



**A STUDY OF PASSIVE COOLING PRINCIPLES IN ARCHITECTURAL
DESIGN IN HOT-ARID CLIMATES: THE CASE OF TUNISIA**

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**IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE
IN ARCHITECTURE DEPARTMENT**

**GAZİ UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES**

JULY 2024

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25/07/2024

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(M.Sc. Thesis)

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July 2024

ABSTRACT

In the last decades, the earth's atmosphere experienced significant and accelerated warming due to human activities involving greenhouse gas emissions. The atmosphere's rising temperatures resulted in global climatic impacts such as heat waves, rising sea levels, heavy rainfall, wildfires, etc. (United Nations, 2023). According to the International Energy Agency (2019), the building sector is responsible for most of the annual energy consumption and global greenhouse gas emissions. Tunisia, the case of this study, is experiencing every year new temperature records matched with an increase in energy loads to satisfy cooling demands. Nevertheless, Tunisia has a rich architectural heritage, which has evolved throughout history to suit its geographical and climatic conditions. This study examines examples of Tunisian vernacular architecture to extract passive cooling techniques used in traditional dwellings. This is followed by a study of modern architectural projects that incorporate these techniques. The collected data is organized into a design guide for future buildings in hot-arid climates. Using the DesignBuilder program, a simulation is carried out to evaluate the efficiency of these passive cooling techniques. A modern house model is used to test different scenarios of passive cooling techniques and assess their impact on reducing heat gain and cooling loads. The simulation results show a significant reduction in annual energy cooling loads, reaching up to 75 % with an enhanced envelope system.

Science Code : 80130

Key Words: : Climate change, global warming, hot-arid climate, energy, Tunisia, vernacular architecture, passive cooling techniques

Page Number : 173

Supervisor : Prof. Dr. Figen BEYHAN

MİMARİ TASARIMDA PASİF SOĞUTMA İLKELERİNİN SICAK-KURU İKLİM BÖLGELERİNDE İNCELEMESİ: TUNUS ÖRNEĞİ

(Yüksek Lisans Tezi)

Samaher ABBESSI

GAZİ ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

Temmuz 2024

ÖZET

Son on yıllarda, dünyanın atmosferi insan faaliyetleri nedeniyle önemli ve hızlı bir ısınma yaşamıştır. Atmosferin sıcaklığının artması; ısı dalgaları, deniz seviyesinin yükselmesi, aşırı yağış, orman yangınları gibi küresel iklim etkilerine yol açmıştır (Birleşmiş Milletler, 2023). Uluslararası Enerji Ajansı'na göre, (2019), inşaat sektörü yıllık enerji tüketiminin ve küresel sera gazı emisyonlarının çoğundan sorumludur. Çalışmanın örneği olan Tunus, her yıl yeni sıcaklık rekoru yaşamaktadır. Bu sıcaklık sorunu, soğutma taleplerini karşılamak için enerji tüketimini artırmaktadır. Bununla birlikte, Tunus'un tarihi boyunca coğrafi ve iklimsel koşullarına uyum sağlayan zengin mimari mirası vardır. Bu çalışmada, geleneksel konutlarda kullanılan pasif soğutma sistemlerini çıkarmak için Tunus yerel (vernaküler) mimarisinin örnekleri analiz edilmektedir. Bunu takiben, pasif soğutma teknikleri benimseyen modern mimari projeler araştırılmaktadır. Toplanan veriler, sıcak-kuru iklimlerdeki gelecekteki binalar için bir tasarım kılavuzunda organize edilmektedir. DesignBuilder programı kullanılarak, bu pasif soğutma tekniklerinin verimliliğini değerlendirmek için bir simülasyon gerçekleştirilmiştir. Farklı pasif soğutma tekniklerinin senaryolarını test etmek ve ısı kazanımını ve soğutma yüklerini azaltmadaki etkilerini değerlendirmek için modern bir ev modeli kullanılmıştır. Simülasyon sonuçları, geliştirilmiş bina kabuğu sistemi ile enerji soğutma yüklerinde %75'e varan önemli bir azalma olduğunu göstermektedir.

Bilim Kodu : 80130

Anahtar Kelimeler : İklim değişikliği, küresel ısınma, sıcak-kuru iklim, enerji, Tunus, vernaküler mimari, pasif soğutma teknikleri

Sayfa Adedi : 173

Danışman : Prof. Dr. Figen BEYHAN

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisor, Prof. Dr. Figen Beyhan, for her unwavering support, guidance, and encouragement throughout my master's degree journey in Architecture. Her expertise and dedication have been invaluable to the successful completion of this thesis.

This achievement is dedicated, first and foremost, to my late father, Mustapha ABBESSI, whose memory continues to inspire me daily. To my mother, Hadia SAKET, my primary source of support and strength, to my siblings, to my partner Adil, and to all my friends, thank you for your support and encouragement.

Special gratitude is extended to the Türkiye Bursları Program for supporting my master's degree education. This journey has been made possible through this invaluable assistance.

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SYMBOLS AND ABBREVIATIONS

The symbols and abbreviations used in this study are presented below, along with their explanations.

Symbols	Explanations
ac/h	Air change per hour
cm	Centimeter
CO₂	Carbon dioxide
h	Hour
kg	Kilogram
kWh	kilowatt hour
kWh/m²	kilowatt hour per square meter
mm	Millimeter
m	Meter
m²	Square meters
m³	Cubic meter
R-value	Thermal resistance
U-value	Thermal transmittance
%	Percentage
°	Degree
° C	Temperature in Celsius

Abbreviations	Explanations
HVAC	Heating, ventilation, and air conditioning
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
NASA	National Aeronautics and Space Administration
NIM	National Institute of Meteorology
PCM	Phase Change Materials
TS	Turkish Standard (Türk Standardı)

Abbreviations**Explanations**

UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific, and Cultural Organization
WHR	Width-to-Height-Ratio
WWR	Window-to-Wall-Ratio



1. INTRODUCTION

Historically, Earth's climate has changed due to natural causes like orbital shifts, atmospheric and surface changes, and variations in solar energy. While these natural factors are still present today, their impact is minimal. In contrast, over the past century, the rapid warming of Earth's atmosphere has been primarily due to human activities, particularly the burning of fossil fuels, which release significant amounts of greenhouse gases, leading to an unprecedented rise in Earth's average surface temperature (NASA, 2010).

The most significant aspect of climate change is global warming, characterized by the rise in Earth's atmospheric and oceanic temperatures, which affects the entire world with regional variations. This increase in global temperature is just the beginning, leading to severe consequences such as rising sea levels, altered precipitation patterns, expanded subtropical deserts, more frequent heat waves, ocean acidification, droughts, and heavy rainfall. These changes negatively impact health, food security, housing, safety, and work. Vulnerable populations, particularly those in developing countries, are already experiencing and will continue to face severe impacts. The future is likely to see a rise in "climate refugees" as people are displaced by these climate-related issues (United Nations [UN], 2023). In 2023, the world experienced unprecedented heat, with global temperatures nearing the critical threshold of 1.5°C above pre-industrial levels. "The era of global warming has ended. The era of global boiling has arrived." So announced United Nations Secretary-General Antonio Guterres as it was confirmed that July 2023 had become the hottest month ever recorded. This year (2024) also is experiencing extreme weather events such as heatwaves, floods, droughts, and wildfires, which caused significant economic losses and displaced millions of people (UN News, 2024; UN Press, 2024).

In both developed and developing countries, as greenhouse gas emissions are the main cause of global warming, the building sector is responsible for 36% of all energy consumption and 40% of global annual greenhouse gas emissions (IEA, 2019). The impact of the building sector on climate change is multifaceted and significant. Construction materials like concrete, steel, and glass have substantial environmental impact due to processes like extraction, manufacturing, and transportation, all of which contribute to carbon emissions. The choice of materials not only affects a building's energy efficiency but also its resilience

to increasing climate challenges. In addition, building design and operational practices play a crucial role in determining energy performance and environmental footprint. Factors such as building orientation, insulation, efficient HVAC systems, and integration of renewable energy sources are pivotal in reducing energy consumption and emissions throughout a building's lifespan. Moreover, the concentration of buildings in urban areas can exacerbate the urban heat island effect, leading to higher temperatures and increased energy demands for cooling. As climate change progresses, buildings also need to adapt to new climatic conditions. Designing resilient buildings that can withstand these challenges while minimizing environmental impact is essential for sustainable development and mitigating further climate change impacts.

Problem situation / Description of the topic

Tunisia, as a country already situated within a hot climate region, undoubtedly experiences the tangible effects of climate change in the form of severe heat waves. Climate surveys and studies conducted in Tunisia provide alarming evidence of the temperature rise records across diverse areas each year. Following the record-breaking heat of 2022, Tunisia experienced its third hottest year on record in 2023. July of that year saw unprecedented temperatures, making it the hottest month ever recorded in Tunisia and shattering multiple maximum temperature records. The peak temperature reached during July 2023 was 49.1°C, recorded at two different stations across the country (National Institute of Meteorology [NIM], 2024). This rise in temperature is accompanied by an increase in energy loads required to satisfy the cooling demands in indoor spaces, especially in residential buildings. However, Tunisia is a developing country that has been suffering from an ongoing economic crisis for at least a decade. Consequently, the government lacks the essential resources to effectively tackle the rising temperatures, and the electricity supply faces continuous interruptions during the summer months due to excessive cooling loads. On the other side, since 1987 Tunisian cities have witnessed an increase in the constructed areas and therefore an increase in the urban temperature average. The overheating of the buildings is explained by the use of modern techniques and materials in construction. Added to that is the lack of planned green spaces within urban areas. To satisfy cooling demands, the use of air conditioners became a common characteristic of city life, and the energy loads in summer exceeded the average of all seasons (Daoud and Dahech, 2012). Consequently, Tunisia is facing a challenging dilemma due to the combination of modern architectural constraints and

the prevailing climate change conditions. Without implementing different strategies in the construction sector to mitigate energy consumption and enhance indoor comfort, the country's social and economic challenges are supposed to escalate.

The ancient wisdom of vernacular architecture has impressive potential solutions for facing harsh weather by providing comfort qualities, climatic adaptability, and economic feasibility, which are required for today's climatic and economic issues. Over the past few decades, architects have increasingly emphasized the efficacy of vernacular architecture principles in terms of sustainability and energy performance. According to Oliver (2003), vernacular architecture is considered one of the most efficient and eco-friendly approaches because it utilizes locally sourced materials in construction, minimizing waste generation, and incorporates passive cooling, heating, and ventilation methods. In this context, sustainability includes respecting local culture, emphasizing indigenous materials and designs, and being mindful of the existing built environment in the specific geographical location. Vernacular architecture places importance on preserving historical structures as cultural landmarks and models for future construction. Tunisia is a country abundant with architectural heritage throughout its various regions. This indigenous architecture, unique to the Tunisian geography and climate, has been carefully designed to help the adaptation of its inhabitants to their environment. Notably, traditional dwellings present an exemplary of energy efficiency and indoor comfort. Vernacular architecture embodies a compelling understanding of the surrounding natural elements, utilizing local materials and construction techniques that minimize environmental impact. Furthermore, traditional dwellings take advantage of passive cooling strategies, harnessing natural ventilation and shading to create comfortable living spaces even during extreme temperatures. The different examples of traditional architecture within Tunisia exhibit distinct features carefully tailored to harmonize with the specific geographical and climatic characteristics of each site. However, a set of shared principles emerges across all the Tunisian dwellings, reflecting a common understanding of how to fit in this environment.

Purpose of the research

This research attempts to develop a design guide tailored for new buildings in hot-arid climates, inspired by the principles of Tunisian vernacular architecture. The guide aims to provide designers with passive cooling techniques and practical instructions to improve

indoor comfort while reducing energy consumption and environmental impact. The study includes an analysis of traditional dwellings in Tunisia to identify effective passive cooling strategies and evaluate their energy efficiency. Using computer simulation, the research evaluates the performance of these techniques and proposes strategies for their integration into contemporary residential buildings.

Importance of research

Awareness of climate issues is growing on a daily basis, leading to an increase in studies and research aimed at addressing these challenges. This study aims to contribute to global efforts by enhancing the role of the building sector in mitigating the effects of climate change. In Tunisia, concerns about climate issues, particularly in the building sector and architectural design, have not yet received adequate attention and there is a lack of sufficient research on the subject. Therefore, this work serves as an appropriate design guide specifically tailored to this context. It provides valuable insights for future studies and can be used in the design of new buildings, thus contributing to the promotion of sustainable practices in the Tunisian construction industry.

2. LITERATURE REVIEW

The study of passive cooling techniques inherent in Tunisian vernacular architecture reveals a wealth of traditional practices designed to mitigate the region's intense heat. Analyzing examples of these vernacular buildings provides valuable insights into how they naturally maintain thermal comfort with zero energy consumption. This literature review first examines specific examples of vernacular architecture in Tunisia to identify and understand the passive cooling strategies employed. Then, it examines the application of these traditional principles in modern architectural contexts. The goal is to demonstrate how these ancient techniques can be effectively integrated into contemporary designs to enhance the sustainability and energy efficiency of modern buildings. Through this dual analysis, the report seeks to bridge the gap between past and present, demonstrating the enduring relevance of vernacular architecture in addressing current environmental and climate challenges.

2.1. Climate Change

Climate change is the framework of this study, so this section provides a comprehensive understanding of climate change, including its causes and manifestations, as a basis for recognizing its profound implications for the built environment. As a major contributor to greenhouse gas emissions and energy consumption, the building sector plays a critical role in both amplifying and mitigating climate change. Understanding this complicated interaction is essential to developing effective architectural solutions. The impact of climate change on humanity is multifaceted, and addressing the challenges posed by climate change in the context of the building sector is critical to promoting sustainability and resilience.

2.1.1. Global impact

First, it is important to understand the difference between the terms "global warming" and "climate change," because sometimes people tend to use these terms interchangeably. "Global warming is just one aspect of climate change. "Global warming refers to the increase in the temperature of the planet's atmosphere, which is a prominent result today in all regions. However, "climate change" encompasses global warming and refers to all the changes that

are happening to our planet, such as rising sea levels, shrinking mountain glaciers, shifts in the seasons of flowers and plants, etc. (National Aeronautics and Space Administration [NASA], 2024a). According to the United Nations, the rise in global temperature is only the beginning of these changes. Other consequences will follow. Climate change can affect our health, ability to grow food, housing, safety, and work. Some of us are already more vulnerable to climate impacts, such as people living in small island nations and other developing countries. In the future, the number of "climate refugees" is expected to increase (United Nations [UN], 2023).

In Earth's history before the Industrial Revolution, the Earth's climate changed due to natural causes such as subtle shifts in its orbit, changes in its atmosphere and surface, and variations in the Sun's energy. These natural causes are still at work today, but their influence is too small. However, the recent warming of the last century is much faster than the warming patterns of the past. This could be explained by artificial causes that are the result of human activities. The unusually rapid increase in the Earth's average surface temperature over the past century is primarily due to the greenhouse gases released by human burning of fossil fuels (NASA, 2010). The figure below shows that, despite ups and downs from year to year, the global average surface temperature of the Earth has risen, especially toward the end of the 20th century. The Earth's temperature was about 0.5 degrees Celsius above the long-term average (1951-1980), with 2020 and 2016 being the hottest years on record (NASA, 2024b).

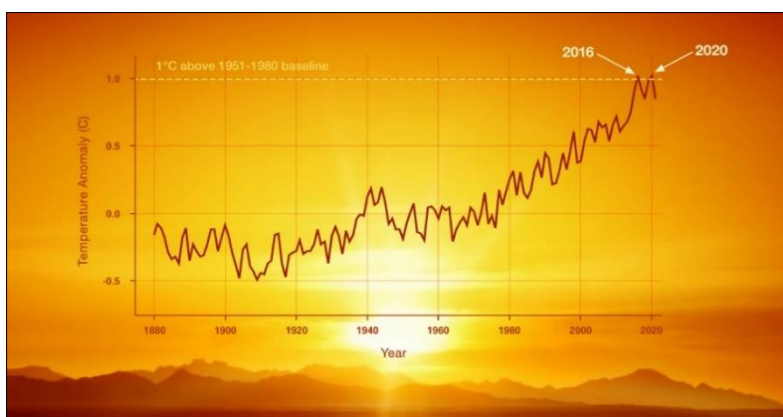


Figure 2.1. The earth's global average surface temperature change between 1880 and 2020 (NASA, 2024a)

According to a special report published by the Intergovernmental Panel on Climate Change [IPCC] (2019), global warming between 2006 and 2015 was about 1.0°C, which is higher

than the average for the period between 1850 and 1900. Estimated human-induced global warming is currently increasing at 0.2°C per decade due to past and ongoing emissions. If temperatures continue to rise at the current rate, global warming is projected to reach 1.5°C between 2030 and 2052.

The graph below shows four possible scenarios of global temperature change according to the four Representative Concentration Pathways (RCPs¹) adopted by the IPCC. The vertical bars on the right show the possible temperature ranges by the end of the century, while the lines show four different projections averaged across a range of climate models. The changes are relative to the 1986-2005 average. RCP 2.6, which represents a global temperature increase of between 1.5 and 2°C , is considered the most optimistic scenario. It is based on the assumption of rapid and widespread implementation of climate policies around the world to help stabilize global temperature change (IPCC, 2019).

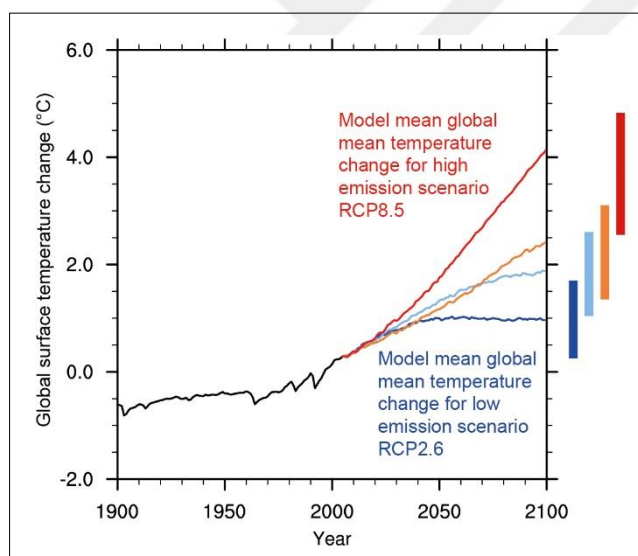


Figure 1.2. Observed and projected changes in global average temperature under the four RCPs (URL-30)

¹The RCPs comprise a set of four GHG concentration trajectories that jointly span a large range of plausible human-caused climate forcing ranging from 2.6 W m^{-2} (RCP2.6) to 8.5 W m^{-2} (RCP8.5) by the end of the 21st century.

2.1.2. Architecture and climate change

As greenhouse gas emissions are the primary cause of global warming in both developed and developing countries, the building sector is responsible for 36% of total energy consumption and 40% of annual global greenhouse gas emissions (Figure 2.3) (International Energy Agency [IEA], 2019). The energy consumed by the building sector is related to the construction method, the materials and techniques used during construction, and the function of the building during its life cycle. The building sector therefore has a potential impact on greenhouse gas emissions and climate change.

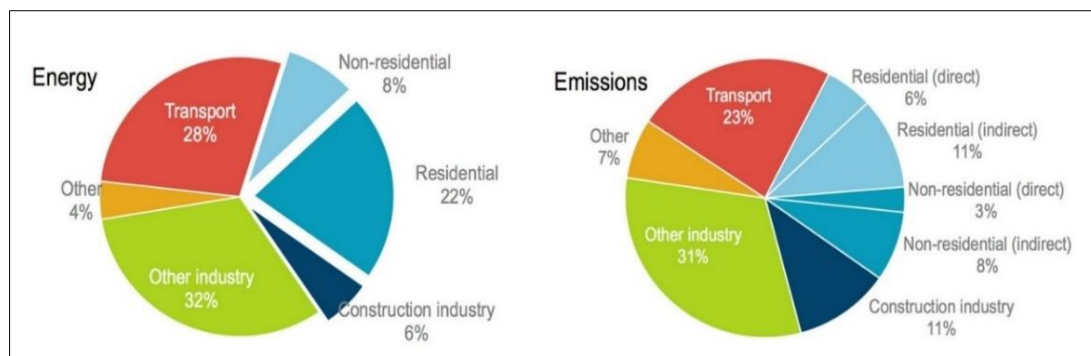


Figure 2.3. Global share of buildings and construction in energy consumption (left) and GHG emissions (right) (IEA, 2019)

Most greenhouse gas emissions from buildings are due to the consumption of fossil fuel-based energy, including the direct use of fossil fuels and the use of electricity generated from fossil fuels. "Significant greenhouse gas emissions are also generated by building materials, particularly insulation materials, and refrigeration and cooling systems (United Nations Environment Programme [UNEP], 2009). In addition, buildings house most of our social, business, cultural, and private activities, as we tend to spend a very large part of our time indoors (often more than 90% of our day). The building sector represents a major challenge in the "battle" to mitigate the causes and effects of climate change. Therefore, human settlements have undoubtedly been identified as one of the main contributors to the current climate crisis (Steemers, 2003). Between 1970 and 1990, direct greenhouse gas emissions from buildings, excluding those due to electricity consumption, increased by 26%. When the electricity required to operate mechanical systems and services such as heating and cooling is included, the total increase in direct and indirect emissions from the building sector is higher (75%) than direct emissions alone (IPCC, 2007).

In hot climates, it is estimated that almost half of the urban peak energy consumption is used to meet air-conditioning cooling demand in summer. As the rate of urbanization in developing countries, like Tunisia, increases rapidly, so does the pressure on energy resources to meet indoor comfort. Therefore, greenhouse gas emissions from buildings will double in the coming decades if nothing is done in the building sector. Moreover, given the uncertain future costs and availability of hydrocarbon-based forms of energy, the development of design strategies for buildings to reduce their dependence on fossil fuels, curb their energy demand, use clean energy sources, and minimize their waste is becoming an imperative goal to be achieved.

Architects, as building designers, play an important role in controlling greenhouse gas emissions from buildings. Through building design and construction management, architects can make choices and implement changes by selecting building materials and construction techniques that are more environmentally friendly. The architect's impact on greenhouse gas emissions goes beyond designing a comfortable and energy-efficient building to include minimizing the urban heat island effect.

2.1.3. Local impact

Defining the local impacts of climate change in Tunisia is crucial to understanding the climatic context of the study case. The impact of climate change varies considerably from one country to another, influenced by various factors such as geographical location, topography, and prevailing climatic conditions. In this section, the specific impacts of climate change on Tunisia will be examined in detail, taking into account its specific climatic and geographical characteristics, and the intricate relationship between these impacts and the local built environment.

The climatic and geographic characteristics of Tunisia have contributed to the magnification of climate change impacts. Despite its proximity to the sea, the country's relatively small land area and the influence of Saharan desert conditions are evident in its climate. Tunisia's predominantly hot climate has further amplified the local manifestation of global warming.

Geography and climate of Tunisia

Tunisia is the northernmost country in Africa, located on the southern shore of the Mediterranean Sea at the junction of the eastern and western Mediterranean basins. Tunisia is surrounded on the west, south, and southeast by two large neighbors: Algeria and Libya, and on the north and east by the Mediterranean Sea (Map 2.1.). The total area of the country is 164000 km² and the length of the coastline is 1300 km (Ministry of Local Affairs and the Environment and UNDP, n.d.).



Map 2.1. Tunisia location on the map, created by author

The Tunisian territory is characterized by different geographies (Map 2.2. (a)): In the north, the Dorsal, an extension of the Saharan Atlas Mountains, crosses Tunisia in a southwest-northeast direction from the Algerian border to the Cape Bon peninsula. In the south of the Tunisian Dorsal lies a hilly region known as the High Steppe in the west and the Low Steppe in the east, these regions are part of the Mediterranean dry woodlands and steppe².

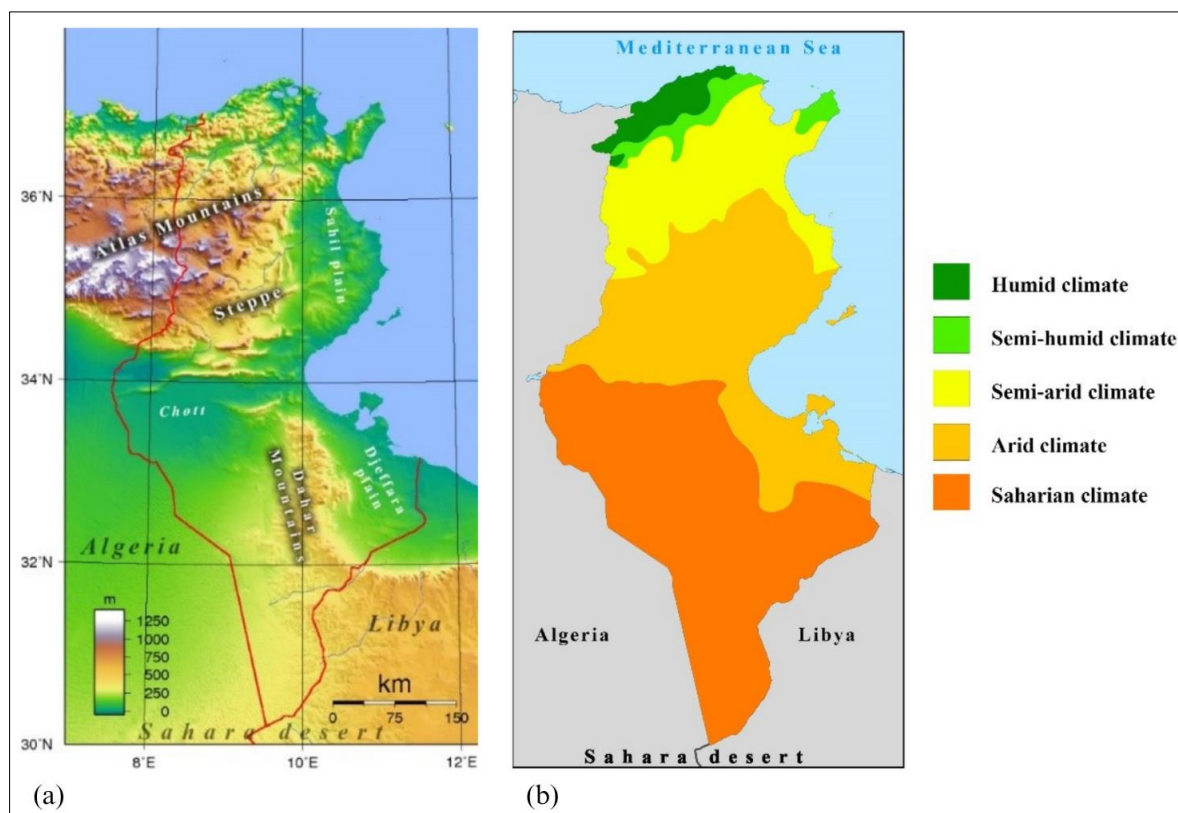
In the southwest of the steppe region, there is a series of salty lake depressions called Chott³. On the eastern coast border lies two large plains: the first extends from north to south called

² Mediterranean forest, woodland, and scrub ecoregion of North Africa. It is located in the southern plateau of the Saharan Atlas Mountains and the northern region of the Sahara Desert.

³ Or *Shatt*, salty lakes, in Arabic language.

Al-Sahil⁴ (the Sahel) and the second is in the south called Djeffara Plain. To the west of the Djeffara plain, a series of low mountains called the Dahar extend from the Libyan border in the southeast to the north. The extreme south is a largely sandy desert, much of which is part of the Sahara Desert (Britannica, 2024).

Tunisia has a Mediterranean climate characterized by hot, dry summers and cool, wet winters. Rainfall, humidity, and wind speed vary according to the country's diverse geography.



Map 2.2. (a) Tunisia relief map Map (URL-31), (b) Bioclimatic regions in Tunisia (Ministry of Local Affairs and the Environment and UNDP, n.d.) modified by author

The relatively high latitude of Tunisia and its geographical extension from the north to the south give it the following succession of climatic zones (Map 2.2. (b)): humid and subhumid in the far north, semi-arid in the north, arid in central Tunisia, and desert (Saharan) in the entire southern part. Most of the Tunisian territory is therefore affected by a hot and dry climate (Ministry of the Environment, 2022).

⁴ In Arabic language, means the coast.

The Tunisian climate is influenced by the Mediterranean climate from the north and the arid desert climate from the south. The northern mountainous regions have a Mediterranean climate with mild, rainy winters and hot, dry summers. The south has a hot, dry, and arid climate as it enters the Sahara, while the eastern coastal border has an arid steppe climate. Tunisia receives relatively low average annual rainfall with 158 mm per year for the whole country and less than 100 mm per year in the south (Climate Change Knowledge Portal, 2021a).

Temperatures vary according to latitude, altitude, and proximity to the Mediterranean Sea. The average annual temperatures are high, between 16°C and 23°C, and they exceed 18°C in three-quarters of the country (Figure 2.4. (b)). In winter the average temperature is 12°C in December and in summer 30°C in July. While winter temperatures can drop a few degrees below 0°C in the mountains of Kroumirie, summer temperatures can reach around 50°C in the shade in the desert regions. The country also enjoys a high level of sunshine, over 3,000 hours per year (Ministry of the Environment and National Institute of Meteorology [NIM], 2023).

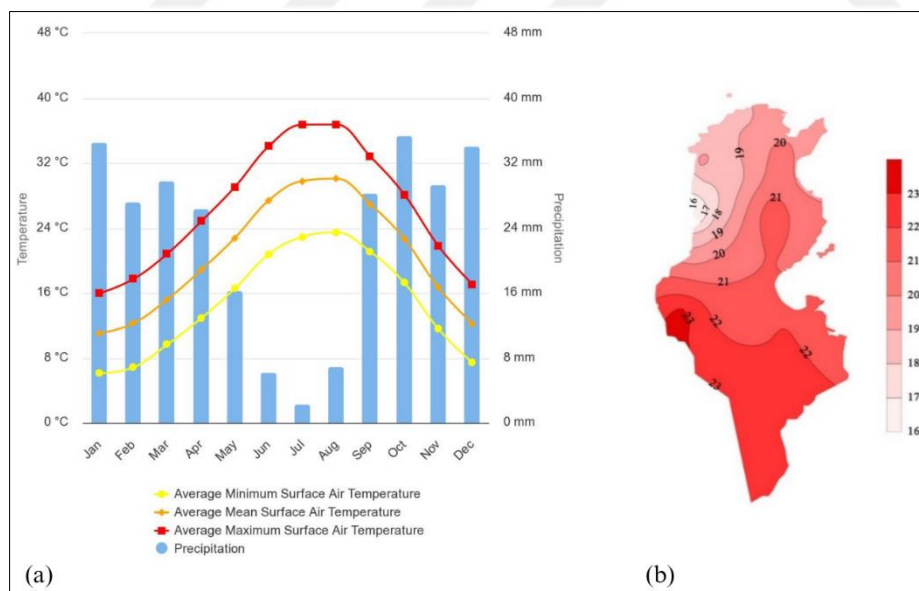


Figure 2.4. (a) Climatic chart of Tunisia 1991-2020 (Climate Change Knowledge Portal, 2021a), (b) Annual temperature average of the year 2020 (NIM, 2020b)

Tunisia's climate is largely influenced by two main types of winds. Along the northern coast, moderate and humid sea winds blow from the south of France, causing a significant drop in temperature and an increase in rainfall during the winter. These winds blow mainly from the

northwest and prevail for most of the year, unlike other wind directions. Conversely, the southern region experiences hot and dry continental winds known as the Sirocco, which originate in the Sahara Desert. These winds persist throughout the year, bringing extremely hot and dry conditions, especially in the summer. Known as the "Chili"⁵ in Tunisia, these winds occur when a surface low-pressure system moves into the Gulf of Gabes (Figure 2.5. (b)). As a result, winds blow from the southwest to the north, crossing Tunisia (Hassanien and Darwish, 2023; Mohamed, 2014; Weather Online, 2024).

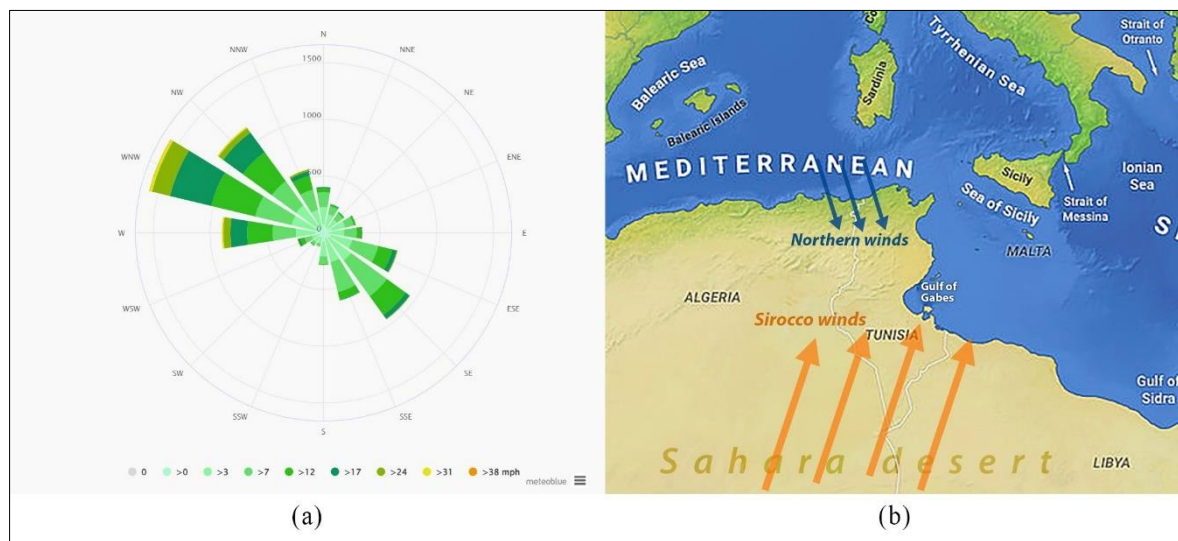
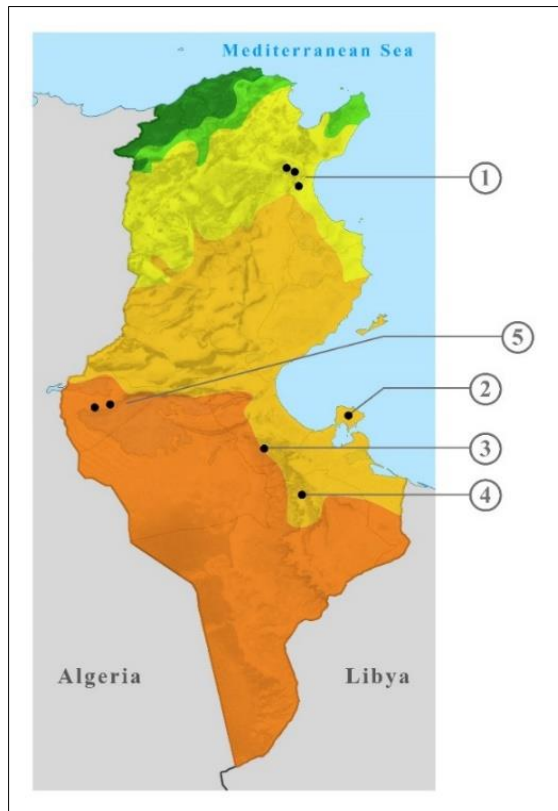


Figure 2.5. (a) Hours per year of wind direction in Tunisia (URL-32), (b) Prevailing winds direction on map (created by author)

Geography and climate of the studied regions

The examples of vernacular architecture that will be the subject of this study are situated in different regions. The selection of these examples is mainly based on architectural considerations, which will be explained in more detail in the section. At this point, the geographical and climatic characteristics of each site are identified, as these affect the analysis of the passive cooling techniques. All the examples studied are located in hot-arid climates, with slight differences in the geographic and climatic data of each region.

⁵ In the local language it means extremely hot winds.



Map 2.3. Studied regions location on map, created by author

The first example is the three villages of Zriba Olia, Takrouna, and Jradou in the northeast. These villages are built on rocky hills close to each other and have the same geographical characteristics. Zriba Olia is located at an altitude of 312 m, Takrouna at 195 m, and Jradou at about 205 m. Despite their proximity to the sea (the coast is at most 30 km away), the climate in these regions is semi-arid, with hot summers and cold winters. The prevailing winds from the northwest are strong and frequent (Ammar and Panerai, 2010).

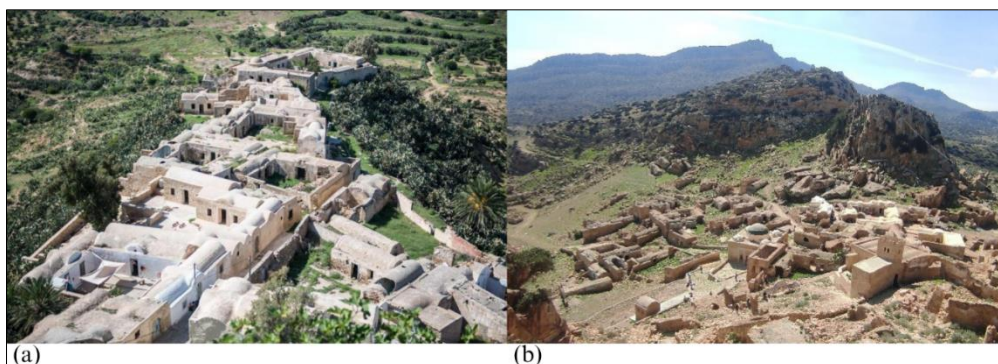


Image 2.1. (a) An overview of Zriba Olia village (URL-33), (b) An overview of Takrouna village (URL-34)

The second example is the island of Djerba in the southeast, designated as a World Heritage Site by UNESCO in 2023. The relief of the island is low and flat and consists of thick layers of gypsum marl and pink travertine that cover the entire area. The flora consists mainly of palm trees, olive trees, and cacti. The island's peculiar location between the Mediterranean and the Sahara creates a Mediterranean climate that tends to be dry. The direction of the winds varies according to the season: from November to March, westerly winds predominate, and from March to October, easterly winds prevail. Saharan winds also blow on the island from the end of spring and during the summer (Djerbi, 2011).



Image 2.2. An overview of Djerba island (URL-35)



Image 2.3. An overview of Matmata village (URL-36)

The third example is the village of underground houses in Matmata in the southeast. The village is located on a plateau at an altitude of 400 m, surrounded by mountain peaks of 515 m. The terrain consists of loess deposits containing clay and gypsum. The climate in this

region is arid and temperatures usually reach 50°C in summer (Golany, 1988).

The fourth example is the villages of Cheninni and Douiret, below the site of Matmata in the southeast. These villages contain troglodyte houses built on terraced mountain slopes. The geology of the mountain is characterized by steep slopes with soft material layers of marble and clay. The mountain peaks could reach over 600 m in height. The climate in this region is desert, but the altitude of the mountains creates a milder microclimate. The geographical position between the Mediterranean Sea to the east and the Sahara to the south results in a temperature difference between day and night and between winter and summer. The prevailing winds in this region are from the southwest (Znidi, 2018).

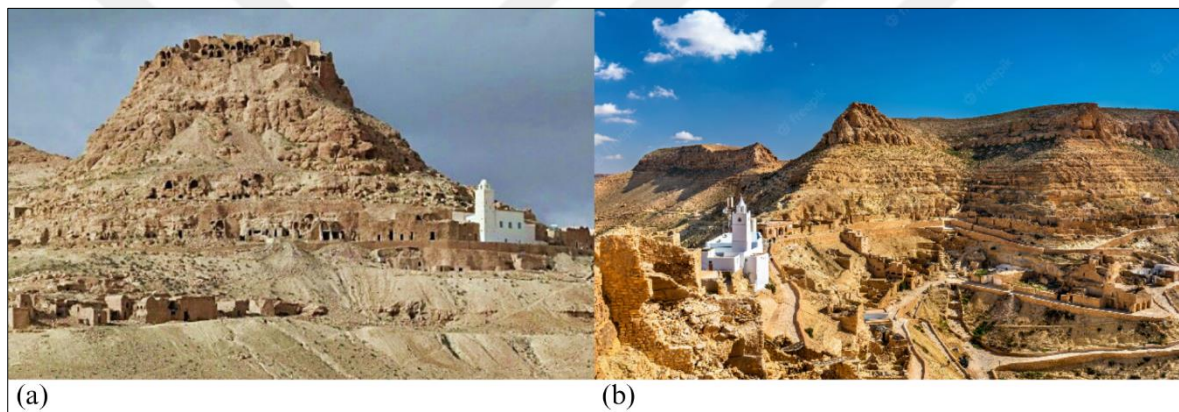


Image 2.4. (a) An overview of Cheninni village (URL-37), (b) An overview of Douiret village (URL-38)

The fifth example is the Djérid region in the southwest, including the old towns of Nafta and Tozeur. This Djérid region is characterized by depressions with salty lakes and palm forests. The land is generally semi-desert and flat. The region is too far from the sea, located on the northern border of the Sahara, and from the north is limited by mountains, which make it the driest and hottest region of the country. The temperature differences between day and night are too important. This region is subject to the hot Sirocco winds at the end of spring. The mild winds from the northeast are warmed when they reach the region (Alkalyouby, 2016; Farid, 2012). The old towns are usually surrounded by paltrees.



Image 2.5. An overview of Nafta city (URL-39).

The table below shows the climate data of each region, including the climate zone, the recorded maximum and minimum temperatures, and the average humidity levels.

Table 2.1. Studied regions' climatic data for the period 2010-2020 (NIM; Weather and Climate, 2024)

Region	Climate type	Record high temperature in summer (°C)	Record low temperature in winter (°C)	Average relative humidity per year (%)
Zriba Olia village	Semi-arid climate	38.92	2.92	64.08
Djerba island	Arid climate	48.95	3.19	51.52
Matmata village	Arid climate	43.11	3.92	51.81
Cheninni and Douiret villages	Arid climate	44.76	4.07	53.79
Djérid region	Desert climate	50.91	3.18	39.82

Impact of climate change in Tunisia

Tunisia shares global concerns about climate change. The irregularity of rainfall, the increase in temperature and the frequency of extreme climatic phenomena are all indicators that expose the Tunisian ecosystems and population to a high vulnerability to the influence of climatic variations. Climate surveys and studies carried out in Tunisia show with certainty that the country is already suffering and will continue to suffer for a long time from the effects of climate issues, especially those related to the increase in temperature, the decrease

in precipitation, and, obviously, the rise in sea level, since Tunisia has a long coastline (1,300 km) compared to its surface area.

According to the graph below, it is clear that the energy sector, primarily represented by the building sector in Tunisia, stands out as the most significant contributor to greenhouse gas (GHG) emissions. This sector alone is responsible for nearly 58% of Tunisia's total direct gross GHG emissions, amounting to approximately 27 million tons of CO₂ equivalent (tCO₂e⁶). Furthermore, the dominant share of these emissions, almost 80%, is in the form of carbon dioxide (CO₂), indicating an exceptionally high carbon emission intensity (Ministry of Local Affairs and the Environment and UNDP, n.d.). The significant energy demand and resulting emissions place the country's economy and climate in an extremely critical and fragile situation. These data highlight the urgent need for targeted interventions and policies to reduce emissions from the building sector in order to mitigate Tunisia's carbon footprint.

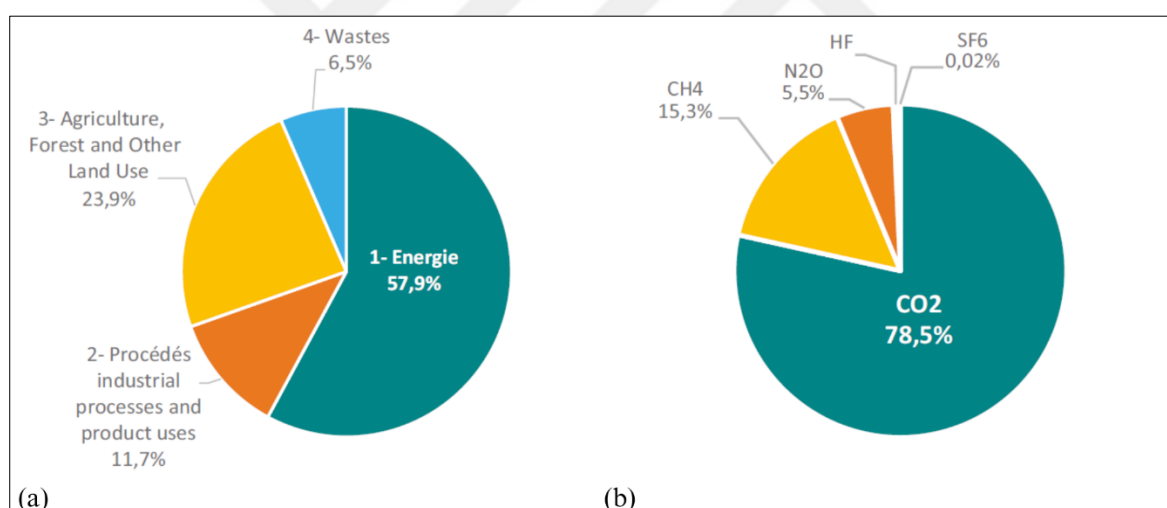


Figure 2.6. (a) Distribution of Tunisia's direct gross GHG emissions per source in 2012 (Ministry of Local Affairs and the Environment and UNDP, n.d.), (b) Distribution of Tunisia's direct gross GHG emission per gas type in 2012

Considering the impact of greenhouse gas (GHG) emissions on Tunisia's climate, it's clear that these emissions produce noticeable results every year, affecting different seasons and regions of the country. Based on data from meteorological stations of the Tunisian National Institute of Meteorology (NIM), Tunisia has experienced significant changes in its climate.

⁶ Tons (t) of carbon dioxide (CO₂) equivalent (e). "Ton" is a way of writing metric ton. "Carbon dioxide equivalent" is a standard unit for counting greenhouse gas (GHG) emissions regardless of whether they're from carbon dioxide or another gas, such as methane.

