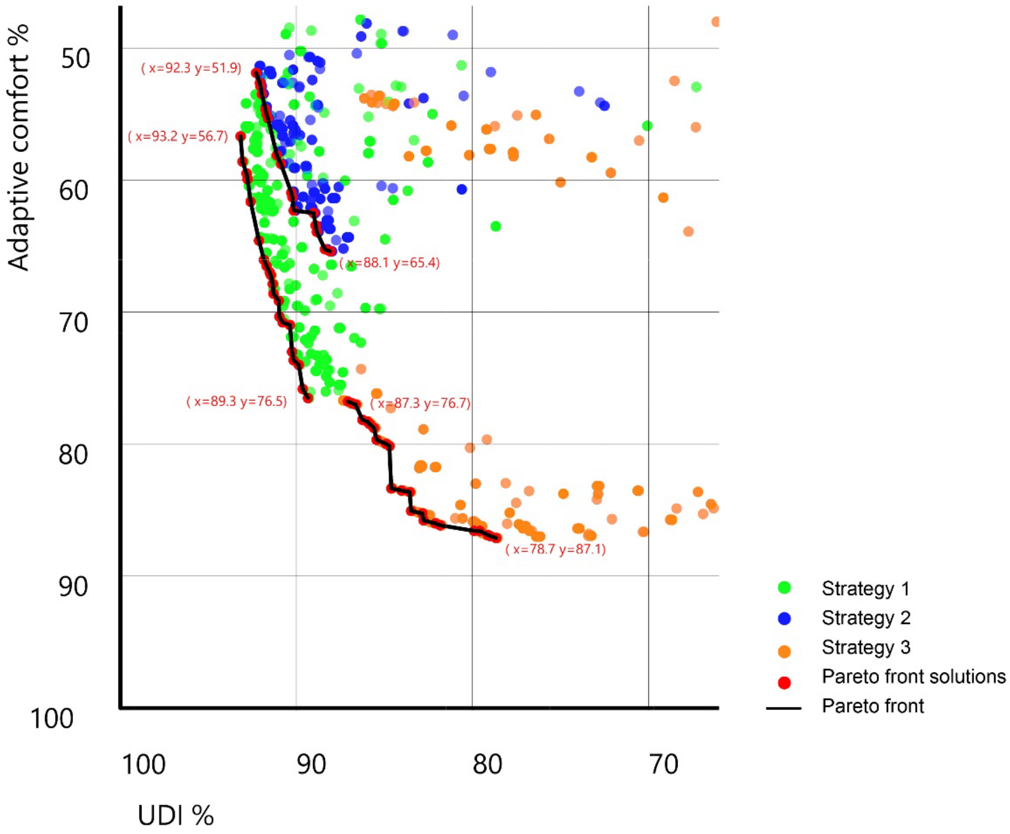


Figure 32 – Fitness results of the optimized strategies (source: work of the author)

For each optimized strategy, two pareto optimal solutions were chosen for further analysis. The first one represents a model with the best Adaptive Comfort score. The second one represents a model with the best UDI score. The chosen building solutions were investigated further to evaluate their energy intensity. They were evaluated under the same conditioning scenarios as the one presented in Study 1. Table 11 below shows the final performance results of the optimal solutions.

Table 11 - Performance results of the optimal solutions for Study 2

	Scenario 1 Unconditioned natural ventilation	Scenario 2 Mix Conditioned	Scenario 3 Mix Conditioned	Scenario 4 Mix Conditioned
	Adaptive comfort % / UDI % / EUI kWh/m2	Adaptive comfort % / UDI % / EUI kWh/m2	Adaptive comfort % / UDI % / EUI kWh/m2	Adaptive comfort % / UDI % / EUI kWh/m2
Strategy 1 opt. Adaptive comfort	76.5 / 89.3 / 74.2	71.8 / 89.3 / 116	99.9 / 89.3 / 128	77.6 / 89.3 / 101.9
Strategy 1 opt. UDI	56.7 / 93.2 / 74.2	81.3/ 93.2 / 111.4	99.5/ 93.2 / 121.1	80.2 / 93.2 / 94.3
Strategy 2 opt. Adaptive comfort	65.4 / 88.1 74.2	79 / 88.1 / 119.3	99.5 / 88.1 / 130.4	81.5 / 88.1 /105.9
Strategy 2 opt. UDI	51.9 / 92.3 74.2	77.4 / 92.3 / 118.2	99.5 / 92.3 / 129.7	79.4 / 92.3 / 106.4
Strategy 3 opt. Adaptive comfort	87.1 / 78.7 / 74.2	89.5 / 78.7 / 135.5	95.2 / 78.7 / 143	89.7 / 78.7 / 85.5
Strategy 3 opt. UDI	76.7 / 87.3 / 74.2	79.2 / 87.3 / 124.3	99.6 / 87.3 / 134.8	94.7 / 87.3 / 91.4

The resulting geometry of the best performing solutions was exported to Rhino viewport to illustrate the morphological differences between different strategies. The selected models can be compared in Figure 30 below.

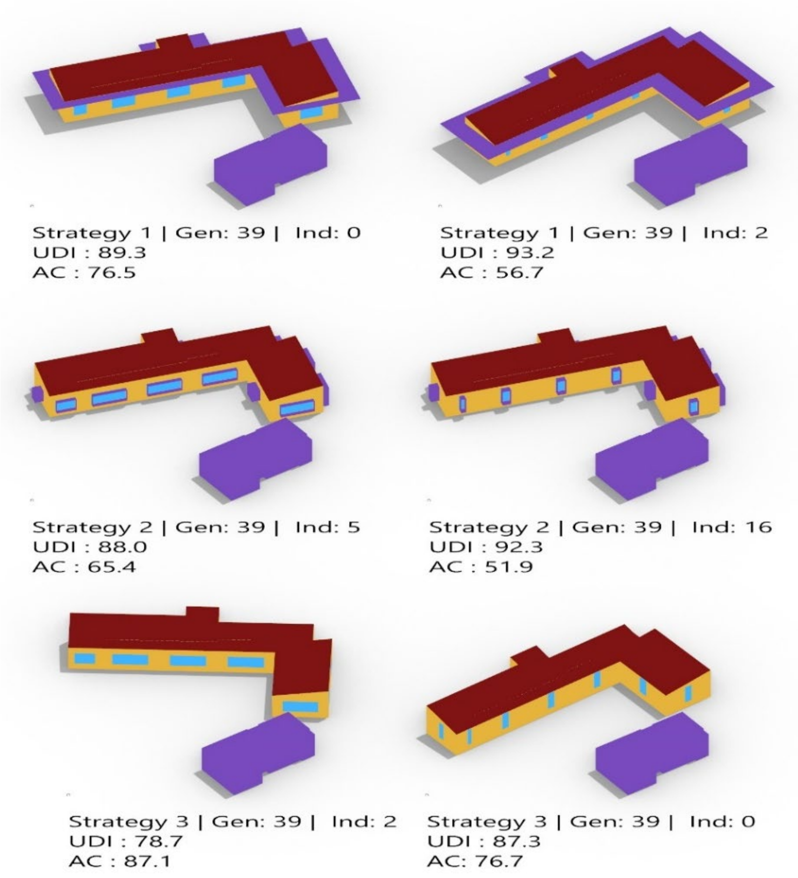


Figure 33 – Geometry of the best performing solutions for each strategy (source: work of the author)

The analysis of the optimization performative results and corelated building parameters for three different strategies brings several conclusions:

- The insulated rammed earth system (Construction 4) was the optimal construction parameter for all evaluated strategies. All the pareto-optimal solutions indicted it as the most effective in terms of thermal comfort. The result shows that constructive materials with strong thermal inertia might perform better than typical solutions (in the context of hot climates), despite having higher thermal transmittance (U= 0,44) then insulated wooden frame (U= 0,20) and thermal brick masonry (U= 0,37) constructions.

