TOWARDS HIGH-PERFORMANCE FACADE DESIGN
AN OPTIMIZATION APPROACH FOR ENERGY EFFICIENT RESIDENTIAL BUILDING

A dissertation presented
by
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Supervised by

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Abstract

Preserving the environment is the most important issue of today’s world in which human being has to reduce energy consumption. Over the last years, building energy efficiency has worldwide considerable interest from the experts and researchers, since buildings are the largest consumer of the final energy consumption.

During the last decade in Algeria, housing construction issues became one of the development priorities. Policies and strategies were set up to tackle the housing demand and to reorganize the sprawling slum areas, providing social houses for the low-income families, the design and the constructional techniques of these buildings, are operated with over-shorter project planning time, it is striving to minimize design costs, neglecting the climate conditions and the sustainability concept. As a result, it has been reported that 37% of the overall energy consumption was attributed to residential buildings.

Otherwise, the architectural facade design, technologies, and strategies, are the most significant contributors to the energy performance and the comfort parameters of the buildings. Thus, the main target of this research is investigating the possibilities of enhancing the indoor thermal comfort, visual comfort, and indoor air quality with less energy consumption through the building facade components, presenting a holistic evaluation and optimization approach. Besides, to provide an adaptive facade design to the local environment, the Algerian hot and dry climate zone was the study context of this research. To fulfill the set of objectives, this research applied an empirical methodology, using a dynamic simulation through Vi-suite add-on for Blender 3D that controls the external application Energy Plus and Radiance to conduct energy performance analysis. The Validation of the modeling and simulation with this software is affected based on real field measurement to determine the error percentage that can occur in the simulation. Furthermore, The existing residential building façade design in Algeria is diagnosed in terms of energy consumption, thermal comfort, visual comfort, and indoor air quality. Also, various facade alternative configurations have been evaluated to define optimum design solutions, for this step a generic virtual model has been created. The optimal combined solutions were applied in a typical existing residential building.

Finally, As energy and other natural resources continue to be depleted, this study contributes to the development of high energy-efficient residential building through the performance facade design parameters that maintain indoor environment satisfaction while consuming fewer of these resources.

Keywords: Facade, Residential Building, Energy optimization, indoor comfort, Hot dry climate, visual comfort, thermal comfort, Energy Plus, Vi-suit

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1. INTRODUCTION

1.1 Background of research

Human activities since the beginning of the industrial revolution in the mid-20th century caused global warming which driving climate changes impacting natural systems on all continents and across the oceans. In addition, these activities increase the greenhouse emissions results from the increased use of fossil fuels in transportation, manufacturing, and communications (U.S. Global Change Research Program, 2009). Furthermore, buildings provide shelter that facilitates our activities and interactions. The method by which we apply technologies in the design and construction process of buildings has direct implications for the amount of energy consumed, globally it is considered the largest consumer of the final energy consumption, it accounts for more than 36% of global final energy use and 39% of energy-related CO2 emissions in 2018.("Global Status Report for Buildings and Construction," 2019). Thus, the issue of the environment resources preservation is considered an important priority of today's world in which human being has to reduce energy consumption. In this context, initiatives and actions are set by different countries, it contributes to the environmental protection, driving strategies and assessment methods for the building stock to achieve the objectives in terms of energy efficiency and climate change. (Díaz López et al., 2019).