Over the period 1978-2012, there has been a notable increase in annual maximum, average, and minimum temperatures, with an average increase of about 2.1°C (Figure 2.7). It is important to note that this increase is not uniform across the country, as there are regional differences. In addition to rising temperatures, there has also been a noticeable shift in the frequency of meteorological and climatic extremes. Specifically, there has been an increase in the number of hot days, indicating a higher frequency of temperatures exceeding certain levels (Figure 2.8) (Climate Change Knowledge Portal, 2021b; NIM, 2020a).

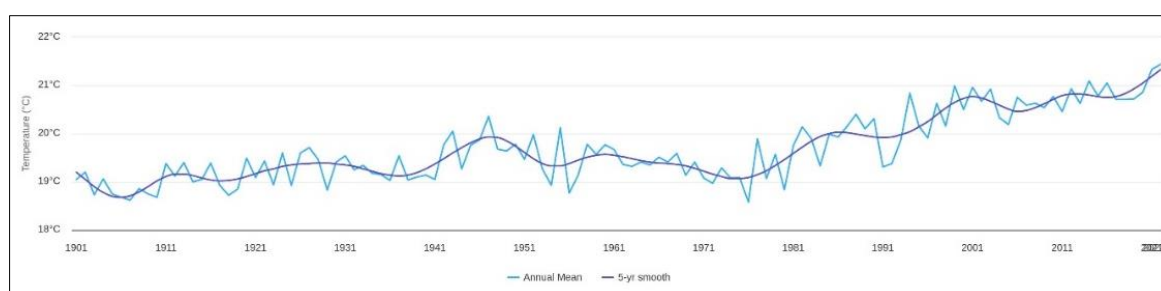


Figure 2.7. Observed annual average mean surface air temperature of Tunisia for 1901-2021 (Climate Change Knowledge Portal, 2021a)

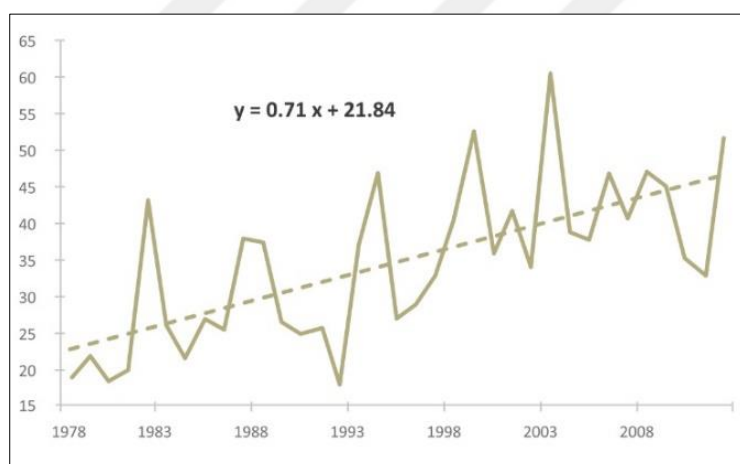


Figure 2.8. Evolution of the number of hot days (Ministry of Local Affairs and the Environment and UNDP, n.d.)

The graph below shows the deviation of the average summer temperatures between 1970 and 2021 compared to the average summer temperatures of the seasonal reference set by the INM between 1981 and 2010. Since the summer of 1994, there has been an exceptional increase in average summer temperatures. The summer of 2021 marked the hottest season in Tunisia's recorded history, with numerous regions setting new temperature records. Data

from 24 primary meteorological stations across the country showed an average temperature of 29.95°C, exceeding the normal reference period (1981-2010) by +2.65°C. This anomaly makes the summer of 2021 the hottest on record (NIM, 2021).

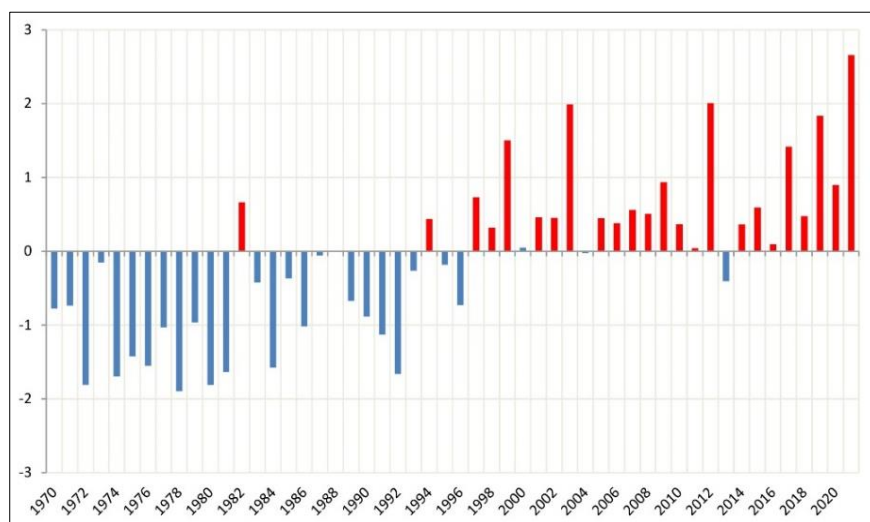


Figure 2.9. 1970-2021 summers average Temperatures deviation from the seasonal reference average of 1981-2010 (NIM, 2021)

According to another study led by the INM, future projections indicate an increase in annual temperatures by 2050 and 2100 under two RCP scenarios⁷: under the RCP 4.5 scenario, temperatures are projected to increase between 1°C and 1.8°C by 2050 and between 2°C and 3°C by the end of the century. Under the more severe RCP 8.5 scenario, temperatures are projected to rise between 2°C and 2.3°C by 2050 and between 4.1°C and 5.2°C by the end of the century. The rate of warming is expected to be lower along Tunisia's coasts, in the north and east, and higher in the west and extreme south. In terms of climate extremes, Tunisia could face more frequent and longer heat waves by 2100, especially under the RCP 8.5 scenario (Ministry of Local Affairs and the Environment and UNDP, n.d.).

⁷ Representative Concentration Pathways (RCP) are climate change scenarios to project future greenhouse gas concentrations adopted by the IPCC.

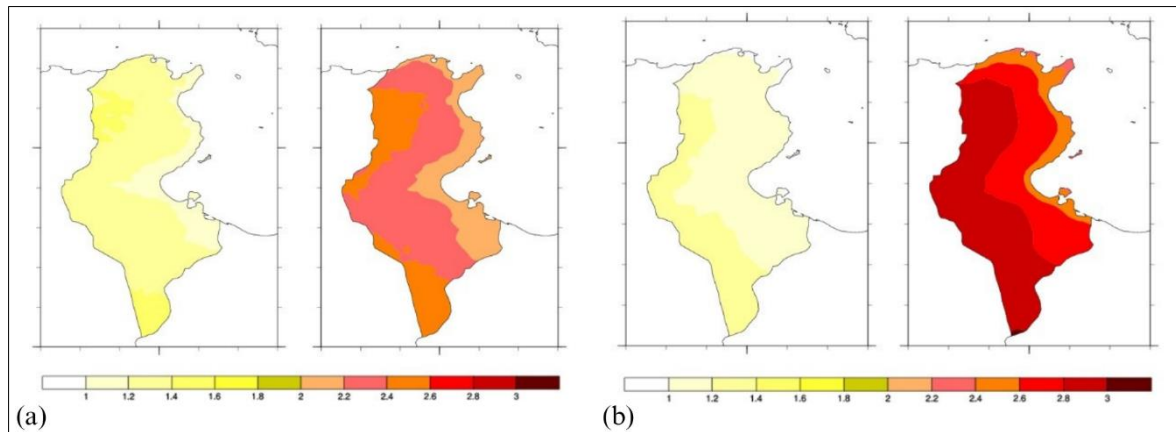


Figure 2.10. (a) Temperature increase by 2050 (left) and temperature increases by 2100 (right) under the RCP4.5 scenario, (b) Temperature increase by 2050 (left) and temperature increases by 2100 (right) under the RCP8.5 scenario (Ministry of Local Affairs and the Environment and UNDP, n.d.)

As a result, the link between climate change and the significant greenhouse gas emissions from the building sector is evident. In recent decades, the pace of urbanization has accelerated, leading to a corresponding increase in the average global temperature. As a developing country, Tunisia is facing a serious challenge in terms of climate change. Moreover, Tunisia's already relatively hot climate makes it particularly vulnerable to the effects of global warming. Recent temperature records for recent summers serve as a stark reminder of the urgent need for efficient and environmentally friendly building strategies. With rising temperatures posing significant challenges to comfort and health, the search for sustainable cooling methods has become an imperative that cannot be delayed.

In this context, traditional architecture emerges as a sustainable solution. Drawing on centuries of wisdom, traditional buildings have developed effective ways to cope with extreme heat without relying on energy-consuming cooling systems. These passive cooling techniques harness natural elements such as the earth, sun, and winds to create comfortable living spaces, even in the harshest of climates. In the next section, the rich heritage of vernacular architecture in Tunisia will be investigated, along with an analysis of how these time-tested cooling techniques can provide viable solutions to the contemporary architectural challenges posed by climate change.

2.2. Vernacular Architecture Sustainable Solutions

The sustainable aspect of primitive solutions in vernacular architecture lies in its reliance on locally available materials and traditional building techniques that are in harmony with the natural environment. These structures blend seamlessly into their surroundings by respecting local climatic and geographic data, allowing them to withstand and respond effectively to natural conditions. Particularly in hot climates, vernacular architecture has developed efficient passive cooling techniques to create fresh indoor spaces, using features such as thick walls, small windows, and courtyards to promote natural ventilation and maintain comfortable temperatures. This style of architecture has allowed people to live in comfortable spaces with zero climate impact and pollution for centuries, demonstrating its remarkable sustainability and resilience. With their durability, longevity, and ability to adapt to changing climates, primitive solutions in vernacular architecture offer a comprehensive approach to sustainability that promotes both environmental responsibility and cultural preservation. Today, vernacular architecture is being recognized by researchers and designers for its sustainable solutions by offering passive techniques for contemporary buildings. These passive solutions have been proven to reduce energy consumption and greenhouse gas emissions. By incorporating vernacular techniques into contemporary design, we can create buildings that are not only environmentally friendly but also culturally rich and socially sustainable, paving the way for a more sustainable future.

This section focuses on vernacular architecture and its essential link to sustainability. Through an investigation of examples of Tunisian vernacular architecture, the aim is to uncover the passive cooling techniques traditionally used. A methodological analysis will be carried out to discover the passive techniques used and to create a design guide for future buildings adopting passive cooling strategies. Subsequently, the passive cooling techniques extracted from vernacular architecture will be explored in modern architectural practices to address the contemporary challenges of climate change and environmental sustainability.

2.2.1. Vernacular architecture and sustainability

The terms 'vernacular architecture', 'traditional architecture', or 'rural architecture' all describe the type of architecture analyzed in this study. The term 'vernacular' originates from the Latin 'vernaculus', meaning 'native to a country' or 'domestic'. It refers to the native

speech or language of a place and has been used in English since 1706 (Online Etymology Dictionary, 2018). Vernacular describes the originality and specificity associated with a particular group of people in a particular region. Vernacular architecture is a term used to describe structures built by people whose design decisions are influenced by the traditions of their culture (Sakr, 2001). Consequently, vernacular architecture includes buildings adapted to the natural environment, typically found in rural areas. This term is not commonly applied to urban centers associated with major civilizations, as vernacular architecture represents a more primitive way of life that is closely tied to nature and uses local building materials and techniques.

The term "vernacular architecture" encompasses many types of buildings that are not professionally designed. It is defined as the dwellings and all other buildings of the people in relation to their environmental contexts and available resources; built by the community using traditional technologies. All forms of vernacular architecture are built to meet specific needs and reflect the values, economies, and ways of life of the cultures that produce them. It may be adapted or developed over time as needs and circumstances change (Oliver, 2003). It has been found that buildings derived from rural traditions remain extraordinarily efficient as dwellings because they are directly related to an economy and way of life that is still very much alive in many rural areas. It is much easier to see the relationship between environment and habitat in these dwellings than in the case of the urban architecture of Western countries (Wolf Tochtermann, 1975). From a sustainable perspective, vernacular architecture, which uses local materials in construction with less waste and uses passive methods for cooling, heating, and ventilation, is considered one of the most efficient environmentally friendly architectures. Sustainability also takes into account the sensitivity of local history and culture, which means respecting local materials and vernacular designs, as well as being sensitive to the existing built environment of a given location and giving priority to the conservation and preservation of old buildings as cultural guides and examples for future buildings (Oliver, 2003).

In the last two decades, developing countries, particularly during the summer season, have faced a significant energy crisis due to high cooling load demands in buildings. Energy consumption in buildings is already high and is expected to rise further due to global temperature increases and population growth. The widespread use of air conditioning systems has exacerbated this issue, contributing significantly to increased energy

consumption (Choudhary et al., 2014). Tunisia, as a developing country, is particularly affected by this issue, experiencing high energy demands during the summer months (July and August). Aside from the adverse climatic impacts of high fossil fuel consumption, Tunisia's economy struggles with high energy costs and scarce resources, leading to frequent electricity supply interruptions during summer.

In this wise, the concept of traditional dwellings evolved to make the best use of cooling solutions. The introduction of mechanical cooling increased the likelihood of achieving complete thermal comfort for longer periods of time, but increasingly led to passive cooling techniques being ignored. Now, with the growing realization of the rapid depletion of non-renewable energy sources and the negative environmental impact of fossil fuel combustion processes, it is accepted that it is unreasonable to continue consuming vast quantities of non-renewable fuels for the air-conditioning of buildings when our ancestors achieved thermal comfort by natural means. Therefore, the reduction of greenhouse gas emissions caused by the use of fossil fuels to meet the cooling needs of buildings has stimulated interest in the adoption of passive cooling techniques for buildings (Choudhary et al., 2014).

In the context of extreme desert conditions, vernacular architecture has demonstrated an ability to address climate control and efficiency through natural means. This architectural approach, as illustrated by Alp and Ahmet Vefik (1990), offers several advantages. First, it relies entirely on natural forces for energy, eliminating the need for additional energy supply. Second, vernacular structures require minimal maintenance, which increases their durability. Third, they reduce environmental impact by operating without reliance on fossil fuels or other polluting energy sources. In addition, these buildings are characterized by the absence of noise and vibration disturbances, contributing to a tranquil living environment. Finally, the practice of building vernacular architecture is economically advantageous because it utilizes locally available materials and traditional construction techniques, thereby minimizing costs while maximizing efficiency.

In conclusion, vernacular architecture represents the culmination of centuries of trial and error, providing architectural solutions tailored to specific sites with specific geographical and climatic regions, and responding to distinct population needs and cultures, while also being an architectural solution to contemporary climatic and economic challenges (Ammar and Panerai, 2010). This study aims to analyze examples of vernacular architecture and

identify its qualities in terms of adaptation to the natural environment and the use of passive cooling techniques. The focus is on primitive residential buildings that use passive cooling techniques to create comfortable living spaces.

The current study aims to analyze Tunisian vernacular architecture to identify the passive cooling techniques employed in traditional houses for maintaining comfortable indoor thermal conditions in hot-arid climates. Therefore, the investigation delves into existing research and academic works related to passive cooling methods in Tunisian vernacular architecture. Despite the numerous studies on Tunisian vernacular architecture, there is a notable gap in studies specifically focused on passive cooling techniques. This research fills that gap, making it the first dedicated examination of how traditional Tunisian architecture employs passive cooling strategies. By exploring these techniques, the study not only contributes to the academic understanding of vernacular architecture but also offers practical insights for modern sustainable building practices in similar climates.

The collected data primarily comes from books detailing Tunisian vernacular architecture. For instance, Ammar and Panerai's (2010) book, *“Histoire de l'architecture en Tunisie de l'antiquité à nos jours”* (History of Architecture in Tunisia from Antiquity to the Present Day), provides a broad overview of Tunisia's architectural heritage, including numerous examples of vernacular architecture. Djerbi's (2011) book, *“L'architecture vernaculaire de Djerba: pour une approche sémi-anthropologique”* (The Vernacular Architecture of Djerba: Towards a Semio-Anthropological Approach), offers an in-depth investigation of Djerba Island's vernacular architecture. Additional works, such as those by Golany (1988), Libaud (1986), Louis and Hallet (2011), etc., examine Tunisian vernacular architecture from social, cultural, and architectural perspectives. Important surveys and seminar reports, like *“Pour la Sauvegarde de l'Architecture et de l'Environnement de Djerba”* (Towards the Preservation of the Architecture and Environment of Djerba) (1975), also provide valuable insights about Tunisian vernacular architecture.

Global studies specifically focused on passive cooling techniques in Tunisian vernacular architecture are lacking. Such topics are usually mentioned within broader studies of specific examples of Tunisian vernacular architecture. In their 2003 research paper, Hill and Woodland examine how environmental and cultural factors influence the structure and sustainability of subterranean settlements in southern Tunisia. The research paper details

how geology and topography significantly impact these settlements, helping to moderate extreme temperatures and humidity while providing shade from the summer sun. The experimental work in this paper demonstrates the effectiveness of earth-sheltered techniques and courtyard designs in regulating indoor temperatures and creating comfortable thermal conditions. The paper also recommends that modern settlement planning in the region should consider these environmental and cultural aspects to ensure successful design.

Numerous papers, including those by Sakr (2001), Toumi et al. (2019), Alkalyouby (2016), etc., provide descriptive analyses of Tunisian vernacular architecture, emphasizing its role in mitigating hot climates and maintaining adequate indoor thermal conditions. However, it's important to note that these studies are primarily descriptive and lack experimental work that could provide empirical evidence for the effectiveness of the passive cooling techniques discussed.

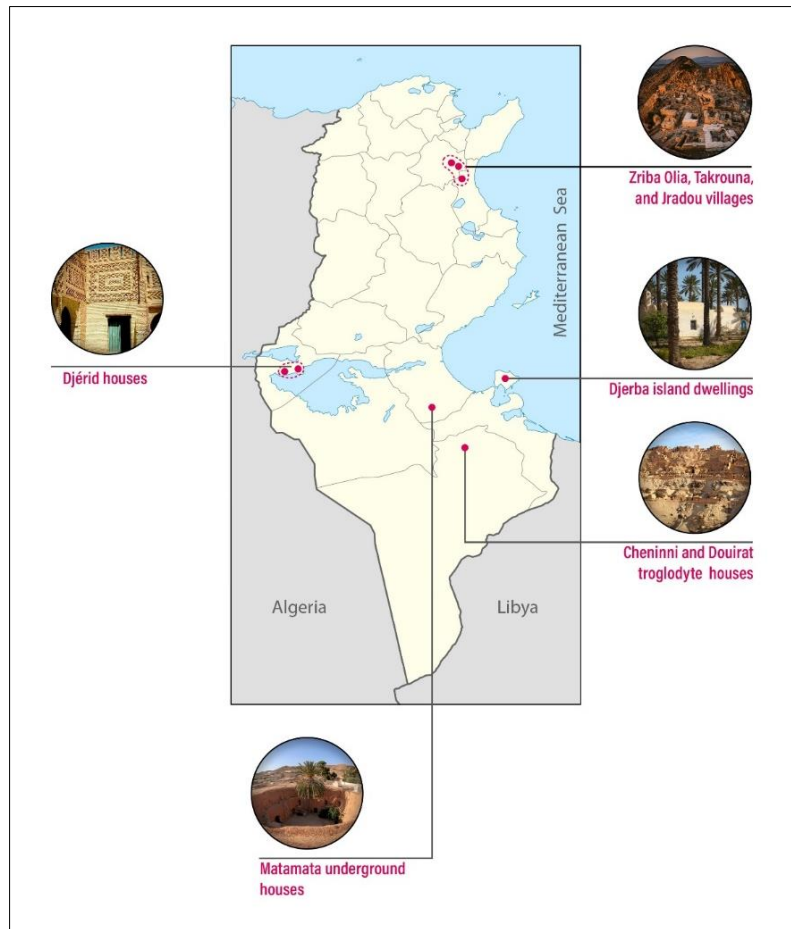
Multiple research papers investigate modern passive cooling techniques and their impact on buildings in Tunisia. For instance, Daouas (2011) explores the optimal insulation thickness, while Mokni et al. (2023) examine the optimal fenestration characteristics. These studies delve into technologically advanced solutions for improving energy efficiency and thermal comfort in contemporary buildings. However, they do not address vernacular architecture. The focus of these works is solely on modern materials and methods, highlighting a gap in research that connects traditional architectural practices with contemporary passive cooling techniques.

In conclusion, the current study is pioneering in its focus on passive cooling techniques within Tunisian vernacular architecture and the potential applications of these traditional solutions to modern architecture in order to address challenging climatic conditions. Furthermore, this research is comprehensive, encompassing the entirety of Tunisian vernacular architecture and systematically investigating passive cooling techniques suitable for hot-arid climates. By bridging the gap between traditional architectural practices and contemporary needs, this study offers valuable insights into sustainable building design in regions with extreme heat.

2.2.2. Passive cooling techniques in Tunisian vernacular architecture

Traditional architecture has a rich variety of techniques developed to enhance the comfort of living spaces. These techniques include hot climate control and ventilation systems tailored to the natural conditions of a particular region and influenced by the cultural background of the inhabitants. These techniques, mainly based on principles of physics, provide comfortable living spaces without relying on fossil fuel energy consumption. Features such as local construction materials, courtyard design, and natural ventilation are common to traditional Tunisian architecture in different regions. The implementation of these techniques varies according to factors such as available materials and climatic data. Tunisia, with its diverse traditional architectural heritage spanning different regions and geographies, is a prime example of this adaptability and richness.

In this research, the focus is on passive cooling techniques, specifically in traditional villages located in the hot-arid climates prevailing in the center and south of Tunisia. Despite the abundance of vernacular buildings throughout Tunisia, only a few examples have been selected for analysis. This selection is based on the availability of comprehensive information on each dwelling example, as most of the dwellings studied are too old and in ruins. The risk of overextending the study, particularly given the similarity of architectural features in many regions, also played a role in the selection process. The selected examples were chosen based on their architectural design and the specific passive cooling techniques employed. Each of the selected examples offers a specific design concept influenced by the climatic, geographical, and cultural context of its area.



Map 2.4. Studied examples of vernacular architecture on map, created by author

In the center-east of Tunisia, there are three popular villages, situated close to each other, built on rocky hills, and reflecting the same architectural characteristics: Zriba Olia, Takrouna, and Jradou villages. These villages are known as "The Mountain Architecture" in the central-eastern part of Tunisia, three popular villages located in close proximity and characterized by similar architectural features - Zriba Olia, Takrouna, and Jradou - were selected. These villages are collectively known as "mountain architecture" in Tunisian architectural literature. In the southeast, the dwellings on the island of Djerba are selected for their rich and distinctive architecture, influenced by the island's natural conditions and the inhabitants' cultural background. Two noteworthy examples of troglodyte architecture in the southeast are also examined: the underground houses of Matmata and the mountain cave houses of Douiret and Cheninni. Although there are more examples of underground and mountain cave houses in the region, these examples are chosen because of the availability of information and the good condition of their structures. Finally, in the southwest, the towns of Tozeur and Nafta were chosen because they represent a specific type of "brick

architecture", known as "Djérid architecture" in reference to the Djérid region.

Adaptation to the site

Adaptation to the site is an essential aspect of traditional architecture, which primarily involves adapting to the geographical and climatic conditions of the region. In Tunisian traditional dwellings, adaptation to the site involves the use of natural elements such as vegetation, earth mass, and orientation to respond to geographical and climatic conditions. These elements play a crucial role in providing protection from the effects of the weather throughout the year, particularly the intense heat of the summer. Vegetation is used strategically to provide shade and cooling. Trees and plants are often planted around dwellings to shield them from direct sunlight, reduce heat gain, and create microclimatic zones. Earth-sheltered techniques, in which earth masses are used to partially or fully bury buildings, act as effective insulators against temperature fluctuations. There are two types of earth-sheltered dwellings that will be presented as examples. Orientation plays a crucial role in maximizing the benefits of natural ventilation and solar gain. Traditional Tunisian dwellings are often oriented to capture prevailing breezes and minimize exposure to the harsh rays of the sun. By integrating building design with these natural elements, traditional Tunisian dwellings achieve passive conditioning, ensuring comfort throughout the year.

On an urban scale, the examples studied in this research vary in their integration into the urban fabric. Some consist of individual dwellings built separately within the landscape, such as those on Djerba Island and in the Matmata region. In contrast, the villages of Zriba Olia, Takrouna, Jradu, and those in the Djérid region feature buildings arranged within the urban fabric of the villages. The troglodyte dwellings of Douiret and Cheninni are constructed side by side in terraced rows that follow the mountain's contours.

The village of Zriba Olia features a complex pattern of streets, with houses clustered closely together. On one side, the streets lead to individual dwellings, and on the other, they connect to urban centers such as squares and livestock markets (Figure 2.11. (a)). The streets have an irregular shape, with varying widths and levels throughout the village. For instance, the streets around the houses are narrow but widen as they approach the village center (Ammar and Panerai, 2010). The narrow, irregularly shaped streets surrounding the houses provide excellent shading and reduce heat gain, making them an effective urban passive cooling

system. In the old villages of the Djérid region, there is a noticeable urban design tendency to align houses in rows along the east-west axis (Figure 2.11. (b)) (Mrabet, 2004a). This orientation strategically minimizes sun exposure on the facades throughout the day, reducing heat gain and enhancing thermal comfort inside the houses. By limiting direct sunlight on the street facades, this urban design effectively contributes to the houses' passive cooling.

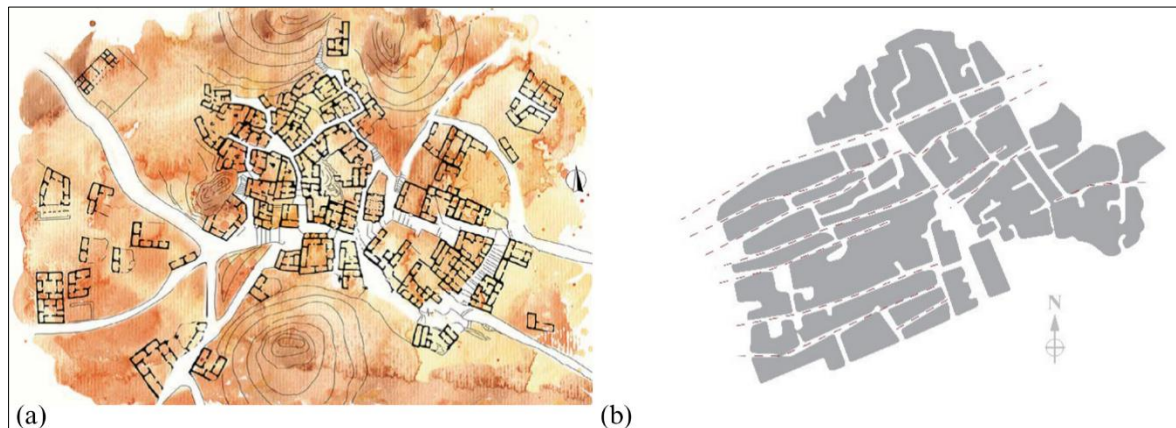


Figure 2.11. (a) Zriba Olia village plan (Bouguerra, 2017), (b) Tozeur old village plan (Dhafer, 2012)

Vegetation

The use of trees and green vegetation near or around a building is a very old and practical solution for protecting the building from solar heat gain. Through the process of evapotranspiration, where they absorb heat from the atmosphere, trees, and green vegetation help to cool the building (Bhamare et al., 2019).

On the island of Djerba, the Menzel⁸ are situated within the inland territory, far from the coastal areas, with even the fishermen's dwellings not being located near the sea. This choice is explained by the necessity for the island inhabitants to position their dwellings within the agricultural plots, which are located at least one kilometer from the sea. The water tables required for agriculture are found within the island. Moreover, Djerbian houses, when built within the palm and olive fields, benefit from natural shading provided by vegetation, offering protection from hot weather and dusty winds (Djerbi, 2011; Wolf Tochtermann, 1975). In the Djérid region, which is a desert area, the inhabitants have also chosen to build

⁸ In the local language, Menzel, is the name of the private plot, including the agricultural spaces and the dwelling of each family.

their homes inside the oases to escape the hot desert weather. The palm trees help to filter the air from the sand, reduce wind speed, protect the houses from intense sunlight, and create shady areas. The presence of watercourses in the palm fields helps to cool the air and create a fresh microclimate inside the village (Mrabet, 2004b).

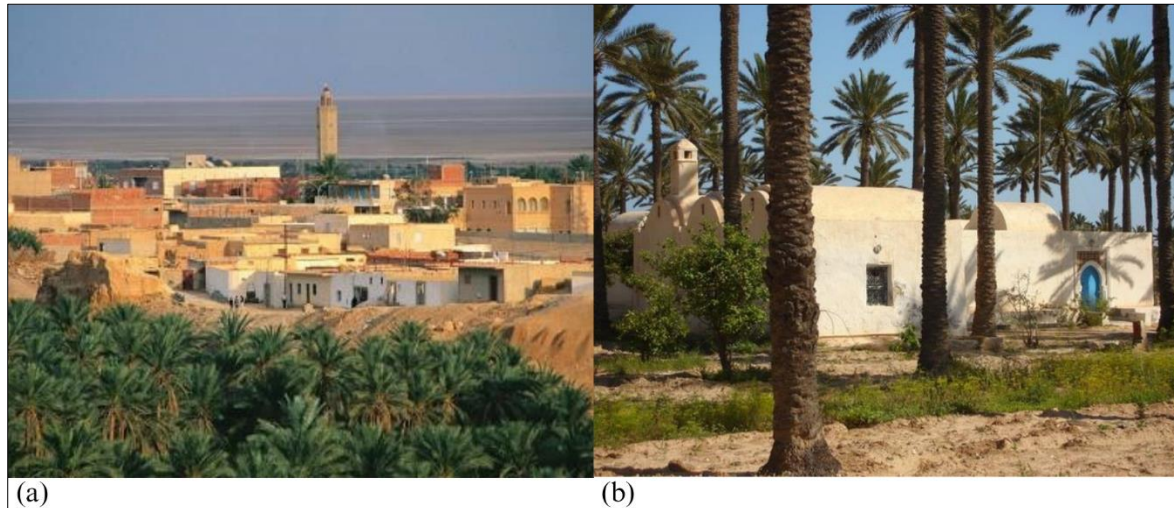


Image 2.6. (a) Village in the Djérid region inside the palm field (URL-40), (b) A traditional Djerbian house inside the palms field (URL-41)

Therefore, in the flat lowlands, the availability of water and vegetation plays a crucial role in determining the location of dwellings. The presence of vegetation, including trees and plants, not only provides shade and cooling but also reduces wind speeds, especially in summer.

Earth-sheltered technique

The earth shelter technique creates a microclimate for buildings that is less harsh than the actual climate of the region and mitigates the effects of heat and wind. The spatial arrangement of the building according to the geography of the site has a significant impact on the energy performance of the building and contributes to the thermal comfort of the indoor spaces (Bhamare et al., 2019). The three villages of Zriba Olia, Takrouna, and Jradu, located on the top of rocky hills, are relevant examples of adaptation to the geography of the site. The constructions of the dwellings follow horizontally the shape and direction of the contour lines of the hills (Image 2.7). The buildings are placed side by side and are supported by the massive rocks present on the site. This creates rows of houses at different levels,

connected by vertical streets and staircases. Buildings that are partially coupled to the relief of the site are more effective in terms of thermal performance (Ammar and Panerai, 2010).

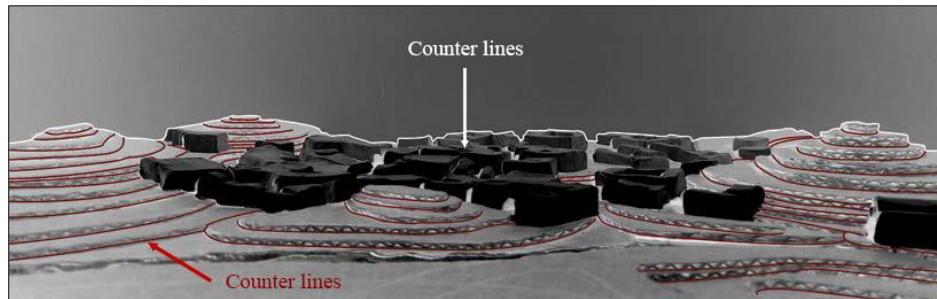


Image 2.7. Architectural model of Zriba Olia village (Bouguerra, 2017)

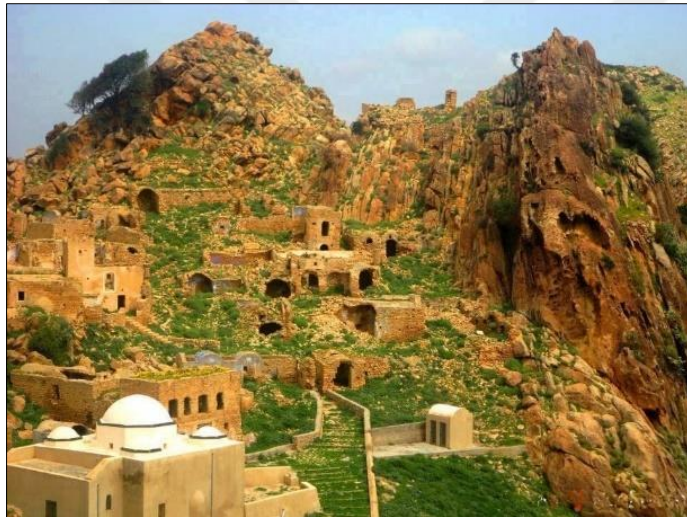


Image 2.8. Top view of Zriba Olia village (URL-72)

The dwellings in the villages of Cheninni and Duirat are an example of effective adaptation to the mountainous terrain by partially digging the houses into the mountainside. The main rooms of the houses are excavated into the mountain, while additional spaces are constructed in front of these cave rooms, separated by a courtyard. The houses are arranged side by side, following the contours of the mountain, creating stacked rows of houses separated by narrow horizontal paths. This spatial arrangement is intended to protect the dwellings from heatwaves and strong winds (Ammar and Panerai, 2010).

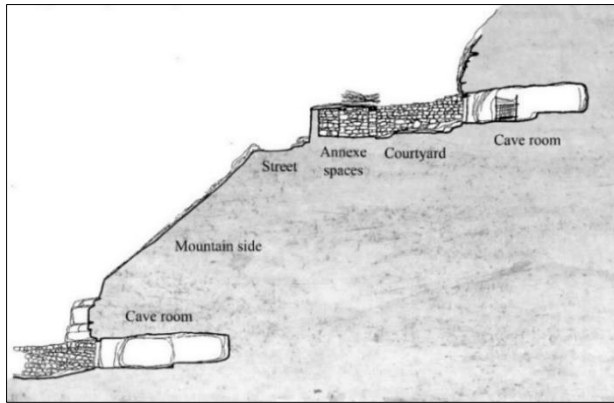


Figure 2.12. Section of Cheninni village houses (Perron and Perron, 1981)

One of the most common forms of site adaptation is the use of earth-sheltered dwellings, an ancient technique designed to withstand harsh weather conditions. Underground structures were originally common in hot, dry climates, suggesting that the earth-sheltered technique was used primarily for cooling rather than heating (Alkaff et al., 2016). The underground houses of the village of Matmata are an example of underground dwellings. The high average temperatures and the soft nature of the soil were the main factors that led the inhabitants to dig their dwellings into the ground in order to improve thermal comfort. These dwellings typically consist of a sunken courtyard and excavated rooms opening onto the courtyard (Sakr, 2001). The inhabitants of Matmata considered the landscape to be an integral part of their homes, shaping it to blend in with their living spaces. By sculpting the earth, they created underground dwellings that took advantage of the earth's natural temperature regulation. This design ensured consistently comfortable indoor temperatures, especially during the scorching summer months.

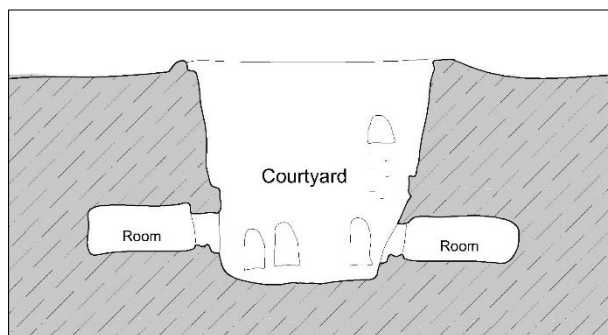


Figure 2.13. A section of an underground house in Matmata (Golany, 1988)



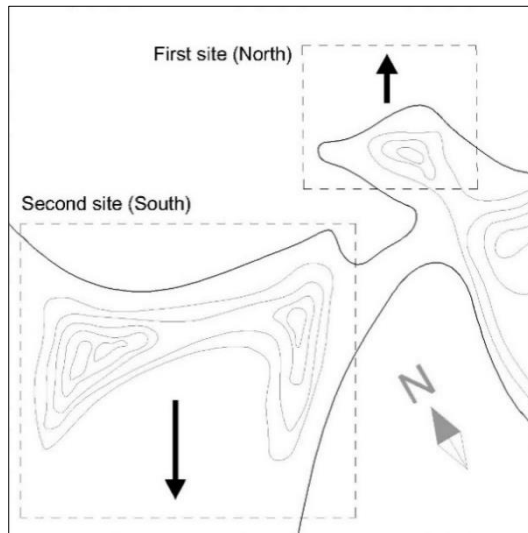
Image 2.9. Picture of an underground house in Matmata (URL-42)

Orientation

Orientation is a key aspect of site adaptation and has a crucial influence on the passive cooling of dwellings. It carefully considers the path of the sun throughout the day and across the seasons, as well as the direction of prevailing winds, particularly hot winds. Orientation plays a fundamental role in maintaining comfortable indoor temperatures by orienting structures to optimize exposure to the sun and harness natural air currents. This strategic positioning not only mitigates the effects of solar heat gain but also facilitates effective ventilation, thereby increasing the passive cooling capacity of dwellings.

In Tunisian culture, there's a general consensus that the optimal orientation for a dwelling, or a specific room, is east-facing first, followed by south-facing, or alternatively southeast depending on the site's geography. This orientation heavily influences the design of the dwelling in most cases, with exceptions found in troglodyte dwellings in regions like Cheninni and Douiret. In nearly all cases, rooms facing southeast are considered the best oriented. This direction allows for favorable morning sunlight while shielding occupants from intense sun radiation and strong winds in the afternoon. Conversely, spaces facing west are generally considered the least desirable due to their exposure to intense sun radiation in the afternoon (Djerbi, 2011). In Cheninni and Douiret, the orientation of troglodyte dwellings is directly influenced by the geographic orientation of the mountainside. In Cheninni, an earlier settlement was organized on a narrow relief of the mountain facing north and northeast. However, this settlement was later abandoned, and a second settlement was established on the southeastern and southwestern slopes of the mountain (Map 2.5.) (Znidi, 2018). The design of the new settlement is therefore closely linked to the choice of a south-

facing orientation, which meets the need for sunlight throughout the year. In addition, the mountain relief provides natural shade, shielding the dwellings on this site from direct afternoon sunlight. This strategic positioning ensures optimal thermal control and lighting throughout the year. The orientation factor will be explained in more detail at the level of the dwelling's interior spaces organization in the next section, *Courtyard house organization*.



Map 2.5. Situation of the two sites of troglodyte dwellings in Cheninni on the map (Znidi, 2018) modified by author

The diagram below illustrates the sun's path in Tunisia. Sun exposure varies throughout the day, with minimal exposure around noon and increased exposure in the early morning and afternoon, starting from 15:00. Surfaces facing west and southwest receive the most sunlight in the afternoon, making west and southwest orientations less favorable. Meanwhile, surfaces facing east and southeast receive sufficient sunlight in the morning and are shaded in the afternoon when temperatures are at their highest. These favorable orientations help to take advantage of the sun in winter but also prevent overheating in summer.

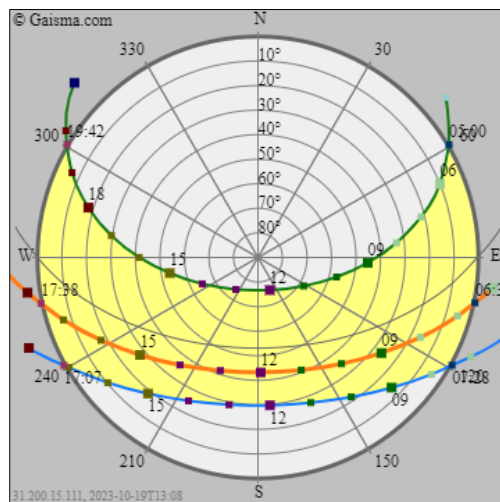


Figure 2.14. Sun path diagram in Tunisia (Gaisma, 2024)

The orientation of the building is greatly influenced by the prevailing winds. As described in *Section 2.1.3, Geography and Climate*, Tunisia experiences northwest winds, which are humid and moderate, and southwest winds, known as the dry and hot Sirocco winds. Therefore, orienting buildings to the east and southeast provides protection from strong winds throughout the year, especially the hot winds during the summer.

Resume table

Traditional Tunisian dwellings demonstrate various methods of adaptation to the site, offering protection from weather effects throughout the year, particularly the intense heat of summer. By strategically aligning with the natural environment, these dwellings are passively conditioned, ensuring comfort year-round without adversely impacting the climate. Vegetation, earth-sheltered techniques, orientation, and consideration of prevailing winds are integral components of this adaptation process. Overall, traditional Tunisian architecture exemplifies a harmonious relationship between human habitation and the natural environment, offering valuable lessons in sustainable design and adaptation to the site. The table below summarizes the three main strategies employed by Tunisian vernacular architecture to ensure optimal adaptation to the site of its buildings.

Table 2.2. Adaptation to the site resume table

Adaptation strategy	Description	Region	Extracted data
Vegetation	Implantation of dwellings in olive and palm fields.	Low and flat lands: - Djerba Island (hot and arid climate). - Djérid region (hot and desert climate).	In low and flat lands, planting vegetation is more feasible, particularly for agricultural purposes. Thus, dwellings use this vegetation as a shield against exposure to the sun's rays and the sandy, hot winds.
Earth-sheltered technique	Partially/horizontally: - Integration with the counter lines of the mountain.	- Mountain villages of Zriba, Takrouna, and Jradu (hot and semi-arid climate).	In the mountainous regions, the geography of the mountains and the high altitudes, with lower temperatures, allow the partial and horizontal excavation of the dwellings.
	- Excavation of spaces on the mountainside.	- Troglodyte dwellings of Douiret and Cheninni villages (hot and arid climate).	
	Totally/Vertically: Dwellings are excavated totally and vertically underground.	Flat and lowlands: - Underground dwellings of Matmata (hot and arid climate).	In extremely hot and arid regions where the soil is soft, underground houses are totally protected from heat and thermally efficient.
Orientation	East, South, Southeast: - Surfaces are exposed to the sun in the morning and shaded in the afternoon. - Surfaces are protected from the prevailing winds of Sirocco.	All the studied regions (hot and arid climate).	According to the sun's path and the prevailing wind directions, the best orientations for a dwelling in Tunisia are the south, the east, and the southeast, and the worst orientations are the west and the southwest.
	West, Southwest: - Surfaces are exposed to the harsh sun in the afternoon. - Surfaces are exposed to the hot Sirocco winds.		

Courtyard house organization

In this section, the architectural organization of the Tunisian courtyard house is analyzed in relation to its adaptation to climatic conditions. The courtyard house configuration is a prominent architectural archetype in Tunisia, developed to effectively mitigate the challenges posed by the region's climatic conditions. Starting with an examination of the spatial arrangement of the Tunisian house around the central courtyard, special emphasis is placed on the orientation factor, which plays a key role in optimizing thermal comfort for the occupants. Subsequently, the physical characteristics of the courtyard are studied, including its dimensions and its importance in regulating the thermal conditions inside the house.

Courtyard house organization

The Mediterranean climate, which is a relatively hot climate with temperature variations from region to region, encourages outdoor activities. Compared to cold climates, buildings in mild and hot climates have larger built areas and are more open to the outside. The courtyard house is a widely used architectural design model in the Mediterranean region, as it helps the inhabitants to benefit from the outdoor spaces and to perform various outdoor activities. The design of the courtyard house plays an important role in the natural climatization and ventilation of the inside spaces, and this has been proven by vernacular architecture throughout history. The model of traditional houses with a courtyard has always been considered one of the great models of urban habitat known in history. (Boudjadja and Benhalilou, 2022). Courtyard houses have an ancient history in Mesopotamia and Egypt thousands of years B.C. Essentially, the courtyard house, which consists of rooms on three or all sides of an open atrium, is associated with Arab culture, but its distribution extended between Sale and Marrakech in the west and India in the east (Olivier, 2003).

Tunisian dwellings tend to have the same architectural type in all regions, with a square floor plan and no openings to the outside except for the entrance door. The rooms are long and narrow, arranged around a rectangular courtyard, which is the center of life in the house (Perron and Perron, 1981). In Tunisia, the courtyard is a fundamental architectural feature that can be found in almost all types of buildings. This introverted spatial design around a central open space (courtyard), around which everything is built, is a perfect adaptation to

climatic requirements. In regions with high temperatures, the arrangement of living spaces around the courtyard allows the creation of shaded areas within the living spaces (Znidi, 2018). The courtyard house design is too ancient in Tunisian architecture, and it is inherited from Roman architecture, where we usually find indoor spaces organized around an atrium, and in its center, there is often a large rainwater tank (Augustin, 1924).