- The Elongated building typology (Configuration 3) was the optimal geometry parameter for all strategies. It shows that the horizontal organization of the volume might be the most effective in terms of capturing the solar gains while oriented in a correct way. By limiting the wall area exposed to the west it might also provide better protection from overheating.

- The WWR parameter for the Western side was always 10% (minimum value) for all optimal solution in all three strategies. This result shows that for achieving both the best thermal and visual comfort western window areas should be reduced.

- Although the optimization results do not show the definite pattern about the influence of window proportions on thermal and visual performance, there is a slight correlation between the results of the best solutions. Among the six solutions presenting the highest performance score in each category (table 4) (figure 4), there is a pattern regarding the window height. The solutions with the best Adaptive Comfort results have more horizontal windows, while in case of the best UDI score, window proportions are more vertical. These results might suggest that horizontal window increase the solar heating potential of the building and results in the higher thermal comfort.

Besides the general conclusions involving all the applied strategies, more detailed analysis of the specific strategies results was performed.

Regarding the use of pergola (Strategy 1), the following observations were made:

One of the optimal solutions achieved the best overall result for UDI, providing visual comfort for 93.2 % of the time. All the optimal solutions reached the maximum shading depth (2m) on the Eastern side. The result shows that in case of the applying large glazing areas to one of the sides, deep horizontal shading should be applied to improve the thermal and visual performance of the building. Despite of significant shading protection, the optimized WWR ratio of the living room windows reached the minimum permitted value (40%). For the optimal solutions, WWR for the southern direction does not exceed 20%. Unexpected results of the comfort and energy consumptions value have been observed while comparing the unconditioned and conditioned scenario of the building operation. In case of unconditioned building the best values of comfort have been achieved in the solution with more horizontal windows and smaller overhangs. In the mix conditioned mode (scenario 2) the same geometry achieved the lower comfort score and higher energy consumption. This behavior is showing, that in some cases air conditioning does not improve the thermal comfort of the occupant but only increase the energy consumption.

Regarding the recessed windows (strategy 2) following observations were made:

The optimal solutions performed slightly worse than in case of Strategy 1 and 3 (in all categories). The orientation of the volume was unchanged regarding all the pareto-optimal solutions. The optimal values for WWR parameter of living room window were slightly higher (50%) then in Strategy 1 and 3 The depth parameter of the recessed windows from east and west had maximum value for all the pareto-optimal solutions (0.4m) These observations might suggest that recessed window strategy allows for applying some bigger window openings as they are protected from the sun in both the vertical and horizontal direction. This might also explain why the depth of the recess was bigger for the east and west direction, as it helps in protecting the building from lower angles of sun radiation.

Regarding the movable blinds (strategy 3) following observations were made:

All the optimal solutions shared the same parameter of exterior blinds, and which were rotated to a 30-degree angle. WWR parameter in the north direction was equal to 20% for all optimal solutions. Besides that, WWR parameter in the southern direction was corelated with thermal performance of the building. Among the optimal solutions, best result of Adaptive comfort was achieved by solutions with the glazing ratio equal to 30% of the wall area. Overall, movable blind shading performed the best in terms of the thermal comfort. The optimal solution achieved 87.1 % comfortable time during the year without the use of any heating and cooling systems (scenario 1). Despite the good passive performance of this design option, the same model did not perform very well when the standard air conditioning setpoints were set. For scenario 3, the energy use intensity of this strategy was much higher than in the previous scenarios and strategies. The possible explanation of this behavior is that by applying the standard cooling setpoints (25) the effectiveness of passive cooling strategies (like ventilative cooling) is being significantly reduced. As can be seen from the model behavior in scenario 4, more flexible cooling setpoints (set to 28) resulted in slightly worse thermal comfort (around 5 % decrease) but allowed for significant reduction of EUI (58KWh/m2). The results suggest that the standard cooling requirement are not considering the potential of passive cooling strategies and might lead to unnecessary increase in energy consumption. It is worth noticing, that one of the solutions presented the most balanced performance in all three categories (for scenario 4). The design option assured: thermal comfort for 94.7 % of the time, visual comfort for 87.3% of the time and relatively low energy consumption (91.4 KWh/m2).

4.3. Results comparison

The comparison of the performative results of the two analysis methodologies proves the efficiency of the proposed bioclimatic framework. In comparison to the reference project investigated in Study 1, the design solutions obtained through explorative optimization process are more adapted to local environmental conditions. The best design solutions presented in Study 2 achieved significantly better comfort and energy performance in most of the scenarios. Table 12 presents the average performance scores of two best solutions for each strategy and scenario.

Table 12 – Average performance results of Study 1 and Study 2

	Scenario 1 Unconditioned natural ventilation	**Scenario 2 Mix Conditioned**	**Scenario 3 Mix Conditioned**	**Scenario 4 Mix Conditioned**
	Adaptive comfort % / UDI % / EUI kWh/m2	Adaptive comfort % / UDI % / EUI kWh/m2	Adaptive comfort % / UDI % / EUI kWh/m2	Adaptive comfort % / UDI % / EUI kWh/m2
Reference building	51.75 / 81.2 / 0	81.1 / 81.2 / 142.45	95.7 / 81.2 / 151.25	62.35 / 81.2 / 127
Strategy 1	66.6 / 91.25 / 0	76.55 / 91.25 / 113.7	99.7 / 91.25 / 125.75	78.9 / 91.25 / 98.1
Strategy 2	58.65 / 90.2 / 0	78.2 / 90.2 / 118.75	99.5 / 90.2 / 130.05	80.45 / 90.2 / 106.15
Strategy 3	81.9 / 83 / 0	84.35 / 83 / 129.9	97.4 / 83 / 138.9	92.2 / 83 / 88.45

In terms of fully passive building operation (Scenario1), Strategy 3 was outperforming the reference building in both the thermal and visual comfort. Adaptive comfort standards were achieved on average 30% longer (in yearly hours) and useful daylight illuminance 2% longer (in yearly hours). For standard conditioning setpoint (scenario 3), Strategy 2 achieved 10% better UDI results and 17% lower EUI. For less energy intensive conditioning Scenario 4, Strategy 3 achieved the Adaptive comfort standards for 30% more hours of the year while obtaining 30% lower EUI then reference building.