During the last decade in Algeria, housing construction issues became one of the development priorities. Policies and strategies were set up in order to tackle the housing demand and to reorganize the sprawling slum areas, providing social houses for the low-income families who live there (Saada, n.d.), (Hadjri, 1992). The design and constructional techniques of these residential buildings, which operated with over-shorter project planning time, it is striving to minimize design costs, neglecting the local climatic conditions, hence, the internal environment of these buildings is artificially controlled to achieve occupant's desire of comfort, and this necessitates a considerable energy consumption. However, performing buildings that maintain occupant's comfort with less energy consumption requires an architectural design that uses appropriate technologies and design principles which respond and adapt accurately to the local climatic conditions (Semahi et al., 2019). Climate adaptive facade is one of the promising concepts that play a key role in the planning of buildings with optimized energy use, it behaves as our third skin, the outside of building fulfills similar to those of human skin and or clothing. This means that facades are not simply barriers between interior and exterior; rather, they are building systems that create comfortable spaces by actively responding to the building’s external environment, and significantly reduce buildings’ energy consumption (Aksamija, n.d.). However, in the Algerian building sector, there is a lack of researches on optimizing the building facade design, and more research is needed on synergies between all the facade components to create energy-efficient buildings through the facade components. Research context

1.2.1 *geographical and climatic conditions*

Geographical and Climatic conditions represent the starting point of the climate-adaptive design for any building, whereas understanding these conditions is crucial for the selection of appropriate design approaches to improve building energy efficiency. The main research context is focused on Algeria. In this section, the current status of the country, geographical, and climatic conditions are introduced.

Algeria is a country located in North Africa, it is the tenth-largest country in the world and the largest in Africa, it has a vast area of 2.381.741 km². With an estimated population of over 42 million. The northeast has a border with Tunisia, the east with Libya, the west with Morocco, the southwest with the Western Saharan territory, Mauritania, and Mali, the southeast with Niger, and the north with the Mediterranean Sea. *Figure.1.*

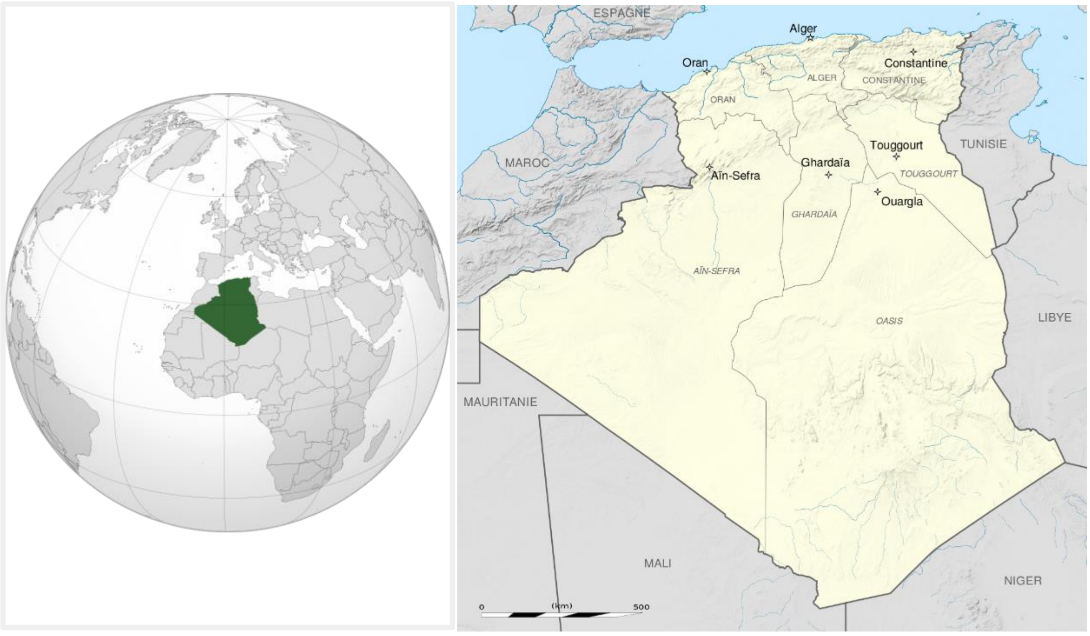


Figure 1.The location of Algeria in the world

The climate of Algeria is varied because the country has a very large area, the northern part has a Mediterranean climate (Classification of Köppen Csa), while the rest of the country has a majority desert climate (Köppen classification BWh). However, between these two major types of climates, there are transitional climates, notably the semi-arid climate (Classification of Köppen BSk) which corresponds to a Mediterranean climate with a dryness no longer limited only to the summer season but also in the rest of the year, it characterizes also by a Mediterranean climate with mountain influences, a little more continental. Nevertheless, Algeria is a country in the subtropical zone where the prevailing climate is hot and dry. *Figure.2.*