Image 2.10. A woman sitting with her children in the courtyard of her underground house in Matmata, Tunisia (URL-42)

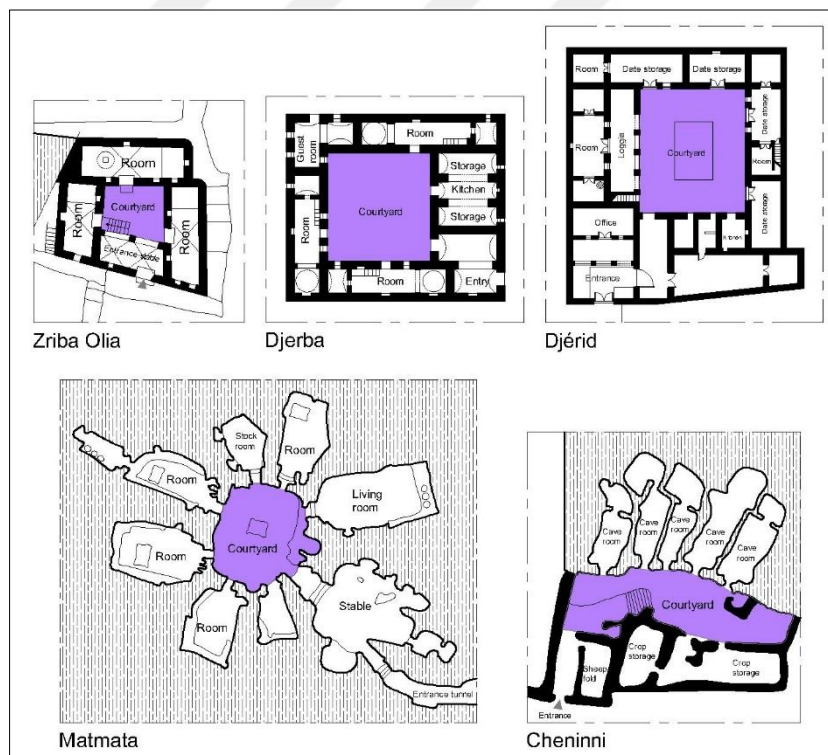


Figure 2.15. Plans of houses from the studied examples showing the courtyard house design, created by author

The courtyard, in Tunisian architecture, guides the evolution of the house design, all spaces are organized around the perimeter of the courtyard and open with large windows and doors into this central space. When the spaces around the courtyard are filled, the creation of a new courtyard for a new house becomes an obvious necessity. The design of the courtyard house may have slight differences according to the region, but the same design principle is observed throughout the country.

In Tunisian dwellings, the organization of the rooms around the courtyard depends on the orientation factor. The rooms are placed chronologically from the best orientation (southeast) to the worst (southwest) according to the importance and function of the room. First, the main room, the head of the family room, is placed in the best orientation, facing southeast. Then the second room is placed perpendicular to the first facing northeast. The third room faces the northwest orientation. Finally, the less occupied spaces, such as the kitchen and storage rooms, are placed in the worst orientation, which is the southwest (Figure 2.16) (Djerbi, 2011). The primary objective of this arrangement is to position the most frequently used spaces, such as the rooms, in optimal orientations to take advantage of favorable thermal conditions. Conversely, less frequently used spaces, such as the kitchen and storage rooms, are located in less favorable orientations, often exposed to intense afternoon sunlight.

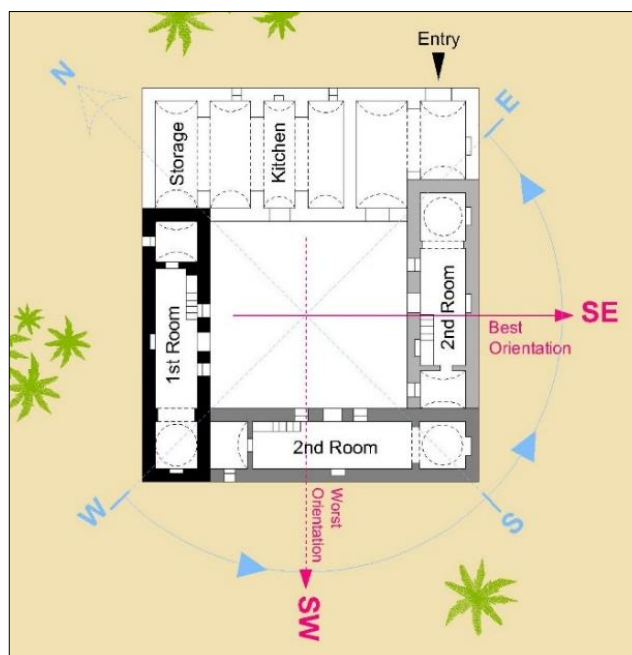


Figure 2.16. The orientation system in Tunisian dwellings (Djerbi, 2011), created by author

In the underground houses of Matmata, the spatial organization is the same as mentioned above, but the entrance tunnel and the kitchens are excavated in the first phase and placed in a good orientation, facing south. This choice aims to protect the entrance tunnel and the façades of the kitchens, which are the most vulnerable façades, from the heavy rain that usually comes from the northeast. In the second phase, the head of the family room and the principal room will be excavated facing east, which is the best orientation. Later, other rooms will be excavated according to the needs of the inhabitants, facing north and west, respectively (Libaud, 1986).

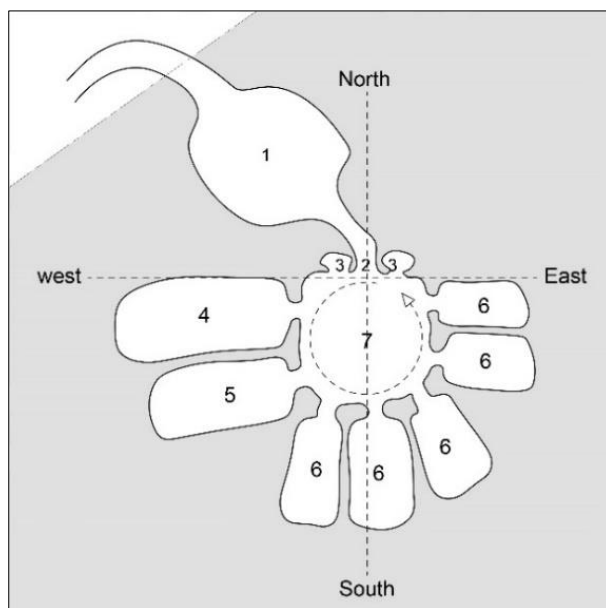


Figure 2.17. Orientation system in underground houses in Matmata. 1-Stable, 2-Entrance tunnel, 3-Kitchen, 4-Family head room, 5-Principal room, 6-Room, 7-Courtyard, (Libaud, 1986)

In Tunisian vernacular architecture, the guiding principle of the orientation system is to strategically position the most frequently used spaces, such as rooms, in optimal orientations, particularly east and south. This positioning ensures protection from the sun and prevailing winds. In contrast, service spaces such as the kitchen and storage rooms are located in less favorable orientations due to their lower occupancy rates. Consequently, the spatial arrangement of the house spaces is carefully determined by climatic data in order to facilitate passive cooling and natural ventilation.

Tunisian courtyard characteristics

In architectural design, there are two types of courtyards, respectively called: 'patio' and 'courtyard'. The patio has a more central position and plays a more complex social function as a place for living and family. Around the patio, according to the dimensions of the house, there could be a gallery on each level. The patio also plays a very important role in the lighting and ventilation of the building (Benyoucef, 2019). Whereas the courtyard is mainly a place of passage and is not always in the center of the building. For this reason, in the English language, a "courtyard house" is a house with a patio in the center (Figure 2.18. (a)), and a "house with a courtyard" is a house with a side courtyard (Figure 2.18. (b)) (Abdulac, 2011). This research is focused on the 'Courtyard House' as it represents the predominant architectural model found within traditional Tunisian dwellings.

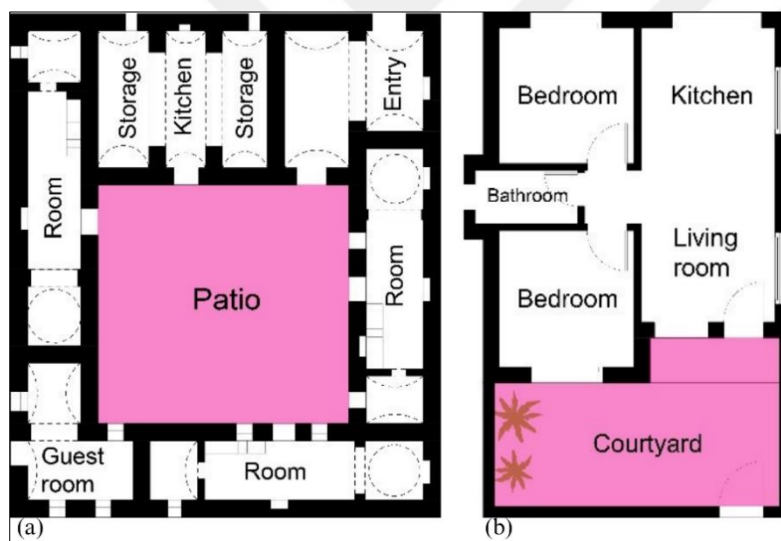


Figure 2.18. (a) Plan of a traditional Tunisian house in Djerba 'courtyard house' (Djerbi, 2011), (b) Plan of a modern house with a courtyard (URL-43)

Courtyard role: A microclimate

On the island of Djerba, the average annual temperature is around 20°C, and in the inland areas, the monthly averages never exceed 30°C, as there are never sub-zero temperatures. This climate does not require excessive protection and favors outdoor activities, thus reducing the demands on the interior spaces of the dwelling (Djerbi, 2011). As an architectural adaptation to the climatic conditions, the Djerbian house is organized around a central courtyard, creating a distinct microclimate. In this architectural typology, the

dwelling are directed inwards, with the patio as the focal point. The presence of water sources, shading elements, and natural light within the patio area all contribute to creating comfortable living conditions for the inhabitants (Tlatli et al., 1975). Thanks to the courtyard, the dwellings are naturally ventilated and protected from the prevailing winds and sandstorms. The fact that one side of the house is always in the shade creates a temperature difference and therefore whirlwinds, especially in the corners. This phenomenon creates a very pleasant natural ventilation in summer. In coastal regions, such as the island of Djerba, temperature fluctuations are caused by variations in the pressure zones between land and sea, resulting in shifts in the direction of the air between day and night. This dynamic naturally promotes natural ventilation inside the courtyard (Al-Zubaidi and Sabah Salman, 2007; Tlatli et al., 1975). The courtyard floor is usually whitewashed with limestone to reflect sunlight during the day, and it offers a large surface area exposed to the cool night sky, which causes radiation loss. This means that during the night the courtyard floor absorbs fresh air and loses heat, and during the day it absorbs heat received from direct solar radiation (Figure 2.19). In addition, the internal facades of the house (those opening onto the patio) are always partially protected from the sun, thanks to the ratio between the height and width of the patio, which creates a temperature difference between the outside and the patio (Fardeheb, 2008; Tlatli et al., 1975).

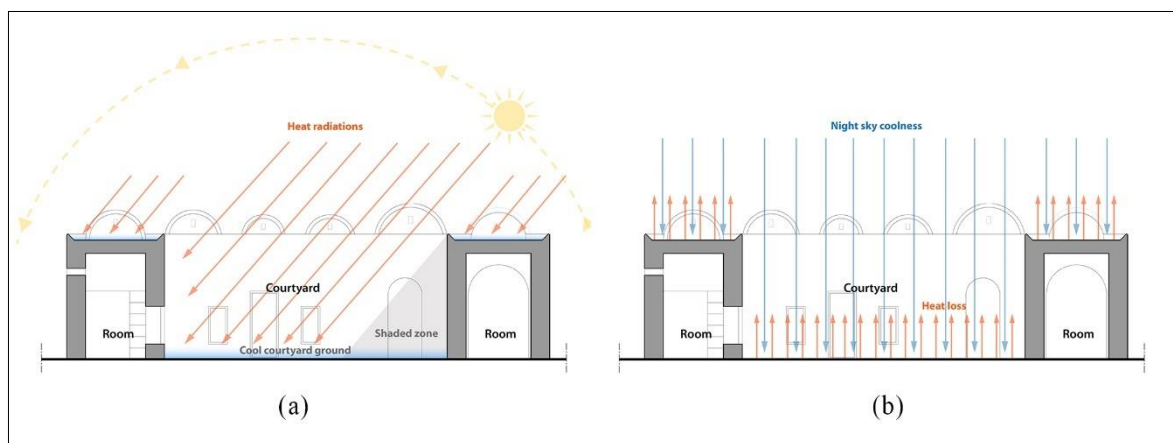


Figure 2.19. Thermal regulation of the courtyard, created by the author

In most cases, the rooms open directly onto the courtyard; however, in certain cases, such as in Djerba and the Djérid region, there may be a transitional space between the courtyard and the rooms, often in the form of an arched loggia (Figure 2.20). Loggias provide additional protection for the rooms from direct sunlight. This architectural feature is common in

traditional Tunisian houses in urban centers, while it is less common in rural dwellings. This disparity can be attributed to the evolutionary trajectory of architectural design in urban areas, which has undergone significant development compared to the simpler and more economically oriented vernacular architecture prevalent in rural areas. In addition, the creation of large courtyards with loggias is more feasible in flat lowlands than in mountainous terrain.

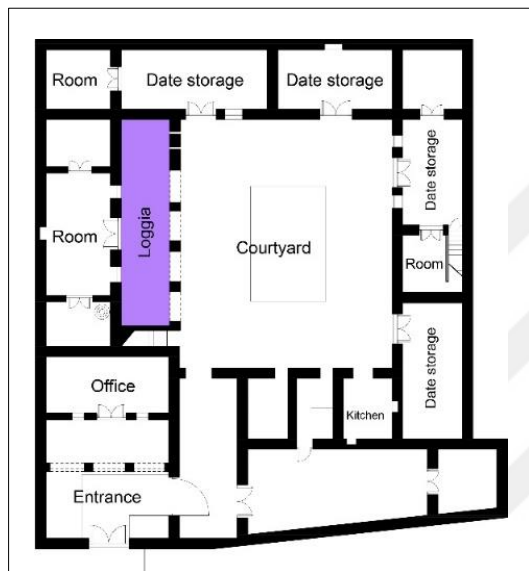


Figure 2.20. A traditional house plan in the Djérid region with loggia (Farid, 2012)

The Matmata underground houses are a very common type of underground courtyard design that follows the introverted design of traditional above-ground dwellings in Tunisia. The design of these dwellings depends primarily on the courtyard, from which the excavation work starts, and the central focal point around which all the rooms and other spaces of the dwelling are distributed (Sakr, 2001). In the underground dwellings, the courtyard plays a double role: it provides the excavated rooms with light, ventilation, and a sense of spaciousness, while at the same time protecting them from harsh weather conditions.

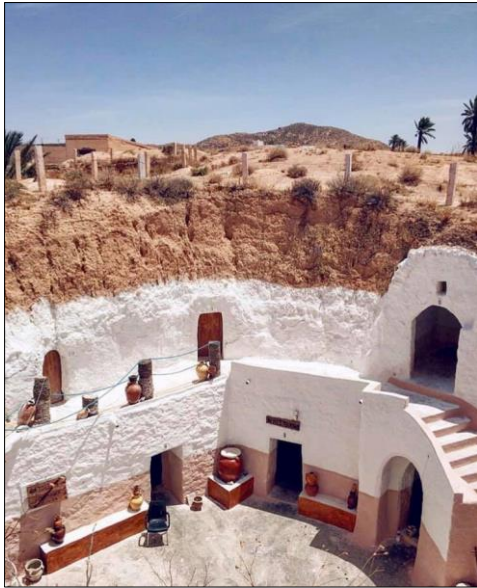


Image 2.11. Underground dwelling in Matmata (URL-44)

The sunken courtyard at Matmata functions as a passive thermal regulator through convection and shading. During the day, the thick loess walls absorb heat from the air and solar radiation, creating a temperature difference of 29°C in the courtyard and 46°C outside. At night, the walls slowly release heat, warming the courtyard (Hill and Woodland, 2003). According to the graph below, the courtyard plays the role of a transitional space between the outside (above ground) and the inside of the dwelling (excavated rooms) in terms of temperature regulation. The courtyard temperature varies less than the outdoor temperature, and the temperature of the main room is relatively stable during the day and night.

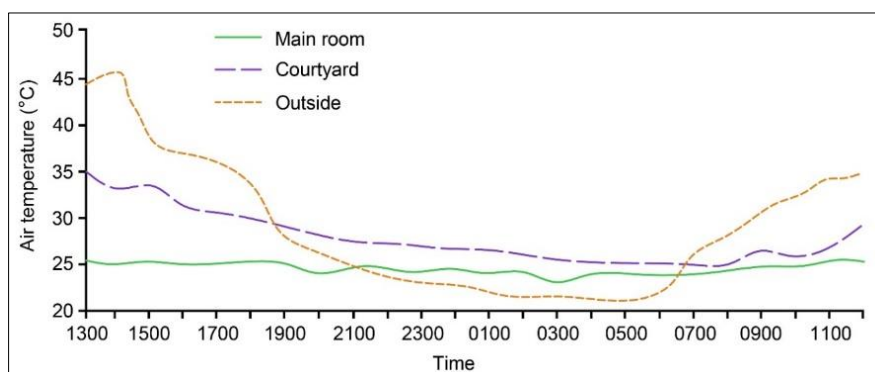


Figure 2.21. Air temperatures recorded at Matmata on 4-5 August 2000 (Hill and Woodland, 2003)

In both above-ground dwellings, as in Djerba, and underground dwellings, as in Matmata, the courtyard plays a crucial role in adapting to harsh climatic conditions by regulating

temperature. The presence of the courtyard creates a microclimate within the dwelling characterized by improved thermal conditions. This microclimatic effect is achieved through several mechanisms, including the moderation of temperature extremes, the provision of natural light, and the facilitation of air circulation. These functions of the courtyard make a significant contribution to the thermal comfort inside the dwelling.

Courtyard dimensions and shapes

In lowland and coastal regions, where the land is relatively flat, courtyards are generally large in size and provide an important source of daylight and natural ventilation to the building interiors. The large size of the courtyards facilitates air movement, which is very important. However, courtyards in mountainous regions have limited sizes due to topographical constraints and climatic conditions that limit the possibility of outdoor activities (Philokyprou et al., 2017). Likewise, in Tunisian architecture, the dimensions of the courtyard are contingent upon the topographical characteristics of the site. In mountainous villages such as Zriba, Takrouna, and Jradou, where dwellings typically occupy smaller areas, courtyards tend to have more constrained dimensions (Ammar and Panerai, n.d.). However, in lowland areas such as the Djérid region and Djerba island, courtyards are typically larger (Figure 2.22). For instance, in the city of Nafta, the dimensions of courtyard sides vary from 10 to 15 meters, with a height of 7 meters (owing to the presence of a first floor) (Alkalyouby, 2016; Augustin, 1924).

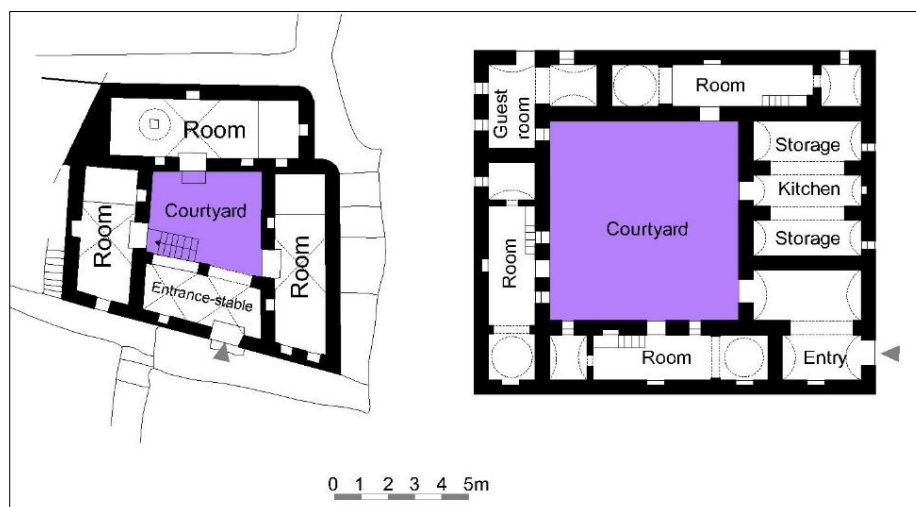


Figure 2.22. Courtyard in two different houses plans: On the left a house in Zriba Olia village (Perron and Perron, 1981), on the right a house in Djerba island (Djerbi, 2011)

In the underground dwellings of Matmata, the courtyard dimensions range from 5 to 10 meters in diameter with a depth of 10 meters, measured from the ground. Thanks to this depth, the courtyard walls are shaded for most of the day (Sakr, 2001). Although it is generally accepted that courtyards with small dimensions are particularly effective in hot climates by providing better protection from heat (Philokyprou et al., 2017), in this case, the courtyards are larger because they are located below ground level, therefore larger dimensions allow for better lighting and ventilation of the excavated rooms. Therefore, the size of the courtyard depends on two main factors: The topographical characteristics of the site and the height (or depth) of the courtyard itself. The low and flat lands, as in the regions of Djerba and Djérid, allow the creation of large courtyards, while the topography of the mountainous regions, as in the villages of Zriba and Takrouna, limits the dimensions of the courtyards. Moreover, when the courtyard is deep, as in the underground houses, or when there is a first floor, the courtyard is larger to allow better lighting of the rooms.

The shape of the courtyards in traditional Tunisian houses is generally rectangular. However, depending on the location of the house, there are irregular and circular shapes. In the mountainous regions, as in the villages of Zriba and Takrouna, or in the troglodyte houses of Douiret and Cheninni, the courtyards are too irregular and sometimes have more than four sides (Figure 2.23. (a)). On the other hand, in low and flat lands, as in the regions of Djerba and Djérid, the shape of the courtyard is straighter and more rectangular (Figure 2.20). There are rectangular courtyards in the underground houses, but circular courtyards are more common. This can be explained by the fact that the curved surfaces of the courtyard walls allow a better distribution of natural daylight and guarantee the lighting of the excavated spaces throughout the day (Figure 2.24) (Habouria, 2016).

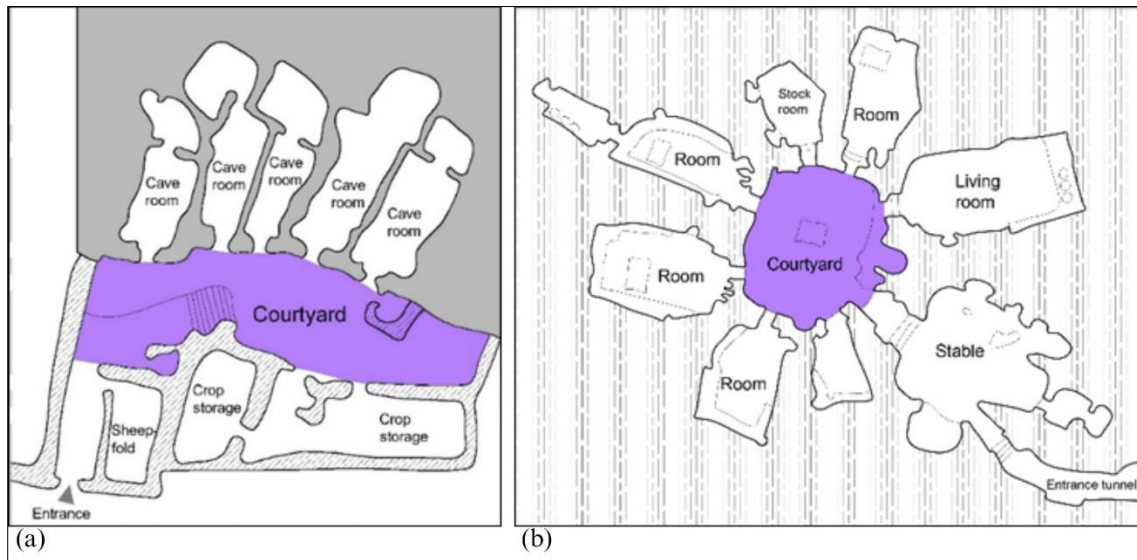


Figure 2.23. (a) Plan of a troglodyte house in Cheninni with a courtyard (Znidi, 2018), (b) A plan of an underground house in Matmata with a circular courtyard (Louis and Hallet, 2011).

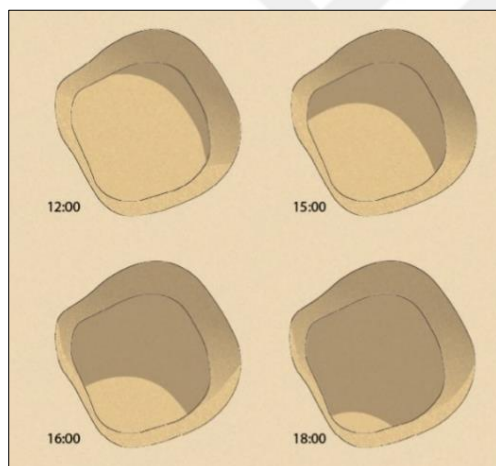


Figure 2.24. Daylight and shadow during a day in an underground courtyard (Habouria, 2016)

The level of the courtyard is always lower than the level of the rooms (20 cm) in order to avoid water infiltration and it is sloped towards the center (cistern) or the entrance in order to drain the water. The leveling of the courtyard also depends on the topography of the site. In flat lands, the courtyard floor is flat and slightly lower than the level of the rooms. In mountainous villages like Zriba Olia and Takrouna, when the slope is low, we find two courtyards in the dwelling: a first one that leads to the rooms and a second one that leads to the service spaces (annexes, stables, etc.) (Figure 2.25), the two courtyards are separated by some steps of level differentiation. Also, in the troglodyte houses of Cheninni and Douiret,

the courtyard is divided into two levels, and the cave rooms are located on the highest level. When the site is narrow and the slope is steep, we find only one courtyard with a sloping floor towards the entrance and the service rooms (Ammar and Panerai, 2010; Znidi, 2018). As a result, when the courtyard is on different levels, the rooms are always on the highest level to get better light and ventilation.

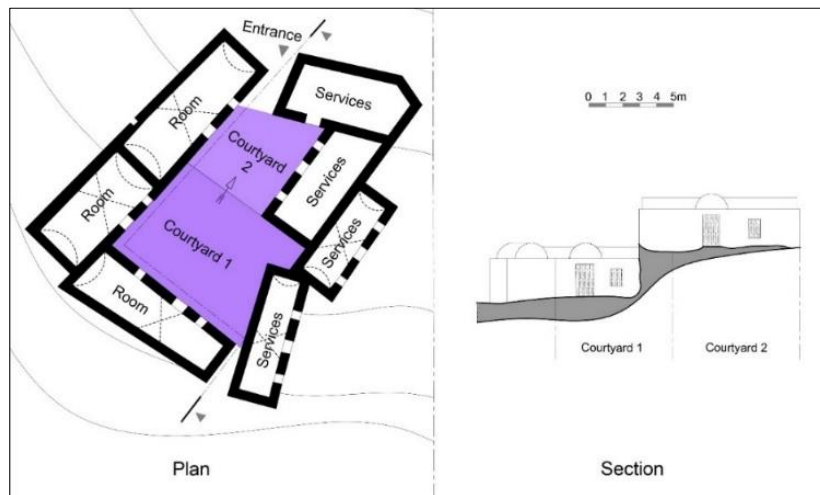


Figure 2.25. A dwelling in Takrouna village with two courtyards, (Boukaddida, 2019) modified by author

In conclusion, the concept of the courtyard in Tunisian dwellings is multifaceted and influenced by various factors. The dimensions and configurations of courtyards are directly influenced by the geographical and topographical characteristics of the site, as well as by the architectural design of the dwelling, including whether it is built above ground or underground, and whether it comprises several floors. Changes in any of these parameters can have a significant impact on the overall design, often prioritizing the maintenance of optimal conditions for passive cooling, natural ventilation, and lighting within the house.

Architectural Equipment

In all traditional Tunisian dwellings, the courtyard plays an important role in the daily life of the inhabitants. The courtyard provides a suitable microclimate for the inhabitants to carry out their daily activities, that's why it is equipped with built benches or "Doukkana"⁹ on each side to sit in the shady zones (Djerbi, 2011). The water source is a very important component

⁹ In local language, the name of the built bench.

of the courtyard, and it plays many important roles, that's why we inevitably find a well or water storage cistern in the middle of each courtyard. Since the climate is dry and rain is scarce, rainwater is collected in the cistern. On hot summer days, water is drawn from the well and used to moisten the courtyard floor in the afternoon to provide coolness and freshness. Plants and trees are often planted in the courtyard to provide evaporation, moisture, and shade. The trees planted are usually palms, thanks to their ability to withstand hot and dry climates. As such, the courtyard represents a carefully crafted microclimate through the incorporation of essential natural elements, including shading, vegetation, and water sources. The shading provided by vegetation contributes to natural cooling, and water sources, such as wells and cisterns, further regulate the microclimate by cooling the air through evaporation and creating a comforting ambiance. These elements create the microclimate of the courtyard by creating a fresh atmosphere and comfortable living spaces.

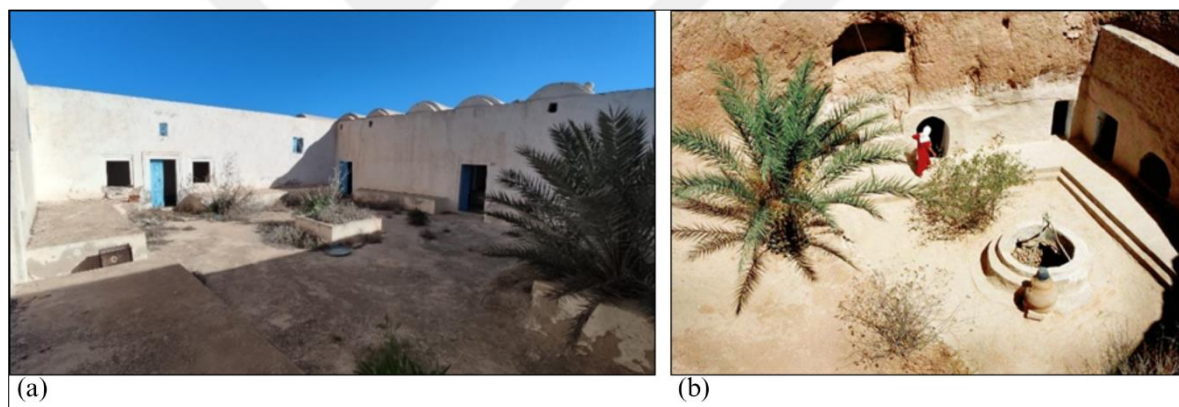


Image 2.12. (a) A Djerbian house courtyard with built benches and vegetation (URL-45),
(b) An underground house courtyard with a well and vegetation (URL-46)

Resume Table

The courtyard in Tunisian vernacular architecture plays a central role in shaping the building and enhancing thermal comfort. Factors such as topography, architectural style, and climatic conditions influence the size and design of courtyards. In addition, courtyards serve as multifunctional spaces that facilitate natural ventilation, provide shade, and encourage community interaction. Natural elements within courtyards, such as shade, vegetation, and water features, contribute significantly to the creation of a comfortable microclimate. As a whole, Tunisian architecture demonstrates adaptive resilience by integrating environmental considerations with cultural traditions to create thermally efficient living spaces. To better

understand the organization of courtyard houses, the following table summarizes the organization of spaces around the courtyard as a function of orientation and classifies the different characteristics of a courtyard.

Table 2.3. Courtyard house organization resume table

House spaces organization system			
Orientation	Spaces	Region	Extracted data
Good orientations (east, south, southeast).	Occupied spaces: rooms. Starting with the most important room (head of the family/main room).	All the studied regions (hot and arid climates).	The most occupied spaces, such as rooms, are placed in the best orientations to minimize their heat gains and create comfortable indoor thermal conditions. The less occupied spaces are placed in the worst orientations that receive a lot of heat gain.
Bad orientations (west, southwest).	Service spaces (kitchen, storage rooms, stable, etc.).		
Courtyard characteristics			
Characteristic	Description	Region	Extracted data
Type/Position	In the center of the house: The courtyard plays a social and a climatic role and is named ‘Patio’.	All the studied regions (hot and arid climates).	The central location of the courtyard makes it more efficient in terms of passive cooling and natural ventilation.
	In the side of the house: the courtyard is mainly a place of passage.	Some rural regions.	
Role	A microclimate: The courtyard is a thermal regulator. It mitigates the effects of harsh weather and creates better thermal conditions for indoor spaces.	All the studied regions (hot and arid climates).	

Table 2.3. (continued) Courtyard house organization resume table

Characteristic	Description		Region	Extracted data
Role	Ventilation and lightening.		The underground houses of Matmata and the troglodyte houses of Cheninni and Douiret.	The courtyard provides a microclimate for the building, allowing for less hot temperatures, shade, reduced heat gain, and natural ventilation of the indoor spaces.
Dimensions	Large courtyard WHR* 1.5:1/2:1		low and flat lands: - Djerba island - Djérid region - Underground houses of Matmata.	The size of the courtyard depends mainly on the geographical characteristics of the site. The flat and lowlands favor the creation of large courtyards, while in the mountainous regions, it is difficult to create spacious courtyards.
	Narrow courtyard WHR 1:1		Mountainous regions: - villages of Zriba Olia and Takrouna. - Troglodyte houses of Cheninni and Douiret.	
Shapes	Rectangular	Regular shape	low and flat lands: - Djerba island - Djérid region	The shape of the courtyard depends mainly on the geographical characteristics of the site. The flat and lowlands favor the creation of rectangular or square courtyards with regular shapes. In the mountainous areas, it is difficult to create courtyards with a regular shape. In the case of underground houses, the circular courtyards are better in terms of ventilation and lighting.
		Irregular shape	Mountainous regions: - villages of Zriba Olia and Takrouna. - Troglodyte houses of Cheninni and Douiret.	
	Circular		Underground houses of Matmata.	

* Width to height ratio.

Table 2.3. (continued) Courtyard house organization resume table

Characteristic	Description	Region	Extracted data
Levels	Flat ground and one level	low and flat lands: - Djerba island - Djérid region Underground houses of Matmata.	The flat and low land favors the creation of the courtyard at the same level as the house spaces. The mountainous land forces the creation of the courtyard on more than one level.
	Sloped and/or two levels	Mountainous regions: - villages of Zriba Olia and Takrouna. - Troglodyte houses of Cheninni and Douiret.	
Natural elements	Water source: well or water cistern.	All the studied regions (hot and arid climates).	Natural elements are essential to create shade zones and humidify the air inside the courtyard.
	Vegetation: Palm or olive tree, or native plants.		

Local construction materials and techniques

A comprehensive study of traditional construction methods reveals not only the efficient use of local materials but also a great focus on thermal performance. Within vernacular architecture, there is a deliberate emphasis on the judicious use of locally available resources to construct habitats that are both durable and thermally efficient. Through careful excavation techniques and strategic resources management, these architectural designs represent timeless principles of sustainability and resourcefulness, ensuring optimal thermal comfort within the built environment.

Thermally efficient construction materials

In Tunisian vernacular architecture, the construction materials used are predominantly local, and the availability of these materials varies from region to region, depending on the geological and geographical characteristics of the site, the flora, and the cultural heritage. Stone, earth, limestone, palm, and olive tree trunks are the main construction materials in

Tunisia and are used in various traditional buildings. However, certain regions show a strong preference for certain materials, largely due to their abundance. For example, in mountainous regions such as the village of Zriba Olia, abundant stone resources dictate its extensive use in the construction of walls, roofs, and floors. On the other hand, in the desert-like Saharan regions of Nafta and Tozeur, clay bricks are more common. Some regions have unique materials not found elsewhere, such as the abundant seaweed along the coasts of the island of Djerba, which is used to waterproof and insulate roofs. The use of these materials varies from region to region, depending on traditional building techniques and climatic conditions. The main materials used in the construction of traditional dwellings are described below, together with their application in the structure of the building.

Stone: limestone, sandstone, marble, and granite are among the available types of stone used in construction (Ammar and Panerai, 2010). These stones are either extracted directly from the construction site or sourced from nearby quarries. Stone finds application in various aspects of construction, including dwelling foundations, walls, roofs (flat, vaulted, or domed), ground pavement, lintels, and fixed furniture. The shape of the stone is determined by its intended use, and it can be employed in its natural state or shaped through cutting. Stone is widely utilized in all Tunisian regions due to its abundant availability. In hot, arid climates, stone provides significant thermal benefits by providing high thermal mass, absorbing heat during the day and slowly releasing it at night to maintain stable indoor temperatures. Stone's durability and resistance to extreme temperature fluctuations make it a long-lasting building material. In addition, as a natural, non-gassing material, stone contributes to healthier indoor air quality and blends in perfectly with the natural environment.

Earth: the earth is employed in various forms in construction, including bricks, rammed earth, clay, or in its natural state, particularly in troglodyte houses. Bricks and pisé are utilized for constructing walls and roofs, while clay serves as a binder and plaster. The use of earth in construction is relatively uncommon, with one notable example being the vernacular architecture of Djérid in southwest Tunisia. Djérid region is renowned for its dwellings made of pisé and baked bricks. Today, traditional brick production is still integral to the local economy of Tozeur, providing employment for approximately twenty families (Dhaher, 2012). Earth, including brick, rammed earth and adobe, offers exceptional thermal benefits in hot-arid climates due to its natural capacity for thermal mass and insulation. These

materials absorb heat during the day and release it slowly at night, stabilizing indoor temperatures. In addition, their density and thickness provide effective insulation against extreme outdoor temperatures, helping to keep interiors cool during hot days and warm during cold nights. Their locally sourced and sustainable nature also reduces environmental impact.

Limestone: limestones play an important role in traditional Tunisian architecture and are abundant throughout the country. Its physical properties make it a very useful material, as it can be combined with clay, sand, aggregates, and other materials to serve various purposes, such as mortar, plaster, binder, insulation, or waterproofing. Limestone's high thermal mass contributes significantly to stabilizing indoor temperatures, while its natural insulating properties effectively reduce heat transfer from the outside environment. In addition, the white color of limestone provides further benefits by reflecting sunlight, improving the overall thermal performance of buildings. These thermal benefits play a critical role in maintaining comfortable living conditions and protecting the building envelope in hot, arid climates.

Palm and olive trees: in some regions, such as the Djérid region, where palm trees are more abundant, the use of palm trunks and leaves in construction is more common. In areas where olive trees are more common, such as Zriba Olia, olive tree trunks and branches are used in construction. Palm and olive tree trunks are mainly used in the construction of roofs as supporting beams and spans.

Sand: sand, extracted from construction sites or riverbeds, is always combined with other materials to make mortars and plasters (Ammar and Panerai, 2010). When used in combination with other materials such as clay and lime, sand contributes to the thermal mass of the building. In addition, the granular nature of sand provides good insulating properties when used in plaster or mixed with other building materials, reducing heat transfer from the external environment. Overall, sand improves the passive cooling and thermal comfort of buildings in hot, arid regions.

Gypsum: gypsum, a mineral abundant in Tunisia, is widely used as a plastering material. After being quarried, gypsum is baked, ground into a fine powder, and mixed with water and other materials such as sand, clay, aggregate, etc. to produce plaster. This plaster is then

applied to both interior and exterior walls, providing a smooth and durable finish. In addition, gypsum is used for decorative purposes, often molded into arches or columns to add ornamental detail to buildings. Gypsum's natural insulating properties effectively help reduce heat transfer, keeping interiors cooler during the day and warmer at night. In addition, gypsum's ability to regulate humidity by absorbing and releasing moisture contributes to a more comfortable indoor condition.

In addition to the primary construction materials (stone, brick, rammed earth, and lime), vernacular architecture often incorporates a variety of secondary materials such as pottery, cactus leaves, and seaweed. These materials, while regionally variable and less commonly used, demonstrate the adaptability and ingenuity of traditional architectural practices. Their availability and use are often dictated by local resources and climatic conditions, which can limit their application to certain regions. Nevertheless, the inclusion of these diverse materials highlights the ingenuity of ancient builders in creating sustainable and contextually appropriate structures. Overall, the used local construction materials have excellent thermophysical properties that make them highly effective in temperature management in hot-arid climates. These materials typically have a high thermal mass, which allows them to absorb, store, and slowly release heat, and a natural insulating capacity that minimizes the transfer of heat from the external environment to indoor spaces. Materials such as lime and certain types of stone can also reflect sunlight, adding to their thermal regulation capabilities. these materials are also durable and sustainable, often locally produced or mined with zero environmental impact and energy consumption. In addition, the use of local materials ensures that structures are better adapted to the surrounding environment.

Resources management

The construction system of the troglodyte dwellings of Cheninni and Douiret, and the underground dwellings of Matmata is too different from the common construction system of the above-ground dwellings in Tunisia. This difference is due to the excavation fact of the dwellings in the mountains or the ground. The construction of walls and roofs is not needed, especially in the case of underground houses of Matmata, and if so, the walls are made of stone rubble without foundations (Ammar and Panerai, 2010). Underground and troglodyte dwellings exemplify the ingenious use of earth as a construction material, maximizing thermal efficiency and minimizing both effort and waste.

The underground houses of Matmata benefit from the unique properties of the local soil, which makes excavation easy. This deep layer of soil, almost free of stones and gravel, contains a mixture of sand, calcium carbonate, clay, and gypsum. Similar to loess, it is both firm and cohesive, making it easy to excavate and shape with conventional hand tools. (Golany, 1988; Sakr, 2001). The excavation begins by selecting a slightly sloping site and marking the circle of the courtyard on the top of the hill. The first phase is the excavation of the courtyard, followed by the excavation of the second-floor rooms, if present. At a depth of 10 meters, the excavation of the courtyard is completed. Next, the entrance tunnel, the rooms, and the cistern are excavated in sequence. The excavated soil is strategically placed around the patio opening to prevent water runoff (Golany, 1988; Habouria, 2016).

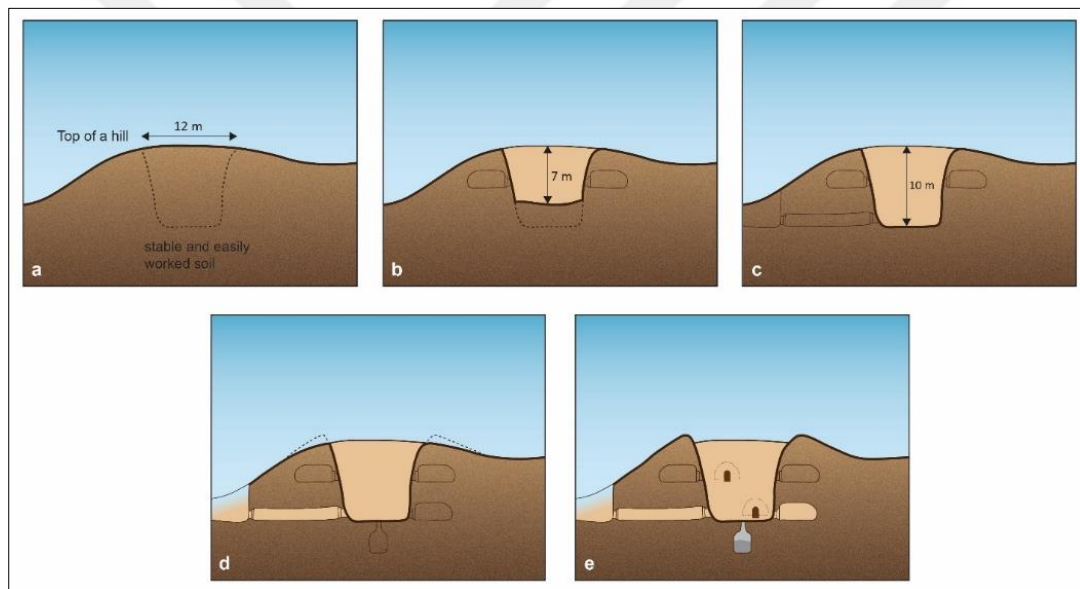


Figure 2.26. Matmata underground houses excavation phases (Habouria, 2016)

The troglodyte houses of Duirat and Cheninni are located in mountainous regions characterized by horizontal stratification of hard (limestone) and soft (marl) rock layers (Figure 2.27). Construction of these cave dwellings begins with the excavation of cave rooms. Excavation proceeds horizontally within the soft rock layer between two harder layers. Stones extracted during excavation are strategically placed at the front to serve as construction materials for external structures, including kitchens, toilets, barns, and courtyard walls (Figure 2.28) (Golany, 1988; Znidi, 2018).