CHAPTER 5

5.1 Conclusions

The tested optimization workflow proved to be helpful in achieving more comfortable and sustainable architecture. The analysis of many pareto-optimal solutions allowed as well to determine several morphological patterns of architectural adaptation. By tracking the correlation between the building parameters and comfort result, some general conclusions regarding the bioclimatic adaptation have been made. Although the generated solutions comprised of only small part of the problem search space; they might have significant impact on decision making process. What is also important from the professional perspective, the presented framework does not imply specific “optimal” solution but propose many design alternatives and performance trade-offs. It is enhancing the creative process by positioning the sustainability issues in the center of the architectural discourse. It is also offering a toolset for the analysis of complex architectural problems. The practicality of the workflow was validated by applying it to concrete use-case of early design stage project. The comparison of the performative results showed that the presented framework is a viable alternative for traditional design practice as it helps to create sustainable projects without compromising the project objectives and restricting the decision-making process. The evaluation of different passive strategies can be also used as the design recommendation for the bioclimatic architecture in the context of South Portugal climate and building tradition.

The following paragraphs summarizes the most important conclusions related to different aspects of the presented work.

<u>Scientific background</u>

The literature review focused on two fundamental aspects of the dissertation, the bioclimatic architecture, and the computational design process, brings a strong theoretical background for development of the bioclimatic framework. The historical evolution of these two concepts gives a deeper understanding of the current sustainable practices and relation between architecture and technology. The bibliographical research underlines the reciprocal relation between natural and built environment. It also shows that traditional vernacular architecture can be a source of knowledge and inspiration for the future designers searching for sustainable solutions. It also highlights the broad applicability of bioclimatic approach and its potential for future advancement. The part of the review dedicated to the computational design process shows that novel design methods offer an interesting conceptual framework that can be effectively used to solve complex design problems. It also shows that performance-driven design integrates the current computational tools with environmentally friendly approach to architecture. Lastly the brief overview of building simulation tools gives a better understanding of the current possibilities in computational design.

Framework

The presented bioclimatic optimization framework synthetized the knowledge from the first two chapters and proposed the design methodology based on exploratory design process. Literature review analyzing existing workflows was an important step to identify the advantages and shortcoming of computational methods. The developed framework proposed an easy-to-follow and flexible design process focused on bioclimatic solutions. The performance-based approach was used as a base of conceptual framework. By performing several tasks in one integrated and open-source design software (Grasshopper), the design process became more integrated and easy-to follow

Framework Application

The application of developed framework in the case study was relatively fast and straight-forward.
The theoretical guidelines could be easily translated to the actual design tasks. Two different studies were developed to compare the effectiveness of the traditional and computational method. The main obstacles considered the technical limitations of the computational tools. In the first place, the data input obtained for the purpose of environmental analysis was a rough approximation of the site real condition. The actual conditions (for example wind speed and direction) might be significantly different which can lead to false assumption about the potential of natural ventilation strategies. Secondly, the generative floor plan plugin (Magnetizing Floor Plan Generator) was not applicable for the desired design purpose as it was not able to fulfil the project constrains. It shows that floor plan design is still one of the most complex design activities that, given the variety of constrains, can be very difficult to parametrize and optimized. Lastly, the technical limitations of the building simulation and optimization software makes the evaluation process time consuming. Because of the long time needed for single evaluation and single threaded character of optimization algorithm, it was possible to evaluate only small fraction of all possible solution. The mentioned factors did not affect the overall integrity of the design process but could result in less effective or less accurate solutions.

Results evaluation

The results of the case study showed that the use and optimization of the bioclimatic strategies can bring significant benefits in terms of thermal and visual comfort as well as energy consumption. The best performance has been achieved by solution combining passive strategies with active shades control (adjustable blinds). The study highlights the importance of reconsidering the existing building standards and requirements when being applied to the passive strategies. As indicated earlier, applying the conventional heating and cooling setpoint for mechanical system in case of mix-mode ventilation can potentially reduce the energetic benefits of the passive strategies. Considering the lack of formalized procedure for the energetic and comfort studies on the passive buildings, the objective value of the obtained results is questionable. However, the main purpose of the study was to compare the performative results of different design approaches, therefore the achieved outcomes are still relevant.

Applicability of work

Although the focus of the study was to analyse the applicability of framework for the professional architectural practise, developed workflow could be potentially used in the academic context as well. Because of the exploratory character of generative design, significant amount of data can be generated along the process. These information can be used by researchers in order to arrive to the general conclusions about the relations between building form and performance.

5.2 Future Work

This chapter presents the ideas for the future research considering different aspects of bioclimatic and computational design. The proposals for upcoming development consider two different aspects of the presented research: Methodology and Tools.

Methodology

In the future studies the presented methodology could be expanded to provide more comprehensive results. Additional design objectives considering the building costs, embodied energy or global warming potential can be added to understand the total environmental impact of bioclimatic architecture. The study comparing the influence of passive and active bioclimatic strategies could improve our understanding of a truly sustainable design. Design methodology can be also improved by considering the air conditioning parameters (heating and cooling setpoints) as a dynamic design variable. The optimization of this factor might lead to much higher energy savings in case of passive solutions. As mentioned before, reliable methodology for adaptive comfort simulations should be developed.

Tools

Several shortcomings of the presented computational tools could be addressed to provide faster and more informed design process.

- Faster and more integrated tools for wind analysis should be developed. They would allow for more accurate evaluation of passive ventilation strategies.
- Generative tools allowing for more intuitive and accurate development of the floor plans should be developed.
- The speed of building optimization could be improved by applying the machine learning models or multithreading processes. The methodology could be also tested using different optimization models and algorithms, which may lead to more optimal results.
- The development of more specific database about locally obtained materials and typical building programs could improve the accuracy and usability of the building simulation software in the design process.