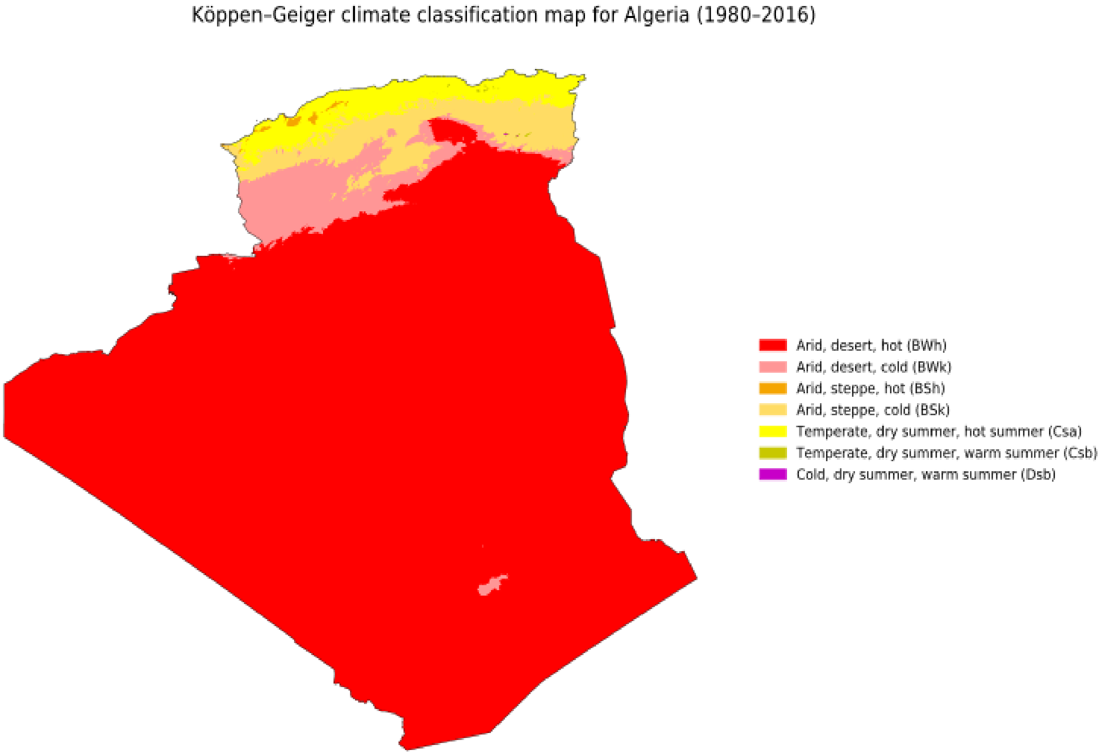


Figure 2. Koppen map climate classification of Algeria (Kottek et al., 2006)

Furthermore, depending on (Ould Henia 2003) more than 85% of Algeria's total surface area is characterized by a hot and dry climate, subdivided into three summer climate zones (E3, E4, and E5) and a winter climate zone (divided into three sub-zones). zones H3a, H3b, and H3c). All these regions are influenced by altitude. *Figure.3.* Illustrate the different zonings as follows: Zone E3 (Presaharan and Tassili), the summers are very hot and very dry, the E4 zone of the Sahara, corresponding to summers more difficult than those of E3, The zone E5 is the hottest in Algeria, Zone H3a (Presaharan), with an altitude of between 500 and 1000 meters, is characterized by very cold winters at night compared to the day, Zone H3b (Sahara), altitude between 200 and 500 meters, the winters are there less cold than those in zone H3a, Zone H3c (Hoggar), with an altitude above 500 meters, with severe winters similar to those of zone H3a, but which persist even during the day.