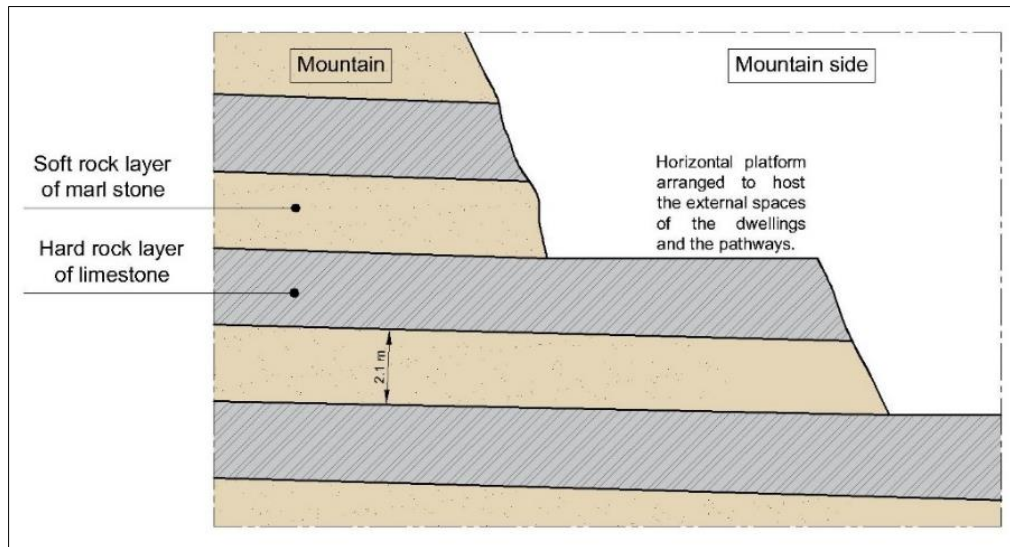


Figure 2.27. Schema of the geological layers of mountain (Znidi, 2018), created by author

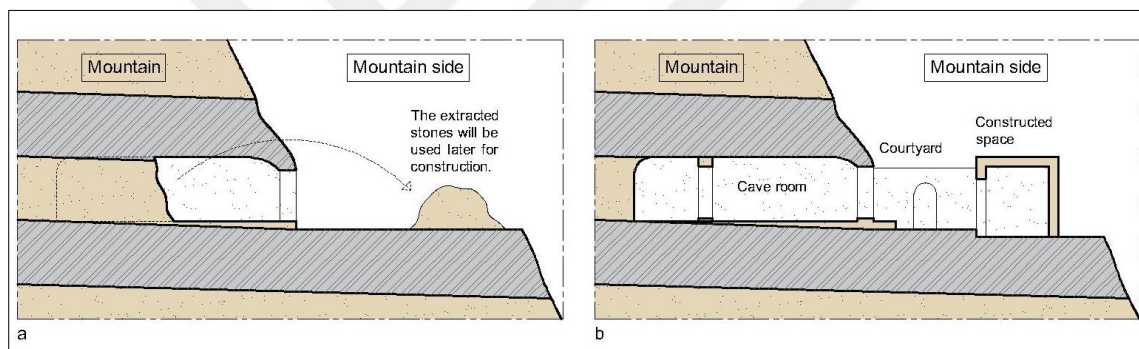


Figure 2.28. Troglodyte houses modeling phases (Znidi, 2018), created by author

The underground and troglodyte houses illustrate how ancient communities ingeniously used locally available construction materials to blend their dwellings into the natural environment. By employing a judicious excavation strategy tailored to the geological strata and nature of the soil, they optimized the use of materials, ensuring efficient construction practices while minimizing waste. This resourceful approach not only contributed to the economy of materials but also promoted the internal thermal comfort of the dwellings, demonstrating the practicality and sustainability of ancient architectural techniques in harmonizing human habitats with the environment.

Resume table

The inhabitants of traditional dwellings in Tunisia developed ingenious methods of assembling local materials to ensure thermal insulation. Inhabitants used materials with high thermal mass and low thermal conductivity, different mortars for wall construction, stratified different layers in roofs, and applied special coatings to exterior surfaces to improve insulation and waterproofing. These techniques demonstrate how local resources can improve indoor comfort.

Such construction methods are part of a comprehensive traditional architecture system designed to blend harmoniously with the natural environment. The table below summarizes the materials used in Tunisian traditional houses, categorized by purpose and region. The availability of each material in a particular region is indicated.

In most cases, building materials are sourced locally, often from the construction site or nearby quarries. In rare cases, materials such as palm trunks are transported from the south to other regions to avoid the high cost of using olive tree trunks. In addition, stone and brick are sometimes used in areas where they do not occur naturally, but their use is limited and in small quantities. This approach maintains a balance between the cost of construction and the functional use of each material.

Table 2.4. Local construction materials and techniques resume table

Architectural elements	Construction material		Region	Availability on site	Extracted Data
Envelope body: - Walls - Roof	Masonry	Stone	- Mountainous regions (Zriba Olia village, Douiret troglodyte houses, etc.) - Djerba island	√	Stone, brick, and earth are essential structural materials that enhance the building's thermal performance due to their high thermal mass and low thermal conductivity.
		Brick	Djérid region	√	
		Earth	Underground houses of Matmata	√	

Table 2.4. (continued) Local construction materials and techniques resume table

Architectural elements	Construction material		Region	Availability on site	Extracted Data
	Binder	- Earth - Lime - Clay	Materials that are available sufficiently in all regions.	√	Earth, lime, and clay provide excellent waterproofing and thermal insulation as binder materials.
	Beams	Palm trunks	- Zriba Olia and Takrouna villages	X	Palm and olive tree trunks, with their strong fibers and lightweight, make excellent supporting beams for roofs. In addition, wood is a sustainable material and helps reduce heat gain through the roof.
			Regions in the south: - Djerba island - Douiret and Cheninni mountains - Djérid region	√	
		Olive trunks	Olive trunks are costly and therefore rarely used as beams.		
Coating - Walls - Roof	Lime plaster (+ sand + aggregate)	Zriba Olia and Takrouna villages		√	Lime, clay, gypsum, and bricks are highly efficient thermal insulation and waterproofing coatings when used on the exterior of the building envelope. The choice of material depends on local availability. For above-ground houses, the addition of sand and aggregate to the plaster increases its resistance to weather influences.
		Djerba island		√	
		Douiret and Cheninni mountains		√	
		Matmata (sand is an option, no aggregate)		√	
	Clay Plaster (+ sand + aggregate)	Djerba island		√	
	Gypsum plaster (+ sand + aggregate)	Douiret and Cheninni troglodyte houses		√	
	Bricks	Djérid region		√	
External surfaces - Roof - Walls - Ground	Limestone-based coating	Limestone is available and used in all regions.		√	Limestone is an excellent insulator and waterproofing material for building envelopes. Its white color also helps reflect a significant amount of sunlight.

Envelope system

The building envelope is an interface that acts as a dynamic filter between the internal and external environments to control the energy flows that, directly or indirectly, enter or leave the indoor spaces. Therefore, it is essential to investigate the design and the materials of the envelope considering orientation, temperatures seasonal variations, surrounding environment, and inhabitants' requirements (Altomonte, 2008). The envelope includes the walls and roof of a building, and both should be well-studied to improve thermal insulation. The traditional Tunisian dwellings represent a well-developed envelope design capable of controlling heat gain during the hottest days of summer. The thick walls, curved roofs, thick coating layer, and external limestone whitewash played a crucial role in making the Tunisian dwelling highly insulated.

Walls

The walls of traditional dwellings have specific structures designed with a focus on high thermal mass enabling them to effectively minimize and delay heat gain. This strategic approach ensures that indoor temperatures remain stable and comfortable, even in the face of external temperature fluctuations. Through their robust construction and thoughtful design, these walls serve as a protective barrier, regulating the transfer of heat and maintaining a consistent indoor climate. Thermal inertia describes the ability of walls to absorb and retain heat during the day and then gradually release it at night. With greater wall thickness comes greater thermal inertia, resulting in a slower transfer of heat between indoor and outdoor spaces. The graph below (Figure 2.29) illustrates how thicker walls made of compressed earth blocks result in reduced temperature fluctuation in interior spaces (Neya et al., 2021).

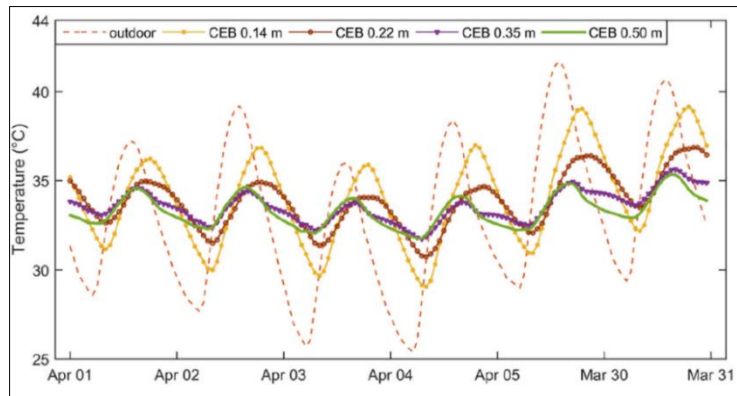


Figure 2.29. Influence of (CEB) wall thickness on a building's thermal response (Neya et al., 2021)



Image 2.13. A picture showing the wall thickness in a ruined dwelling in Zriba Olia village (URL-47)

The walls of Djerba dwellings are built with travertine stones and bonded with three different mortars (Figure 2.30. (a)) according to their location in the wall. Thermal insulation is basically allowed by the thickness of the walls, which provides sufficient thermal inertia to provide a phase shift between indoor and outdoor temperatures during the extreme seasons. The thickness of the walls varies from 50 to 60 cm, and it is the same value from the foundations to the top of the wall (Djerbi, 2011; Tlatli et al., 1975). In the Djérid region, the high temperatures influenced the construction of houses, resulting in unique features that set them apart from other traditional dwellings. The walls in this region are significantly thicker, ranging from 65 cm to 1 meter, specifically designed to minimize heat gain and maintain cooler indoor temperatures. The wall core is made of brick or rammed earth and is covered with brick cladding that contains decorative geometric patterns (Alkalyouby, 2016; Ammar

and Panerai, 2010). Thus, Tunisian dwellings benefit from the thermal inertia of the walls by using materials with high thermal mass (stone, brick, etc.) and setting a specific thickness of the walls ranging from 50 cm to 1 m, which significantly improves the thermal insulation of the building.

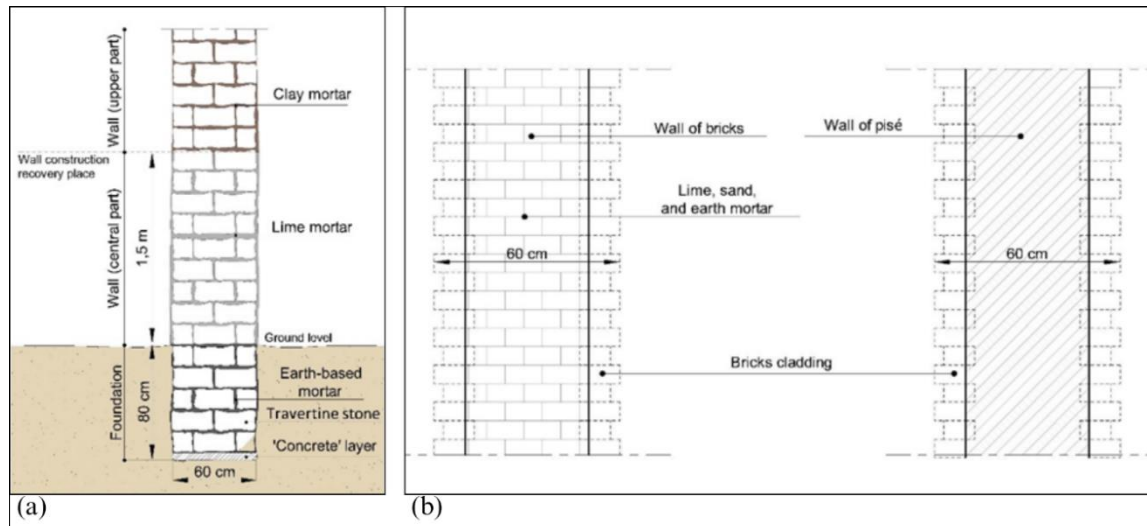


Figure 2.30. (a) Djerbian house wall construction technique (Djerbi, 2011), (b) Djérid dwellings walls details (Alkalyouby, 2016; Ammar and Panerai, 2010)

The underground dwellings of Matmata and the troglodyte houses of Douiret and Cheninni exemplify the use of the thermal mass of the earth to create comfortable indoor conditions. The natural properties of the earth and mountains help to balance indoor temperatures with outdoor conditions. During warmer periods, excess heat indoors is released outdoors, creating a cooler atmosphere. Conversely, during colder weather, stored heat from the environment is released indoors, providing warmth (Toumi et al., 2019). In Matmata, the earth cover above the rooms is 6 to 7m thick. This soil cover serves not only as a heat insulator but, more importantly, as a heat retainer. During summer, the heat travels from the surface and eventually reaches the rooms during the winter (Figure 2.32), conversely, during winter the cold is transmitted to the rooms in summer (Figure 2.31) (Golany, 1988). As a result, the inside ambient temperature of the rooms remains consistently comfortable throughout the year. The cave rooms in Douiret and Cheninni are fresh in summer and warm in winter. During the day, the superficial layer of the mountain gradually accumulates heat from the outside environment, while the intermediate layer, where the rooms are excavated, remains cool (Figure 2.32). During the night, the superficial layer, heated during the day, reflects some of its heat back into the cold atmosphere outside. The difference between the

geothermal temperature and the superficial layer temperature contributes to making the intermediate layer feel warmer than the outside (Figure 2.31) (Znidi, 2018). The underground houses and mountain cave dwellings are outstanding examples of adaptation to harsh weather conditions, particularly in the use of the earth's natural heat exchange process. By effectively using the earth's innate ability to regulate heat, the inhabitants of these dwellings have successfully created indoor environments that remain thermally balanced.

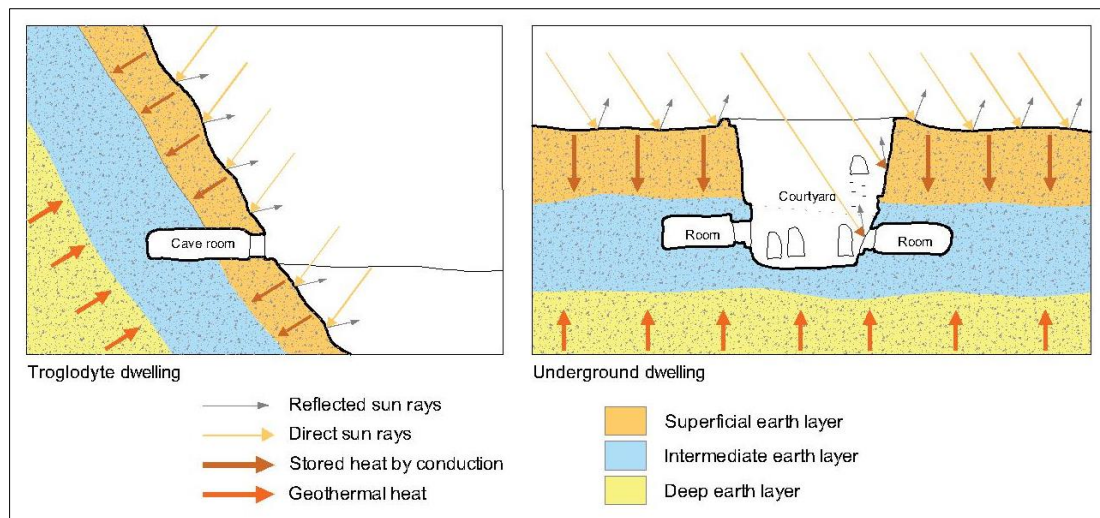


Figure 2.31. Earth's thermal behavior during the night/winter, created by author

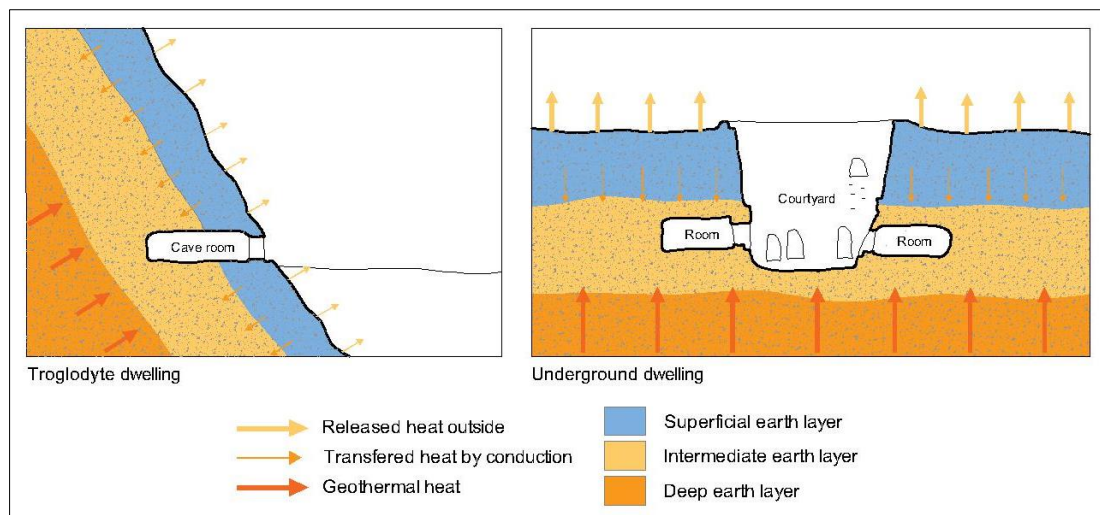


Figure 2.32. Earth's thermal behavior during the day/summer, created by author

Roof

In regions with hot-arid climates, flat roofs are susceptible to significant direct solar gain by being fully exposed to the sun's rays throughout the day. In contrast, vaulted or domed roofs provide natural shade by exposing only a small portion of their surface to direct sunlight, which varies with the path of the sun. This limited exposure reduces the intensity and duration of solar gain compared to flat roofs, resulting in a slower rise in indoor air temperature and less drastic temperature peaks. Besides, a curved roof provides a larger surface area for convective heat transfer, making it more effective at cooling. In addition to reducing solar gain, curved roofs benefit from receiving a moderate amount of cool breezes from prevailing winds, regardless of their direction. This airflow helps keep the roof surface cool even on hot summer days (Abraar, 2018). The use of domes and vaults in the roof design greatly enhances the natural ventilation of the building, especially when a vent is added at the top. This technique will be further explained in the next section, Natural ventilation.



Image 2.14. Dwellings in Zriba Olia village covered with vaulted roofs (URL-48)

In Tunisian architecture, three types of roofs are prevalent: flat, vaulted, and domed. Vaulted and domed roofs are more commonly used in dwellings due to their thermal advantages. In the studied examples of vernacular architecture, most dwellings feature vaulted roofs, including underground and troglodyte homes with curved ceilings. Generally, domes are reserved for sacred spaces such as mausoleums and mosques. In the villages of Zriba and Takrouna, all the dwellings are covered with vaults. Since the different rooms have the same shape, a long rectangle, the roof is covered with a barrel vault along its length, and in the middle, there is an additional vault perpendicular to the first, forming a groin vault (Image 2.15. (b)). In this

way, the vaults are always partially exposed to the sun and absorb less solar radiation than the flat roof. In Djerba, the rooms, which are divided into three different spaces, have a specific roof design: the central zone, which is a transitional space, is covered with a flat roof; the summer space, to the right of the entrance, is located on an upper level accessible by a staircase covered with a flat roof; and the winter space, to the left, is covered with a dome. The service spaces are covered with barrel vaults (Ammar and Panerai, 2010; Djerbi, 2011).

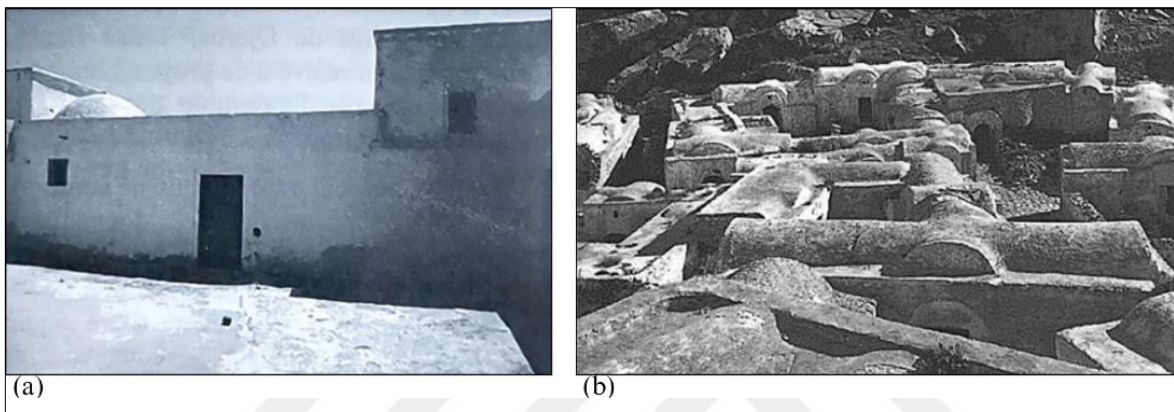


Image 2.15. (a) A picture of a Djerbian room (Djerbi, 2011), (b) A picture of the dwellings' roofs in Zriba Olia village (URL-49)

In the underground houses of Matmata and the troglodytic houses of Cheninni and Douiret, the ceilings of the excavated rooms are vaulted because the vaulted roof shape plays an important role in temperature regulation by maximizing the surface area in contact with the earth. The greater the surface area in contact with the earth, the more heat can be absorbed (Hill and Woodland, 2003). In addition, since the rooms have no openings except for the door, the curved shape of the ceiling allows for better diffusion of daylight. As an exception, the houses in the Djérid region are completely covered with flat roofs. However, the height of the rooms is significant and could reach 10 m to create better air circulation (Image 2.16. (b)) (Alkalyouby, 2016). In this instance, the flat roof did not pose a problem, as the considerable height and the ventilation openings in the upper part of the walls played an important role in cooling the rooms.



Image 2.16. (a) A vaulted ceiling in an underground house in Matmata (URL-42), (b) A room in the Djérid region (l'Union Européenne, 2001)

The structure of flat roofs in traditional dwellings is relatively common, with slight variations in the used materials. Roof beams are typically made of wood, mainly palm trunks, as olive trees are culturally significant and therefore rarely used (Dghari-Ounissi, 2002). Palm trunks are cut lengthwise into two pieces and placed side by side. In some cases, as in the Nafta dwellings, the trunks are separated by 1 to 1.5 m, and on the top are placed logs of olive wood, forming spans. Usually, a mixture of aggregates (fine stones) and a mortar of clay (or sand) is placed on top of the trunks. In the case of mountain troglodyte dwellings, this first layer is made up of large flat stones and two successive layers of smaller stones to fill in the gaps. The whole is held together with gypsum mortar (Ammar and Panerai, 2010). In Djerba dwellings, before proceeding with the aggregate and mortar layer, palm trunks are covered with a layer of seaweed¹⁰ as a thermal insulation layer. Seaweed, collected from the island's coasts where it is washed ashore by the waves and sun-dried, is used as a thermal insulation material for the flat roofs. Finally, a sloped layer of mortar is applied to facilitate water drainage, followed by an outer layer of lime plaster for waterproofing and heat reflection. Typically, the thickness of flat roofs is around 35 cm (Tlatli et al., 1975). The traditional flat roof structure exemplifies an efficient thermal insulation technique. By layering local materials in a precise stratification, these roofs transmit less heat and reflect more solar radiation, maintaining stable indoor temperatures despite the harsh outdoor climate. This combination of materials ensures structural integrity and optimizes thermal regulation, demonstrating the ingenuity of traditional Tunisian architecture. Figure 2.33

¹⁰ Posidonia, a seagrass species that is endemic to the Mediterranean Sea.

below illustrates this combination of local materials in the roof structure of a Djerbian dwelling, which represents the most complex roof design in Tunisian vernacular architecture.

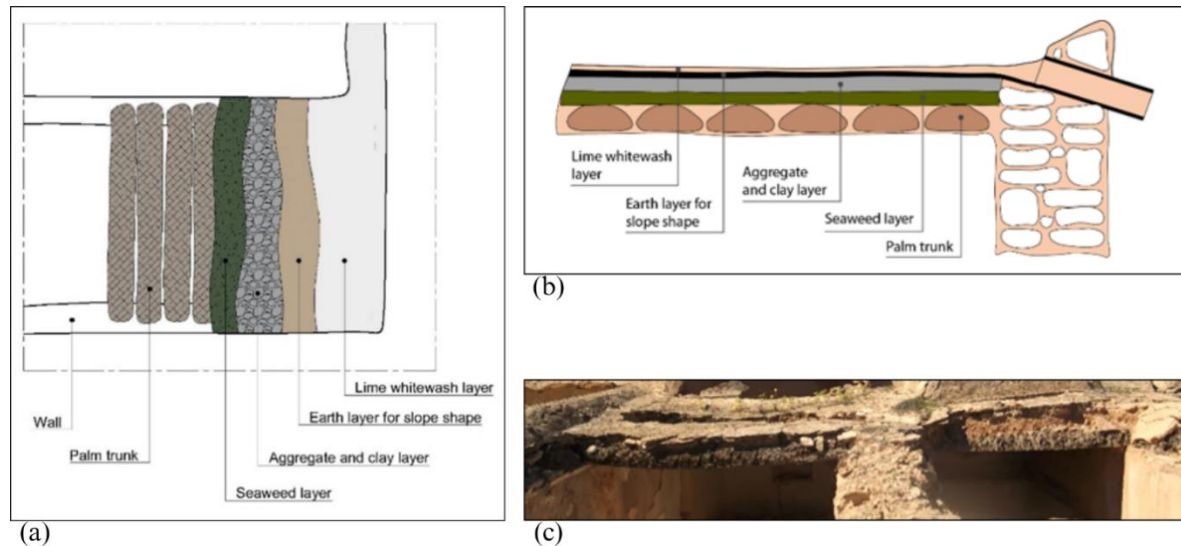


Figure 2.33. (a) Roof structure top view, (b) Roof structure section, (c) Photo of deteriorated Djerbian house showing the roof structure (Djerbi, 2011), modified by author

The barrel vault is the most common and widely used type of vault in traditional dwellings. The vaults are built with small stone masonry bonded with plaster mortar. An additional layer of mortar (clay or earth) is placed on top of the masonry. In the case of the mountain troglodyte dwellings, firstly the layer of mortar is applied on top of palm trunk formwork, and then the stone masonry is applied. Finally, the outside and inside of the vault are whitewashed with lime (Ammar and Panerai, 2010; Djerbi, 2011). In the villages of Takrouna and Zriba Olia, the vaults are made of stone and brick masonry. The first layer of the vault is made of hollow bricks (as a lost formwork) and the second layer is made of stone masonry (Fig). Finally, the outside of the vault is plastered with lime, and the inside with lime mixed with 'Nila'¹¹ powder (El Abdi, 2020).

¹¹ A blue powder extracted from the *Indigofera suffruticosa* plant and used in many fields.

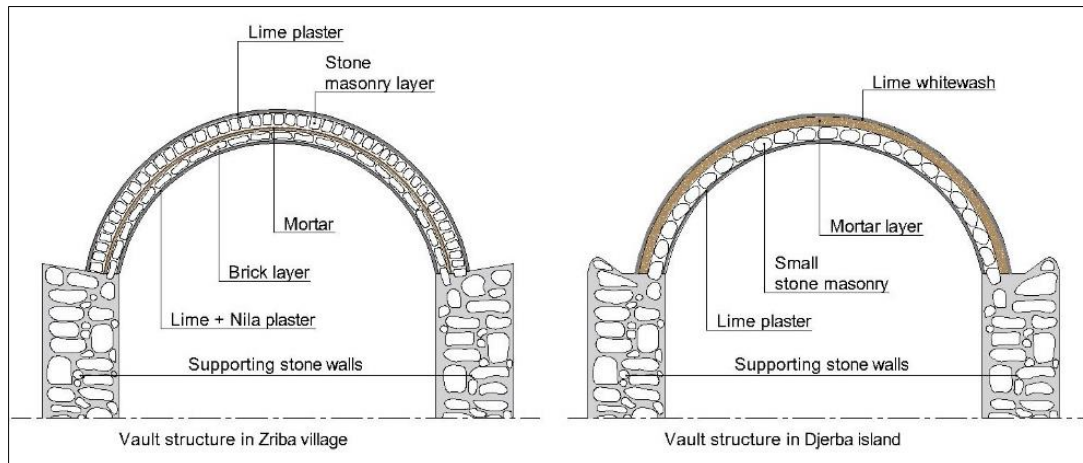


Figure 2.34 Vault structure (created by author)

The use of domes in dwellings is most common on the island of Djerba. The small domes (2 - 2.5m Ø) are built with small stone masonry. The larger domes are made of round pottery with a cylindrical shape and different diameters at the ends (Figure 2.35). This difference in diameter helps to achieve the desired curvature of the dome. In the intrados, these potteries remain visible. The extrados, however, are plastered with mortar and whitewashed with lime. This type of pottery is a good thermal insulator, specifically made for this purpose in the island's pottery workshops. The total thickness of the dome is about 10 to 15 cm (Tlatli et al., 1975).

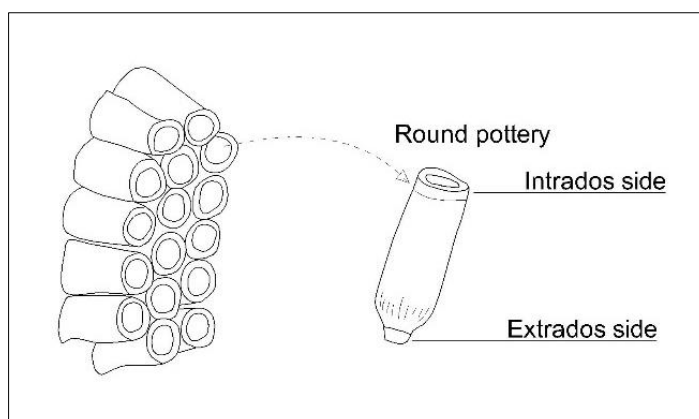


Figure 2.35. Round pottery used for dome construction (Djerbi, 2011)

Envelope coating

In traditional architecture, the exterior coating layer of the building envelope plays a crucial role in mitigating heat gain. This layer is meticulously designed, from the choice of plaster materials to the surface texture, with the specific intention of reflecting heat and minimizing heat absorption. By effectively reducing heat gain, the coating layer protects indoor spaces from the harsh climate, maintaining a cooler and more comfortable environment.

Coating layer

A coating layer is a few centimeters thick layer, applied above the wall core to protect the masonry from external weather influences like rain and wind while improving its thermal insulation. Traditional Tunisian dwellings often feature a common coating layer comprising a first layer of earth mortar followed by a second layer of sand and lime plaster or sand and crushed limestone mixed with gypsum. Depending on the dwelling's location, extra waterproofing materials such as ash, marble powder, clay powder, grog, or crushed shells could be added (Ammar and Panerai, 2010). In the Djerbian houses, the coating layer substance is composed basically of sand with lime or clay, according to the purpose of use, which gives two types of plasters: clay plaster and lime plaster (Tlatli et al., 1975). In Takrouna village, lime mixed with sand and aggregate gives a perfect coating substance for waterproofing and isolation (El Abdi, 2020). In Douiret, both gypsum and limestone are used for coating, they are extracted from the natural site and baked, then mixed with sand and used as a plaster for the walls and vaults (Ammar and Panerai, 2010; Znidi, 2018). In the underground houses of Matmata gypsum and limestone are used as plasters for coating the interior surfaces of the rooms (Sakr, 2001).

In summary, the coating layer is basically composed of lime, gypsum, and earth (clay). For the above-ground houses, these materials are usually mixed with sand and aggregates to allow better protection of the walls from external weather influences and to improve the thermal insulation of the building envelope; for the underground and troglodyte houses, the plaster materials are simply mixed with water, and eventually with sand, and applied to the internal surfaces of the excavated rooms.

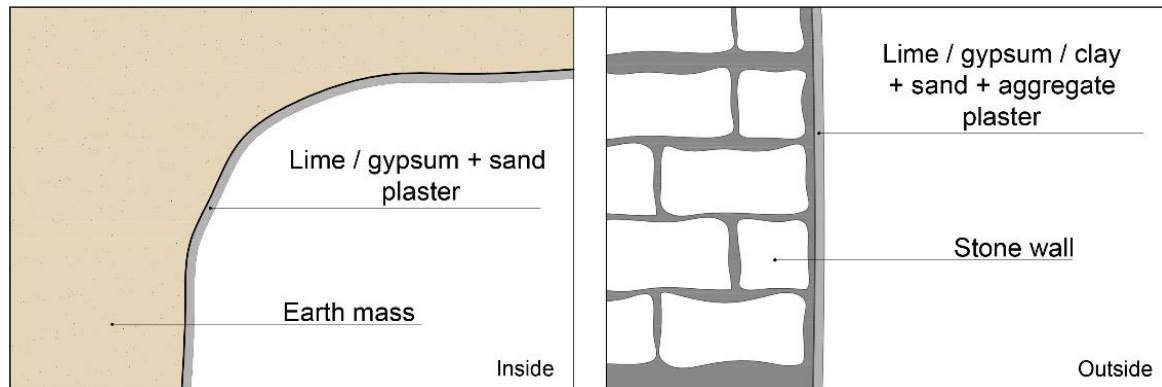


Figure 2.36. Details of coating layers on the inner surface of an underground/cave room wall, and on the external surface of an above-ground house wall (created by author)

Limestone whitewash

Tunisian dwellings are distinguished by their white color due to the widespread use of limestone whitewash on the exterior walls and roof surfaces. External limestone plaster plays a crucial role in improving the thermal efficiency of the building envelope. Thanks to its white color, limestone whitewash reflects between 55% and 80% of the incident sunlight. Lime plaster is also known for its ability to improve the thermal inertia of a building in summer by delaying heat transfer. Limestone acts as an insulator, reducing the temperature amplitude in summer and delaying the maximum temperature at night (Dabaieh et al., 2015; Stéphan et al., 2014). Traditionally, limestone whitewash is applied periodically to the building envelope, especially on the outside, every year or every season, to repair cracks, protect the wall surfaces, and improve the thermal insulation (Djerbi, 2011). The courtyard facades are also whitewashed with limestone plaster to reduce heat gain and reflect daylight into the rooms. In the underground houses of Matmata, only the lower walls of the courtyard where the rooms are located, are whitewashed with limestone (Image 2.17. (b)) (Golany, 1988). Also from the inside, lime plaster is applied to the walls of the rooms to absorb humidity and reflect daylight. This is especially important in the case of underground and troglodyte houses, where there are no openings except the doors, which could pose a problem of poor ventilation and lighting.

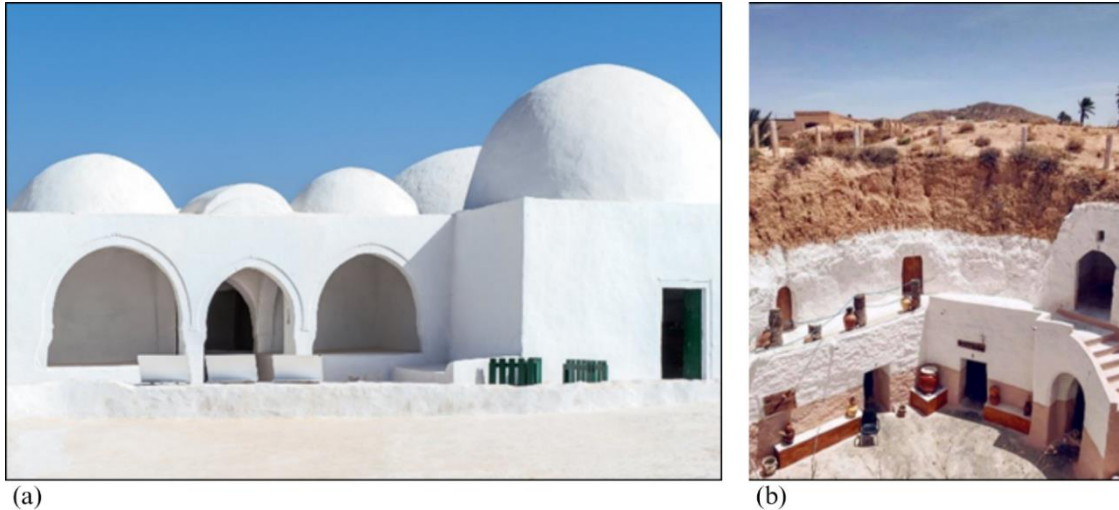


Image 2.17. (a) A mosque in Djerba whitewashed with lime plaster (URL-50), (b) Underground house in Matmata whitewashed with lime plaster (URL-44)

Texture

The texture of the exterior wall surfaces plays an important role in cooling. The exterior surfaces of Tunisian homes are treated with a slightly wrinkled texture, intentionally created at the level of the coating layer. Unlike a smooth surface, this texture creates zones of shade on the wall surface throughout the day, reducing the area exposed to the sun's rays (Djerbi, 2011).



Image 2.18. The texture of the exterior wall in a Djerbian house (URL-51)

In the Djérid region, there is a specific type of cladding that is applied to the façades using locally produced bricks. This cladding contains geometric patterns formed by the recesses of the bricks, creating shaded zones on the façades, and protecting the walls from direct sunlight. In the case of the earth-rammed wall, the bricks penetrate relatively into the wall

body to create a recessed effect on the surface. In the case of brick walls, the bricks on the edges are recessed to create geometric patterns (Figure 2.37). In general, brick cladding is applied to the upper part of the walls, starting from the top of the windows and doors on the ground floor and covering the whole façades on the first floor. This can be explained by the fact that the façades of the first floor are more exposed to the sun due to the ratio between the height and the width of the courtyard. In the lower part of the wall, a plaster of lime or gypsum is applied to the walls (Ammar and Panerai, 2010; Augustin, 1924).

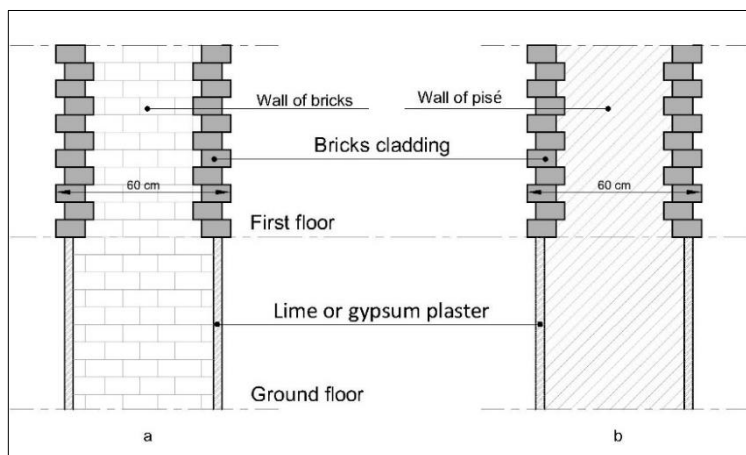


Figure 2.37. Tozeur walls cladding details (created by author)



Image 2.19. Brick cladding in a house façade in Nafta (URL-52)

Envelope Opacity

In traditional architecture, the window-to-wall ratio is deliberately kept low to minimize heat penetration into the building. Tunisian dwellings typically feature enclosed external facades

with minimal openings, except for the entrance door. If windows are present, they are small in size. In contrast, facades opening onto the courtyard have larger openings. This arrangement serves to shield the dwelling from the intense heat of the external environment while allowing it to benefit from the more moderate microclimate within the courtyard. In Djerba dwellings, exterior facades are predominantly opaque, featuring only an entrance door and a few narrow windows situated high on the walls or serving as air vents for vaults. Occasionally, small circular apertures made from pottery pipes or jar necks (ranging from 6 to 18 cm in diameter) are embedded in the masonry during construction, functioning as ventilation outlets in the summer. In contrast, within the courtyard, each room's facade typically includes one door flanked by two large windows on each side (Djerbi, 2011).



Image 2.20. Courtyard façades of a Djerbian house (URL-53)

In the Djérid region, houses do not have windows on the outside and have different types of openings in the courtyard. The standard windows are rectangular and have dimensions of 80 x 120 cm, placed in the lower part of the walls. On the upper part of the walls, there is a special type of opening called Al-tiyaq¹², placed as a series of narrow windows with dimensions of 20 x 70 cm (Image 2.21. (a)). Al-tiyaq openings are placed within the decorative patterns of the bricks and they allow natural ventilation of the rooms without too much exposure to sunlight. The width of the doors is standard and ranges from 75 cm to 1 m for single-sided doors and 1.55 m for double-sided doors (Alkalyouby, 2016; Perron and Perron, 1981). In the villages of Zriba Olia and Takrouna, the walls are closed on the outside and open in the courtyard with narrow windows. In some cases, the rooms have no openings other than the door and the narrow ventilation apertures above the door (Image 2.21. (b)) (Ammar and Panerai, 2010). The troglodyte houses of Cheninni and Douiret, the built part of the house has no openings on the outside and only narrow openings in the courtyard. The

¹² Name of the small openings in Arabic language.

cave rooms of Cheninni and Douiret and the underground rooms of Matmata have no openings except for the doors (Znidi, 2018). In mountainous regions, the low window-to-wall ratio is explained by the wind factor, which has a stronger effect in high altitudes. The underground houses of Matmata have no openings in the courtyard except the doors. The absence of windows ensures better temperature regulation by minimizing heat exchange and allows structural durability by reducing risks of weaknesses in the walls over time.

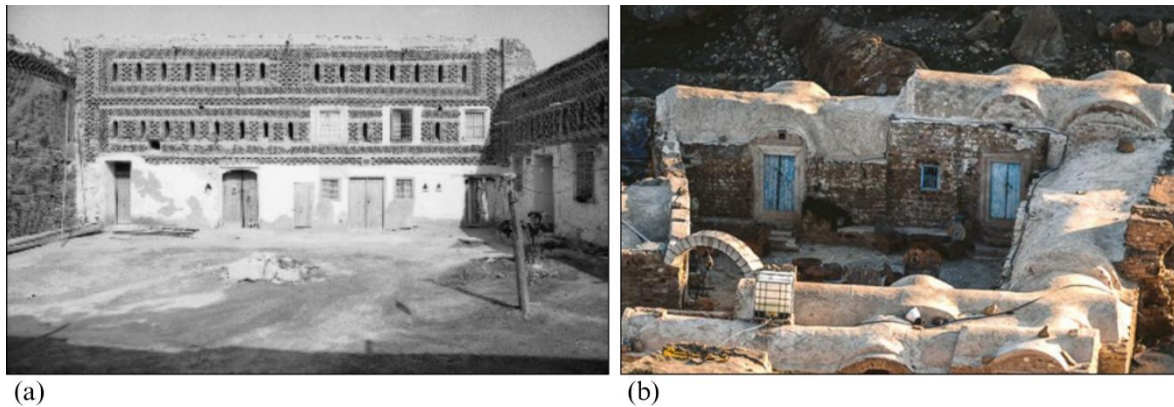


Image 2.21. (a) Courtyard façades of a house in the Djérid (Abachi, 2000), (b) Courtyard façades of a house in Zriba Olia (URL-48)

In summary, the courtyard house design profoundly influenced the construction of the building envelope, determining its overall opacity from both external and internal perspectives. This balance between enclosure towards the exterior and openness towards the interior facilitated optimal thermal insulation performance within the envelope system.

Resume table

In conclusion, the envelope systems of traditional dwellings exhibit distinctive characteristics that contribute to their thermal efficiency in hot-arid climates. These characteristics include the strategic placement and orientation of thermal mass elements, such as stone walls and vaulted roofs, which leverage natural materials to regulate indoor temperatures effectively. Additionally, the careful selection and application of coatings and natural insulation materials, coupled with thoughtful design features like limited window openings and courtyard design, further enhance thermal performance by minimizing heat gain and maximizing natural ventilation. By integrating these elements into their architectural designs, traditional dwellings demonstrate a holistic approach to thermal

efficiency that balances environmental adaptation with cultural and functional considerations. The table below summarizes the techniques used to enhance the traditional building's envelope system, providing a comprehensive overview of their thermal optimization strategies.

Table 2.5. Envelope system resume table

Envelope characteristics	Variable features	Region	Extracted Data
Walls	High thermal mass materials: stone/brick walls.	All the studied regions (hot and arid climates).	Materials with high thermal mass, thick walls, and the earth-sheltered technique give the building a high thermal mass, which slows heat transfer between the interior and exterior environments and maintains a constant indoor temperature.
	Thick walls: wall thickness ranges between 50 cm and 1 m.		
	Earth's thermal mass: When the dwelling is underground or excavated in the mountain.	Underground houses of Matmata and the troglodyte houses of Cheninni and Douiret.	
Roof	Flat roof: rarely used, insulated, and coated with natural materials. Designed with a high ceiling level.	Djérid region (hot and desert climate).	A curved roof shape, especially a vaulted roof, is more effective in terms of heat gain and natural ventilation than a flat roof, especially in hot and arid climates with specific prevailing wind directions.
	Barrel and groin vaults, with air vent: widely used to cover living spaces.	Mountain villages of Zriba Olia and Takrouna (hot and semi-arid climates).	
	Domes: rarely used in residential buildings.	Djerba Island (hot and arid climate).	

Table 2.5. (continued) Envelope system resume table

Envelope characteristics	Variable features	Region	Extracted Data	Envelope characteristics
Envelope coating	Coating layer	Above-ground dwellings: Mixture of lime/gypsum, earth (clay), sand, and aggregate.	All the studied regions (hot and arid climates).	Lime, gypsum, and clay are very good insulation and waterproofing materials when applied to the surface of the building envelope. From the outside, when sand and aggregate are added to the coating layer, they provide better protection from weather effects.
		Excavated dwellings: Mixture of lime/gypsum, and sand.	Inside surfaces of the underground houses of Matmata and the troglodyte houses of Cheninni and Douiret.	
	Limestone whitewash	Solar rays' reflection: the white color of the lime plaster reflects between 55% to 80% of the incident sunlight.	All the studied regions (hot and arid climates).	The limestone whitewash efficiently reflects a significant portion of the incident solar radiation and therefore contributes efficiently to the cooling of the building.
	Texture	Wrinkled texture: a texture created on the level of the external surfaces.	All the studied regions (hot and arid climates).	The textures created at the level of the exterior surfaces create shade zones and reduce heat gain through the walls.
		Brick cladding: Geometric patterns created by the recess of bricks on the outside surfaces of the walls.	Djérid region (hot and desert climates).	
Envelope opacity	On the outside facades: Rare and narrow openings to reduce heat gain.	On the courtyard facades: Larger openings to profit from the courtyard's mild microclimate.	All the studied regions (hot and arid climates).	The courtyard design directs the opacity of the envelope, which is closed to the outside and open to the courtyard. The oriented opacity helps to reduce heat gain and naturally ventilate the dwelling.
	On the courtyard facades: Larger openings to profit from the courtyard's mild microclimate.			

Natural ventilation

Traditional Tunisian dwellings benefit from a passive natural ventilation system that improves indoor air circulation and cools the building in the summer through three main components: courtyard design, strategic openings positioning, and roof design. The central courtyard acts as a natural reservoir for cooler air that is drawn into the living spaces, while strategically placed windows and doors create cross-ventilation pathways by harnessing natural air currents. In addition, the roof design such as curved roof shapes, vaults, and domes with air vents at the top capture and direct wind into the building while facilitating the release of warm air, working together to efficiently harness and direct wind direction and speed to maintain a comfortable indoor environment.