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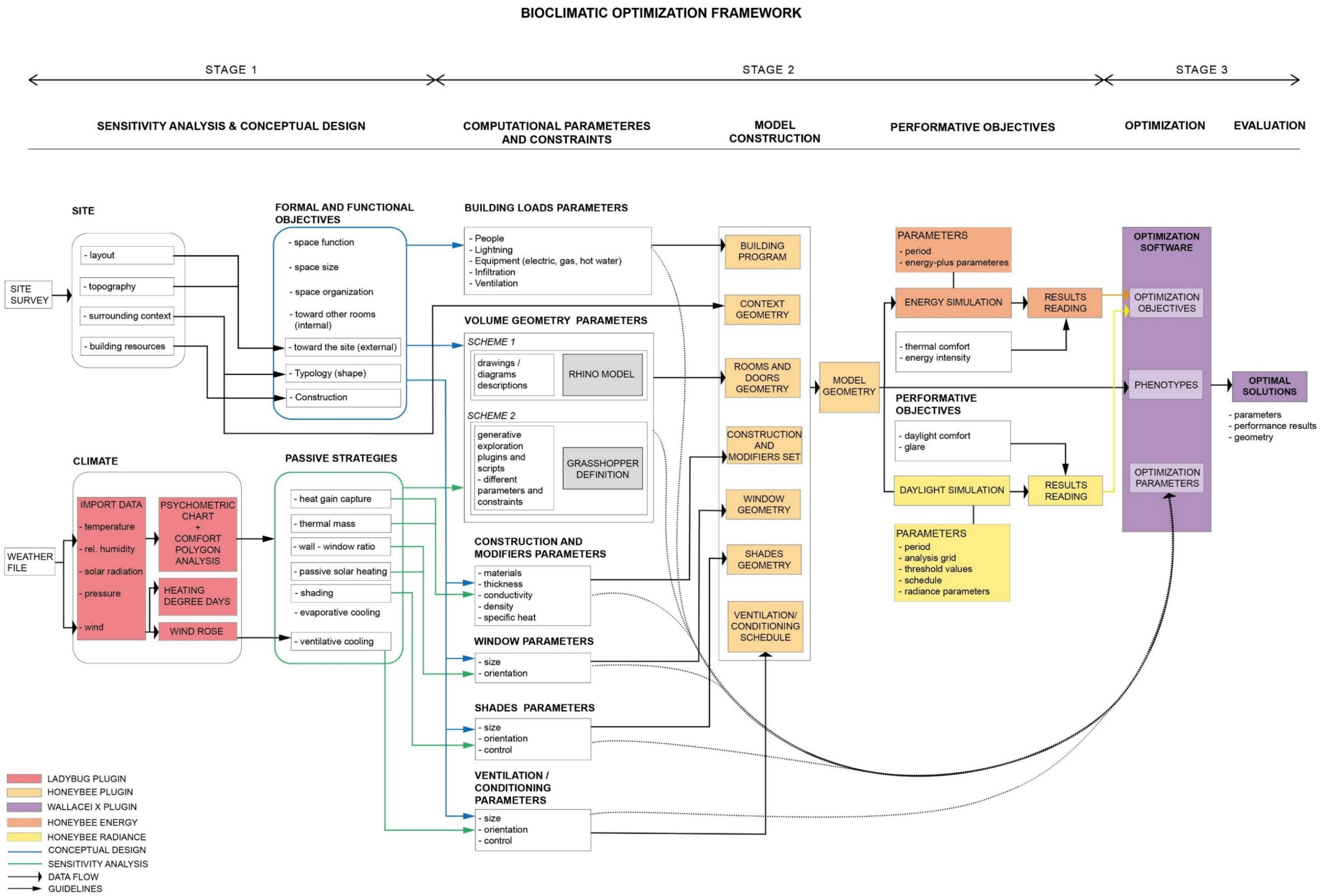

Figure 16 – Bioclimatic optimization framework graph (source: work of the author)

Case study comparison

Table 1 – Case study comparison

Caldas, L. & Rocha, J. (2001)	public building	Oporto, Portugal Phoenix, USA Chicago, USA	optimization of the envelope design in relation to predefined volume and organization	composition of the façade based on original design: exact window location (according to compositional axis), window proportions (horizontal or vertical) minimum values of interior illuminance	windows height and width, depth of the shading element (overhang)	minimize annual energy load (mwh)	Oporto / 10% of annual energy load
Konis, K.; Gamas, A.; & Kensek, K. (2016)	office building	Los Angeles, USA Helsinki, Finland Mexico City, Mexico New York City, USA	exploration of the building shape and envelope design	constant floor area	building geometry parameters: footprint geometry and proportions, number of floors, use of courtyard, orientation towards north WWR by orientation, use of shading element, wall type, window type	minimize EUI (kwh/m2) maximize UDI (%)	Los Angeles / 27% in UDI, 4% in EUI Helsinki / 29% in UDI, 7% in EUI Mexico City / 35% in UDI, 20% in EUI New York City / 65% in UDI, 30% in EUI
Toutou, A.; Fikry, M. & Mohamed, W. (2018).	multifamily residential building	Cairo, Egypt	optimization of the envelope design in relation to predefined volume and organization	optimization of selected faces	WWR by orientation shading geometry parameters: depth, width, rotation wall material, glass material	minimize EUI (kwh/m2) maximize UDI (%)	Cairo / 110% in UDI, 3.5% in EUI
Giuffrida, G.; Detommaso, M.; Nocera, F. & Caponetto, R. (2021)	single family residential building	Catania, Italy	optimization of the passive strategies and building materials in relation to predefined geometry and organization	minimum thermal transmittance requirements	use of passive strategies: natural night ventilation, shadowing element, combination of both. type of insulation	maximize thermal indoor comfort (adaptive)(%) minimizing cooling energy needs (kwh/m2)	Catania / thermal indoor comfort 340% cooling energy need 35%

Geometry parameters

Table 2 – Geometry parameters

	Wall-window ratio	Window sill height	Window Height
North	0.1 - 0.5	0.9	1 - 1.8
East	0.1 - 0.5	0.9	1 - 1.8
South	0.1 - 0.5	0.9	1 - 1.8
West	0.1 - 0.5	0.9	1 - 1.8
East with view	0.4 - 0.7	0	2.1

Construction type	Layout	Rotation angle (degrees)
Construction 1-4	Configuration 1-3	-20, 0, 20

	Shading strategy 1 (pergola)	Shading strategy 2 (recessed windows)	Shading strategy 3 (adjustable blinds)					
	Horizontal shading depth (m)	**Recess depth (m)**	**Shades Depth (m)**	**Shades distance**	**Shades thickness (m)**	**Shades angle (degrees)**	**Shades position**	**Shades control setpoint (ºC)**
North	0.5, 1, 1.5, 2	wall thickness + 0, + 0.2, + 0.4	0.06, 0.08, 0.1	= depth	0.005	15, 30, 45	interior, exterior	26
East	0.5, 1, 1.5, 2	wall thickness + 0, + 0.2, + 0 4	0.06, 0.08, 0.1	= depth	0.005	15, 30, 45	interior, exterior	26
South	0.5, 1, 1.5, 2	wall thickness + 0, + 0.2, + 0.4	0.06, 0.08, 0.1	= depth	0.005	15, 30, 45	interior, exterior	26
West	0.5, 1, 1.5, 2	wall thickness + 0, + 0.2, + 0.4	0.06, 0.08, 0.1	= depth	0.005	15, 30, 45	interior, exterior	26
East with view	0.5, 1, 1.5, 2	wall thickness + 0, + 0.2, + 0.4	0.06, 0.08, 0.1	= depth	0.005	15, 30, 45	interior, exterior	26