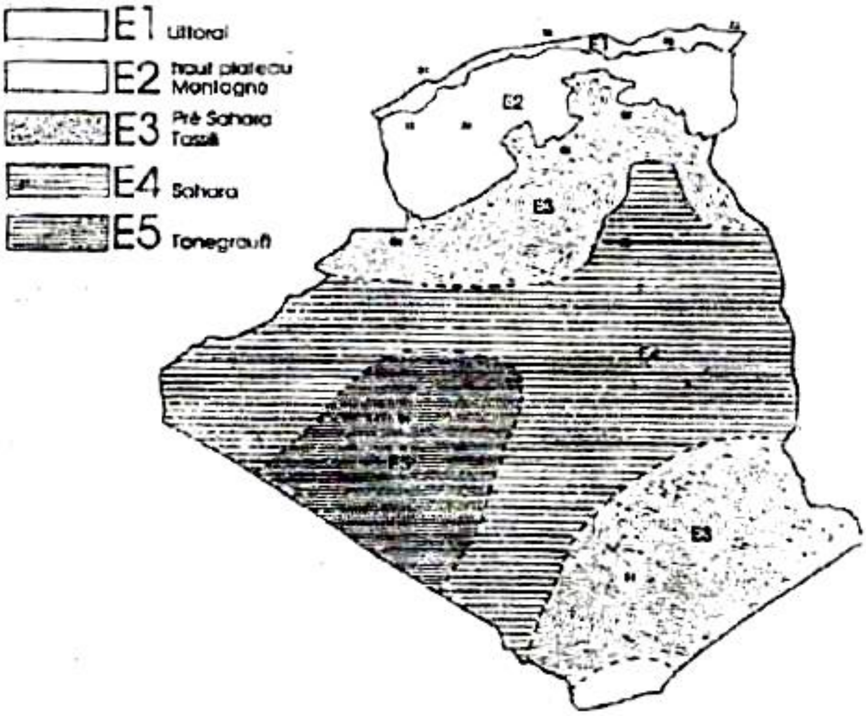


Figure 3. Climate zoning in Algeria (Ould-Henia, 2003)

1.2.2 Energy Production /consumption in Algeria

This section presents the primary energy production and consumption in Algeria, all the data are based on the balance sheet of the Algerian ministry of energy (“benational_2018-edition-2019_5dac85774bce1.pdf,” n.d.).

1.2.2.1 Primary energy production

The structure of commercial primary energy production remains dominated by the natural gas 56% natural, followed by the oil, the natural gas condensate, Liquefied petroleum gas (LPG). as illustrated in the graph below. In 2018 the primary electricity production increased from 635 to 783 GWh, driven by the increase of the hydraulic production sector, and 17% of solar origin. The increase in hydroelectricity production follows very favorable rainfall in 2018, where production was 117 GWh compared to 56 GWh in 2017. *Figure.4.*