As mentioned earlier in this study, in traditional Tunisian dwellings, the courtyard plays a crucial role in the natural ventilation and cooling of the building, especially during the summer. This central open space acts as a natural reservoir where cooler air accumulates due to shading and the presence of vegetation and water features, further lowering the air temperature. The courtyard facilitates upward air movement, creating a pressure difference that draws cooler air into the living spaces while expelling warmer air. In mountainous lands, due to the effect of stronger winds, the courtyard size is narrower, allowing for more controlled natural ventilation. In contrast, in flat lowlands, where wind effects are less pronounced, the courtyard is larger to enhance and capture more natural ventilation.

The Tunisian dwelling design, characterized by an enclosure from the outside and an openness towards the inside, emphasizes the strategic positioning of openings in order to benefit optimally from the microclimate of the courtyard. In the external facades, the openings are rare, small, and placed in the upper part of the walls, for some houses there could be no openings on the external walls except for the entrance door. On the other hand, in the courtyard facades, the openings have larger dimensions and are placed in the lower part of the walls. Consequently, openings are divided into two categories: inlets and outlets. The inlets are the windows and doors that open on the courtyards and allow the flow of fresh air into the rooms. The outlets are the narrow openings, usually placed in the upper part of the external walls, that allow the release of hot air outside the building. When the outlets do not exist in the exterior walls, they are placed on the upper part of the walls of the courtyard, as in the Djérid region, or on top of the doors, as in the village of Zriba Olia. On the island

of Djerba, the outlets are the small circular pottery apertures mentioned in the previous section, embedded in the wall during construction. In summer, these apertures are opened to allow natural ventilation, and in winter they are closed with rags (Djerbi, 2011).

The natural ventilation system is driven by the difference in air pressure between the courtyard and the rooms. In summer, fresh air is drawn from the courtyard to the rooms through the inlets. As the air circulates through the rooms, it warms up, becomes lighter, and rises upwards. The rising warm air is then expelled outside through the outlets, ensuring a continuous flow of fresh air throughout the summer. By using both cross-ventilation and the stack effect principles, this system improves airflow and cooling, maintaining a comfortable indoor environment (Figure 2.38) (Choudhary et al., 2014).

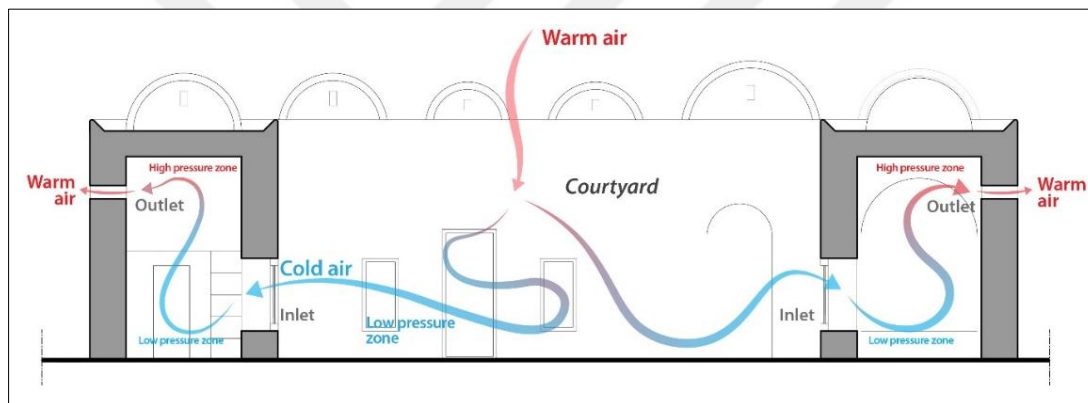


Figure 2.38. Natural ventilation system in traditional dwellings (created by author)

The curved roof shape of traditional dwellings is essential for promoting natural ventilation, especially when equipped with air vents at the apex. On the outside, curved roofs are efficient at capturing moderate cool breezes from prevailing winds, regardless of their direction. On the inside, the raised interior height created by domes and vaults facilitates the upward movement of warm air. As air flows over a cylindrical or spherical surface, its velocity increases at the apex, resulting in reduced pressure and the release of warm air through the vent. This natural ventilation process helps maintain comfortable indoor temperatures. Air vents serve as outlets in this system. In regions with multidirectional prevailing winds, domed roofs are preferred, while areas with stable wind directions, such as Tunisia, favor vaulted roofs perpendicular to the wind axis. In addition, the integration of a pool or fountain under the dome or vault further cools the circulating air, improving overall thermal comfort.

Curved roofs with vents are effective in hot-arid climates, especially where dusty winds make wind towers impractical (Abraar, 2018; Alp, 1990; Dabaieh et al., 2015).



Image 2.22. Air vents placed in the vaults and domes of a Djerbian house

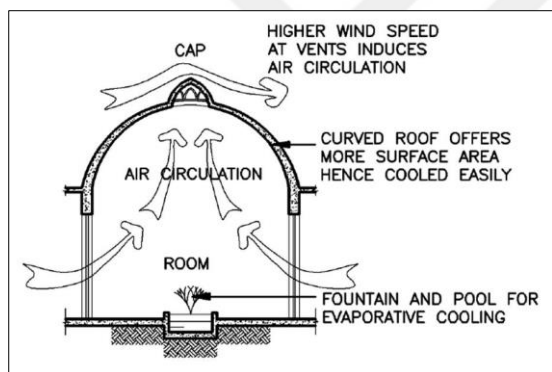


Figure 2.39. Induced ventilation through the curved roof and air vents (Alp, 1990)

Resume table

Tunisian traditional architecture excels in passive natural ventilation techniques, leveraging the region's climate to enhance comfort and sustainability. Dwellings are typically designed with courtyards and strategically placed openings that promote airflow, cooling the interior naturally. Features like curved roofs and air vents facilitate the movement of air while reducing heat.

Table 2.6. Natural ventilation resume table

Natural ventilation elements	Description	Region	Extracted Data
Courtyard	Being a mild microclimate, the courtyard provides fresh air to the indoor spaces.	All the studied regions (hot and arid climates).	The courtyard is essential for cooling the hot air coming from the outside and transferring it to the inside.
Openings	Inlets: Openings in the courtyard facades that transfer fresh air to the rooms. These openings are placed in the lower part of the wall, and they have large dimensions.	All the studied regions (hot and arid climates).	Natural ventilation is effectively allowed when the rooms have inlet and outlet openings placed in different positions on the walls, preferably placed in different walls to create cross ventilation, with different dimensions.
	Outlets: Openings in the exterior walls of the dwelling that release hot air. These openings are located in the upper part of the walls and are narrow.		
Roof design	Curved roof shape: domed or vaulted roofs benefit better from the cold wind, enhance the stack effect by adding height to the interior space, and facilitate the release of hot air to the outside.	All the studied regions (hot and arid climates).	The curved roof shape, especially the vault, with a vent at the top, placed perpendicular to the prevailing wind direction, enhances natural ventilation, and helps passively cool the building.
	Air vent: added at the apex of the curved roof, acts as an outlet and improves airflow.		

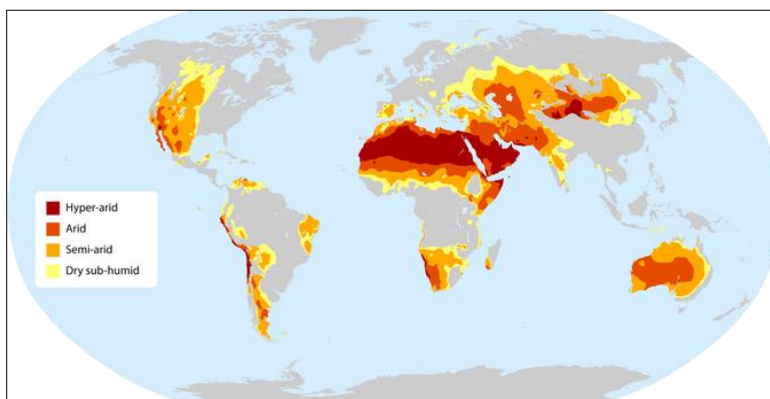
2.2.3. Vernacular architecture principles in modern architecture

In the past, vernacular architecture principles have proved to be highly efficient in terms of adapting to climatic conditions and preserving the environment. With zero fossil fuel consumption and without polluting the environment, these techniques provide effective ways to maintain comfortable indoor temperatures. However, as modernization progressed, these sustainable practices were replaced by new technology-driven solutions. This shift away from traditional methods has occurred for many reasons, including functional and technical limitations.

In recent years, there has been a growing recognition of the importance of returning to these traditional architecture principles, driven by the urgent need to address climate change. Rising temperatures and increasing pollution have prompted a reassessment of building design and construction techniques. As a result, there is a renewed interest in applying traditional architectural passive cooling techniques in modern architecture. By integrating these time-tested methods into modern designs, architects, and designers are finding innovative ways to improve thermal comfort while minimizing energy consumption and environmental impact.

This section explores the application of the extracted passive cooling techniques from the previous section in modern architecture and presents examples of projects that have successfully applied these principles. These examples illustrate how the wisdom of the past can inspire sustainable solutions for addressing the challenges of present and future buildings.

In Tunisia, the application of vernacular architecture principles is notably absent, mainly due to economic and cultural factors. Therefore, the focus shifts to regions with hot-arid climates, similar to the predominant climate in Tunisia, and with an architectural heritage closely linked to the Tunisian architectural heritage. Countries such as Morocco, Egypt, the Arabian Peninsula, Iran, and others, as shown on the map below, have a rich heritage of vernacular architecture and can serve as valuable sources of modern projects that incorporate sustainable approaches.



Map 2.6. Arid climate regions global map (URL-9)

Adaptation to the site

Adaptation to the site is a fundamental aspect of traditional architecture, allowing buildings to be compatible with their natural surroundings. However, this critical step is often neglected in modern architecture for several reasons. First, modern buildings are often located in urban areas, which imposes additional design constraints that lead to neglect of climatic and geographic factors such as orientation and sun path. In addition, economic concerns often take precedence over climate-responsive measures, despite the long-term financial implications of excessive energy consumption for air conditioning. Finally, political and cultural factors, such as a lack of collective awareness of climate issues, constrain the adoption of sustainable strategies and policies in the building sector. Nevertheless, many designers around the world have succeeded in developing strategies to adapt their projects to the climatic conditions of their sites, drawing inspiration from traditional methods of vernacular architecture.

Vegetation

The use of vegetation to save energy and reduce indoor temperatures is not a new concept in modern architecture and is an economic and ecological solution. For both dry and humid climates, strategically planted vegetation around the building helps effectively mitigate the solar heat gain of buildings and significantly reduces the air-conditioning loads (Bhamare et al., 2019). In hot-arid climates, the choice of vegetation type should take into consideration the intense solar radiation, high air temperature, and lack of precipitation. The vegetation used must be able to withstand long-term water shortages and provide dense shade. There is a wide range of vegetation types adapted to hot-arid climates. For evergreen trees, there are palms and olive trees, as observed in Tunisia, which are quite resistant to drought and provide shade throughout the year. Deciduous trees include *Celtis Australis*, Oak (*Quercus afares*), Fig, Acacia, Eucalyptus, etc., which are resistant to drought and high temperatures and are efficient in terms of mitigating the hot-arid provide intense shade in summer. Among the plants, there are xerophytes, succulents, sedums, and grasses, which can store water for a long time and withstand high solar radiation. All these species of trees and plants have been present in the Tunisian territory throughout history and climate.

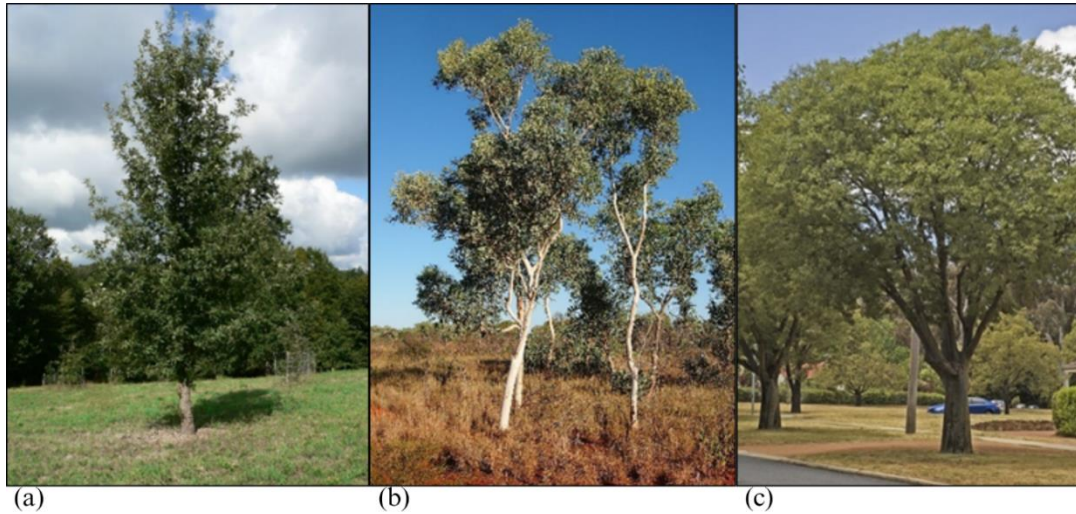


Image 2.23. (a) *Quercus afares* (URL-10), (b) *Eucalyptus* (URL-11), (c) *Celtis Australis* (URL-12)

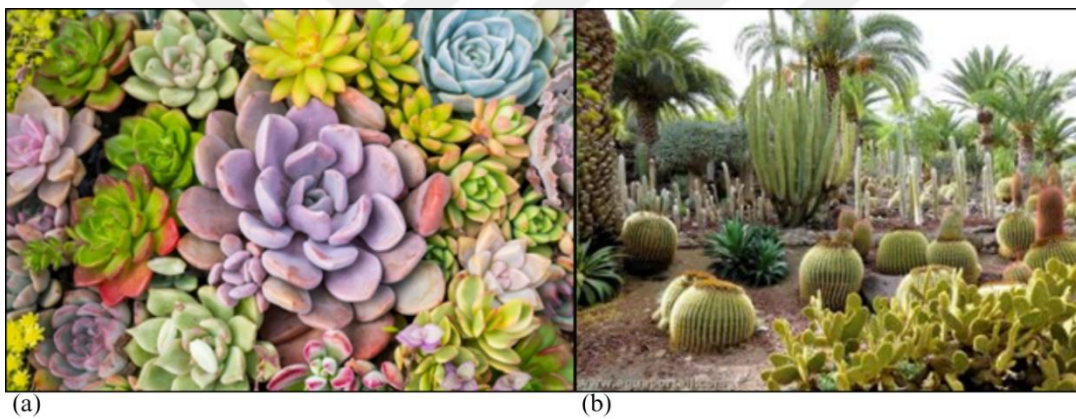


Image 2.24. (a) Succulents (URL-13), (b) Xerophytes (URL-14)



Image 2.25. (a) Grasses, (b) *Sedum* (URL-16).

When planting vegetation around a building, many climatic factors must be considered to create a wise application. The prevailing wind speed and direction, average temperature and humidity, and site geography are the most important data that should be studied before applying vegetation. Designing the landscape according to these parameters will help to control the wind speed and direction, reduce the heat gain, and humidify the air (Barakat et al., 2017). The physical characteristics of the tree or plant are also important in determining the species to be used. Tree type (deciduous or evergreen), tree canopy, tree shape and dimensions, tree location (orientation), and distance from the building are important factors in determining the efficiency of vegetation in cooling the building.

Today, many architects are integrating vegetation into their designs as a passive solution to the increasing hot temperatures, thus encouraging the use of vegetation as a design element in future buildings. The Zen Villa, built in 2024, is located in a desert region with a very hot and dry climate in Kuwait (Image 2.26). The villa is surrounded and merged with trees in order to benefit from the temperate microclimate that this landscape creates. The trees used are mainly palm and olive trees, planted around the house and inside the courtyard. The house also has a central courtyard, and the exterior surfaces are painted white, reminiscent of Tunisian vernacular architecture. The design of the house is minimalist with a low height and level to immerse in the natural environment (fikrr architects, 2024).

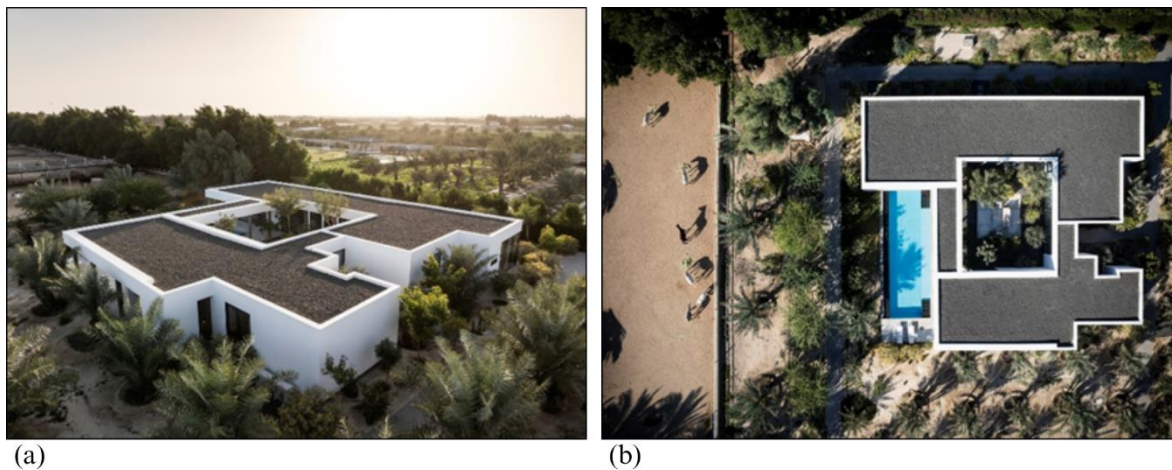


Image 2.26. Zen Villa (fikrr architects, 2024)

On an urban scale, vegetation (trees, plants, and green surfaces) can provide solar protection that slows the urban heat island effect through shading and evapotranspiration. Vegetation also moderates the wind flow to individual houses, providing natural ventilation and convective cooling to exterior building surfaces (ALAMAH, 2012). Many examples of modern cities around the world use the concept of bioclimatic zones to mitigate the effects of hot-arid climates. The city of Msheireb in Doha is one of the most sustainable cities in the world (Image 2.27. (a)), integrating natural elements such as native trees and green species adapted to survive in arid conditions to reduce the need for landscape irrigation. The City of Adelaide in Australia actively promotes the greening of public spaces by planting indigenous trees and plants and increasing the amount of green space (Image 2.27. (b)). This process effectively reduces the air temperature, helps in economic development, and increases biodiversity. The Diplomatic Quarter in Al-Riyadh City reflects well the principles of vernacular architecture by using palm trees for afforestation (Image 2.27. (c)). The surrounding areas of the city are extensively landscaped, and each central residential area has its intensively cultivated local park (ARUP, 2018).



Image 2.27. (a) Msheireb city (URL-17), (b) Adelaide city (URL-18), (c) Diplomatic Quarter (URL-19)

Earth-sheltered technique

Earth-sheltered houses have become a source of inspiration for many architects to solve the constraint of thermal comfort with consideration of energy consumption. Since the 1940s, earth-sheltered buildings have been incorporated into contemporary architecture around the world as a way to preserve the environment. After the energy crisis of 1973, the concept of earth-sheltered buildings received more attention, especially because of its suitability as a climate protection strategy and energy-saving solution (Sakr, 2001).

In Tunisian traditional architecture, two types of earth-sheltered dwellings are observed: horizontal and vertical excavated houses. In modern architecture, however, many earth-sheltered house designs vary according to the site's geography and the building's function. Features determining the type of earth-sheltered design include the number of surfaces in contact with the earth, the height of the house from ground level, the thickness of the earth layer, and the presence or absence of a courtyard. Each design impacts thermal comfort, daylighting, and natural ventilation differently. Figure 2.40 below attempts to classify and simplify the various earth-sheltered designs into five distinct types (Hassan and Arima, 2014; Prelvukaj et al., 2018).

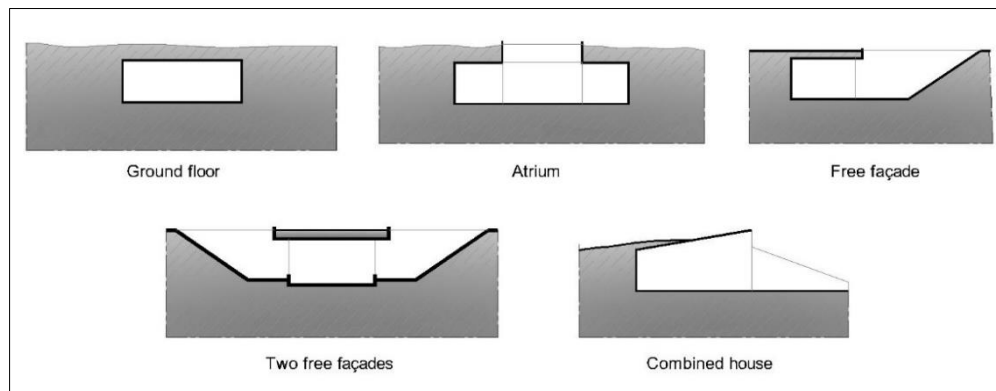


Figure 2.40. Earth-sheltered design variations (Hassan and Arima, 2014; Prelvukaj et al., 2018)

In Tunisia, the culture of earth-sheltered buildings has been lost and the old troglodyte houses have been abandoned without maintenance and only a few families still live there. However, there are many relevant examples of modern earth-sheltered houses inspired by the old Tunisian architecture. One of the most significant is the Aloni House on the island of Antiparos in Greece. The design of this house won the 'Greek Piranesi Award' in 2009 for responding to the environmental needs of controlling natural light, passive heating and cooling, and natural ventilation. The site of the house is located between two hills. The design of the house merges with the slopes of the two hills, using the earth's mass as a shelter from the hot weather. Therefore, two sides of the house are coupled with earth and two sides are facing the outside with a massive stone wall. The house design includes two open sky courtyards for natural ventilation and light (Prelvukaj et al., 2018). Sheltered by the earth and ventilated by courtyards, the design of the Aloni house recalls the underground houses of Matamata in Tunisia.

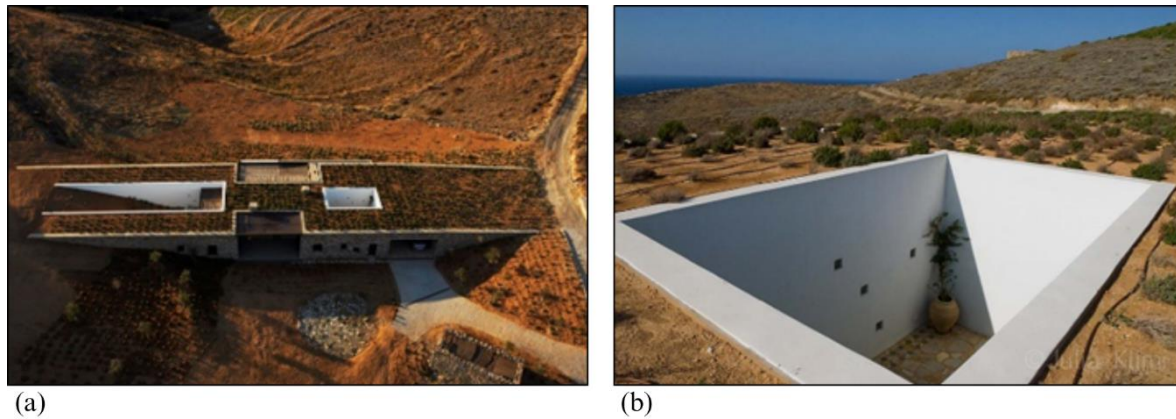


Image 2.28. The Aloni House (URL-20; URL-21)

Orientation

As noticed in the Tunisian vernacular architecture, the orientation of the building is a very important factor that contributes efficiently to passive cooling. However, in modern architecture, this factor is not taken into consideration as much as it should be for many reasons. In the past, the orientation of the building depended mainly on the natural characteristics of the site. However, today, since most of the new buildings are built within the cities, the orientation of the building depends mainly on the orientation of the street and the direction of accessibility. Similarly, the arrangement of the interior spaces of the building also depends on the neighboring buildings and the position of the street. Therefore, orientation is a parameter that should be taken into consideration by urban designers when planning cities after studying the prevailing wind direction and the sun's path in the region. Thus, architects could place their designs in a conventional direction determined by the city design that takes into account the climatic data of the region.

In Tunisia, at the building scale, the culture of energy-efficient design is not yet widespread, and the main goal of architectural design is to respond to functional and aesthetic concerns. The orientation factor is neglected by both the designer and the inhabitants and is only considered for privacy purposes, such as facing the neighboring buildings, and for aesthetic reasons, such as facade decoration. At the urban scale, the Tunisian regulations are still poor in terms of respecting the orientation factor and are not respected or seriously implemented with a lack of supervision by the state. All these constraints have led to a loss of connection

between architectural design and its natural environment, and to the creation of buildings with poor thermal performance.

On a global scale, there are many examples of sustainable cities using orientation-based design, such as Masdar City in Abu Dhabi. Masdar City has demonstrated how vernacular principles, including orientation, are still relevant to today's concerns by successfully creating energy-efficient and climate-responsive cities. The orientation of the city's streets depends on providing optimal shade and minimizing heat gain. If streets were oriented along a north-south axis, sun rays would penetrate the urban fabric by reaching the building's principal facades, increasing cooling loads, and if streets were oriented along an east-west axis, lateral facades would be over-exposed to sun rays, thereby increasing cooling loads. Therefore, the northeast-southwest orientation of the urban fabric was adopted as the best orientation solution by providing optimal shading for the building surfaces (Figure 2.41) (Ghodsi, 2012)

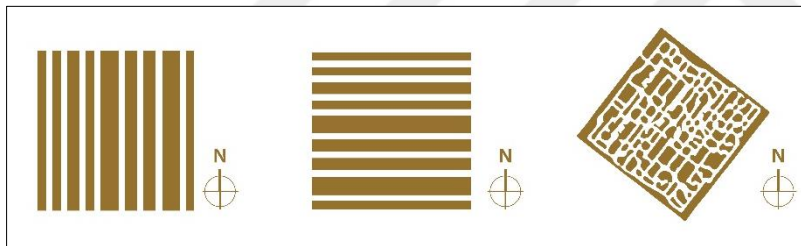


Figure 2.41. Masdar city streets orientation (Ghodsi, 2012)



Image 2.29. Masdar city top view (Abtar, 2014)

Courtyard house organization

The model of the traditional house with a central courtyard has always been considered one of the greatest models of residential buildings known in history and is still in use today. This architectural device continues to be a source of inspiration to help buildings adapt to the world of today and tomorrow, in the spirit of sustainable development. The design of the Courtyard House serves as an appropriate reference for the bioclimatic adaptation of housing in the era of Energy-saving and sustainable development (Boudjadja and Benhalilou, 2022). In Tunisia, the courtyard is no longer in use. Most of the vernacular houses in rural areas with a courtyard design are abandoned, and the old houses in urban areas are converted into museums, restaurants, etc., and their courtyards are covered with glass to provide protection from rain without reducing sunlight. However, the glass cover could have acoustic disadvantages such as reverberation of sound and poor thermal performance on hot days (Abdulac, 2011).



Image 2.30. Traditional Tunisian house converted to restaurant (URL-22)

In modern Tunisian architecture, it is difficult for the concept of the courtyard to resist the new constraints of contemporary life. Urban regulations, rapidly rising land costs, and significant demographic pressures are strongly encouraging the abandonment of the courtyard. Indeed, building a small block of apartments on top of each other is more profitable than building a single house, with or without a courtyard (Abdulac, 2011). For this reason, the concept of the courtyard is missing in modern Tunisian houses and the absence of its climatic benefits is reflected in the level of increasing energy consumption for air conditioning.

There are many modern examples of houses with a central courtyard design around the world. The "Courtyard House" in the village of Boliqueime in Portugal reflects the Tunisian house design. The climatic conditions of the site are close to the Tunisian climate with mild winters and hot-dry summers. Located in the center of the house, the patio is a distribution space around which the house is organized. With a square plan and a tree in the middle, this patio regulates the daylight in the house and is a refuge from the strong winds that sometimes blow in the region. The circulation between the interior spaces is partially made through the patio, which allows the creation of windows on both sides of the rooms, thus providing a thorough and constant natural cross-ventilation of the spaces. The configuration of this house eliminates the need to use artificial air conditioning for most of the year (cal30.arquitectos, 2022).



Image 2.31. The Courtyard House pictures (cal30.arquitectos, 2022)

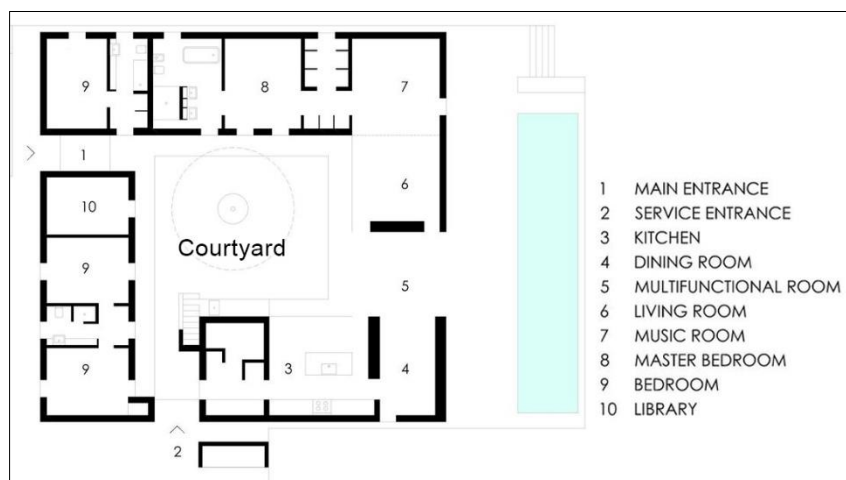


Figure 2.42. The Courtyard House plan (cal30.arquitectos, 2022)

In modern architecture, the courtyard house design may not be reproduced as it was in the past, however, it could be successful with slight modifications. For example, the circulation between the indoor spaces could be partially or totally inside and not cross the courtyard, because in winter the circulation in an outdoor space (the courtyard) is difficult. In this manner, the patio will still be functional in terms of use, especially in hot climates. Therefore, the adaptation of the courtyard to modern architecture should be established without changing its configuration or its position (in the center of the house), but by altering the spaces surrounding it. Besides, according to a simulation work carried out by Fezzioui et al., (2012), the courtyard house design is more efficient in reducing air conditioning energy in hot climates than in cold climates.

Local construction materials and techniques

Today, the use of locally available construction materials is an essential feature of sustainable architectural design. The use of local materials has many advantages in terms of both climatic issues and the thermal performance of the building. In addition, in dry-hot climates, local construction materials with high thermal resistance and high thermal capacity, such as stone and brick, help to reduce the heat flow into the interior spaces through direct conduction (Givoni, 1998). In modern architecture, the use of local materials reduces the energy required to transport raw materials, thereby reducing CO₂ emissions from the transportation process. This approach also promotes local economic development. Natural materials such as wood and stone can be used in their natural state with little processing, reducing energy consumption and GHG emissions from factories that produce modern materials such as concrete (Gökşen et al., 2017). In summary, the use of local construction materials is an advantageous choice, starting from the initial extraction steps of these materials to their thermal performance during the lifetime of the building. In addition, once used, natural materials can be easily recycled with minimal energy consumption, making the recycling process easier and less polluting.

In Tunisia, local construction materials are being abandoned in favor of modern materials such as hollow bricks and concrete. Since the second half of the 20th century, most new buildings have been constructed with modern materials. Especially in cities, modern materials are easier to implement and facilitate the construction of tall, multi-story buildings. In addition, the lack of government regulations encouraging the use of traditional materials

allowed the proliferation of thousands of concrete and hollow brick buildings in a short period of time, including illegal houses. Buildings constructed with modern materials have poor thermal performance and contribute to increased cooling loads and the urban heat island effect. According to a study by Dahech and Marwen (2015), buildings with modern construction materials such as hollow bricks, concrete, and large glass windows, record considerable overheating ($+4^{\circ}\text{C}$) in the middle of the day compared to a building constructed with local materials.

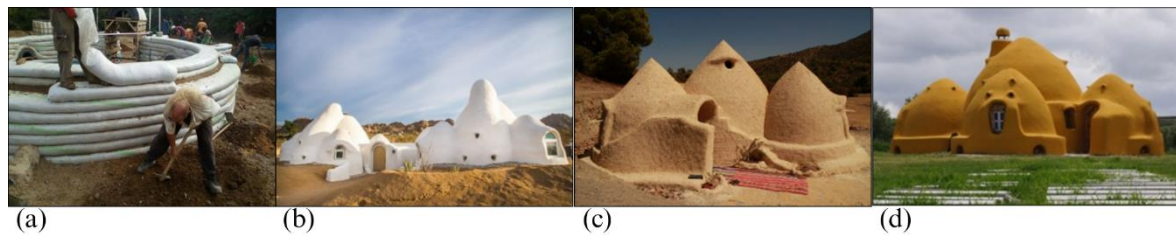


Image 2.32. (a) Construction of eco-dome (Tunisie.co, 2017), (b) Eco-dome in Siliana governorate (URL-23), (c) Ezzine eco-dome (URL-24), (d) Dar Baya eco-Dome (L'instant-m, 2024)

In modern times, the eco-dome construction technique, which utilizes ecological and locally sourced materials, is being implemented in various rural regions of Tunisia. The eco-dome is a structure based on the "SuperAdobe" ecological technique developed by the Iranian American architect Nader Khalili, using the earthbag house concept. The technique is based on the assembly of closed sandbags, piled, and secured with wire. These bags are then stacked with great precision until the height of the vault is equal to the diameter of the circle, and then covered with clay plaster. This technique is used to build round domes that are resistant to fire, earthquakes, and floods, and are environmentally friendly (Bsila, 2019). There are many examples of eco-domes in Tunisia, designed by associations and financed by international organizations to promote ecotourism and rural development. Dome Ezzine and Dar Baya are eco-domes that opened in 2017 and 2019, respectively. Located in a rural region in northwestern Tunisia, in the Beja governorate, these domes were created to welcome guests to enjoy the surrounding natural environment. Another eco-dome near Jebel Bargou, in Siliana governorate, is built with local materials (clay, sand, plaster, bags of earth) at a cost of 14 000 Tunisian dinars ($\approx \$4\,400$). This dome is organized as a pottery workshop and a pavilion to promote local handicrafts. These eco-domes provide thermal and acoustic insulation and are also water-impermeable. The inside of the dome is fresh and cool in the summer and warm in the winter (Bsila, 2019; L'instant-m, 2024; Tunisie.co, 2017).

On a global scale, many modern architects adopted a sustainable approach in their projects, based on the use of local construction materials to improve the local economy and preserve the environment. One such architect is Hasan Fathy, known for his pioneering work in sustainable and vernacular architecture. Fathy advocates the use of traditional construction techniques and local materials to create structures that are in harmony with their surroundings, and he has expressed that the efficiency of vernacular architecture is linked to the region's local construction materials, climatic conditions, and socio-economic culture (Abraar, 2018). Fathy designed many residential projects using local materials, mainly mudbrick and stone. The Chilean Nitrate Company Renthouse, in Safaga, Egypt, was the first contemporary attempt to use mudbrick, following the Nubian structural technique. The Hamed Said House, in Cairo, Egypt, is the first documented application of mudbrick construction and is still standing. The Abd al-Rahman Nassif House, in Saudi Arabia, was built with stone blocks recovered from the demolition of traditional tower houses in the old city, which the client tried unsuccessfully to save. The Akil Sami House in Dahshur, Egypt, was built with local limestone due to a government ban on the use of mudbricks and the unsatisfactory structural strength of the soil in the area (Serageldin, 2007).

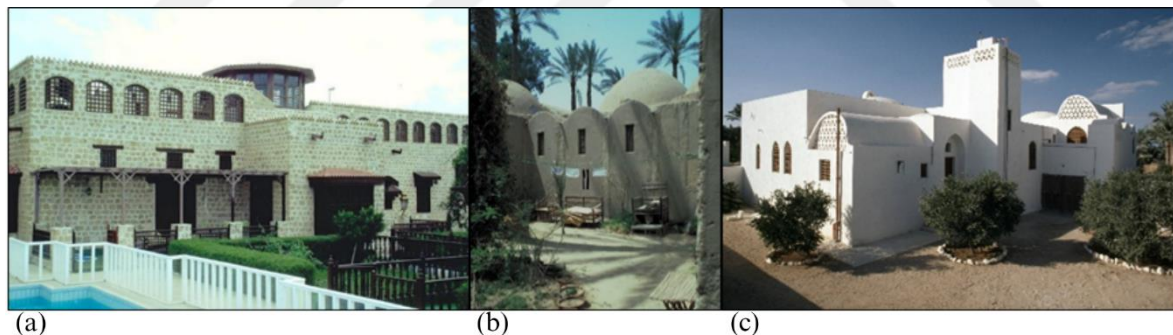


Image 2.33. (a) The Abd al-Rahman Nassif House, (b) The Hamed Said village, (c) The Akil Sami House (Serageldin, 2007)

In recent years, there have been many projects around the world constructed with local construction materials with the aim of encouraging sustainability and preserving the environment. Especially in Morocco, the culture of using brick and stone in rural regions is still in use today for better thermal performance and less materials cost. A school extension in the Merzoug region, in Morocco, is inspired by the local vernacular architecture using local construction materials and techniques with a contemporary look, performant bioclimatic functioning, and earthquake-proof design. The building has foundations made of

local natural stone, adobe walls, and a wood and earth flat roof. The exterior surfaces are covered with a plaster made with 2 types of earth, straw, and sand, and the interior surfaces are polished with "nouss-nouss"¹³ plaster made of earth and gypsum to create breathable interior surfaces. Thanks to the walls' thermal mass the building remains cool during the day, but warmer through the night until the morning (BC architects, 2018).



Image 2.34. The Merzoug school extension pictures (BC architects, 2018)

Envelope system

Modern architecture has developed various solutions to improve the thermal performance of building envelope systems through technological advances. However, the principles of vernacular architecture, such as thermal mass, curved roof shape, and coatings, continue to be used in modern buildings because of their effectiveness and sustainability.

Thermal mass

The thermal mass of a building is a crucial factor in determining its thermal performance efficiency. In hot-dry climates, buildings made with high thermal mass materials exhibit better thermal performance. During the day, the building envelope's thermal mass absorbs solar radiation and heat, storing it within the structure due to the mass's absorbing properties. The optimal amount of thermal mass should be determined to balance the heat gain rate, ideally designed to be 36 kg per square meter of floor area (Beyhan, 2024).

¹³ In arabic language “half-half”.

Nowadays, new buildings globally are constructed with modern materials that have low thermal mass, leading to increased heat gain. The structure of the modern Tunisian building is far different from traditional building structures. The most common construction materials are hollow bricks and reinforced concrete. The thickness of the walls varies depending on the size of the hollow bricks used; exterior walls typically have a thickness of 35 cm for double hollow brick walls and 25 cm thickness for single hollow brick walls. Roofs are typically constructed of hollow brick and reinforced concrete with a thickness of 33cm (Figure 2.43). These configurations represent the most common wall and roof structures in modern residential buildings in Tunisia. According to the study by Dahech and Marwen (2015), new buildings with a low thermal mass present low thermal performance due to the light thickness of walls made of hollow bricks. The poorly insulated envelope with low thermal mass increases heat gain, especially in summer which causes overheating.

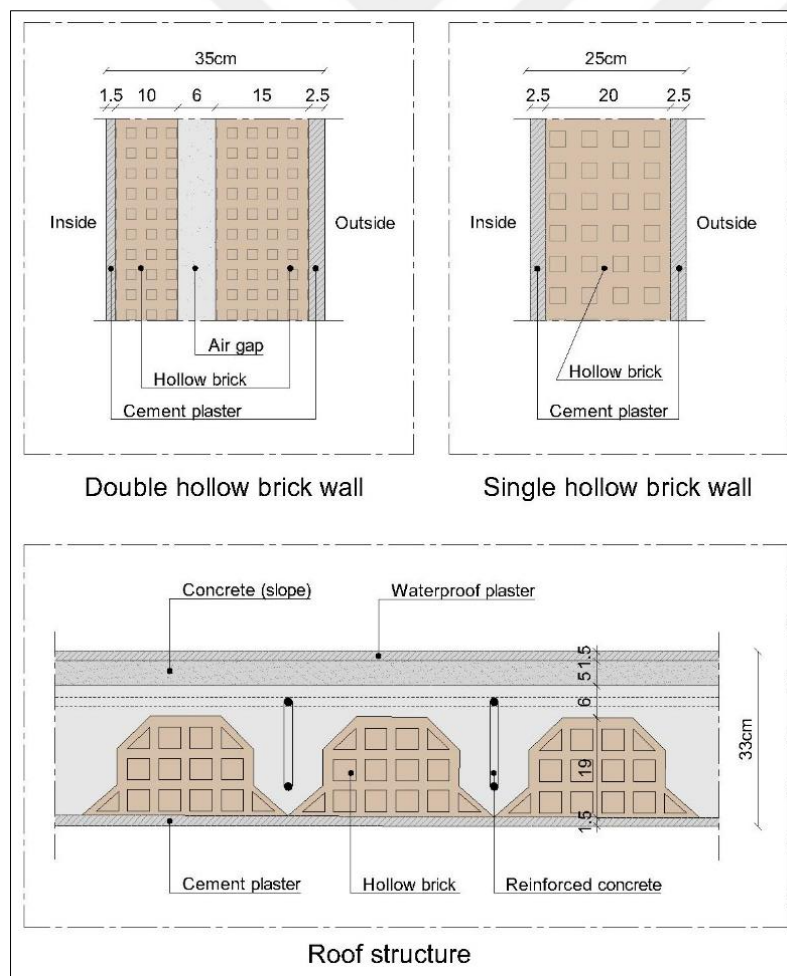


Figure 2.43. Details of the modern Tunisian buildings structure (created by author)

Around the world, many modern buildings, as mentioned in the previous section, are constructed with high thermal mass materials, such as brick and stone, which improves their thermal performance. The Great Wall in Australia is an efficient example of the use of thermal mass, using a rammed earth facade for 12 semi-buried houses along a length of 230 m. The facade is 45 cm thick and consists of sandy clay soil rich in iron, gravel, and pebbles, with water from a local well used as a bonding element. The entire structure is built at the epicenter of a deep sand hill and includes residential houses along with a chapel and a conference room. This project is reminiscent of Tunisian vernacular architecture by also using the thermal mass of the earth to passively cool the house. The residences have the best thermal mass available, making them naturally cool in the summer (Abraar, 2018; Rosselli, 2015). Built in 2011, the Guelmim Technology School in Morocco is a great example of modern architecture incorporating high thermal mass walls. Using traditional building techniques adapted to the region's climate, the school effectively manages indoor temperatures. The thick walls, known for their high thermal mass properties, absorb and store heat during the day and release it at night, reducing reliance on mechanical heating and cooling. This design choice is complemented by strategically placed windows that minimize solar gain (Beyhan, 2024).

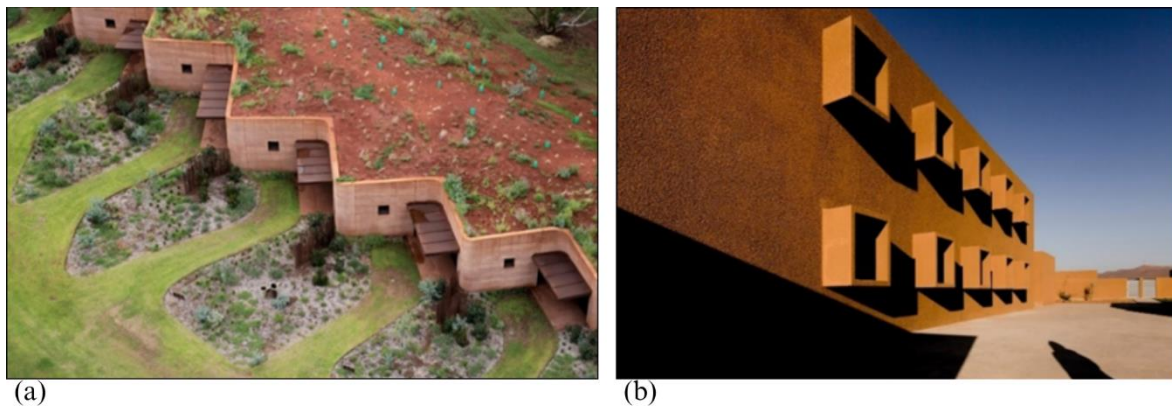


Image 2.35. (a) The Great Wall in Australia (URL-27), (b) Technology school of Guelmim (URL-26)

Phase Change Materials (PCMs) offer a promising solution to enhance the thermal mass of buildings, thereby improving thermal insulation. PCMs are substances that store and release large amounts of thermal energy when they undergo a phase transition, such as from solid to liquid and vice versa, at specific temperatures. When integrated into building materials like plaster, drywall, or concrete, PCMs absorb excess heat during warm periods, effectively

buffering temperature fluctuations within the building. This process helps stabilize indoor temperatures, reducing the need for active heating and cooling systems and lowering energy consumption. Additionally, PCMs can be tailored to match specific climate conditions and building designs, further optimizing their effectiveness. There are critical factors that determine PCM efficiency such as the melting temperature, the location of the PCM layer within the wall, the thickness of the PCM layer, the type of envelope (whether wall or roof), and whether a double-layer PCM system is used in the wall. The PCM with a low melting temperature (21°C) favors heating energy savings, while the PCM with a high melting point (29°C) favors cooling energy savings. In hot-arid regions like Tunisia, optimal PCM placement near indoor spaces can significantly reduce energy needs. For instance, a PCM with a melting temperature of 29°C has been found to provide the highest reduction in energy consumption, making it particularly suitable for enhancing thermal insulation in such climates. PCM application can achieve up to a 41.6% reduction in energy demand in the Tunisian climate (Dardouri et al., 2023).