Construction parameters

Table 3 – Construction parameters

Construction 1 - Wooden Frame - Roof	Thickness (m)	Conductivity W/(m*K)	Density (kg/m3)	Specific heat (J/kg*K)	Thermal resistance (m2*K)/W	Thermal transmittance W/(m2*K)
Ceramic Tiles (LUSA) 10 mm [1]	0,01	0,6	1950(	1000	0,0167	
Air Gap 30 mm	0,03	0,25	1,23	1005	0,1200	
OSB 12 mm [2]	0,012	0,13	590	1450	0,0923	
Rock Wool 120 mm [3]	0,12	0,039	160	1030	3,0769	
OSB 22 mm [2]	0,022	0,13	590	1450	0,1692	
Wooden Finish Pine 22 mm [4]	0,022	0,12	500	2300	0,1833	
					3,6585	0,2733
Construction 1 - Wooden Frame - Exterior Walls	Thickness (m)	Conductivity W/(m*K)	Density (kg/m3)	Specific heat (J/kg*K)	Thermal resistance (m2*K/W)	Thermal transmittance (W/m2*K)
White Coating mortar and reinforcing net 25 mm [5]	0,025	1	2138	940	0,025	
EPS Expanded Polystyrene 40 mm [6]	0,04	0,038	30	1100	1,052631579	
OSB 12 mm [2]	0,012	0,13	590	1450	0,092307692	
Rock Wool 140 mm [3]	0,14	0,039	160	1030	3,58974359	
OSB 12 mm [2]	0,012	0,13	590	1450	0,092307692	
Gypsum boards 12 mm [7]	0,012	0,16	800	1090	0,075	
					4,926990553	0,202963653
Construction 1- Wooden Frame -Interior Walls	Thickness (m)	Conductivity W/(m*K)	Density (kg/m3)	Specific heat (J/kg*K)	Thermal resistance (m2*K/W)	Thermal transmittance (W/m2*K)
Gypsum boards 12 mm [7]	0,012	0,16	800	1090	0,075	
Metal frame with air gap 100mm	0,1	0,25	1,23	1005	0,400	
Gypsum boards 12 mm [7]	0,012	0,16	800	1090	0,075	
					0,550	1,818
Construction 1- Wooden Frame - Floor	Thickness (m)	Conductivity W/(m*K)	Density (kg/m3)	Specific heat (J/kg*K)	Thermal resistance (m2*K/W)	Thermal transmittance (W/m2*K)
Pine wood panels 12 mm [4]	0,012	0,12	500	2300	0,1000	
Cork roll mate 2 mm [8]	0,002	0,065	250	1900	0,0308	
OSB 22 mm [2]	0,022	0,13	590	1450	0,1692	
Rock Wool 160 mm [3]	0,16	0,039	160	1030	4,1026	
OSB 12 mm [2]	0,012	0,13	590	1450	0,0923	
Air Gap 30 mm	0,03	0,25	1,23	1005	0,1200	
Concrete slab 250 mm [9]	0,25	2,3	2322	831	0,1087	
					4,7236	0,2117

Construction 2 - Thermal brick masonry - Roof	Thickness (m)	Conductivity W/(m*K)	Density (kg/m3)	Specific heat (J/kg*K)	Thermal resistance (m2*K/W)	Thermal transmittance (W/m2*K)
Ceramic Tiles (LUSA) 10 mm [1]	0,01	0,6	1950	1000	0,0167	
Air Gap 30 mm	0,03	0,25	1,23	1005	0,1200	
Expanded Insulation Corkboard 120 mm [10]	0,12	0,04	110	1560	3,0000	
OSB 30 mm [2]	0,03	0,13	590	1450	0,2308	
					3,3674	0,2970
Construction 2 - Thermal brick masonry - Walls	Thickness (m)	Conductivity W/(m*K)	Density (kg/m3)	Specific heat (J/kg*K)	Thermal resistance (m2*K/W)	Thermal transmittance (W/m2*K)
White Coating mortar and reinforcing net 25 mm [5]	0,025	1	2138	940	0,0250	
EPS Expanded Polystyrene 60 mm [6]	0,06	0,038	30	1100	1,5789	
Thermal brick Preceram 24 cm [11]	0,24	0,22	819	1000	1,0909	
Cement plaster 20 mm + White lime plaster 5 mm [5]	0,025	1,3	2000	940	0,0192	
					2,7141	0,3684
Construction 2 - Thermal brick masonry - Interior Walls	Thickness (m)	Conductivity W/(m*K)	Density (kg/m3)	Specific heat (J/kg*K)	Thermal resistance (m2*K/W)	Thermal transmittance (W/m2*K)
Cement plaster 20 mm + White lime plaster 5 mm [5]	0,025	1,3	2000	940	0,0192	
Lightweight aerated concrete blocks 120 mm [12]	0,12	0,18	600	1000	0,6667	
Cement plaster 20 mm + White lime plaster 5 mm [5]	0,025	1,3	2000	940	0,0192	
					0,7051	1,4182
Construction 2 - Thermal brick masonry - Floor	Thickness (m)	Conductivity W/(m*K)	Density (kg/m3)	Specific heat (J/kg*K)	Thermal resistance (m2*K/W)	Thermal transmittance (W/m2*K)
Terracotta tiles 25 mm [13]	0,025	1	2000	1000	0,0250	
Floating concrete layer 20 mm [9]	0,02	2,3	2322	831	0,0087	
Thermal Insulation Floormate 200 / 80 mm [14]	0,08	0,029	35	1500	2,7586	
Concrete slab 250 mm [9]	0,25	2,3	2322	831	0,1087	
					2,9010	0,3447

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Construction 3- Rammed Earth - Roof	Thickness (m)	Conductivity W/(m*K)	Density (kg/m3)	Specific heat (J/kg*K)	Thermal resistance (m2*K/W)	Thermal transmittance (W/m2*K)
Ceramic Tiles (LUSA) [1]	0,01	0,6	1950	1000	0,0167	
Air Gap	0,02	0,25	1,23	1005	0,0800	
Expanded Insulation Corkboard 120 mm [10]	0,12	0,04	110	1560	3,0000	
OSB 30 mm [2]	0,03	0,13	590	1450	0,2308	
					3,3274	0,3005
Construction 3- Rammed Earth - Wall	Thickness (m)	Conductivity W/(m*K)	Density (kg/m3)	Specific heat (J/kg*K)	Thermal resistance (m2*K/W)	Thermal transmittance (W/m2*K)
Lime plaster 20 mm + White lime wash [15]	0,02	1,3	2000	940	0,0154	
Rammed earth wall 500 mm [16]	0,5	0,628	1980	1800	0,7962	
Lime Sand Render 25 mm [15]	0,025	0,8	650	1200	0,0313	
					0,8428	1,1865
Construction 3- Rammed Earth - Interior Wall	Thickness (m)	Conductivity W/(m*K)	Density (kg/m3)	Specific heat (J/kg*K)	Thermal resistance (m2*K/W)	Thermal transmittance (W/m2*K)
Lime Sand Render 25 mm [15]	0,025	0,8	650	1200	0,0313	
Prefabricated earth blocks 100 mm [17]	0,2	0,778	2000	2050	0,2571	
Lime Sand Render 25 mm [15]	0,025	0,8	650	1200	0,0313	
					0,3196	3,1292
Construction 3- Rammed Earth - Floor	Thickness (m)	Conductivity W/(m*K)	Density (kg/m3)	Specific heat (J/kg*K)	Thermal resistance (m2*K/W)	Thermal transmittance (W/m2*K)
Terracotta tiles 25 mm [13]	0,025	1	2000	1000	0,0250	
Floating concrete layer 20 mm [9]	0,02	2,3	2322	831	0,0087	
Thermal Insulation Floormate 200 / 80 mm [14]	0,08	0,029	35	1500	2,7586	
Concrete slab 250 mm [9]	0,25	2,3	2322	831	0,1087	
					2,9010	0,3447