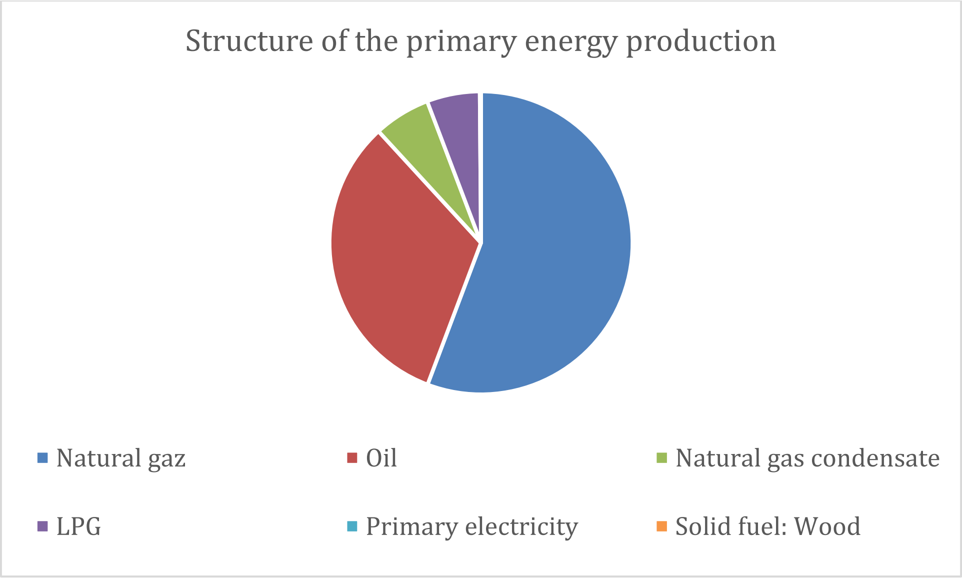


Figure 4.Primary energy production in Algeria

1.2.2.2 National energy consumption

The structure of national energy consumption is dominated by natural gas (38%) followed by electricity (28%) and liquid products (27%), as illustrated in *Figure.5*. Also, it is reported that In 2018 the natural gas consumption increased by 17.4%, and the electricity consumption 4.9%, all driven by the growing needs of customers, particularly those of households.

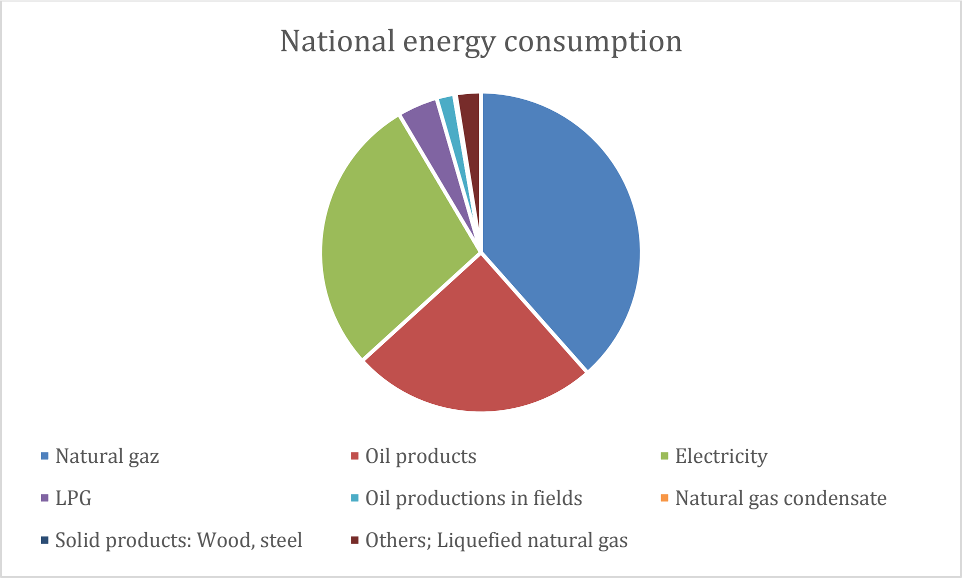


Figure 5.National energy consumption of the produced primary energy

1.2.2.3. *National consumption by sectors*

The structure of final energy consumption in Algeria is dominated by the “Households & agriculture” sectors (46.6%), followed by transport (32%) and finally the “industry and public works” sector 22% as it is reported by the Algerian ministry of energy. Furthermore, the energy consumption of the residential building sector has steadily increased between 2017 and 2018 by 3%, it is responsible of 37% from the overall energy consumption, and 41 % compared to the industrial and the transport sectors. *Figure.6.*