Roof design

In Tunisia, as in all hot-arid climates around the world, domed and vaulted roofs are often replaced by flat roofs in modern architecture. Despite their efficient thermal performance, domed and vaulted roofs are neglected for several reasons. First, there is a perception of increased construction cost and complexity compared to flat roofs. Second, the flat roof structure is used to conceal the utilities and services used in buildings, such as electrical, water, and HVAC installations. In addition, flat roofs offer more usable space, making them desirable for various purposes such as roof gardens, recreational areas, solar panel installations, etc., and allow for the addition of further extensions to the building. Finally, the popularity of modern building materials such as lightweight concrete and metal, which have a lower thermal mass, has also contributed to the decline of domed and vaulted roofs. These materials are often favored for their affordability and ease of construction but lack the thermal performance of traditional materials used in the construction.

Flat roofs with air gaps and water ponds are innovative structures designed to significantly enhance the thermal performance of buildings, especially in hot-arid climates. The flat roof with an air gap utilizes an empty space inside the roof structure as a thermal buffer (Figure 2.44), effectively reducing heat transfer from the roof to the building interior during hot

periods and minimizing heat loss in cooler conditions. This design reduces the reliance on mechanical cooling and heating systems, thereby lowering overall energy consumption. On the other hand, flat roofs with water ponds are energy-efficient and environmentally friendly passive cooling techniques. Water, with its high volumetric heat capacity, serves as an ideal thermal mass. The cooling action of a water pond is driven by the vapor pressure difference between the water surface and the surrounding air, promoting evaporation that cools the roof surface and nearby air. The cooling potential of the roof pond technique varies depending on local climatic conditions, illustrating its versatility and effectiveness in different variations (Figure 2.45) (Bhamare et al., 2019; Dabaieh et al., 2015).

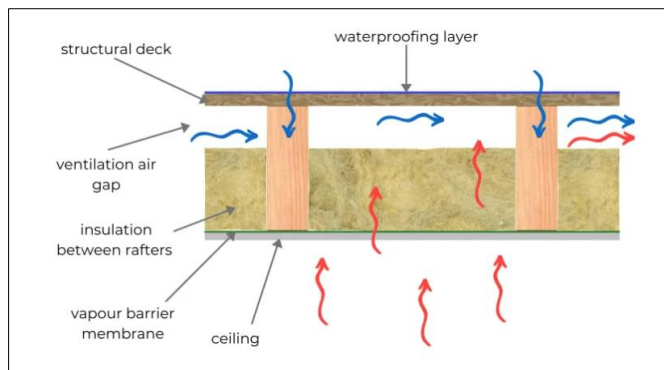


Figure 2.44. Flat roof with air gap section (URL-28)

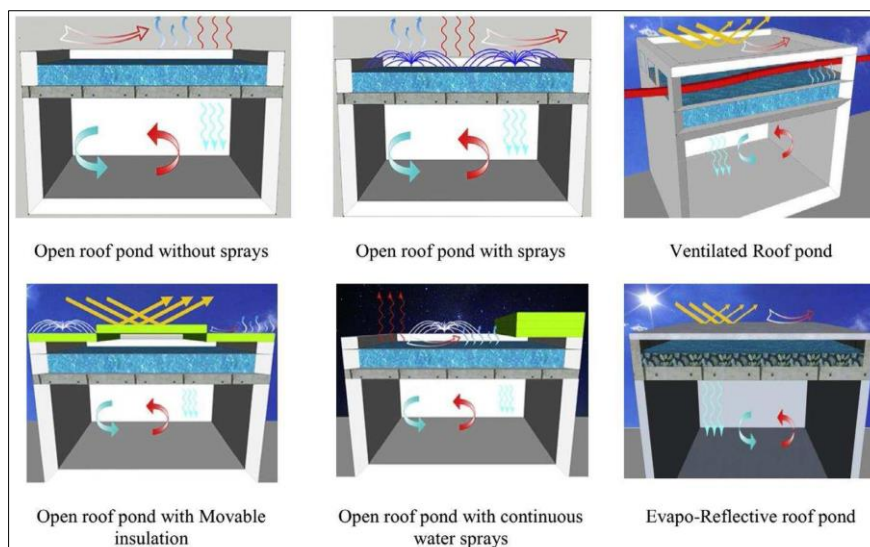


Figure 2.45. Flat roof with water pond variations (Bhamare et al., 2019)

Domed and vaulted roofs remain a symbol of cultural heritage and their practical benefits in hot-arid climates were often dismissed in modern architecture. However, as sustainability becomes increasingly important in new building design, there is a resurgence of interest worldwide in these traditional roof forms for their energy-efficient properties and climatic suitability. In modern architecture, domes and vaults have changed their shapes and materials to meet inhabitants' needs. Combined with technology solutions, domes and vaults have infinite shapes and structures that help them enhance their function. Al-Nazlah Center in Fayoum, Egypt, is a pottery workshops that produce special pots used for construction since the ancient Egyptian civilization. The workshops themselves are constructed with ancient techniques using typical pots as construction material. Each pot has a hollow cavity and a diameter of 25 cm, bonded with clay material of 7 mm thickness. The pots are interlocked to form load-bearing structures such as walls, vaults, and domes. The geometric iterations in the roof construction helped to diffuse the sun's rays outside the building and added an important layer to lower the temperature inside. This construction technique recalls the use of pottery to build domes in the traditional architecture of the island of Djerba, in Tunisia, as mentioned in the previous section (El Setouhy and Oriental Group Architects, 2023).

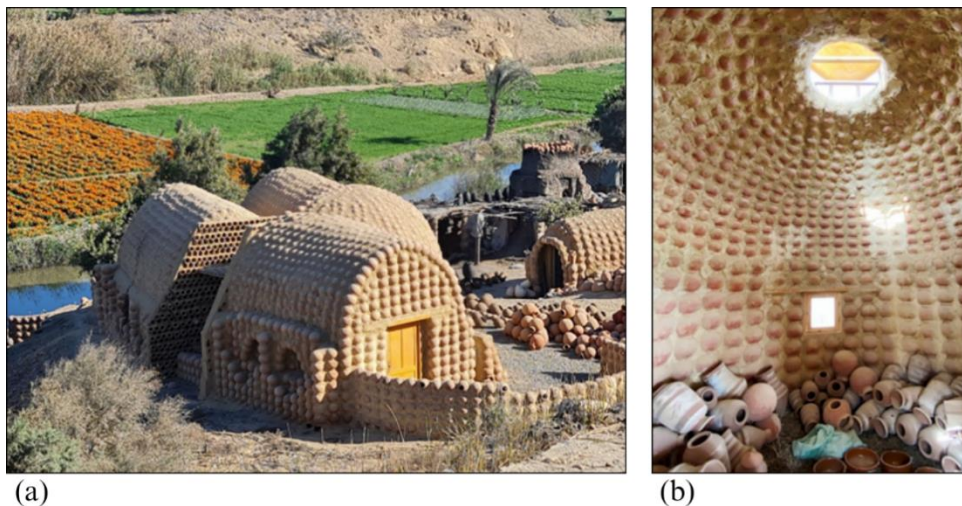


Image 2.36. (a) Al-Nazlah workshops, (b) Inside view of a workshop with a dome (El Setouhy and Oriental Group Architects, 2023)

Green roofs offer a modern and effective solution for enhancing the thermal performance of the roof. Since the 1970s, in response to the new challenges associated with urban development, many countries have been experimenting with the additional technical and

scientific benefits of green roofs. It has become evident that these systems can play an interesting role in managing rainwater, protecting, and restoring biodiversity, and improving thermal comfort and quality of life in the city. There are three types of green roofs that differ essentially according to many parameters such as the thickness of the growing substrates, the additional loads on the roof structures, the type of vegetation to be grown, and the degree of maintenance required (Figure 2.46). For hot-arid climates, the extensive green roof is the most suitable type with a substrate thickness between 6 and 18 cm and extensively cultivated plants that resist such a climate. This type of green roof does not require high maintenance and irrigation and its implementation, and costs are suitable (Bedoui, 2023).

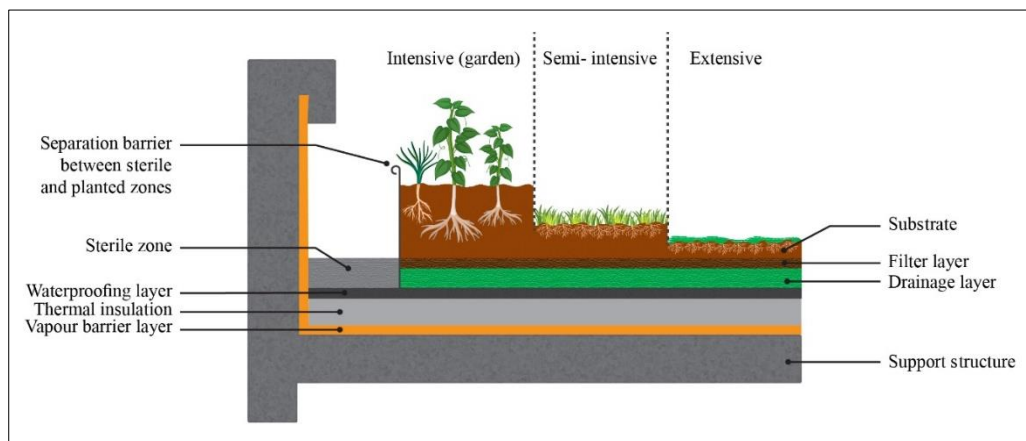


Figure 2.46. Green roof types and structure, created by author



Image 2.37. Extensive green roof (URL-73)

Green roofs have many advantages, especially for highly urbanized areas in hot-arid climates. The vegetation cover plays a crucial role in protecting the building from external weather influences by thermally insulating the envelope and delaying heat exchange. Especially in summer, the plant's evapotranspiration process contributes widely to cooling

the building surface and as a result, it reduces energy loads for air conditioning. On the urban scale, the vegetation cover mitigates the heat island effect, reduces pollution and carbon emissions, and creates microclimates that enhance biodiversity (Tran, 2020).

In the southern Mediterranean countries, green roofs are still not implemented and there are no specific regulations for these systems. Even the regulations for rooftop gardens are very brief and do not describe in detail the technical characteristics of these facilities (Bedoui, 2023). In Tunisia, green roofs have begun to make a modest appearance, with a private company specializing in green walls and roofs currently implementing about 1.5 hectares of such installations. However, their application remains largely decorative and has not yet gained widespread adoption. Green roofs are primarily found in residential buildings, restaurants, and cafes, serving as attractive design elements rather than functional components for enhancing thermal performance or promoting sustainability.

Envelope coating

The building's external surfaces play a critical role in determining the building's thermal performance. As the primary interface with the outside environment, these surfaces are the first barrier to the effects of the weather. Consequently, careful attention to the envelope's external surface has been a common subject of interest in both traditional and modern architectural practice. A variety of modern solutions, developed with advanced technology, have been employed to address the thermal performance of the building envelopes and minimize heat gain. Some of these solutions are inspired by traditional architecture principles.

Thermal insulation

In traditional vernacular architecture, thermal insulation and waterproofing were achieved through the thermal mass of the building envelope and by applying a thick layer of plaster, as described in the previous section. However, as technology advanced, newer and more efficient techniques and materials were developed to provide superior insulation for buildings. These modern methods include the use of advanced insulation materials such as expanded polystyrene (EPS), extruded polystyrene (XPS), mineral wool, and reflective foil insulation. In addition, innovative construction techniques such as cavity wall insulation,

exterior insulation, and cool roof systems have been introduced to improve thermal performance. These advances not only provide better insulation but also contribute to the energy efficiency and environmental sustainability of modern buildings.

The use of thermal insulation in building walls and roofs reduces heat transfer into or out of the building due to temperature differences between the interior and exterior. Additionally, it helps in extending periods of thermal comfort without reliance on mechanical air-conditioning, especially during interseason periods. As a result, by reducing the heat gain factor, thermal insulation reduces energy loads for conditioning and thus reduces the annual energy cost. However, the magnitude of energy savings as a result of using thermal insulation varies according to the building type, the climatic conditions at which the building is located as well as the type, thickness, and location of the insulating material used. In hot climates, insulation is placed on the outer face of the wall or roof so that the thermal mass of the wall is weakly coupled to the external environment and strongly coupled to the internal space (Al-Homoud, 2004; Kamal, 2012).

The implementation of thermal insulation is regulated by codes in many countries that take into account factors such as local climate, building energy codes, and cost considerations. As a result, the efficacy of thermal insulation is no longer in question; rather, the focus is on determining what type of insulation to use and how best to implement it. In Tunisia, regulations do not yet include the mandatory use of thermal insulation in buildings, resulting in limited and unorganized implementation. As a result, the thermal performance of new buildings is too deficient and the energy loads, especially for cooling, are constantly increasing. Currently, the most common method of thermal insulation in modern buildings is the integration of an air gap in the external walls, as shown in Figure 2.43. Among the insulation materials used, expanded polystyrene (EPS), extruded polystyrene (XPS), and rock wool (RW) are the most available in local markets (Saafi and Daouas, 2018). However, their use is often influenced by factors such as cost and familiarity among clients and builders. This situation highlights the need for strong policies and standards to promote the adoption of thermal insulation to ensure energy efficiency and improved comfort in buildings throughout Tunisia.

The thermal insulation of the building envelope is one of the most effective measures and, in the Tunisian climate, can generate energy savings of up to 30% (Saafi and Daouas, 2018).

According to Daouas (2011), economic parameters such as insulation cost, energy cost, inflation, discount rates, and building lifespan have a significant impact on optimal insulation and energy savings. In hot-arid climates, like in Tunisia, wall orientation has a small effect on optimal insulation thickness, but a significant impact on energy savings. Insulation has the most economical effect with the south orientation, followed by the north, west, and east orientation (Daouas, 2011).

Envelope finish

In Mediterranean regions, whitewashing houses is a tradition that has been used for centuries as a means of reducing heat gain. In modern architectural design and in particular, in the context of global warming, there is a growing recommendation to use whitewash to help cool buildings and mitigate the urban heat island effect. Researchers and manufacturers have been developing a wide range of coating materials incorporating advanced technologies to increase their reflective efficiency. However, due to the increased costs associated with some advanced coatings, the application of white coatings to exterior surfaces remains the primary goal with respect to economic constraints (Marsden, 2023). Since the roof represents the envelope's most exposed surface to sun rays, applying a white coating to the roof could significantly reduce the building's heat gain. According to a simulation work by Rawat and Singh (2022), light-colored reflective paints applied on the roof of a non-conditioned building increase the comfort hours to 12–17 hours more than the base case with a conventional roof used in a hot-dry climate, in India.

The white color is a distinctive feature of Tunisian dwellings, known for its high albedo, which effectively reflects sunlight. Recently, there has been a growing tendency among inhabitants to use darker colors for the exterior surfaces of their buildings. Despite the aesthetic purposes, dark-colored surfaces are not suitable for the Tunisian climate, which is characterized by high levels of sunlight. As a result, buildings with dark surfaces absorb more heat, leading to overheating of the indoor spaces. This highlights the importance of considering climate-appropriate design choices to ensure thermal comfort and energy efficiency in Tunisian architecture.



Image 2.38. A modern villa in Tunisia with white painting (URL-56)

As observed in traditional vernacular architecture, textures are often applied to exterior walls to create shaded areas and reduce heat gain. Today, there are a variety of methods for creating texture on walls, ranging from traditional techniques to modern innovations. These methods include stucco, roughcast, stone cladding, brickwork, textured paints, and wood cladding. Each of these techniques offers unique properties that help reduce heat gain and improve thermal comfort in hot climates. Textured wall surfaces are also more sustainable, requiring less maintenance and less susceptibility to cracking.



Image 2.39. A textured wall painting (URL-59)

Stone and brick cladding are traditional techniques for adding texture to walls, enhancing aesthetics, and cooling buildings. These materials increase thermal mass, regulating interior temperatures by absorbing less heat and creating larger shaded areas on exterior surfaces, thereby reducing heat gain. Sustainable and durable, they offer long-term protection against weathering. In hot climates like India and Iran, brick cladding is extensively used due to its

availability and simplicity, echoing the traditional brick architecture of Tunisia's Djérid region. Similarly, adobe and mud cladding provide passive cooling through high thermal mass and natural insulation, reducing reliance on mechanical cooling systems. Made from locally available materials, adobe and mud cladding offer low embodied energy and minimal environmental impact.

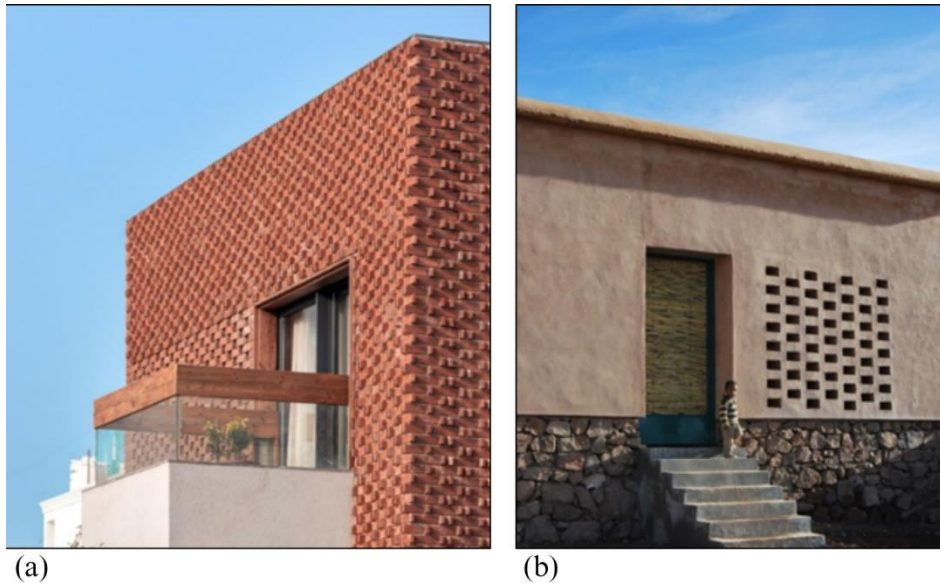


Image 2.40. (a) Brick cladding on a house façade in India (URL-57), (b) A school walls plastered with mud (BC architects, 2018)

Envelope opacity: Window-to-Wall-Ratio (WWR)

In vernacular architecture, the proportion of window area to wall area was typically determined intuitively and without detailed calculations. Factors such as facade orientation and position relative to the courtyard influenced window position and size. Despite the lack of precise calculations, this approach often resulted in thermally efficient and well-placed windows. Windows were strategically placed to maximize natural light while minimizing direct sunlight and heat gain. Today, the window-to-wall ratio (WWR) is a global measurement in buildings that represents the proportion of exterior wall area that is covered by glazing (windows). WWR affects building energy use and occupant comfort by controlling heat transfer, solar heat gain, air infiltration or ventilation, and daylighting (Troup et al., 2019).

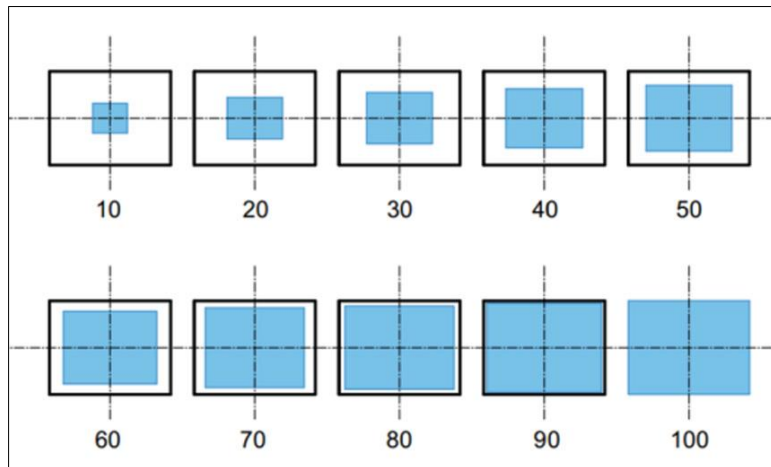


Figure 2.47. The different window-to-wall ratios (Ochoa et al., 2012)

Regulations for WWR vary around the world, influenced by factors such as climate, energy efficiency goals, and building energy codes. Local building codes often specify minimum and maximum WWR based on energy efficiency, sustainability, and occupant comfort in buildings. Many countries have set minimum WWR requirements as part of energy efficiency standards to reduce energy consumption for heating and cooling. Green building certifications often include WWR as a sustainability criterion to encourage the use of sustainable design strategies. In developing countries like Tunisia, regulations still do not seriously take WWR into account in buildings, resulting in low thermal performance and high energy consumption for cooling. This lack of regulation is due to several economic, cultural and political reasons. The Tunisian climate is hot, but we often feature buildings with large, glazed areas for aesthetic and commercial purposes, which increases heat gain. Therefore, to address these issues, policies need to be changed and regulations on energy efficiency in buildings should be established. The implementation of the WWR is a very essential requirement to promote energy efficient building design and reduce energy consumption, especially for cooling.

In hot-arid climate regions, the temperature swings are too high between day and night and in summer and winter, so the optimum WWR is recommended to be 10% (Alwetaishi, 2019). In Tunisia, the 10% WWR is the best choice for a single-family house compared to 40% WWR and could reduce energy consumption by 5.7% (Ihm and Krarti, 2012). The function of the building has an impact on the WWR, and the choice is based on the need for cooling and heating, ventilation, and natural lighting.

Additionally, as observed in vernacular architecture, the orientation, and the courtyard design help to define the WWR for each façade. In hot-dry climates, buildings often experience intense sunlight and high temperatures, making it essential to consider the placement and size of windows according to the sun's path and wind direction. According to a study by (Alwetaishi (2019), the south and east directions are the worst in terms of heat gain through windows in all the locations. According to Alwetaishi and Tak (2020), WWR should not exceed 35%, 25%, and 20% for northwest, southeast and southwest building facades, respectively. The design of a courtyard in buildings sets the lowest WWR on the outside facades and the highest WWR on the inside facades. This approach is based on leveraging the courtyard's protective qualities, shielding the inside facades from intense sunlight and winds prevalent in hot climates. The outer facades, facing directly outward, are exposed to harsh environmental conditions and direct solar radiation. In the study of Asfour (2020), the WWR within a building with a courtyard is 30%, given with shading devices. This WWR value provides a better balance between daylight availability and glare reduction.

In addition to the WWR, the selection of the appropriate glazing and shading devices is critical to maximizing the effectiveness of windows in a building. The glazing type plays a critical role in controlling heat transfer and daylighting, while shading devices significantly reduce solar heat gain.

Glazing

Glazing is responsible for the absorption of a large amount of heat by the building, about 45-60% of the building cooling loads are generated due to the windows' heat gain in cases where WWR is 20-30% of the walls (Bhamare et al., 2019). An important amount of solar rays (89%) that hit the windows are transmitted to the indoor spaces by the untreated glass, and only 5% of the solar rays are absorbed and 6% are reflected (Figure 2.48) (Marchwinski, 2014).

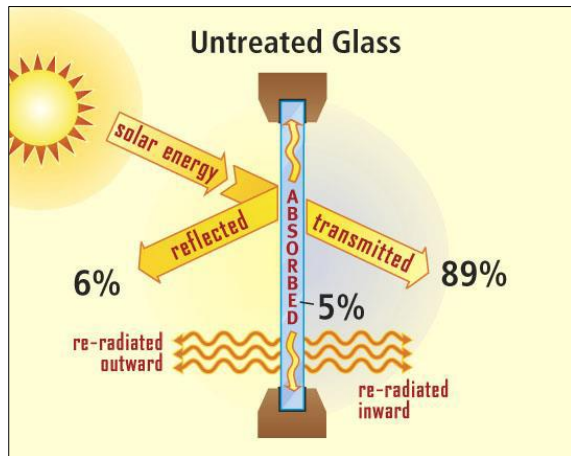


Figure 2.48. The solar radiation transfer mechanism of untreated glass (URL-61)

Considering the significant impact of openings on the energy efficiency of buildings, various window technologies have been developed to reduce heat gain, such as multi-layer glass, multi-pane glazing, tinted glass, glass with low emissivity, and reflective coatings, multi-pane glazing with substitute gases, vacuum glazing, electrochromic glazing, solar cell glazing, etc. (Aguilar-Santana et al., 2019).

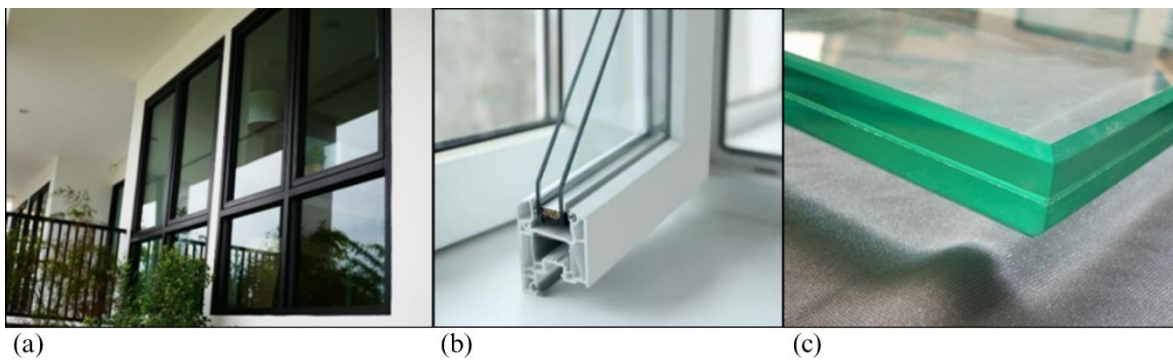


Image 2.41. (a) Tinted glass (URL-62), (b) Multi-pane glazing (double) (URL-63), (c) Multi-pane glazing (double) (URL-63)

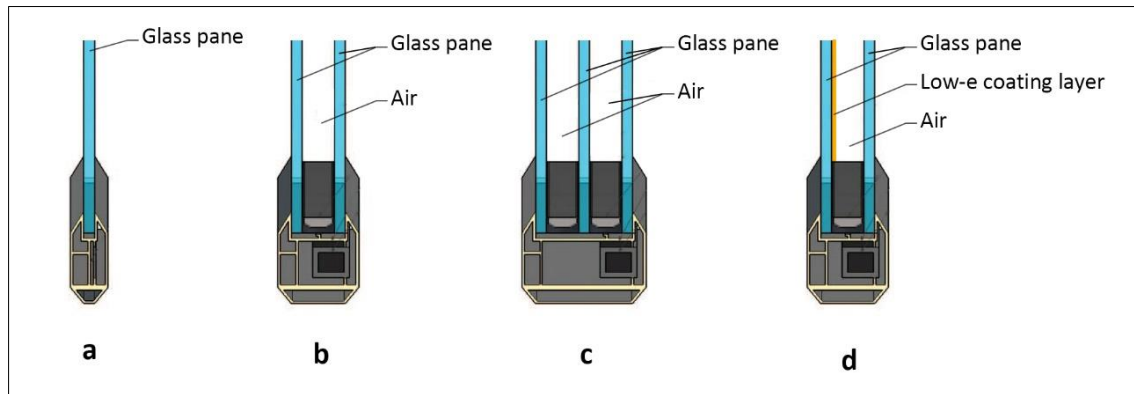


Figure 2.49. Sections of different glazing types, from left to right: single glazing, double glazing, triple glazing, vacuum glazing (Aguilar-Santana et al., 2019)

In Tunisia, there is no specific regulation about the type of glazing used in buildings. Different types of glazing are produced by local and foreign companies, but the most widespread types of glazing used in residential buildings are single and double glazing with a normal air gap. According to a simulation work established by Soussi et al., (2013), The most efficient type of glazing for buildings in Tunisia is the double pane glazing with low emissive coating and argon gas. The low emissive coating significantly reduces radiant heat transfer between the glazing panes, and the argon gas reflects heat better than normal air in summer and prevents interior heat loss in winter. However, since the Tunisian climate is characterized by a high level of solar resources, this type of glazing reduces cooling loads only by 8%. Therefore, the installation of shading devices in front of the windows is very important.

Shading devices

Shading is a passive technique that protects the building from solar heat gain and reduces the use of artificial lighting by providing natural daylight while shading. As such, shading is considered an important aspect in the design of energy-efficient buildings, particularly for reducing cooling loads in hot climates. Shading can be provided by devices such as overhangs, horizontal louvers, light shelves, blind systems, etc. Shading devices could be either fixed and require no energy source or could be mechanical devices that use active energy (Bhamare et al., 2019).

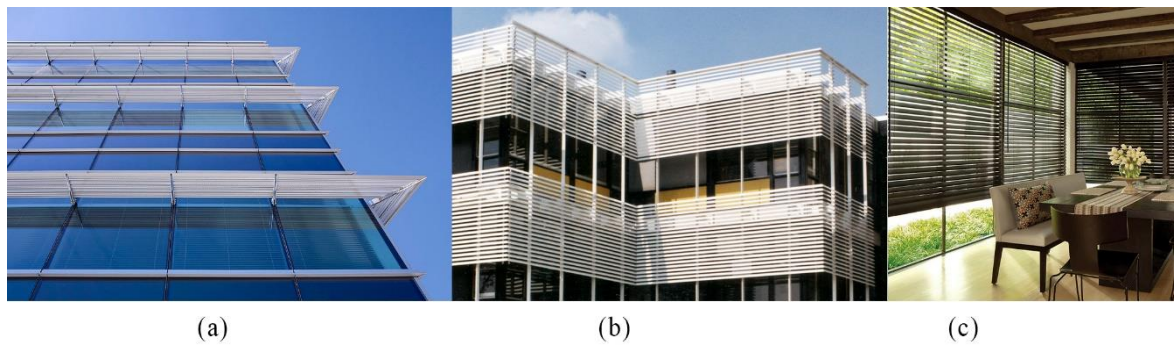


Image 2.42. Overhangs(URL-65), Louvers (URL-66), Blinds (URL-67)

Shading devices are an effective solution for reducing heat gain and cooling requirements of buildings when placed in certain orientations. For example, simple fixed overhangs are very effective at shading south-facing windows in the summer when sun angles are high. When sun angles are low in winter, the sun's rays can penetrate the house under the overhangs (Choudhary et al., 2014).

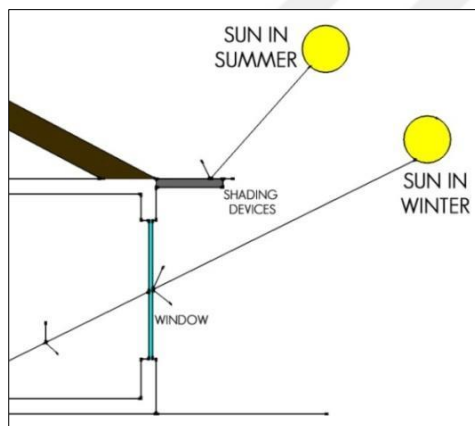


Figure 2.50. Overhang shading in a building (Kahoorzadeh et al., 2014)

The Mashrabiya, a traditional Islamic architectural feature, serves as an effective shading device, especially in hot climates. Originating in the Middle East, Mashrabiya are intricate wooden lattice screens typically placed over windows or balconies. The Mashrabiya design allows air to circulate while blocking direct sunlight, reducing solar heat gain and creating shaded spaces. Mashrabiya serves as an optimal tool for shading and ventilation, especially when a water pot is placed inside. This addition cools and humidifies the air, enhancing the Mashrabiya's effectiveness in creating a comfortable indoor environment. Inspired by this traditional element, a wide range of modern shading devices have been developed in modern

architecture. These modern adaptations include external perforated surfaces made of metal, wood, concrete, brick, etc., all designed to provide similar benefits of solar control and ventilation. The material, dimensions, and location of the Mashrabiya depend on the orientation and design of the building (Beyhan, 2024).

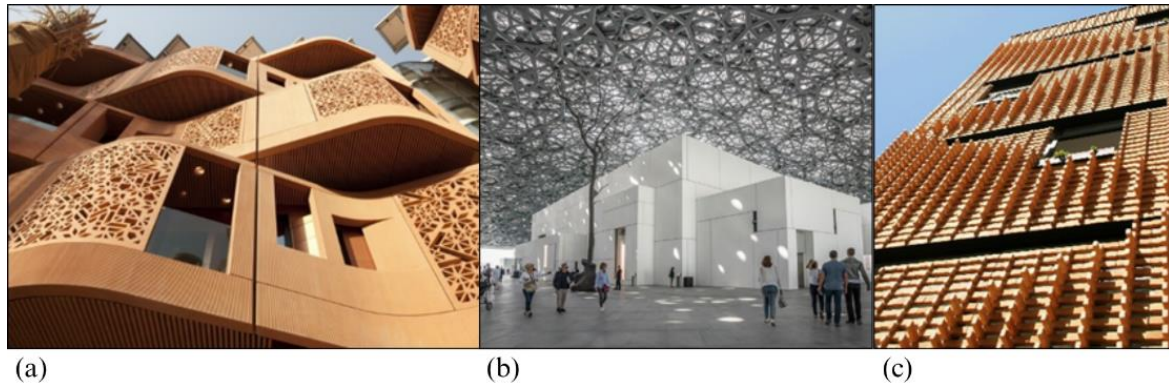


Image 2.43. Modern designs of Mashrabiya (URL-68; URL-69; URL-70)

Natural ventilation system

The courtyard design, combined with strategically positioned windows, defines a passive natural ventilation system that is neglected in today's architecture. While historically known for its efficient passive cooling and ventilation, this design is often replaced in favor of mechanical ventilation systems, resulting in increased energy consumption. Therefore, promoting the integration of passive ventilation tools is critical to achieving more sustainable building practices.

Typical architectural designs of residential buildings worldwide often prioritize cost, aesthetics, and function over passive ventilation as a primary design element. While these factors are important, they often overshadow the benefits of passive ventilation. As a result, many buildings rely heavily on mechanical ventilation systems, neglecting the potential of natural airflow and ventilation. By prioritizing passive ventilation strategies in architectural design, buildings can achieve improved indoor air quality, thermal comfort, and energy efficiency, contributing to healthier and more sustainable living environments.

In modern architecture, there are many ways to create natural ventilation, either by wind pressure or by thermal buoyancy (stack effect) depending on the building design. The single-sided and cross-ventilation are generated by the wind pressure. The single-sided ventilation

requires one or more windows only on one side of the room (Figure 2.52. (a)), and cross-ventilation requires two windows or more facing each other on two different sides of a room (Figure 2.52. (b)) (Baker and Steemers, 2005). This ventilation mechanism is the simplest to implement in architectural design and the most widely used in modern buildings.

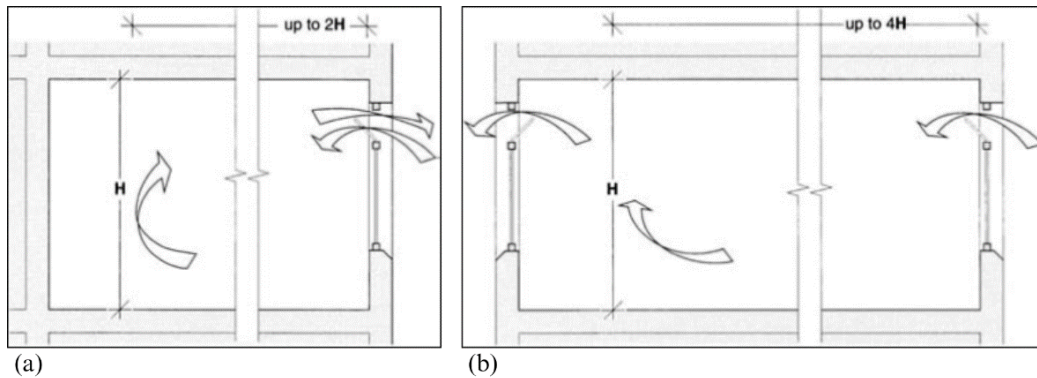


Figure 2.52. (a) Single sided ventilation, (b) Cross ventilation (Baker and Steemers, 2005)

The "Stack extract" effect generates natural ventilation through thermal buoyancy and wind-induced negative pressure on the roof, particularly effective for low-height buildings. While wind initiates the "Stack" and "extract" effects, the absence of wind causes the "Stack" to revert to an "extract" function (Baker and Steemers, 2005). This traditional ventilation system has many modern applications in different projects.

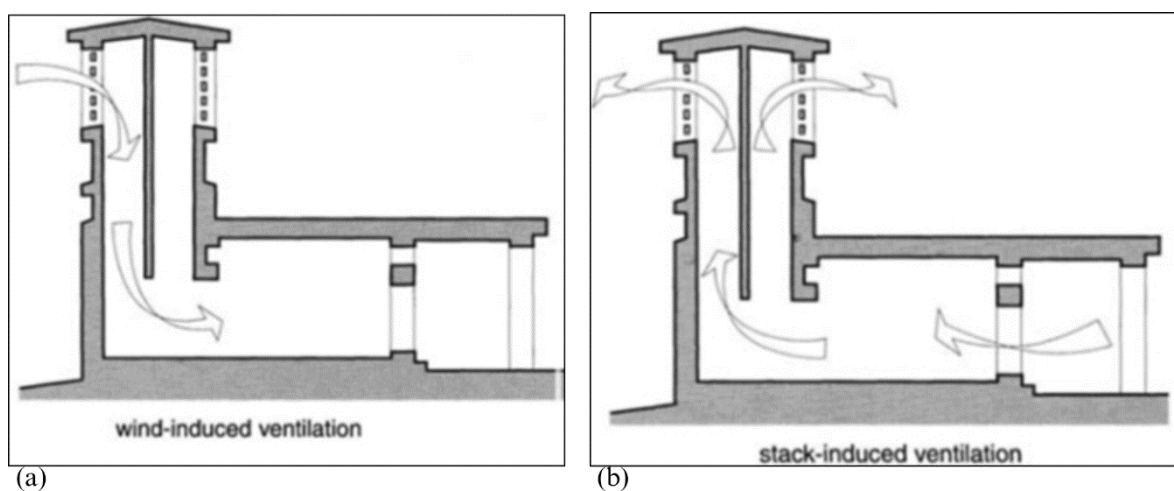


Figure 2.51. 'Stack extract' effect (Baker and Steemers, 2005)

A wind tower is an ancient passive ventilation technique still used in modern architecture. It is an architectural feature on the roof of a building that supplies fresh air to the interior and exhausts polluted air through windows or other openings. Common in Middle Eastern countries, wind towers have been used for about three thousand years to ventilate and cool buildings in hot-dry or hot-humid climates. They function as natural ventilation systems by drawing outside air into the building using the principles of wind and chimney effect. Wind towers use pressure differentials to draw in fresh air and expel polluted air, making cost-effective use of renewable wind energy. In hot-arid climates where wind intensity is higher, wind towers have narrow openings and long shafts to capture cooler, fresh air from higher elevations. The greater the height, the more effective the airflow due to increased pressure differentials. According to the Bernoulli effect, air is accelerated through smaller sections, increasing ventilation efficiency. In addition, in hot-arid regions, wind towers often incorporate water features to increase humidity and cooling through evaporation, making indoor spaces more comfortable (Yılmaz Yücel, 2024).



Image 2.44. The 'Barjeel' modern wind tower in Dubai (URL-74)

Many projects around the world feature traditional techniques for creating natural ventilation. The Casa Attico house in Brazil represents a specific building design that uses the wind tower and courtyard design to harness natural ventilation. On the ground floor, the house is shaped like a wind machine with a wind tower placed in the center of the courtyard. From the east, the wind enters the courtyards and circulates geometrically according to the shape of the walls, breaking the wind and ventilating the four symmetrical bedrooms. At the

tower level, the wind rises between the two layers of brick that compose the structure of the tower walls, creating natural ventilation for the facade (Atelier Matteo Arnone, 2024).



Image 2.45. The Casa Attico house patio and wind tower Picture (Atelier Matteo Arnone, 2024)

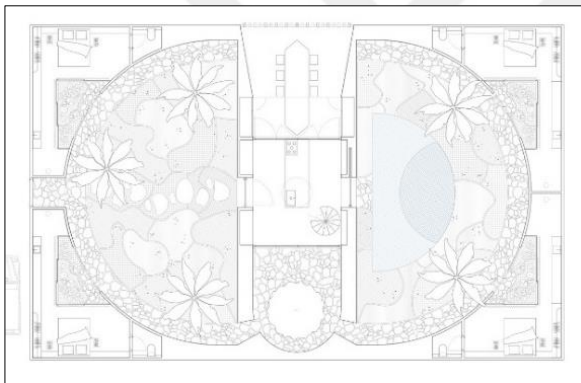


Figure 2.53. The Casa Attico house plan (Atelier Matteo Arnone, 2024)

2.2.4. Findings summary

In this section, an analysis of different examples of Tunisian vernacular architecture was carried out in order to identify the passive cooling techniques used at different levels of the design. This was followed by an examination of the application of these techniques in modern architecture, with examples of contemporary buildings that have adopted these traditional methods. In addition, alternative technological solutions were explored to provide further impact for passive cooling.

The wide range of passive cooling solutions, both traditional and modern, will be organized into a design guide in the next part of this study. It is important to note that from the

beginning of this section, these solutions have been analyzed at different design levels. During the analysis of Tunisian vernacular architecture and its principles in modern architecture, passive cooling solutions were examined according to the following stages:

- Adaptation to the site
- Courtyard house organization
- Local construction materials and techniques
- Envelope system
- Natural ventilation

At each design level, various passive cooling solutions were identified and will be systematically organized into a design guide, taking into account climatic data (sun path, wind direction, etc.). The different solutions obtained from this literature review are summarized in the table below, organized according to each design level:

Table 2.7. Findings summary table

Design levels	Passive cooling techniques	Details
Adaptation to the site	Vegetation	Solutions at this level depend mainly on the geographic and climatic data of the site.
	Earth-sheltered technique	
	Orientation	
Courtyard house organization	Spaces organization	Courtyard design characteristics are defined by traditional architecture.
	Courtyard position	
	Courtyard role	
	Courtyard dimensions	
	Courtyard shape	
	Courtyard levels	
	Natural elements	
Local construction materials and techniques	Envelope body (walls and roof)	- High thermal mass materials
	Coating (walls and roof)	- Local materials and techniques
	External surfaces (walls, roof, and ground)	
Envelope system	Thermal mass	- High thermal mass materials - Thick walls - PCM
	Roof design	- Advanced flat roof structure - Curved roof shape - Irregular roof shape - Green roof

Table 2.7. (continued) Findings summary table

Design levels	Passive cooling techniques	Details
	Envelope coating	- Thermal insulation - External finish color and texture
	Opacity	- WWR - Glazing type - Shading devices
Natural ventilation	Openings	Strategic dimensions and positioning
	Architectural elements	E.g. courtyard, wind tower, wind catcher, etc.

The order and number of design levels will be reorganized in the design guide to better synchronize building design levels with the adaptation of passive cooling techniques. Additionally, the various solutions under each design level will be reorganized in the guide according to factors such as geographic and climatic data, as well as the specific objectives of these techniques, including reducing heat gain, reflecting solar rays, and increasing humidity levels.



3. MATERIALS AND METHOD

This section has developed a design guide based on the data collected from the literature review and traditional architecture in Tunisia. The design guide aims to compile and adapt passive cooling techniques from literature and traditional architecture to suit residential buildings in hot-arid climates. The process has involved a structured review of the identified strategies, followed by their adaptation and integration into modern design principles. This will ensure that traditional methods are preserved and optimized for contemporary use, providing a practical and sustainable solution for improving thermal comfort and energy efficiency.

The growing global demand for fossil fuel energy, driven by the need to maintain comfortable indoor conditions in the context of climate change, has significantly increased the carbon footprint of building energy consumption, thereby aggravating the climate crisis. Consequently, the development of architectural design strategies aimed at creating energy-efficient buildings has become imperative. This study conducts a comprehensive literature review to identify passive cooling techniques used in architectural designs in hot-arid climates, with a particular focus on vernacular architecture in Tunisia. A database is created by analyzing traditional Tunisian dwellings with an emphasis on passive cooling methods and by examining their application in modern architectural contexts alongside the investigation of alternative, technologically advanced techniques. The study resulted in the development of a design guide that categorizes and organizes passive cooling strategies into seven different Design Levels for residential buildings, tailored to the characteristics of hot-arid climates, with a specific emphasis on Tunisian climatic data. This design guide outlines potential passive design solutions for improving thermal comfort, considering different climatic and technical constraints at each level.

The Design Levels (Figure 3.1) were followed throughout the analysis process and during the compilation of the database, which was essential to the creation of the design guide. Similarly, this hierarchical structure was respected in the development of simulation scenarios.