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Construction 4- Rammed Earth + Insulation - Roof	Thickness (m)	Conductivity W/(m*K)	Density (kg/m3)	Specific heat (J/kg*K)	Thermal resistance (m2*K/W)	Thermal transmittance (W/m2*K)
Ceramic Tiles (LUSA) [1]	0,01	0,6	1950	1000	0,0167	
Air Gap	0,02	0,25	1,23	1005	0,0800	
Expanded Insulation Corkboard 120 mm [10]	0,12	0,04	110	1560	3,0000	
OSB 30 mm [2]	0,03	0,13	590	1450	0,2308	
					3,3274	0,3005
Construction 4- Rammed Earth + Insulation - Wall	Thickness (m)	Conductivity W/(m*K)	Density (kg/m3)	Specific heat (J/kg*K)	Thermal resistance (m2*K/W)	Thermal transmittance (W/m2*K)
White Coating mortar and reinforcing net 25 mm [5]	0,025	1	2138	940	0,0250	
EPS Expanded Polystyrene 60 mm [6]	0,06	0,038	30	1100	1,5789	
Rammed earth wall 400 mm [16]	0,4	0,628	1980	1800	0,6369	
Lime Sand Render 25 mm [15]	0,025	0,8	650	1200	0,0313	
					2,2721	0,4401
Construction 4- Rammed Earth + Insulation - Interior Wall	Thickness (m)	Conductivity W/(m*K)	Density (kg/m3)	Specific heat (J/kg*K)	Thermal resistance (m2*K/W)	Thermal transmittance (W/m2*K)
Lime Sand Render 25 mm [15]	0,025	0,8	650	1200	0,0313	
Prefabricated earth blocks 100 mm [17]	0,2	0,778	2000	2050	0,2571	
Lime Sand Render 25 mm [15]	0,025	0,8	650	1200	0,0313	
					0,3196	3,1292
Construction 4- Rammed Earth + Insulation - Floor	Thickness (m)	Conductivity W/(m*K)	Density (kg/m3)	Specific heat (J/kg*K)	Thermal resistance (m2*K/W)	Thermal transmittance (W/m2*K)
Terracotta tiles 25 mm [13]	0,025	1	2000	1000	0,0250	
Floating concrete layer 20 mm [9]	0,02	2,3	2322	831	0,0087	
Thermal Insulation Floormate 200 / 80 mm [14]	0,08	0,029	35	1500	2,7586	
Concrete slab 250 mm [9]	0,25	2,3	2322	831	0,1087	
					2,9010	0,3447

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Assigned modifiers, reflectance factor of the specific constructive systems (%) [18 19]

Table 4 – Assigned modifiers

Construction 1 - Wooden Frame	Name	Reflectance factor (%)
Roof exterior	Ceramic Tiles (LUSA) 10 mm	0,32
Wall exterior	White Coating mortar and reinforcing net 25 mm	0,7
Roof interior	Wooden Finish Pine 22 mm	0,35
Wall interior	Gypsum boards 12 mm	0,8
Floor interior	Pine wood panels 12 mm	0,35
Windows	Generic Double Glass	0,8
Shades	Aluminum Matte	0,6
Construction 2- Thermal brick	Name	Reflectance factor (%)
Roof exterior	Ceramic Tiles (LUSA) 10 mm	0,32
Wall exterior	White Coating mortar and reinforcing net 25 mm	0,7
Roof interior	OSB 30 mm	0,35
Wall interior	Cement plaster 20 mm + White lime plaster 5 mm	0,7
Floor interior	Terracotta tiles 25 mm	0,25
Windows	Generic Double Glass	0,8
Shades	Aluminum Matte	0,6
Construction 3- Rammed Earth	Name	Reflectance factor (%)
Roof exterior	Ceramic Tiles (LUSA)	0,32
Wall exterior	Lime plaster 20 mm + White lime wash	0,7
Roof interior	OSB 30 mm	0,35
Wall interior	Lime Sand Render 25 mm	0,4
Floor interior	Terracotta tiles 25 mm	0,25
Windows	Generic Double Glass	0,8
Shades	Aluminum Matte	0,6
Construction 4- Rammed Earth + Insulation - Wall	Name	Reflectance factor (%)
Roof exterior	Ceramic Tiles (LUSA)	0,32
Wall exterior	White Coating mortar and reinforcing net 25 mm	0,7
Roof interior	OSB 30 mm	0,35
Wall interior	Lime Sand Render 25 mm	0,4
Floor interior	Terracotta tiles 25 mm	0,25
Windows	Generic Double Glass	0,8
Shades	Aluminum Matte	0,6

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Table 10 – Pareto-solutions parameters