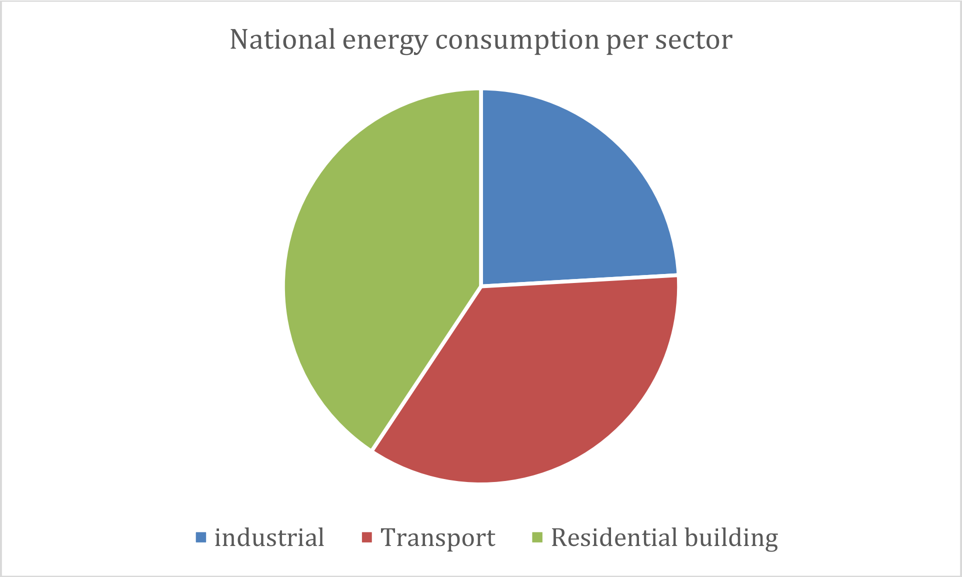


Figure 6. Energy consumption in Algeria by sector

Housing issues in Algeria became greater and actions had to be taken to face the overwhelming crisis. Policies and strategies were set up to tackle the housing demand and to reorganize the sprawling urban areas. (Saada, n.d.),(Bah et al., 2018). Although a lot is done by the State in housing delivery, a greater demand is still expressed, nearly 200000 houses are built annually. *Figure.7.* shows the development of the housing sector in Algeria from 2006 to 2015.

Moreover, a study from the national agency for the promotion and rationalization of the energy used (APRUE) indicates that the needs of the residential sector will be multiplied by 2.7 in 2020 as it is concluded by the research of (Ghezloun et al., 2011).

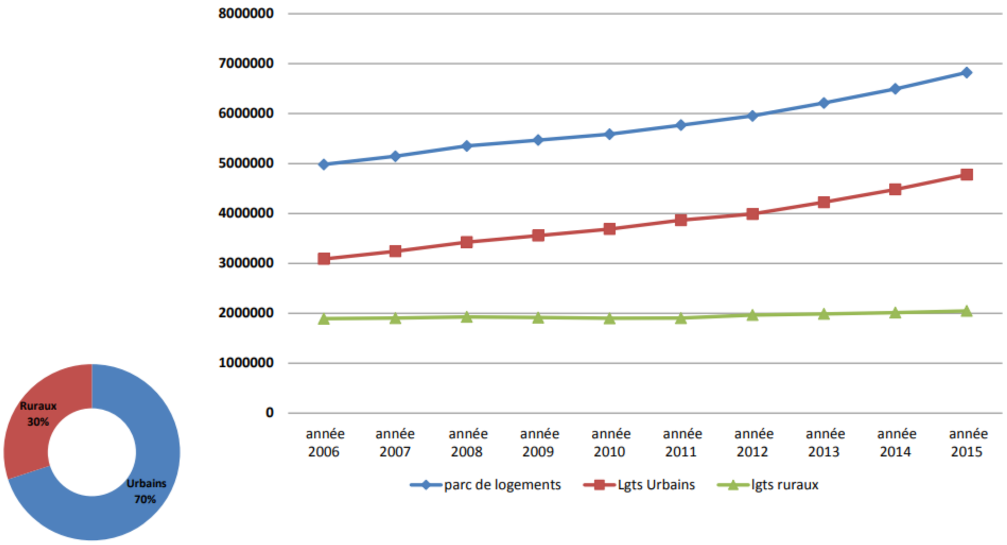


Figure 7. The residential building demand in Algeria between 2006 and 2015 (Kamel Dali APRUE.2017)