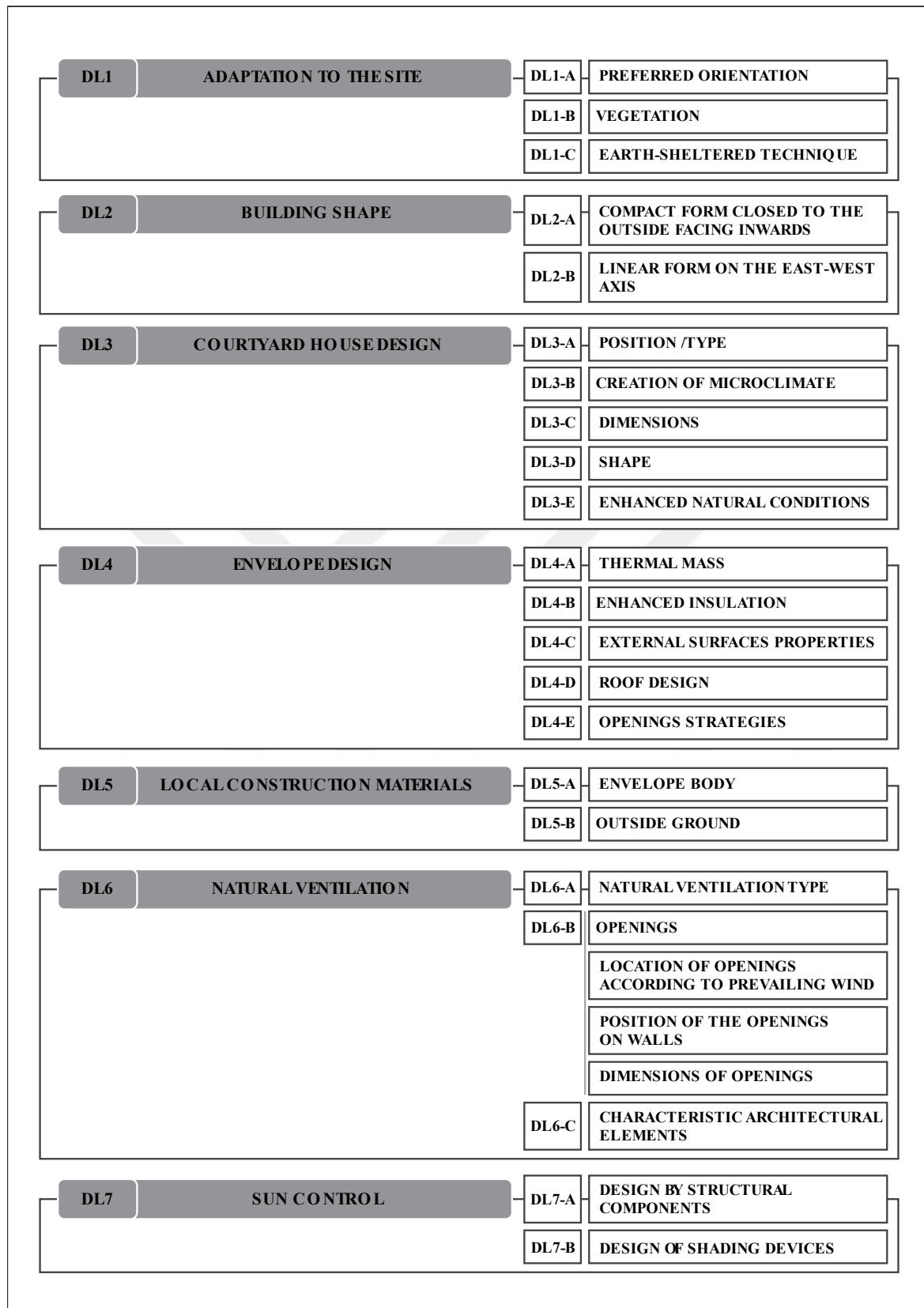


Figure 3.1. Design Levels

The process begins with adaptation to the site, emphasizing important geographic and climatic considerations to optimize building placement. The second Design Level involves the general spatial configuration of the building, which can either be a compact form closed to the outside and facing inwards or a linear form oriented along the east-west axis. The third Design Level focuses on the spatial organization of the house, particularly emphasizing the courtyard house design typical of Tunisian dwellings and explores how courtyards can enhance thermal performance. The fourth Design Level considers various strategies for thermal regulation at the building envelope level, including thermal mass, thermal insulation, external surface properties, roof design, and openings strategies. The fifth Design Level examines the use of local construction materials and techniques, assessing their effectiveness in minimizing heat gain and highlighting the significant thermal benefits of using natural and local materials. The sixth Design Level considers passive ventilation techniques to improve indoor air circulation. It explores how to enhance natural ventilation through the strategic use of openings (location, position, dimensions) and characteristic architectural elements (wind towers, wind catchers, and courtyards). The final Design Level focuses on optimizing solar control through the strategic use of structural components and shading devices. This includes the integration of architectural elements that effectively manage solar heat gain and improve thermal comfort within the building design.

Each Design Level incorporates key passive cooling strategies and tools, taking into account essential climatic factors such as temperatures, wind direction, sun path, etc. These strategies are precisely tailored to the hot-arid climate of Tunisia. Notably, each passive cooling technique can serve multiple purposes in passively cooling the building. For example, the courtyard house design not only effectively reduces heat gain through strategic orientation and shading, but also promotes natural ventilation and maintains optimal relative humidity levels. The selection of each technique depends on the desired climatic conditions, including indoor temperature, ventilation, humidity, and shade, as well as the feasibility and effectiveness of each technique. In modern architectural practices, advances in technology have resulted in a vast array of passive cooling techniques and materials, making it difficult to provide a thorough list of all possible solutions. Nevertheless, this guide focuses on the most widely used and experienced techniques, ensuring that they are consistent with the climatic data relevant to the region under consideration. The selection and implementation of passive cooling solutions is primarily guided by thermal and climatic calculations, with cost considerations over the life cycle of the building also playing a critical role. The seven

Design Levels are integral components of a comprehensive design approach that aims to provide comfortable indoor thermal conditions while reducing dependence on fossil fuels and minimizing greenhouse gas emissions. Each passive cooling technique can influence and enhance thermal performance goals at different levels of the design. The design solutions presented in this guide are intended to be implemented in an integrated manner to form a cohesive and sustainable design approach. By following this comprehensive framework, architects and designers can achieve significant improvements in the thermal comfort of residential buildings in hot-arid climate regions while adhering to the principles of sustainability and energy efficiency. This guide serves as a practical tool for the effective implementation of passive cooling techniques, ensuring that buildings can maintain a comfortable indoor environment with minimal environmental impact. The following pages contain the design guide organized according to the seven Design Levels (DL).

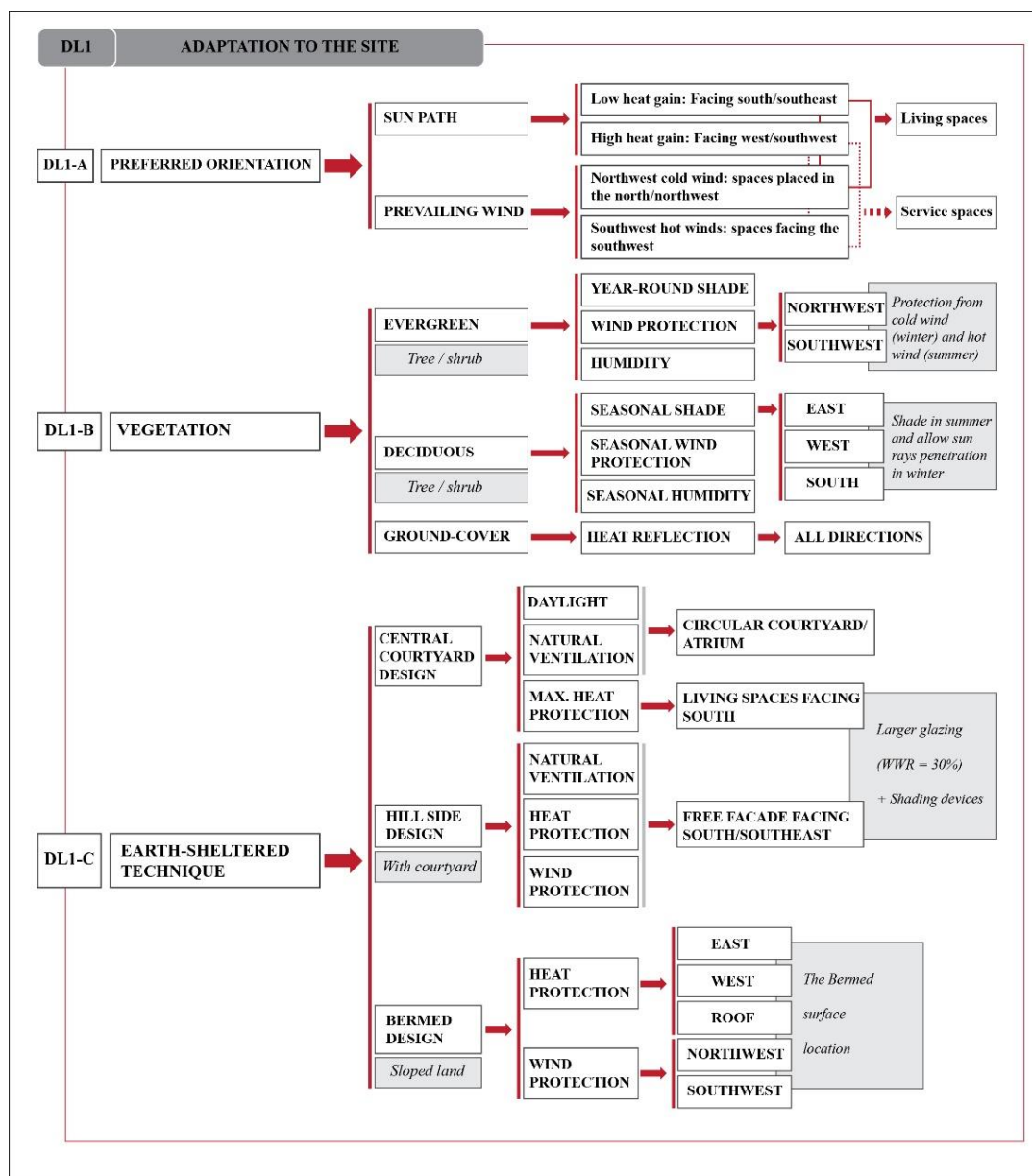


Figure 3.2. Design Level 1: Adaptation to the site

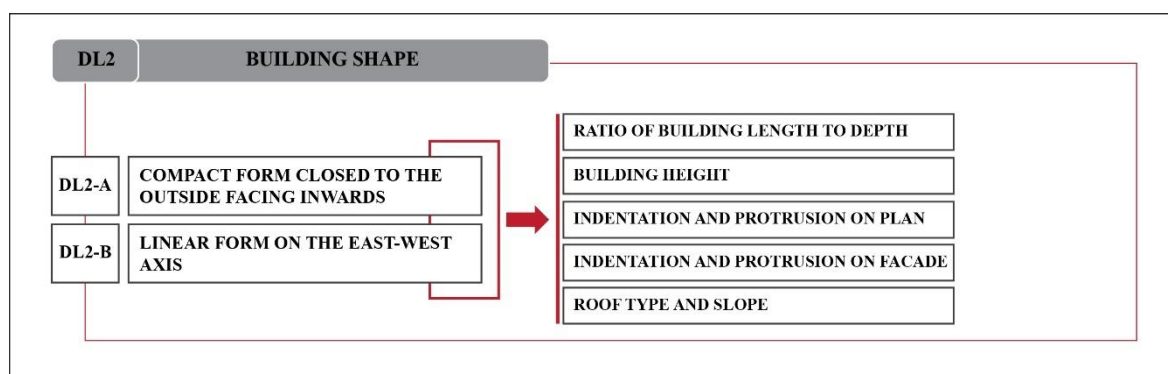


Figure 3.3. Design Level 2: Building shape

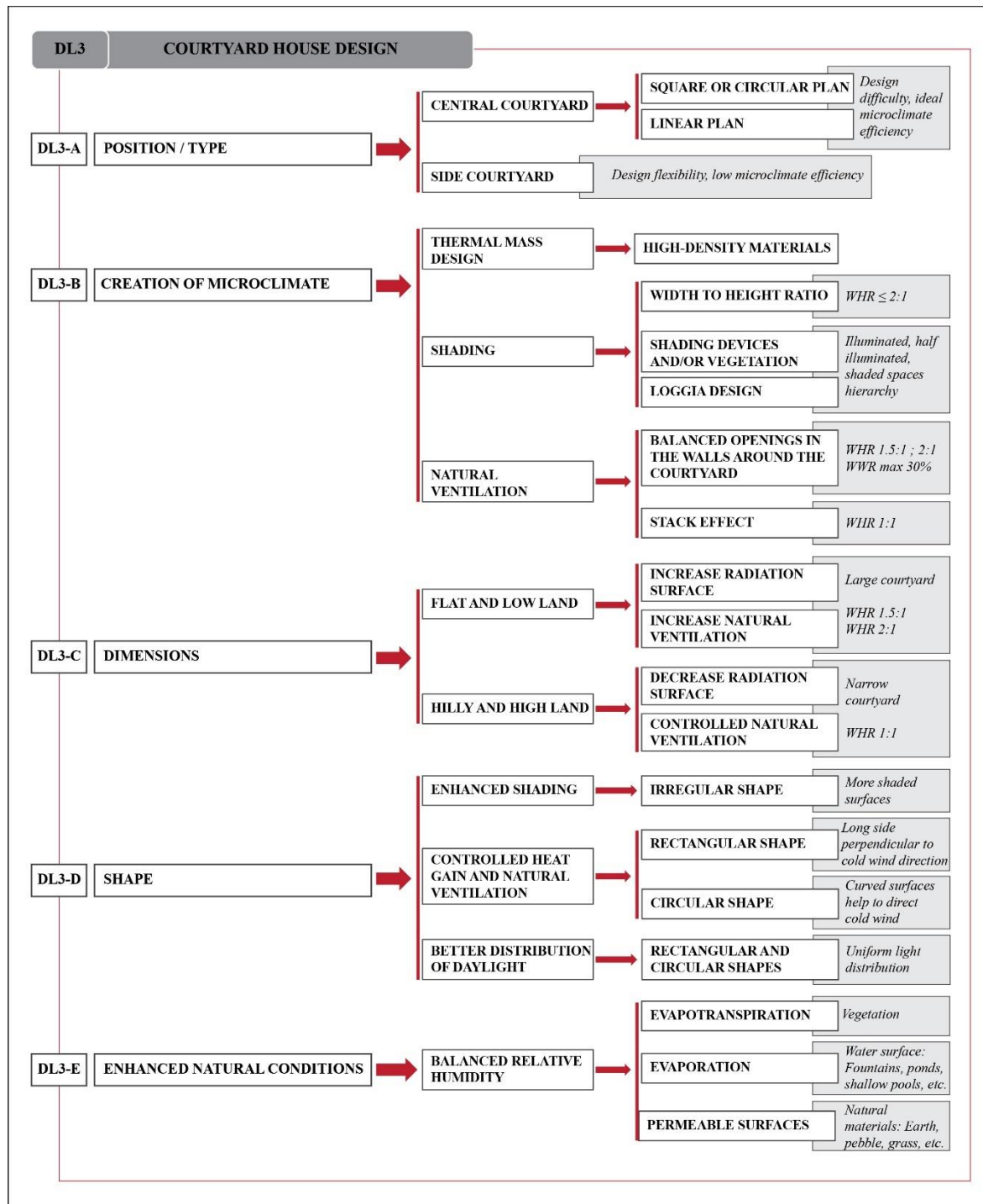


Figure 3.4. Design Level 3: Courtyard house design

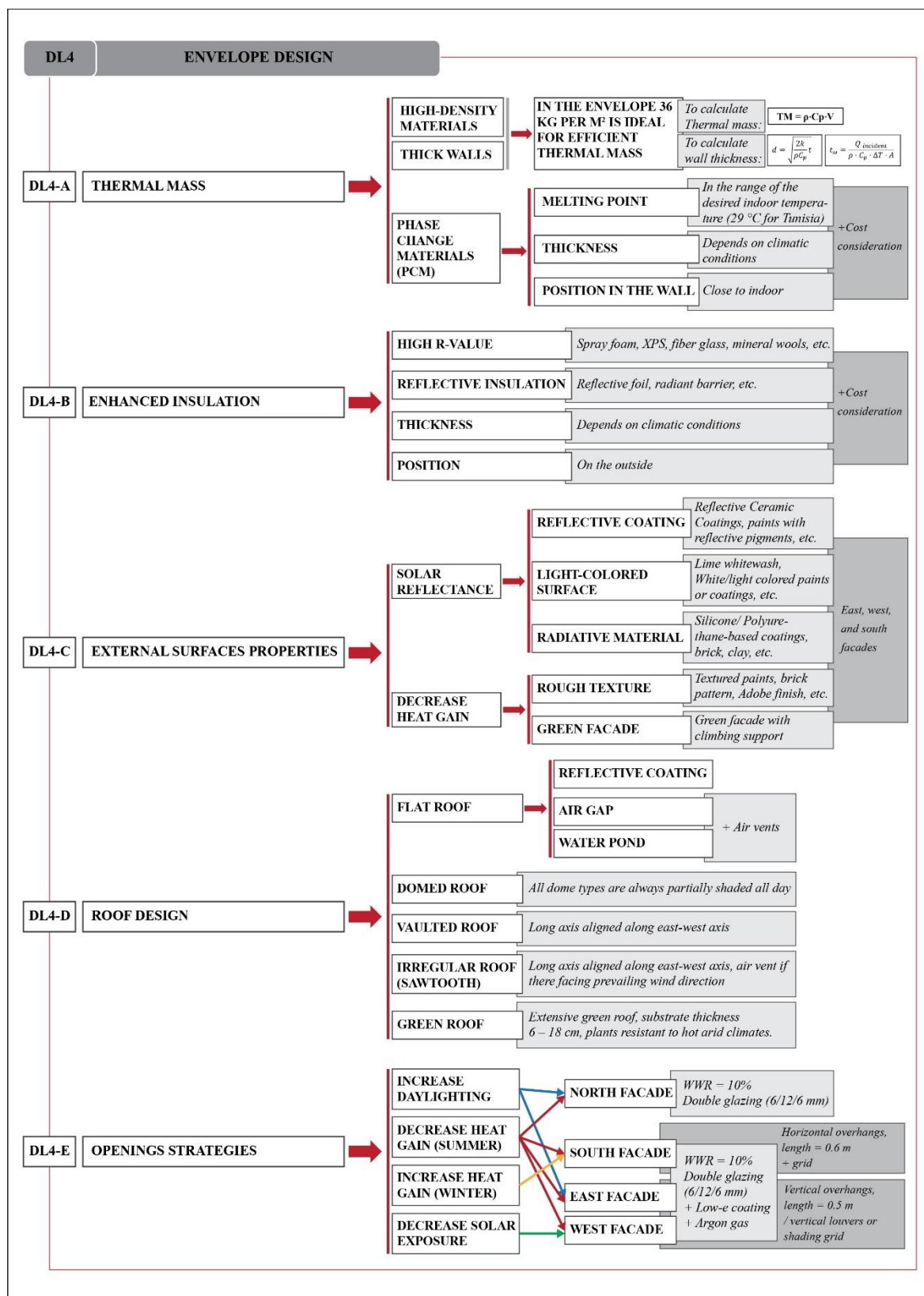


Figure 3.5. Design Level 4: Envelope design

Table 3.1. Symbols explanation

d = Heat penetration depth (m), k = Thermal conductivity of the material (W/m·K), ρ = Density (kg/m ³), C_p = Specific heat capacity (J/kg·K), t = Time period (usually 24 hours for diurnal cycles),	$t\omega$ = Wall thickness (m), $Q_{incident}$ = Total incident heat (Joules or kWh) ΔT = Temperature change (K or °C), A = Surface area of the wall (m ²)
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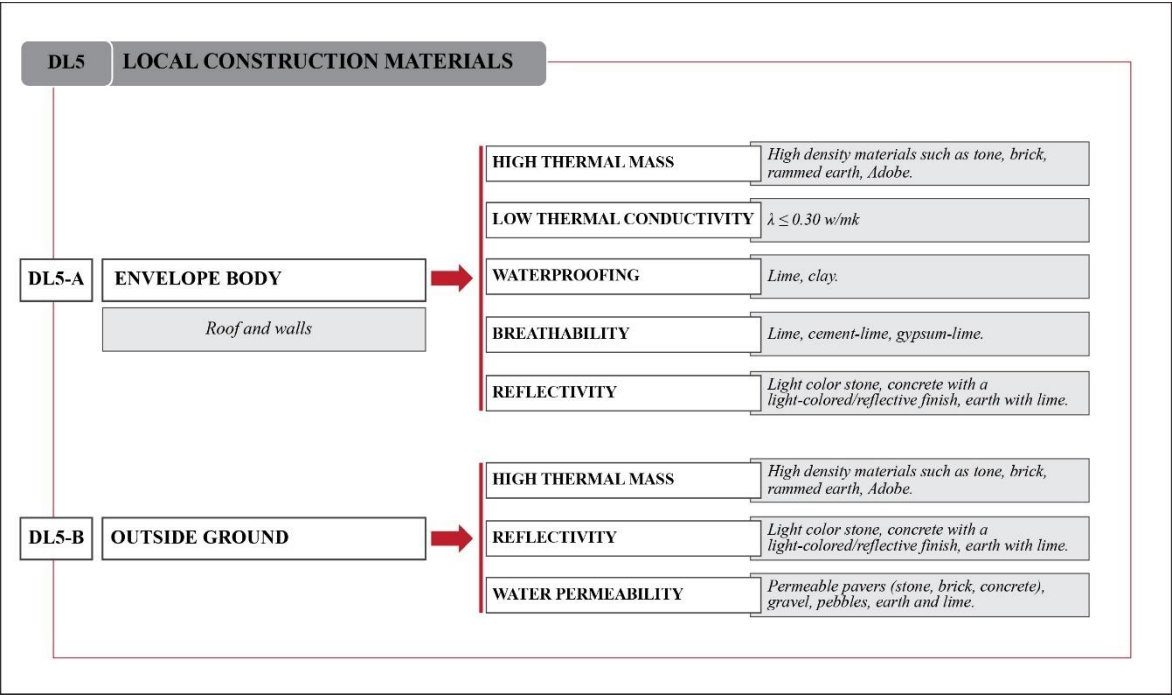


Figure 3.6 Design Level 5: Local construction materials

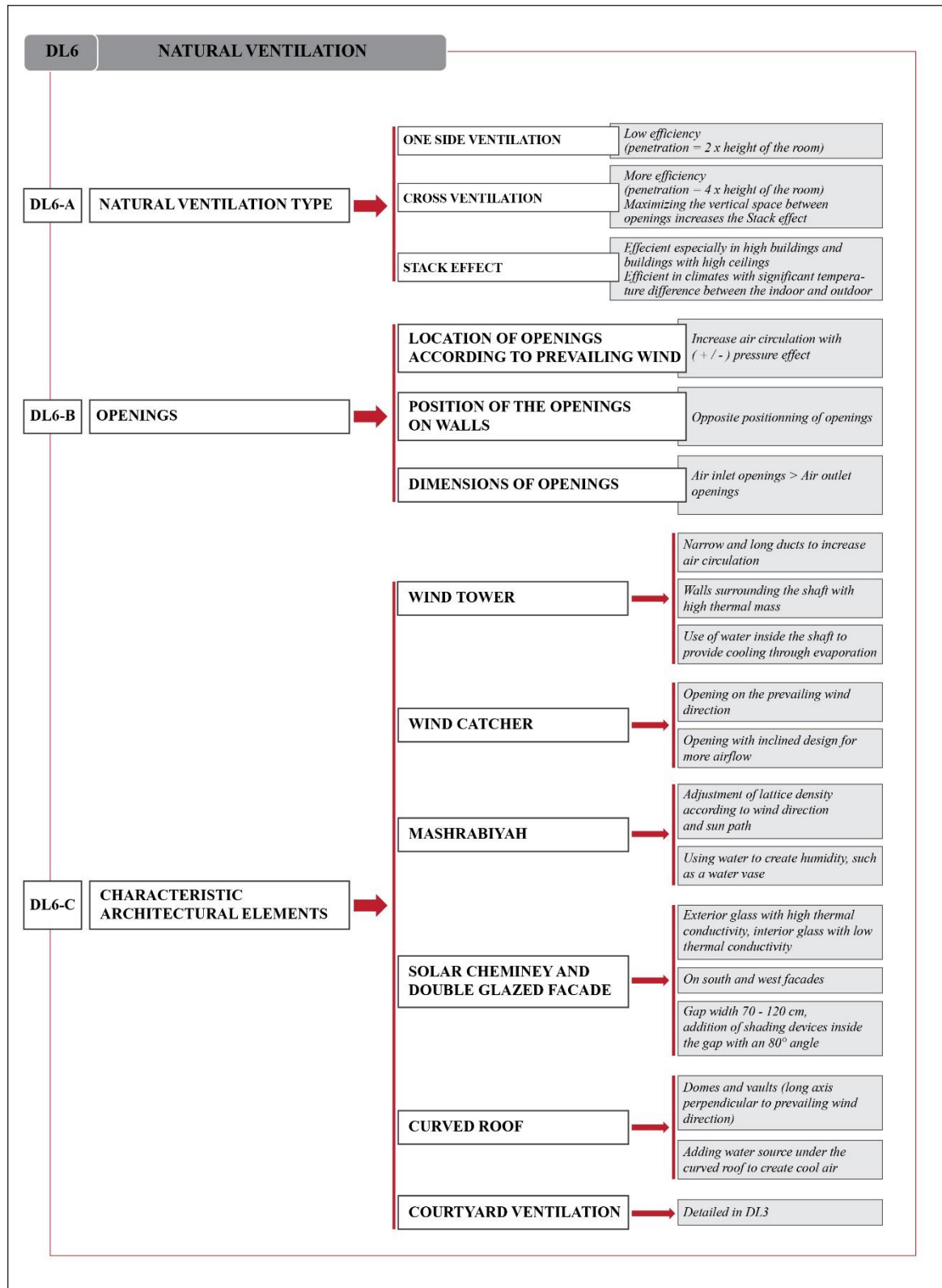


Figure 3.7. Design Level 6: Natural ventilation

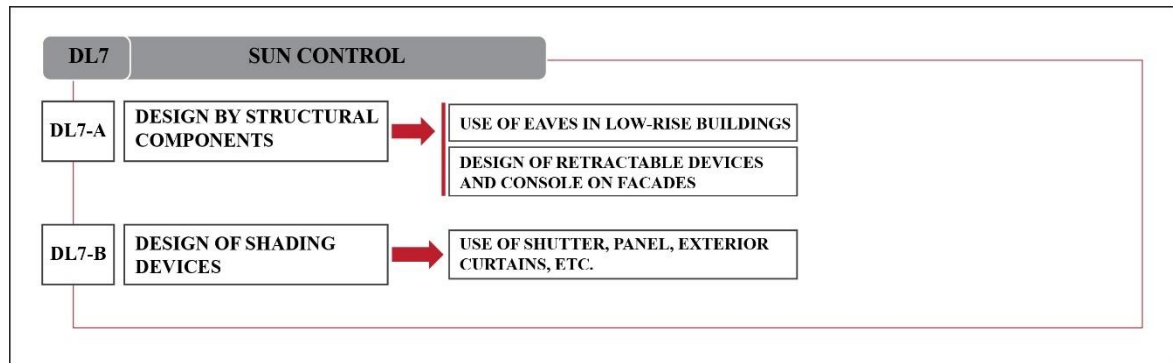


Figure 3.8. Design Level 7: Sun control

3.1. Base case

To test the efficiency of the passive cooling solutions outlined in the design guide, a model of a typical Tunisian house was created. This model represents a single-story house with a rectangular plan, designed to accommodate a family of five. The layout includes a living room, kitchen, three bedrooms, a WC, and a bathroom, encompassing a total built area of 133 m² with a ceiling height of 3 meters. The building's longer side is oriented along the east-west axis to minimize solar exposure on the long facades (16.33 meters), which comprise most of the living spaces (rooms 2 and 3, and the salon) facing south.

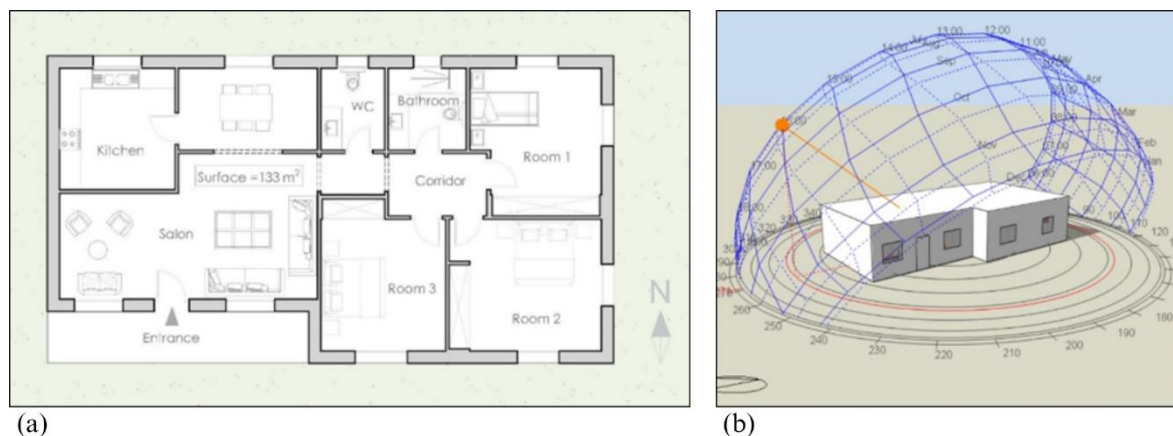


Figure 3.9. (a) The house model plan, (b) Rendered view of the house model

The sizes and positions of the openings are determined by the interior spaces' requirements for daylighting and ventilation. Windows are placed on the south, east, and north facades, while the west facade remains entirely opaque. The window-to-wall ratio (WWR) for each facade and for the entire house is provided in the table below, as generated by the simulation

program. The windows are placed on the interior side with an external reveal of 25 cm to protect the glass from the sun's rays in summer.

Table 3.2. Window-to-wall ratio for each façade

	North (315-45°)	East (45-135°)	South (135-225°)	West (225-315 °)	Total
Wall area [m ²]	57.16	30.91	57.16	30.91	176.13
Window area [m ²]	6.07	2.88	6.60	0.00	15.55
WWR [%]	10.63	9.33	11.54	0.00	8.83

The building materials and techniques used in this model reflect those commonly used in modern Tunisian construction. Detailed descriptions of the exterior walls and flat roof structure can be found in the previous section, "2.2.3." in "Envelope System". Additional details on the building structure are provided in the table below.

Table 3.3. Base case construction details

Building detail	Description	Thickness
Main structure type	Heavy-weight hollow brick and reinforced concrete	-
Exterior wall structure	Double hollow brick wall with a 6 cm air gap	35 cm
Interior wall structure	Single hollow brick wall	10 cm
Roof structure	Flat roof - hollow brick and reinforced concrete	33 cm
Glazing template	Single clear glass	6 mm
Insulation	No insulation	-

The mechanical conditioning systems for heating and cooling are selected based on the most commonly used options in Tunisia. The chosen cooling system is an electrically powered split unit without fresh air intake, while the heating system utilizes natural gas-powered radiators. Only the living spaces are equipped with the conditioning systems. Mechanical ventilation is not activated; instead, only natural ventilation is considered in the simulation calculations.

Table 3.4. Power-based systems in each space

Space \ System	Cooling	Heating	Office equipment	Domestic hot water	Catering
Salon	X	X	X		
Rooms (1, 2, 3)	X	X	X		
Dining room					
Kitchen				X	X
WC				X	
Bathroom				X	

The base case model site is located in the city of Kairouan in central Tunisia. The geography of this region is flat and the city is far 50 km from the east coast and its elevation is 64 m above sea level. Kairouan has a hot-arid climate characterized by extremely hot-dry summers with mean maximum temperatures often reaching 35°C and mild winters with mean low temperatures around 5-10°C. The city receives low annual rainfall, averaging 300-400 mm, with an average of 38.8 days of rain (≥ 1.0 mm) per year. Kairouan enjoys abundant sunshine year-round, with 3,075.5 hours of sunshine per year, and generally low humidity, especially in summer, with 49% relative humidity in the driest month, July. The prevailing winds are from the northwest, with occasional hot, dry winds from the Sahara (NIM, 2018).



Map 3.1. Kairouan location on map

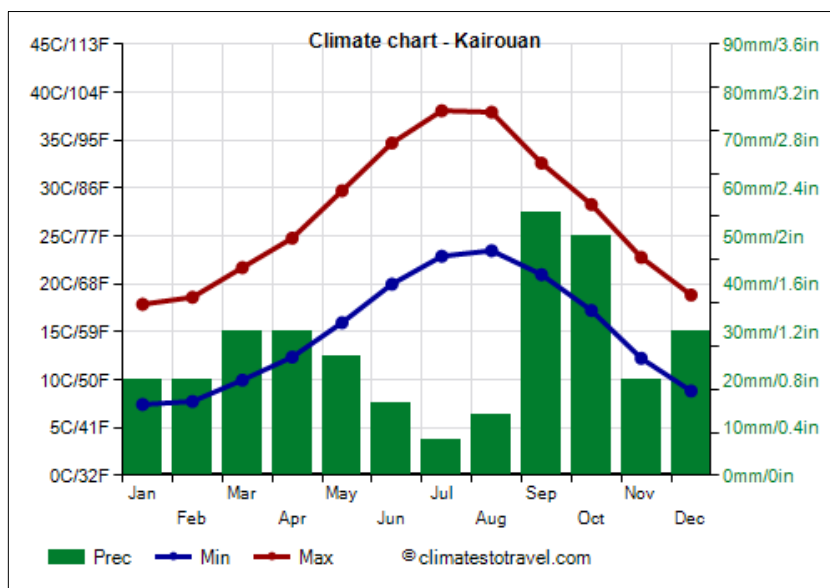


Figure 3.10. Climate chart of Kairouan (URL-71)

Kairouan is one of the most vulnerable regions in Tunisia to the effects of climate change due to the lack of planted lands and the increase of urban areas. The hottest temperature measured from 1949 to April 2023 was reported by the Kairouan weather station in August 2021, with a temperature record of 50.3°C (World Meteorological Organization, 2021). The severe climatic conditions in Kairouan with the temperature records due to global warming require effective passive cooling and thermal regulation strategies in building design.

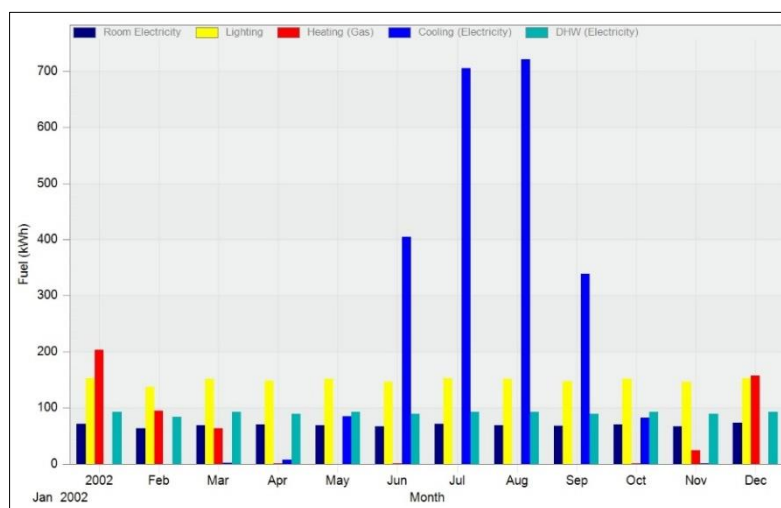


Figure 3.11. Energy consumption per month for different systems

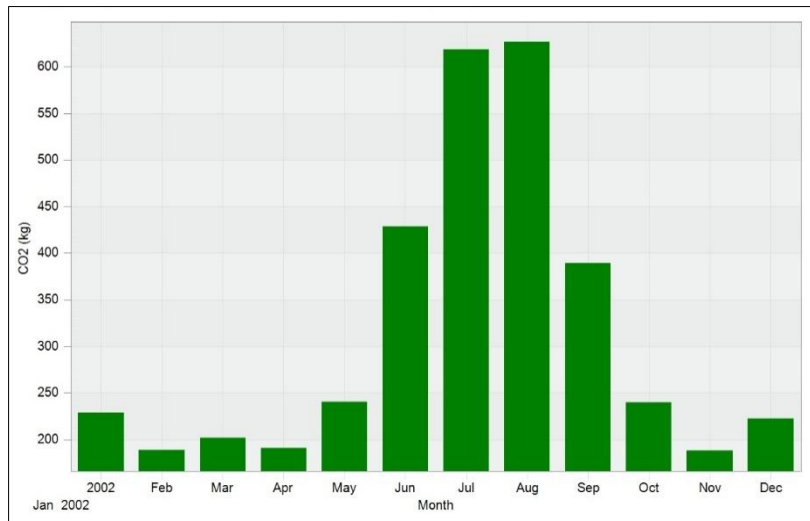


Figure 3.12. Carbon dioxide production per month

The efficiency of passive cooling techniques will be evaluated based on the energy consumption required to meet cooling demands. For the base model, the graph below indicates that the majority of annual energy consumption is attributed to the cooling system, particularly during June, July, August, and September, with an annual consumption totaling 3825.96 kWh, which represents 35.6% of the total annual energy consumption. This high energy usage correlates with elevated carbon production rates during the same months. Consequently, mechanical cooling in residential buildings emerges as the primary consumer of fossil fuel energy and the largest contributor to carbon dioxide emissions.

3.2. Simulation tool

The simulation tests are conducted using advanced building energy simulation software that enables the creation of realistic building models and environmental conditions. The results of the simulations provide valuable practical insights. As one of the most important and advanced technologies for carbon reduction in the building sector, Building Energy Modeling (BEM) has increasingly become a practical and supportive method for energy-efficient design to improve energy performance. BEM has attracted increasing attention for applied research to optimize energy efficiency at multiple levels, such as different stages during the entire building life cycle and different spatial scales (building scale, district or community scale, and building sector scale) (Pan et al., 2023). In recent decades, building energy simulation has helped architects and engineers in building design and provided more

support in other fields, such as thermal analysis, initial operation, and pre-construction building evaluation. In order to achieve a more efficient building design, it is crucial to carefully consider the environmental issues that influence the energy performance of the building (Algburi, 2018). The program used to test the passive cooling techniques studied in this research is DesignBuilder, a building modeling simulation software that uses EnergyPlus as its simulation engine. Developed by the U.S. Department of Energy, this tool assists users, designers, engineers, and researchers in evaluating building energy performance and improving designs for improved energy efficiency. This software is widely used today by engineers and academic researchers for its tremendous capabilities, especially in comparing different design scenarios and helping to select the best and most energy-efficient design option. The DesignBuilder database has been an incredible help in early design decisions and energy testing (Hensen et al., 2004). The hourly weather data file is one of the largest dynamic demand data files in energy modeling programs. DesignBuilder includes a large worldwide database of hourly weather data. The user can select the weather file data template that corresponds to the region being studied or the nearest location from the library (Grag et al., 2017). Each geographic area has a special weather file that specifies the outside temperature, solar radiation, and atmospheric conditions for every hour of the year at that location. The weather data file in DesignBuilder software is regularly typical data obtained from hourly measurements at a particular location by the meteorological office or the National Weather Service (Pyrgou et al., 2017).



4. SIMULATION ANALYSIS AND RESULTS DISCUSSION

This section of the study presents detailed simulations to evaluate the effectiveness of passive cooling techniques by creating scenarios consistent with the design guide. These simulations focus on evaluating the reduction in energy consumption required for cooling, particularly during the summer months. In each scenario, different combinations and implementations of passive cooling methods are applied taking into account climatic factors. The goal is to evaluate the effectiveness of strategies for improving thermal comfort and reducing reliance on mechanical cooling in hot-arid climates.

4.1. Creation of simulation scenarios

Different scenarios were considered to test the passive cooling solutions efficiency in enhancing the building's thermal performance and reducing cooling loads. These solutions were progressively combined to improve the overall thermal performance of the building. The scenarios were chosen based on several factors. A limited number of scenarios was established because the design guide contains a wide range of passive cooling solutions that could not all be tested in this study. Therefore, 15 scenarios were created, with at least one scenario for each design level. Regarding the design of the default model, which already responds in some cases to the design guide rules, certain solutions were excluded from simulation tests. For example, since the default model is already oriented toward the south, the orientation factor was not tested in the adaptation to the site level. Additionally, some solutions implementation was difficult in modern architectural practices such as the earth-sheltered technique, since most of the new residential buildings are located on flat lands within cities. Therefore, this technique is not considered in simulation scenarios. Some scenarios encompassed more than one design solution because they formed an integral part of a whole design approach. For instance, the courtyard house design includes the creation of a central courtyard with specific dimensions, shape, and openings that should be present together to create an efficient passive cooling solution, as mentioned in the design guide. Finally, solutions were chosen based on their applicability, market availability, and cost. For example, the choice of Rockwool (RW) thermal insulation considered the material's thermal efficiency, cost, and availability in Tunisian markets, where the default model is located. The same considerations are applied to external surface finish choices. In the case of the roof

design, since flat roofs are already the most common in Tunisia, testing more advanced roof structures (such as flat roofs with an air gap or water pond) excluded budget considerations and technical constraints.

Table 4.1. Simulation scenarios

Design Level	Solutions	Scenarios
Adaptation to the site	Vegetation	S ₁ : deciduous trees on the east, west, and south sides.
Building shape	Linear form on the east-west axis	S ₀ : the default model linear form aligned along the east-west axis
Courtyard house design	Courtyard design (position, microclimate, dimensions, shape)	S ₂ : square courtyard (6.7 x 6.7 m) S ₃ : rectangular courtyard (3.65 x 12 m)
Envelope design	Thermal insulation	S ₄ : RW insulation
	External surfaces finish	S ₄ : white colored finish S ₅ : Dark-colored (grey) finish S ₆ : brick cladding
	Roof design	S ₇ : flat roof with air gap S ₈ : flat roof with water pond S ₉ : curved roof (with domes) S ₁₀ : curved ceiling (with vaults)
	Openings	S ₁₁ : glazing type: double glazing (6/13/6mm) + lowe coating + Argon gas S ₁₂ : glazing dimensions (WWR=12%) S ₁₃ : windows position (air control openings) S ₁₄ : shading devices
Local construction materials	Choice of the walls, roof, ground, and coating materials.	S ₁₅ : thick hollow brick walls, gypsum coating, roof reflective coating, and compacted earth ground.
Natural ventilation	Courtyard design	S ₂ – S ₃
Sun control	Shading devices	S ₁₄

At the level of Adaptation to the site, the first simulation scenario (S₁) involves the integration of vegetation around the house. Deciduous trees are selected for their ability to provide seasonal shade in the summer while allowing solar gain in the winter months when heating is required. In the simulation software, the trees are represented by "component blocks" with transmittance values that change seasonally to emulate the behavior of deciduous foliage.

Blocks simulating trees with heights of 4 to 6 meters and a square base with sides of 1.5 to 2 meters are added to the model. The solar transmittance value is set to 0.1 in the summer, to block sunlight, and to 0.7 in the winter to allow most sunlight to pass through during the cold months, which reflects the typical solar transmittance for deciduous trees (Kumakura et al., 2013). The trees are strategically placed on the east, west, and south sides of the house to reduce heat gain during the warmer months.

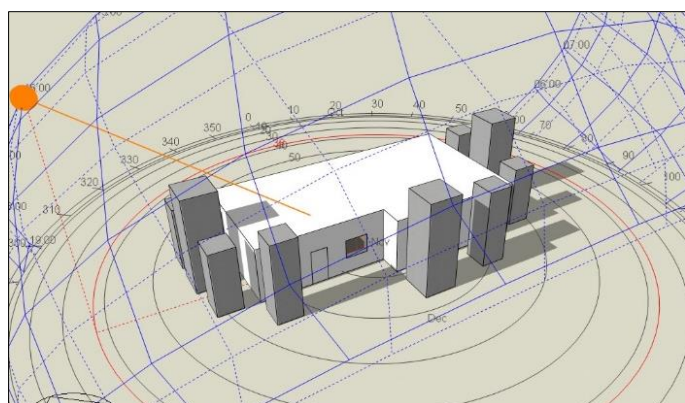


Figure 4.1. View of tree blocks added on the east, west, and south sides at 16:00

The following scenarios (S_2 and S_3) evaluate the efficiency of the courtyard design. The first house model is inspired by traditional Tunisian architecture with a central square courtyard (6.7 x 6.7 m). However, the second house model has a courtyard design with different characteristics: a long, rectangular courtyard (3.65 x 12 m) surrounded by spaces on three sides and enclosed by a 2-meter-high wall on the fourth side. In both designs, the living spaces face southeast, northeast, and northwest to minimize solar exposure, while the service spaces (S_2) face southwest.

The program in the two courtyard models is the same as in the base case, the same spaces are organized around the courtyards, and circulation between them is entirely outdoor. The courtyards are oriented along the northeast-southwest axis, perpendicular to the prevailing cold wind direction (northwest-southeast), allowing indoor spaces to benefit from cool breezes. The courtyard walls are 3.5 m high, resulting in a width-to-height ratio (WHR) between 1.5:1 and 2:1 for the S_2 , which is appropriate for the flat and lowland area. The large openings in the two courtyards' facades correspond to a window-to-wall ratio (WWR) of 30%, optimizing daylighting and taking advantage of the courtyard's microclimate.

Conversely, windows on the exterior facades are small to minimize heat gain and positioned high on the walls to enhance natural ventilation.