Name	Construction type	Layout	Rotation angle	Overhang - North (m)	Overhang - East (m)	Overhang - South (m)	Overhang - West (m)	WWR - North	WWR - East	WWR - South	WWR - West	WWR - View	Window height (m)	Results
Gen_39 Sol_0	Construction 4	Configuration 3	0	1	2	1	1,5	0,2	0,2	0,2	0,1	0,4	1,2	UDI=89.3 Adp.Comfort=76.5
Gen_39 Sol_1	Construction 4	Configuration 3	20	1,5	2	1,5	2	0,4	0,5	0,1	0,1	0,4	1,6	UDI=93.2 Adp.Comfort=56.7
Gen_39 Sol_2	Construction 4	Configuration 3	20	1,5	2	1,5	2	0,4	0,5	0,1	0,1	0,4	1,6	UDI=93.2 Adp.Comfort=56.7
Gen_39 Sol_3	Construction 4	Configuration 3	0	1	2	1	1,5	0,2	0,4	0,2	0,1	0,4	1,2	UDI=89.3 Adp.Comfort=76.5
Gen_39 Sol_4	Construction 4	Configuration 3	20	1	2	1	2	0,3	0,2	0,1	0,1	0,4	1,2	UDI=92.1 Adp.Comfort=64.6
Gen_39 Sol_5	Construction 4	Configuration 3	20	1,5	2	1	2	0,4	0,4	0,1	0,1	0,4	1,2	UDI=92.6 Adp.Comfort=61.6
Gen_39 Sol_6	Construction 4	Configuration 3	0	1	2	1	2	0,2	0,4	0,2	0,1	0,4	1,2	UDI=89.6 Adp.Comfort=75.8
Gen_39 Sol_7	Construction 4	Configuration 3	0	1	2	1	1,5	0,3	0,2	0,2	0,1	0,4	1,2	UDI=89.9 Adp.Comfort=74
Gen_39 Sol_8	Construction 4	Configuration 3	0	1	2	1,5	2	0,2	0,2	0,2	0,1	0,4	1,2	UDI=90.8 Adp.Comfort=70.8
Gen_39 Sol_9	Construction 4	Configuration 3	20	1,5	2	1,5	2	0,4	0,5	0,1	0,1	0,4	1	UDI=92.8 Adp.Comfort=59.9
Gen_39 Sol_10	Construction 4	Configuration 3	20	1,5	2	1,5	2	0,4	0,5	0,1	0,1	0,4	1,2	UDI=93 Adp.Comfort=58.6
Gen_39 Sol_11	Construction 4	Configuration 3	0	1,5	2	1,5	1,5	0,2	0,2	0,2	0,1	0,4	1,2	UDI=90.4 Adp.Comfort=71
Gen_39 Sol_12	Construction 4	Configuration 3	0	1	2	1,5	1,5	0,3	0,2	0,2	0,1	0,4	1,2	UDI=91 Adp.Comfort=69.1
Gen_39 Sol_13	Construction 4	Configuration 3	20	1,5	2	1,5	1,5	0,4	0,2	0,1	0,1	0,4	1,2	UDI=92.8 Adp.Comfort=59.5
Gen_39 Sol_14	Construction 4	Configuration 3	0	1,5	2	1,5	2	0,3	0,5	0,2	0,1	0,4	1,2	UDI=91.3 Adp.Comfort=68.6
Gen_39 Sol_15	Construction 4	Configuration 3	0	1,5	2	1	2	0,3	0,4	0,2	0,1	0,4	1,2	UDI=90.1 Adp.Comfort=73.6
Gen_39 Sol_16	Construction 4	Configuration 3	0	1	2	1	2	0,3	0,2	0,2	0,1	0,4	1,6	UDI=91 Adp.Comfort=70.3
Gen_39 Sol_17	Construction 4	Configuration 3	0	1	2	1	2	0,3	0,2	0,1	0,1	0,4	1,2	UDI=91.7 Adp.Comfort=66.5
Gen_39 Sol_18	Construction 4	Configuration 3	20	1,5	2	1,5	2	0,3	0,4	0,2	0,1	0,4	1,2	UDI=91.8 Adp.Comfort=66
Gen_39 Sol_19	Construction 4	Configuration 3	0	1	2	1,5	2	0,2	0,4	0,2	0,1	0,4	1	UDI=90.2 Adp.Comfort=73
Gen_39 Sol_20	Construction 4	Configuration 3	20	1,5	2	1,5	2	0,3	0,4	0,2	0,1	0,4	1	UDI=91.3 Adp.Comfort=67.9
Gen_39 Sol_21	Construction 4	Configuration 3	0	1	2	1	1,5	0,3	0,2	0,1	0,1	0,4	1,2	UDI=91.5 Adp.Comfort=67
Gen_39 Sol_22	Construction 4	Configuration 3	20	1,5	2	1,5	2	0,3	0,4	0,2	0,1	0,4	1,2	UDI=91.8 Adp.Comfort=66
Gen_39 Sol_23	Construction 4	Configuration 3	0	1	2	1,5	2	0,4	0,5	0,2	0,1	0,4	1,2	UDI=91.4 Adp.Comfort=67.2
Gen_39 Sol_24	Construction 4	Configuration 3	20	1,5	2	1,5	2	0,4	0,5	0,1	0,1	0,4	1,2	UDI=93 Adp.Comfort=58.6

Pareto-solutions parameters | Strategy 2

Table 10 – Pareto-solutions parameters

Name	Construction type	Layout	Rotation angle	Recess - North (m)	Recess - East (m)	Recess - South (m)	Recess - West (m)	WWR - North	WWR - East	WWR - South	WWR - West	WWR - View	Window height (m)	Results
Gen_39 Sol_0	Construction 4	Configuration 3	0	0,4	0,4	0,2	0,4	0,5	0,3	0,2	0,1	0,5	1,6	UDI=91.1 Adp.Comfort=55.8
Gen_39 Sol_1	Construction 4	Configuration 3	0	0,2	0,4	0,2	0,4	0,4	0,3	0,1	0,1	0,5	1,6	UDI=92 Adp.Comfort=52.9
Gen_39 Sol_2	Construction 4	Configuration 3	0	0,2	0,4	0,2	0,4	0,4	0,3	0,2	0,1	0,5	1,6	UDI=90.9 Adp.Comfort=58.8
Gen_39 Sol_3	Construction 4	Configuration 3	0	0,2	0,4	0	0,4	0,4	0,1	0,1	0,1	0,5	1,6	UDI=91.8 Adp.Comfort=54.6
Gen_39 Sol_4	Construction 4	Configuration 3	0	0,4	0,4	0,2	0,4	0,4	0,3	0,3	0,1	0,5	1,2	UDI=89 Adp.Comfort=62.5
Gen_39 Sol_5	Construction 4	Configuration 3	0	0,2	0,4	0	0,4	0,4	0,3	0,3	0,1	0,5	1,2	UDI=88.1 Adp.Comfort=65.4
Gen_39 Sol_6	Construction 4	Configuration 3	0	0,4	0,4	0,2	0,4	0,4	0,3	0,3	0,1	0,5	1,6	UDI=88.8 Adp.Comfort=63.9
Gen_39 Sol_7	Construction 4	Configuration 3	0	0,4	0,4	0	0,4	0,4	0,3	0,2	0,1	0,5	1,6	UDI=90.2 Adp.Comfort=61.3
Gen_39 Sol_8	Construction 4	Configuration 3	0	0,2	0,4	0	0,4	0,4	0,1	0,1	0,1	0,5	1,6	UDI=91.8 Adp.Comfort=54.6
Gen_39 Sol_9	Construction 4	Configuration 3	0	0,2	0,4	0	0,4	0,4	0,1	0,2	0,1	0,5	1,4	UDI=90.1 Adp.Comfort=62.3
Gen_39 Sol_10	Construction 4	Configuration 3	0	0,2	0,4	0,2	0,4	0,5	0,3	0,1	0,1	0,5	1,2	UDI=92.1 Adp.Comfort=52.6
Gen_39 Sol_11	Construction 4	Configuration 3	0	0,2	0,4	0	0,4	0,4	0,2	0,1	0,1	0,5	1,2	UDI=91.6 Adp.Comfort=55.3
Gen_39 Sol_12	Construction 4	Configuration 3	0	0,2	0,4	0	0,4	0,4	0,1	0,1	0,1	0,5	1,4	UDI=91.7 Adp.Comfort=55
Gen_39 Sol_13	Construction 4	Configuration 3	0	0,4	0,4	0,2	0,4	0,4	0,2	0,3	0,1	0,5	1,2	UDI=89 Adp.Comfort=62.5
Gen_39 Sol_14	Construction 4	Configuration 3	0	0,4	0,4	0	0,4	0,4	0,3	0,2	0,1	0,5	1,8	UDI=90.3 Adp.Comfort=61
Gen_39 Sol_15	Construction 4	Configuration 3	0	0,4	0,4	0,2	0,4	0,4	0,3	0,3	0,1	0,5	1,4	UDI=88.9 Adp.Comfort=63.4
Gen_39 Sol_16	Construction 4	Configuration 3	0	0,4	0,4	0,2	0,4	0,5	0,3	0,1	0,1	0,5	1,6	UDI=92.3 Adp.Comfort=51.9
Gen_39 Sol_17	Construction 4	Configuration 3	0	0,2	0,4	0,2	0,4	0,4	0,3	0,2	0,1	0,5	1,6	UDI=91.1 Adp.Comfort=58.1
Gen_39 Sol_18	Construction 4	Configuration 3	0	0,4	0,4	0	0,4	0,5	0,3	0,1	0,1	0,5	1,6	UDI=92 Adp.Comfort=53.5
Gen_39 Sol_19	Construction 4	Configuration 3	0	0,2	0,4	0	0,4	0,4	0,1	0,3	0,1	0,5	1	UDI=88.4 Adp.Comfort=65.2