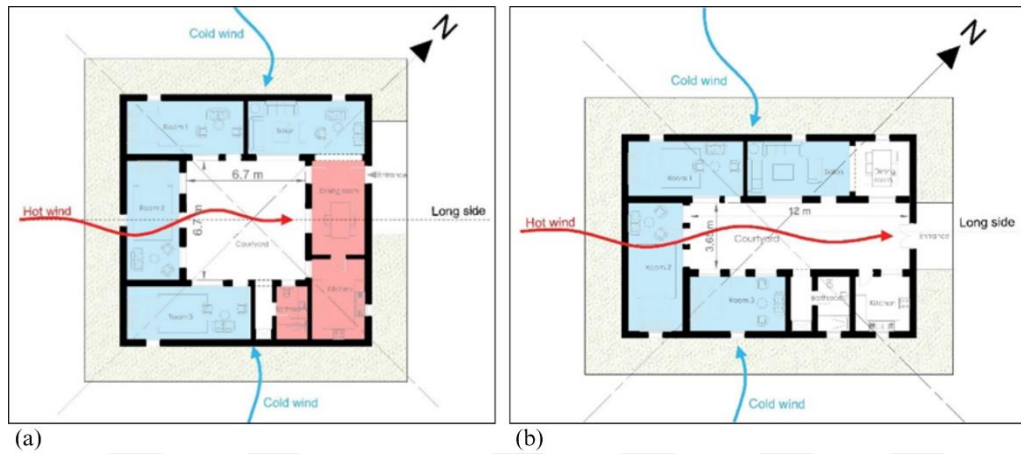


Figure 4.2. (a) House with square courtyard plan (S₂), (b) House with rectangular courtyard plan (S₃)

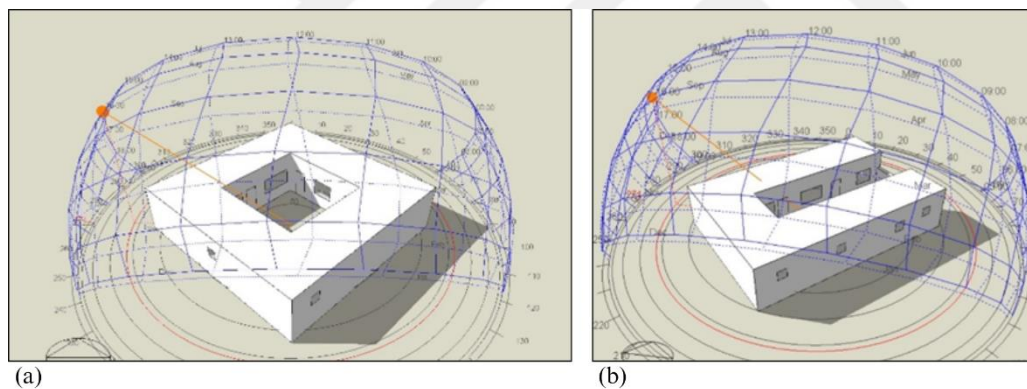


Figure 4.3. (a) House model with square courtyard (S₂) (a), (b) House model with rectangular courtyard (S₃)

Scenario S₄ involves testing the impact of thermal insulation on the building's thermal performance. Rock wool (RW) is selected due to its thermal effectiveness, cost efficiency, environmental sustainability, and wide availability. RW insulation will be installed on the exterior surfaces of both the walls and the roof. The existing double hollow brick walls will be replaced with 30 cm thick single hollow brick walls, eliminating the need for the air gap insulation system. The roof structure will remain unchanged, with RW insulation added on top to improve thermal resistance.

In Tunisian regulations, specific guidelines for thermal insulation implementation are absent. Therefore, regulations from other countries, tailored for hot-arid climates, are being considered. The Turkish Standard (Türk Standardı) TS 825 provides detailed recommendations for thermal insulation in buildings. This standard outlines maximum U-values for various building components in hot-arid climates where $5000 < \text{CDD}_{10^\circ\text{C}}^{14}$, these U-values serve as benchmarks for determining insulation thickness in different building elements (Ereser, 2022). Therefore, to assess thermal insulation efficiency, insulation thicknesses of 5.3 cm for the exterior walls and 8.1 cm for the roof have been implemented.

Table 4.2. The recommended maximum U-values for hot-arid climate regions in 2013 by the Turkish Standard

	Walls	Roof	Floor
U-value ($\text{W/m}^2\text{°C}$)	0.66	0.43	0,66
	5.3	8.1	5.3

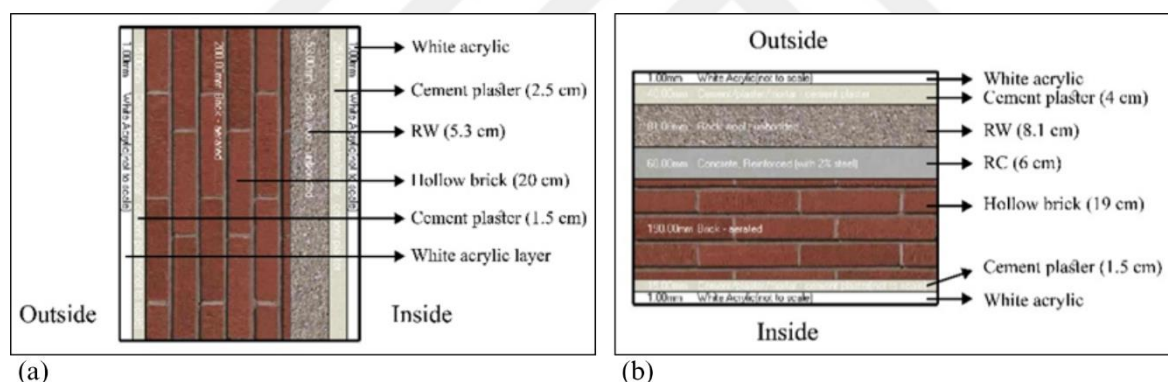


Figure 4.4. (a) RW insulation in the wall structure, (b) RW insulation in the roof structure

The next three scenarios evaluate the impact of exterior surfaces finishes in reducing heat gain. The first two scenarios focus on the effect of surface color, testing white (S_4) and grey (S_5) colors with smooth textures on the exterior walls and roof. The third scenario evaluates the effect of surface texture (S_6), keeping the white painting on the roof while adding brick cladding to the walls to create shaded areas and increase the building's thermal mass.

¹⁴ Climate classification based on **Cooling Degree Days (CDD)**, location with $5000 < \text{CDD}_{10^\circ\text{C}}$ has more than 5000 Cooling Degree Days when using a base temperature of 10°C .

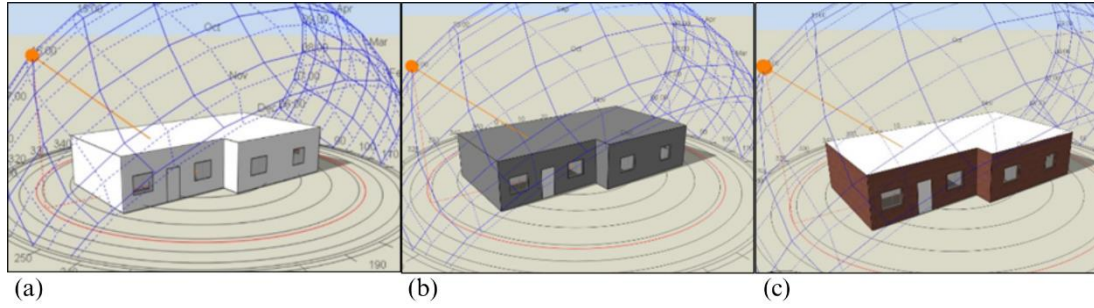


Figure 4.5. (a) 5th scenario, (b) 6th scenario, (c) 7th scenario

The next four scenarios (S_7 , S_8 , S_9 , and S_{10}) evaluate the roof design's impact on cooling the house. Two scenarios aimed to improve the thermal performance by changing the flat roof structure, and two scenarios aimed to change the roof shape. Scenario S_7 involves a flat roof design with an air gap (Figure 4.6. (b)), while scenario S_8 involves a flat roof design with a water pond (Figure 4.6. (a)). Technical changes were made to the flat roof structures to accommodate the creation of the air gap and the water pond.

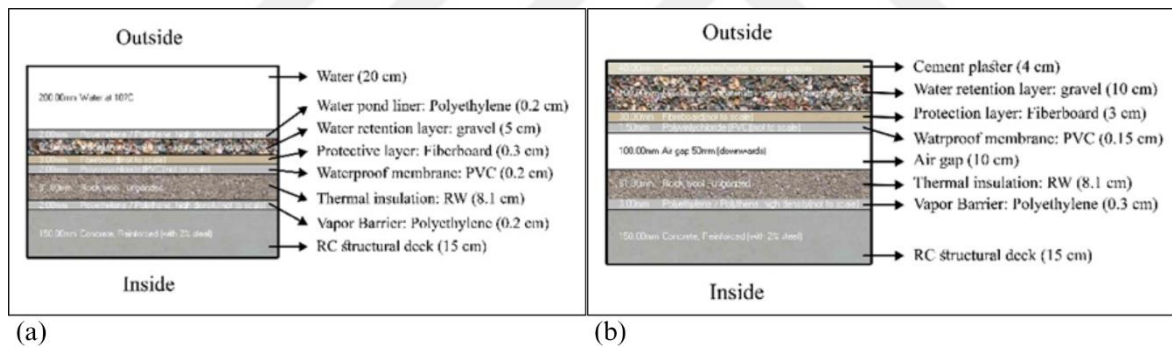


Figure 4.6. (a) Structure of flat roof with water pond (b) Structure of flat roof with air gap

Two roof shape scenarios are considered: the addition of domes (S_9) and the creation of vaulted ceilings (S_{10}). In scenario S_9 , the impact of domes on thermal performance and cooling loads is evaluated by adding domes to living spaces, including bedrooms and the salon. These domes, constructed using traditional brick techniques and a thick layer of plaster, are placed in a central position on top of the living spaces. Traditional hemispherical dome has a radius that is equal to its height, and a height that is one-third of the space's width ($H = W * 1/3$), ensuring that the dome's dimensions are both functional and proportional to the dimensions of the space it covers. Therefore, the dome over room 1 has a radius of 1 m, the domes over rooms 2 and 3 have a radius of 1.3 m, and the dome over the salon has a radius of 1.4 m (Figure 4.7. (a)). This addition increases the ceiling height of the

living spaces from 3 to 4 m for room 1, to 4.3 for rooms 2 and 3, and to 4.4 m for the salon. Scenario S_{10} considers multi-level residential buildings and suggests increasing the ceiling height by 1.2 m (Figure 4.7. (b)). This scenario involves the creation of a vaulted ceiling inside while maintaining a flat roof on the outside. This design allows the interior spaces to benefit from the curved ceiling shape, which enhances the stack effect and natural ventilation.

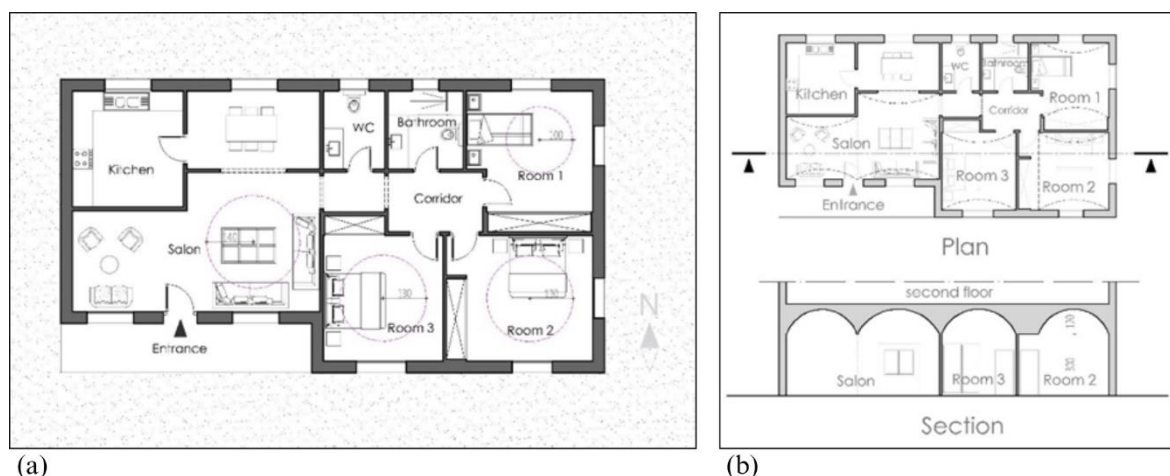


Figure 4.7. (a) S_9 added domes on plan, (b) S_{10} created vaulted ceilings on plan and section

Finally, in the last set of scenarios (S_{11} , S_{12} , S_{13} , and S_{14}) the glazing and shading devices of the openings are tested. In scenario S_{11} , the single glazings (6 mm) of the windows are replaced with double glazing (6/13/6 mm) to reduce heat gain. The thermal conductivity of the windows' glazings on the south and east facades is improved by adding low emissivity (low-e) coatings and argon gas between the glass panes. In scenario S_{12} , the glazing size impact on the building's thermal performance is evaluated by increasing the WWR from 8.83% to 12%. In scenario S_{13} , to enhance natural ventilation, air control openings are added above or below the existing windows to help control airflow indoors. Considering the prevailing wind direction (northwest-southeast) in the studied region, openings are placed below the windows on the north and west façades to serve as inlets. On the south and east façades, openings are added above the windows to serve as outlets. These air control openings are Vasistas windows with glazing that has the same characteristics as the main windows glazing, double glazing (6/13/6 mm). In room 3, which has only one exterior wall, both inlet and outlet openings are installed below and above the same window. In the salon,

where there is no window on the west façade, the opening is added to the wall at the same height as the window's lower edge (Figure 4.8).

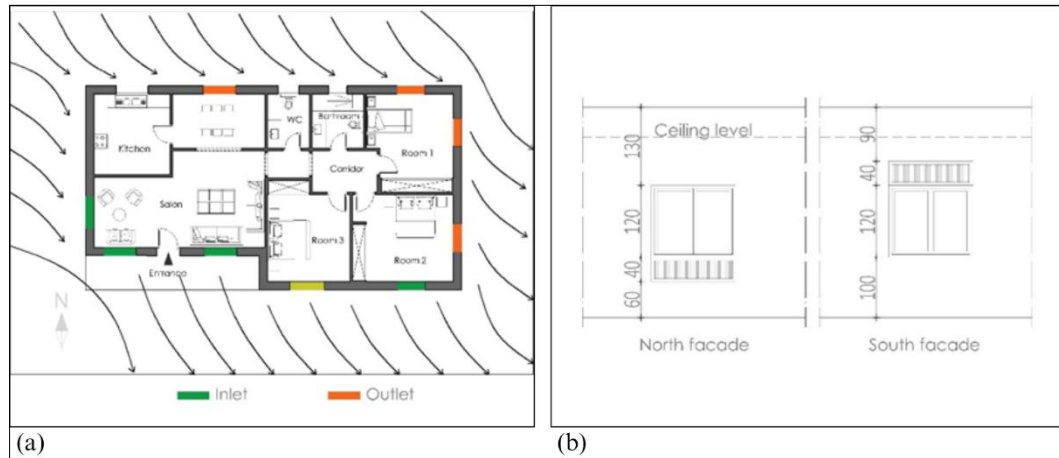


Figure 4.8. (a) Air control openings position according to prevailing wind direction, (b) Air control openings positions on facades

In scenario S_{14} , exterior shading devices, overhangs, and grids are added to the south and east windows to reduce the amount of solar gain. In the east façade, vertical grids were placed to block horizontal sun rays, in the south façade vertical grids and horizontal overhangs were placed to block the summer vertical sun rays in the afternoon, in the north façade no shading devices were added to profit from daylight.

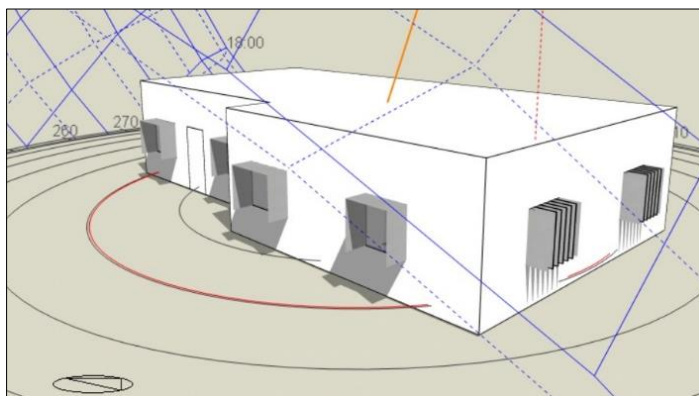


Figure 4.9. Shading devices added on the house model

For natural ventilation, the air change rates will be evaluated under the previous scenarios to determine which solutions are most effective at increasing air movement. Passive natural ventilation solutions are integrated into different scenarios from which the most efficient methods of promoting air movement within the building are determined. The simulation

results of the different previous scenarios will help identify design characteristics that maximize ventilation, improving indoor air quality and thermal comfort.

In scenario S₁₅, the choice of construction materials and techniques is optimized to enhance the building's thermal performance. The thermal efficiency of the exterior hollow brick walls is improved by increasing their thickness from 35 cm to 40 cm, adding thermal mass. The existing roof structure is retained, with a reflective coating added to the exterior surface to reflect solar rays. Additionally, a thick layer of gypsum plaster is applied to the outer surfaces of both the walls and the roof to further reduce heat gain. For the ground floor, a traditional method is employed: a layer of compacted earth and gravel is used to enhance thermal performance, topped with a waterproof membrane, a layer of cement, and ceramic tiles.

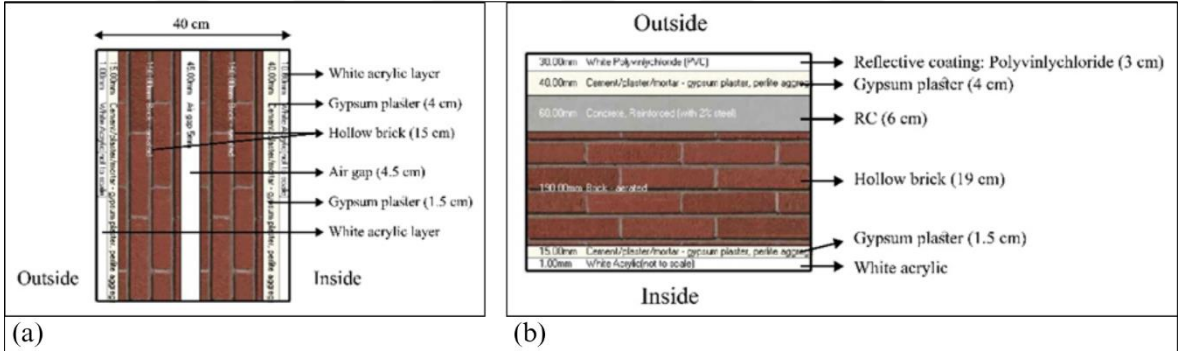


Figure 4.10. (a) Wall structure, (b) Roof structure

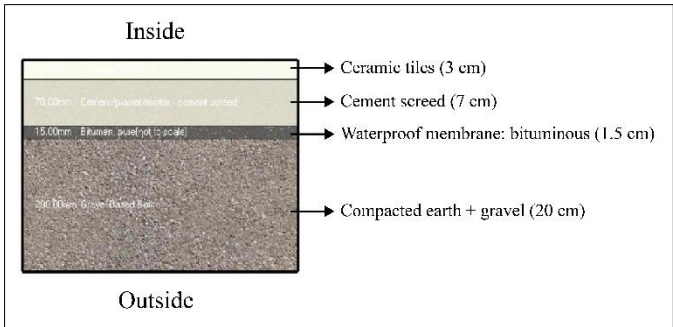


Figure 4.11. Ground floor structure

4.2. Scenarios results and discussion

This part of the study presents a comprehensive analysis of the energy consumption for cooling, comparing the base case model with the different models implementing the passive cooling techniques. The effectiveness of these techniques, including courtyard designs, enhanced glazing, shading devices, etc., is evaluated by comparing their cooling energy consumption to the base case. Key metrics such as cooling energy consumption, total energy consumption per area, relative humidity levels, and air change rate are assessed for each scenario. The results, detailed in the comparative table below, highlight the energy savings and efficiency of each passive cooling technique, providing valuable insight into their potential to reduce energy consumption and improve passive cooling in buildings.

Table 4.3. Comparative table of scenarios results

Scenarios	Annual cooling energy (kWh)	Annual cooling energy per area (kWh/m ²)	Total energy per area (kWh/m ²)	Annual cooling energy reduction (%)
Base case (S ₀)	3825.96	53.50	172.27	-
S ₁	3088.16	-	163.48	19.28
S ₂	1359.00	16.21	177.67	69.70
S ₃	1351.17	18.05	183.06	66.26
S ₄	2193.68	-	149.73	42.66
S ₅	2250.83	-	151.65	41.16
S ₆	2056.33	-	150.90	46.25
S ₇	1936.90	-	150.63	49.37
S ₈	1599.93	-	162.69	58.18
S ₉	1545.61	-	143.47	59.60
S ₁₁	1178.21	-	139.02	69.2
S ₁₂	1527.98	-	136.39	60.06
S ₁₃	1196.47	-	138.78	68.73
S ₁₄	974.95	-	145.69	74.51

According to the comparative table, the results demonstrate a significant impact of the adopted passive cooling techniques on reducing cooling loads. While some scenarios show a slight increase in heating loads, explained by the increase in total energy consumption per area, the primary focus remains on the effectiveness of these passive strategies in reducing cooling loads. The percentage reduction in cooling loads, which varies across different passive solutions, directly reflects the decrease in heat gain achieved by each technique. This highlights the varying efficiency of each passive cooling solution in reducing the need for mechanical cooling, ultimately contributing to improved energy efficiency in buildings.

In the first scenario, the introduction of deciduous trees around the house led to a notable reduction in cooling loads, achieving a decrease of 19.28%. This significant improvement is due to the shading provided by the trees, which minimizes direct solar radiation and heat gain within the building. However, a slight reduction in ventilation rates was observed, from 1.12 air changes per hour (ACH) to 1.08 ACH during the peak summer months of July and August. This decrease is likely caused by the trees' attenuation of wind flow around the house. Additionally, the presence of deciduous trees resulted in a minor increase in relative humidity (Figure 4.12), particularly noticeable in September, due to the evapotranspiration process where trees release moisture into the air. Overall, while the deciduous trees significantly enhance cooling efficiency, they also introduce slight changes in ventilation and humidity levels.

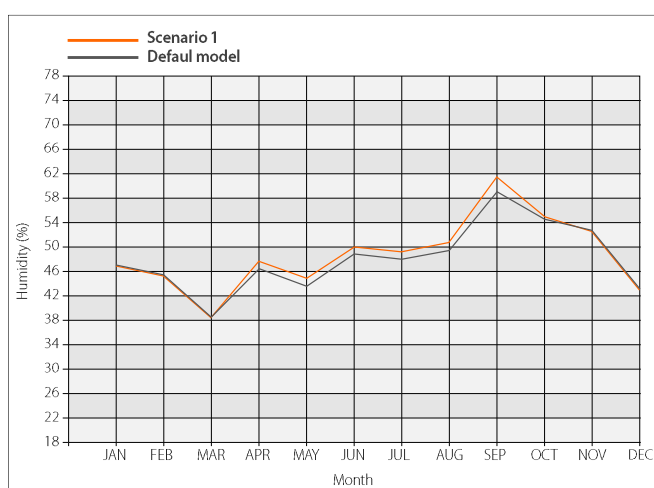


Figure 4.12. Humidity levels comparison

In the second and third scenarios, the implementation of courtyard designs resulted in a substantial decrease in cooling loads, underscoring the effectiveness of this passive cooling design. The comparison, based on cooling energy consumed per area for greater precision, accounted for the larger areas of the courtyard houses compared to the default model. The square courtyard (6.7 x 6.7 m) saw an impressive 69.70% reduction in cooling loads, while the rectangular courtyard (6 x 8 m) achieved a 66.26% reduction. In both cases, the courtyard house design performed exceptionally well in passively reducing heat gain by more than half, however, the square courtyard performed better. According to the graph below (Figure 4.13. (a)), in cold months, the courtyard models exhibit lower air change rates compared to the default model, however, from June to September, the courtyard models begin to exhibit higher air change rates, with peaks around June and July, achieving 1.55 ACH in S₂ and 1.62 ACH in S₃ compared to the default model's 1.12 ACH. Consequently, the air change rate in the courtyard models remains elevated throughout the summer months, helping to passively cool the house. The long rectangular courtyard performed better in natural ventilation because it provides longer surfaces exposed to cool breezes. In addition, the graph below (Figure 4.13. (b)) shows that the courtyard models consistently maintain higher relative humidity levels (52-69%) throughout the year compared to the default model (39-59%) indicating a more balanced and comfortable indoor climate.

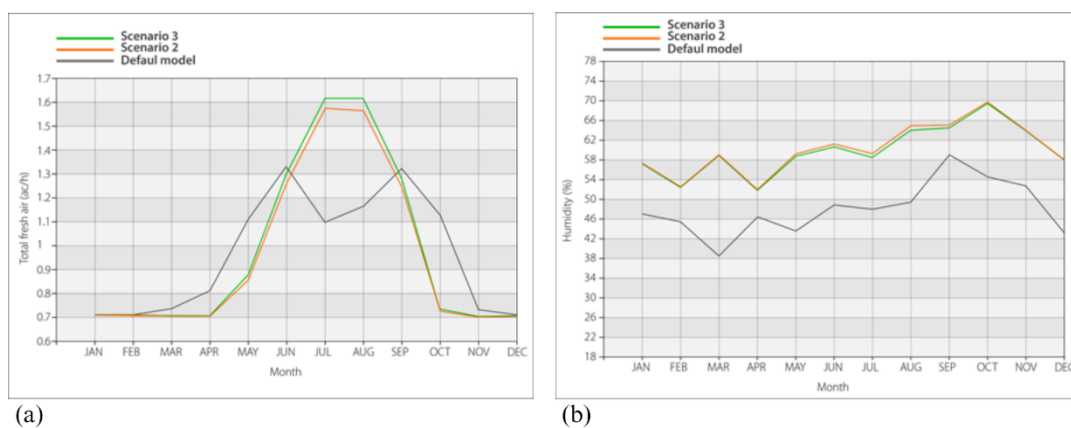


Figure 4.13. (a) Air change rates comparison, (b) Humidity levels comparison

The increase in total energy consumption per area for courtyard houses is attributed to their larger sizes, which necessitates more energy for additional uses such as lighting and heating. This is a logical outcome, as the reduction in heat gain from the courtyard design naturally leads to an increase in heating loads during cooler periods. However, the overall benefits of

reduced cooling loads and enhanced natural ventilation underscore the effectiveness of courtyard designs in improving energy efficiency and indoor comfort.

In the fourth scenario, the addition of rock wool insulation to the walls and roof of the default model significantly contributed to reducing heat gain. This enhancement in the building envelope's thermal performance resulted in a notable decrease in annual cooling loads by 42.66%. The improved insulation effectively minimized heat transfer through the walls and roof, maintaining a more stable indoor temperature and reducing the need for mechanical cooling. Consequently, the total energy consumption per area also saw a reduction, decreasing from 172.27 kWh/m² to 149.73 kWh/m². Moreover, the thermal insulation contributed to reducing both cooling and heating loads, highlighting its dual benefits. The annual energy required for heating decreased from 2199.50 kWh to 1712.51 kWh, indicating the insulation's effectiveness in maintaining indoor comfort across seasons. Thermal insulation emerges as an optimal solution for reducing heat gain in summer without increasing heating loads in winter, promoting a more sustainable and cost-effective approach to managing indoor climate conditions year-round.

After maintaining the rock wool insulation, in the three Scenarios S₄, S₅, and S₆, changing the colors and textures of the exterior envelope surfaces did not have a significant impact on reducing heat gain (Figure 4.14). Changing the surface color from white to grey (S₅) resulted in a negligible increase in cooling loads by 57.15 kWh, indicating that white surfaces are slightly more effective at reflecting solar radiation. On the other hand, the addition of brick cladding (S₆) to the walls showed a marginally better impact, reducing cooling loads by 137.35 kWh. This improvement can be attributed to the brick texture, which creates shaded zones on the surface, and the added thermal mass provided by the 10 cm thick brick cladding.

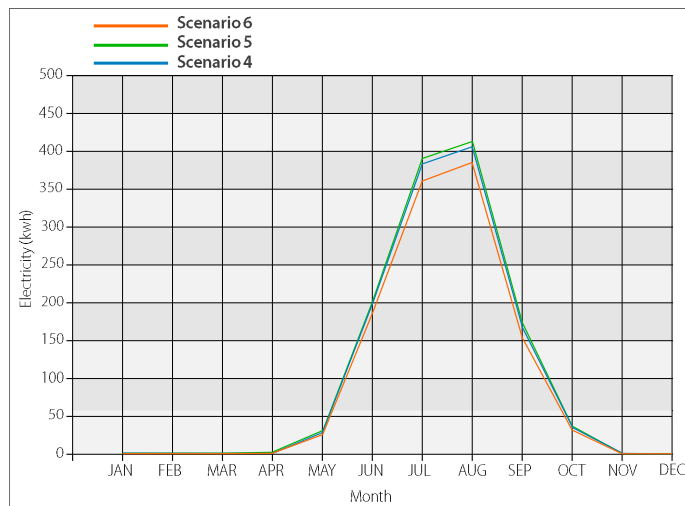


Figure 4.14. Cooling energy consumption comparison

Despite these minor variations, the overall influence of external surface texture and color on heat gain and, consequently, on energy consumption for cooling, remains minimal. This suggests that while surface characteristics (color and texture) can contribute to thermal performance, they do not play a pivotal role in significantly reducing heat gain in comparison to other passive cooling strategies.

With the brick cladding on the walls and the white coating on the roof, the enhanced roof designs in scenarios S_7 , S_8 , and S_9 significantly impacted cooling loads. The flat roof with an air gap (S_7) showed a modest improvement in thermal performance, reducing cooling loads from 2056.33 kWh to 1936.90 kWh. The flat roof with a water pond (S_8) and the domed roof (S_9), however, demonstrated more substantial impacts, reducing cooling loads to 1599.93 kWh and 1545.61 kWh, respectively. The flat roof with an air gap proved less efficient in reducing heat gain. In contrast, the traditional dome design had a notable effect on passive cooling, significantly decreasing heat gain. The total energy consumption per area decreased for both the flat roof with an air gap and the domed roof, however, the total energy consumption per area increased for the flat roof with a water pond, which can be attributed to the increased heating loads due to the reduced heat gain during winter. Regarding natural ventilation (Figure 4.15 (a)), the domed roof was the most effective, with the dome's curved shape enhancing air circulation. For humidity levels (Figure 4.15 (b)), the flat roof with a water pond performed best, increasing the humidity level thanks to the presence of water within the roof structure. Conversely, the domed roof exhibited the lowest humidity level among the three scenarios.

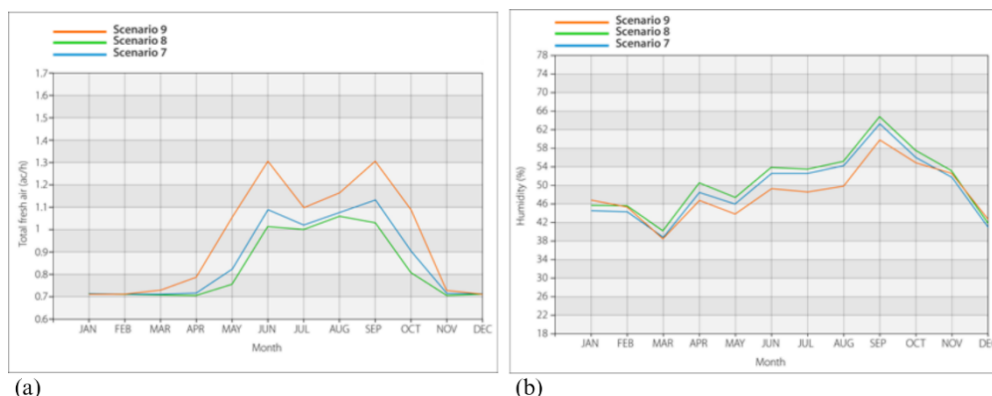


Figure 4.15 (a) Air change rates comparison, (b) Humidity levels comparison

This analysis highlights how different roof designs vary in their effectiveness in reducing cooling loads, improving natural ventilation, and regulating indoor humidity levels. Among these designs, the domed roof stands out as the most efficient overall, significantly reducing cooling loads and improving natural ventilation. However, by incorporating an air vent at the top of the dome and introducing a water source underneath, the design could further enhance natural ventilation and humidity levels. This adjustment is particularly beneficial in hot-arid climates, where increasing humidity levels as recommended in the design guide would increase its effectiveness.

In the final set of scenarios, which included the domed roof design, changes to the glazing type, dimensions, and position, as well as the addition of shading devices, significantly impacted cooling loads. In scenario S_{11} , changing the glazing type reduced cooling loads to 1178.21 kWh and decreased the annual total energy use per area to 139.02 kWh/m². The enhanced glazing reduces heat transfer year-round: in winter, it minimizes heat loss and thus lowers heating loads, while in summer, it decreases heat gain and thus reduces cooling loads. This demonstrates the superior thermal performance of double-glazed windows over single-glazed alternatives and highlights the improved insulating properties of low-e coatings and argon gas, which effectively minimize heat transfer through the windows. In scenario S_{12} , increasing the glazing size led to a rise in cooling loads to 1527.98 kWh and a reduction in annual total energy use per area to 136.39 kWh/m². The reason for this is that the larger glazing surface allows for greater heat gain in winter, thus lowering heating loads, but negatively impacts cooling loads in summer by allowing more heat to enter the space. In scenario S_{13} , the addition of air control openings above and below the windows did not impact cooling loads. Compared to scenario S_{11} , changes in the annual cooling loads, total

energy use per area, and reduction in cooling loads were negligible. In terms of natural ventilation, however, the graph below shows that the addition of air control openings slightly enhanced the air change rate inside the house for most months of the year (from March to October), except during the colder months.

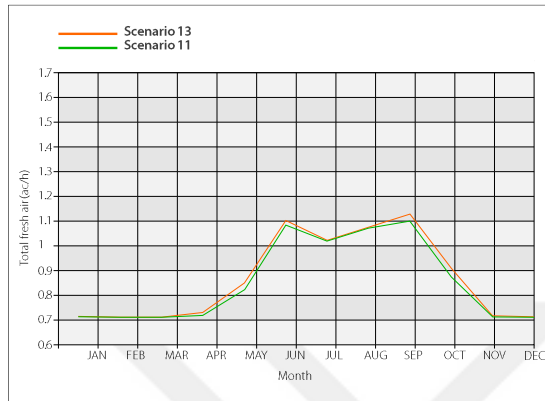


Figure 4.16. Air change rates comparison

Finally, the introduction of shading devices (S_{14}) further reduced the cooling loads to 974.95 kWh and increased the total energy consumption per area to 145.69 kWh/m². This slight increase can be attributed to the fact that the shading devices partially block solar heat gain during colder months, which increases heating demands. To optimize energy efficiency, adjustable or retractable shading devices are recommended, allowing sunlight to enter in winter for passive heating benefits while maintaining their role in reducing cooling loads in summer. After applying scenarios S_4 , S_5 , S_6 , S_7 , S_8 , S_9 , S_{10} , S_{11} , S_{12} , S_{13} , and S_{14} , the overall reduction in cooling loads due to the enhanced building envelope and glazing is an impressive 74.51%. Thanks to the strategic implementation of passive cooling solutions, this significant improvement led to a decrease in cooling loads, dropping from 3825.96 kWh in the default model to 974.95 kWh, highlighting the effectiveness of these enhancements in improving energy efficiency.

The conducted simulation tests demonstrated the efficiency of various passive cooling techniques and provided detailed insights into their operational mechanisms and impacts on building performance. Adding vegetation, particularly deciduous trees, has proven to significantly enhance building thermal performance, as demonstrated in S_1 . The inclusion of trees resulted in a notable 19.28% reduction in cooling loads, highlighting their effectiveness in mitigating heat gain and lowering energy consumption. Beyond their cooling benefits,

trees also play a crucial role in humidifying the air, which is a vital characteristic in hot-arid climates. Additionally, trees act as natural windbreaks, attenuating the impact of strong winds, particularly hot winds during summer months. Vegetation extends its benefits beyond individual buildings to the urban scale, offering solutions to combat climate change by reducing urban heat islands and improving air quality. It serves not merely as a tool for building, but as an integral natural component essential for sustainable urban development. Embracing vegetation, therefore, not only reconnects buildings with nature but also ensures permanently improved living conditions and environmental resilience.

The Courtyard House, a traditional design, has demonstrated remarkable thermal performance in a contemporary context. Simulation results underscore its effectiveness, with significant heat reduction achieved even with a simplified version. The data shows that central courtyard designs can reduce cooling demand by nearly 70%, emphasizing the importance of integrating this design into modern architectural practices. Even without advanced cooling technologies such as thermal insulation and enhanced glazing, the courtyard design showed impressive results and therefore warrants serious consideration and attention. Coupled with the courtyard design, further passive cooling techniques could potentially reduce cooling energy demands to near zero, closely aligning with the goals of sustainable architectural design. Particularly in hot-arid climates, such as Kairouan, the courtyard design proved invaluable for cooling efficiency. It facilitates passive ventilation, ensuring continuous air circulation without the noise and privacy concerns often associated with modern home designs. In addition, the courtyard design maintains comfortable humidity levels, especially during the driest days of summer. The key parameters to ensure the efficiency of the courtyard design are the central position and proportional dimensions. In the case of the long rectangular courtyard, the thermal performance was lower because it did not follow the WHR regulation mentioned in the design guide. In short, the courtyard design offers an optimal solution with multiple benefits: stable indoor temperatures, improved air circulation, and comfortable humidity levels, all achieved with minimal energy consumption. Its integration into modern building practices represents a significant step toward sustainable and climate-responsive architecture. The courtyard tested in this study is a central open-air courtyard suitable for low-rise residential buildings. However, for high-rise residential buildings, designing an atrium is recommended to passively contribute to cooling the building.

Thermal insulation is a key tool for significantly improving thermal performance. In Tunisia, where buildings predominantly rely on mechanical cooling, thermal insulation achieves a remarkable 42.66% reduction in cooling energy demand, while also providing a reduction in heating energy consumption. This dual benefit highlights its critical role in ensuring stable indoor temperatures throughout the year. Thermal insulation is not only optimal but mandatory for maintaining consistent indoor thermal conditions, making it a fundamental component of energy-efficient building design.

Architectural details, such as the finish of exterior envelope surfaces, may provide only a modest reduction in cooling demand, but their consideration is critical because of their broader impact, especially at the urban scale. These details are integral parts of a holistic design approach that works in synergy with other architectural features. Traditional finishes such as whitewash or brick cladding not only contribute to the passive cooling approach but also offer environmental benefits by being less intrusive and more cost-effective in the long term than modern industrial cladding. Their inclusion therefore supports a sustainable and economically viable approach to building design.

The simulation results demonstrate that roof design is a critical factor in the thermal efficiency of a building. Modifying the flat roof structure has a significant impact on cooling loads, depending on the materials and layers used. Adding an air gap provides modest improvements in reducing cooling loads and increasing natural ventilation. While a flat roof with a water pond effectively reduces cooling loads and increases humidity, it also results in higher heating loads. Implementing a water pond is more complex and costly, and roof access is essential in Tunisian dwellings, making this option less practical. In contrast, changing the shape of the roof by adding domes or vaults over living spaces significantly reduces cooling loads. Despite the lack of insulation in the curved roof structure, the domes and vaults perform well thermally due to their shape, which provides partial shade throughout the day. The curved roof shape naturally improves ventilation without the need for additional vents. Domes and vaults are simple and cost-effective to construct, making them an optimal solution for maintaining comfortable indoor conditions. The only drawback is a reduction in humidity levels, which can be mitigated by adding indoor water sources. Each roofing solution has its advantages and disadvantages; however, the traditional curved roof remains the most effective and well-adapted to the local climate, balancing practicality, cost, and thermal performance.

Enhanced glazing solutions, such as multi-pane glazing, low-e coatings, and argon-filled gaps, consistently demonstrate a positive impact on reducing heat gain and, consequently, cooling loads. These advanced glazing technologies improve thermal performance by minimizing the amount of heat entering through windows, resulting in more efficient cooling. Increasing the opening size improved thermal performance during the cold months, but had a negative effect during the hot summer months. Therefore, for residential buildings in hot-arid climates, it is recommended to maintain a lower window-to-wall ratio (WWR) of about 10% for better thermal performance. If an increase in WWR is necessary, it should be accompanied by the use of technologically advanced types of glazing, such as electrochromic and thermochromic glass, which can introduce cost constraints. The position of the air control openings does not significantly affect the passive cooling of the house; however, it does slightly improve airflow. This modest impact on natural ventilation is due to the presence of internal separation walls, which block the benefits of the prevailing wind's varying pressures. Therefore, in addition to opening the doors, it is recommended to create ventilation openings in the internal separation walls to facilitate better airflow. The addition of shading devices further enhances the openings' performance by significantly reducing heat gain. However, it is advisable to use shading devices primarily during the hotter months to ensure that they do not block beneficial solar gain during colder periods, which helps with passive heating. Openings play a critical role in the overall thermal performance of a building envelope, as they often represent a significant source of heat gain. Therefore, the implementation of technological improvements in windows is essential to achieve better thermal efficiency. The simulation results clearly show that the more advanced technological solutions are applied to the glazing, the greater the improvement in thermal performance. This highlights the importance of integrating high-performance glazing and strategically placed openings and shading devices into building designs to optimize energy efficiency and indoor comfort.



5. CONCLUSION

This study investigated the effectiveness of passive cooling techniques in architectural design for hot-arid climates, with a particular focus on Tunisia. Traditional passive cooling techniques have proved effective in providing indoor comfort and significantly reducing energy consumption for cooling demands. Historical and contemporary evidence supports the resilience and practicality of these techniques. The analysis of traditional Tunisian architecture revealed that vernacular designs inherently incorporated optimal solutions to address climate challenges. Features such as courtyards, thick building envelopes, and strategic natural ventilation enabled traditional buildings to maintain comfortable indoor environments with zero energy consumption and carbon dioxide emissions. Deeply rooted in local climates and cultural practices, these solutions provided valuable insights for modern sustainable designs. The global movement to revive and incorporate vernacular architecture principles, particularly in terms of passive cooling, into modern buildings, demonstrated its effectiveness in creating sustainable and climate-responsive designs. Modern architectural projects increasingly demonstrated that passive cooling techniques were not only feasible in contemporary buildings but also highly adaptable to new technologies. By integrating strategies such as natural ventilation, high thermal mass envelope, and strategic shading with advanced building systems, architects significantly enhanced energy efficiency and indoor comfort. This blend of traditional passive methods with advanced technology reduced reliance on mechanical cooling, leading to substantial energy savings and lower carbon footprints.

The integration of passive cooling techniques into architectural design, as demonstrated through simulation tests, has proven to be highly effective in reducing cooling loads and enhancing thermal performance. Traditional elements such as courtyards and domes, as well as the incorporation of vegetation, further emphasize the importance of climate-responsive design. Advanced solutions, including improved glazing, shading devices, and innovative roof designs, have proven highly effective in reducing cooling loads and improving thermal performance. Thermal insulation proved to be a critical component in maintaining stable indoor temperatures, thereby significantly reducing energy consumption. The simulation results consistently highlighted the positive impact of these strategies, demonstrating their feasibility and adaptability in modern architecture. Traditional passive cooling techniques,

when strategically combined with advanced techniques, produce impressive results in reducing heat gain. By using these methods, buildings can achieve near-zero cooling energy requirements, ensuring a comfortable indoor environment while promoting sustainability and energy efficiency. Traditional techniques in particular stand out as the most effective solutions, combining cost-effectiveness with exceptional thermal performance that is well suited to the local climate. Innovations such as thermal insulation, enhanced glazing, shading devices, etc. can be seamlessly integrated with traditional passive strategies, enhancing their effectiveness and relevance in today's architectural context. This adaptability underscores the potential for passive cooling methods to contribute to sustainable building practices in both new construction and renovation.

The design guide developed in this research aims to equip designers with effective passive cooling strategies for their new projects. By integrating these strategies at various design levels, architects and builders can achieve energy-efficient buildings that maintain comfortable indoor conditions in hot-arid climates. This guide will also serve as a source of inspiration for governmental organizations to establish regulations tailored to the specific challenges imposed by hot-arid climates. By promoting the construction of buildings that are adapted to local climatic conditions, the design guide aims to reduce energy consumption and minimize carbon emissions in the building sector. Furthermore, this design guide represents a pivotal step towards transitioning the building sector from its current architectural practices to a more sustainable future. It provides a roadmap for overcoming existing building constraints and embracing innovative, eco-friendly solutions, ultimately fostering a built environment that harmonizes with the natural climate while promoting sustainability. The integration of passive cooling techniques is essential to mitigate the urban heat island effect and promote a more sustainable urban environment. By reducing overall heat absorption and enhancing natural ventilation, this approach significantly reduces the need for mechanical cooling systems, thereby reducing energy consumption and greenhouse gas emissions.

Limitations:

There are several constraints on the practical implementation of passive cooling strategies. One important constraint is site-specific conditions such as orientation, local climate, and the surrounding environment. For example, urban areas with limited space may not fully

benefit from passive cooling strategies such as planting vegetation or adopting the courtyard house design. The changing climate data also poses a challenge to the efficiency of passive cooling techniques. As climate conditions evolve, the performance of these strategies can fluctuate. Techniques that are effective in the current climate may need to be adapted or re-evaluated to respond to more extreme temperatures or changing weather patterns. In addition, the integration of traditional passive cooling techniques into modern architecture may face resistance due to cultural or aesthetic preferences. Some stakeholders may prefer contemporary designs that do not easily accommodate features such as courtyards or domed roofs.

Recommendations:

Implementing passive cooling techniques depends on various project details, such as the natural characteristics of the site, project surface area, program requirements, and budget. Therefore, selecting the appropriate passive cooling solution must consider all these factors.

Integrating traditional techniques with modern solutions is crucial for achieving optimal energy outcomes. Continuous monitoring of the performance of passive cooling techniques in buildings is essential to update strategies based on new research and technological advancements, ensuring ongoing optimization and improvement of thermal performance. To ensure the long-term effectiveness of certain passive cooling solutions such as water ponds or green roofs, it is critical to implement regular maintenance practices. Consistent maintenance is necessary to prevent performance issues caused by neglect, weathering, or deterioration. Establishing a maintenance schedule and addressing any issues promptly will help preserve the benefits of these advanced techniques and maximize their effectiveness over time.

Budget can be a significant constraint, therefore further research should establish a balance between the cost, efficiency, and payback period of passive cooling techniques. This will help identify the most cost-effective solutions and encourage investments in energy efficiency improvements.

Advocacy for policies and incentives that support passive cooling strategies in building design is necessary. Without government regulations and support from non-governmental

organizations, promoting the construction of energy-efficient buildings becomes challenging and often unattainable. Strong recommendations for such support are crucial to drive progress in this area.

Furthermore, providing training for architects, builders, and planners on the benefits and implementation of passive cooling techniques is essential, and raising societal awareness and promoting a culture of sustainable building practices is even more important to encourage wider adoption of these strategies.



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Gazili olmak ayrıcalıktır