Pareto-solutions parameters | Strategy 3

Table 10 – Pareto-solutions parameters

Name	Construction type	Layout	Rotation angle	Shades width and separation	Shades angle	Shades position	WWR - North	WWR - East	WWR - South	WWR - West	WWR - View	Window height (m)	Results
Gen_39 Sol_0	Construction 4	Configuration 3	20	0,1	30	exterior	0,2	0,4	0,1	0,1	0,4	1,8	UDI=87.3 Adp.Comfort=76.7
Gen_39 Sol_1	Construction 4	Configuration 3	-20	0,08	30	exterior	0,2	0,5	0,3	0,1	0,4	1,2	UDI=78.6 Adp.Comfort=87.1
Gen_39 Sol_2	Construction 4	Configuration 3	-20	0,08	30	exterior	0,2	0,4	0,3	0,1	0,4	1,2	UDI=78.7 Adp.Comfort=87.1
Gen_39 Sol_3	Construction 4	Configuration 3	0	0,1	30	exterior	0,2	0,3	0,3	0,1	0,4	1,8	UDI=79.9 Adp.Comfort=86.6
Gen_39 Sol_4	Construction 4	Configuration 3	-20	0,08	30	exterior	0,2	0,4	0,2	0,1	0,4	1,2	UDI=81.8 Adp.Comfort=86.1
Gen_39 Sol_5	Construction 4	Configuration 3	20	0,08	30	exterior	0,2	0,4	0,2	0,1	0,4	1,8	UDI=84.6 Adp.Comfort=83.3
Gen_39 Sol_6	Construction 4	Configuration 3	-20	0,08	30	exterior	0,2	0,4	0,1	0,1	0,4	1,2	UDI=84.7 Adp.Comfort=80.1
Gen_39 Sol_7	Construction 4	Configuration 3	0	0,1	30	exterior	0,2	0,4	0,1	0,1	0,4	1,8	UDI=86.2 Adp.Comfort=78.1
Gen_39 Sol_8	Construction 4	Configuration 3	-20	0,08	30	exterior	0,2	0,4	0,1	0,1	0,4	1,8	UDI=85.4 Adp.Comfort=79.7
Gen_39 Sol_9	Construction 4	Configuration 3	20	0,08	30	exterior	0,2	0,4	0,2	0,1	0,4	1,2	UDI=83.6 Adp.Comfort=83.6
Gen_39 Sol_10	Construction 4	Configuration 3	20	0,08	30	exterior	0,2	0,4	0,1	0,1	0,4	1,2	UDI=86.6 Adp.Comfort=77
Gen_39 Sol_11	Construction 4	Configuration 3	0	0,08	30	exterior	0,2	0,4	0,2	0,1	0,4	1,8	UDI=83.5 Adp.Comfort=85
Gen_39 Sol_12	Construction 4	Configuration 3	20	0,08	30	exterior	0,2	0,4	0,2	0,1	0,4	1,4	UDI=84 Adp.Comfort=83.5
Gen_39 Sol_13	Construction 4	Configuration 3	-20	0,08	30	exterior	0,2	0,4	0,2	0,1	0,4	1,8	UDI=82.8 Adp.Comfort=85.8
Gen_39 Sol_14	Construction 4	Configuration 3	0	0,08	30	exterior	0,2	0,4	0,1	0,1	0,4	1,2	UDI=85.6 Adp.Comfort=78.8
Gen_39 Sol_15	Construction 4	Configuration 3	-20	0,1	30	exterior	0,2	0,4	0,1	0,1	0,4	1,4	UDI=84.9 Adp.Comfort=80
Gen_39 Sol_16	Construction 4	Configuration 3	-20	0,08	30	exterior	0,2	0,4	0,2	0,1	0,4	1,4	UDI=82.1 Adp.Comfort=86
Gen_39 Sol_17	Construction 4	Configuration 3	0	0,08	30	exterior	0,2	0,4	0,2	0,1	0,4	1,4	UDI=82.8 Adp.Comfort=85.2
Gen_39 Sol_18	Construction 4	Configuration 3	-20	0,08	30	exterior	0,2	0,4	0,3	0,1	0,4	1,4	UDI=79 Adp.Comfort=86.9
Gen_39 Sol_19	Construction 4	Configuration 3	0	0,1	30	exterior	0,2	0,4	0,1	0,1	0,4	1,4	UDI=85.8 Adp.Comfort=78.5
Gen_39 Sol_20	Construction 4	Configuration 3	0	0,1	30	exterior	0,2	0,4	0,3	0,1	0,4	1,2	UDI=79.1 Adp.Comfort=86.9
Gen_39 Sol_21	Construction 4	Configuration 3	20	0,08	30	exterior	0,2	0,4	0,1	0,1	0,4	1,6	UDI=87.1 Adp.Comfort=76.8
Gen_39 Sol_22	Construction 4	Configuration 3	0	0,1	30	exterior	0,2	0,3	0,3	0,1	0,4	1,6	UDI=79.6 Adp.Comfort=86.6
Gen_39 Sol_23	Construction 4	Configuration 3	0	0,1	30	exterior	0,2	0,4	0,1	0,1	0,4	1,6	UDI=86 Adp.Comfort=78.3
Gen_39 Sol_24	Construction 4	Configuration 3	20	0,08	30	exterior	0,2	0,4	0,1	0,1	0,4	1,4	UDI=86.8 Adp.Comfort=76.9