1.2 Climate Facade Design concept development, research, and applications

This section reviews the important contents of studies on the architectural facade design. The importance of the facade system is presented, focusing on the emerging climatic adaptiveness concept and building energy efficiency, as well as the main design strategies. The main features of the high-performance facade and its impacting parameters that provide comfort's occupants and building energy efficiency are highlighted. The influence of the orientations, selection of window-to-wall ratio, shading elements, external wall structure are presented. Finally, the related research gaps in the study context are identified.

1.3.1 *Climate design principles and strategies*

The main goal of architecture has always been the protection of human beings from the exterior environmental conditions, attempting to achieve human comfort in the indoor climate. The industrial revolution led to radical changes in the building design, new materials and technologies were incorporated (Manvi, 2017). As a consequence, the massive use of non-renewable energy that seeks to maintain comfort in modern buildings has an ecological footprint (Hardy, 2003). Throughout history, climate adaptability can be found in the earliest human settlements and buildings it has been termed "vernacular architecture", which we still find many worthy examples to study (Nguyen et al., 2019). The design of the basic house varies greatly from region to region according to the natural resources available and the prevailing climate. *Figure.8.*

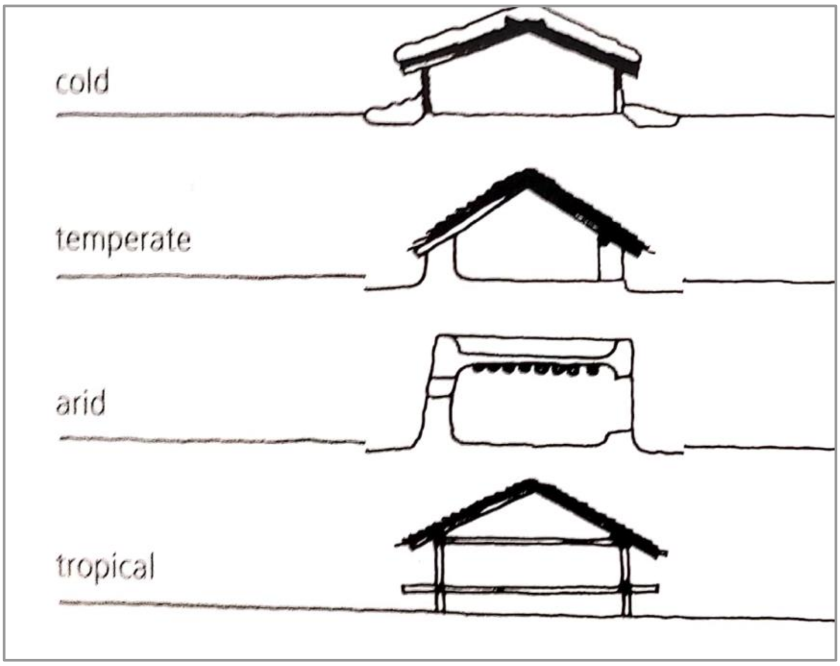


Figure 8. Climatic design typologies in the different climatic zones. (Hindrichs, 2007)

Otherwise, the described approach was scientific popularized by Victor Olgyay in his seminal work Design with Climate: Bioclimatic Approach to Architectural Regionalism (Olgyay, 1963), and a few years later by (Givoni, 1976) in his book Man, climate, and architecture, Both studies believed that incorporating climate data as a basis for architectural design marks a crucial milestone, it is the major determinant of the built form’s configuration, the facade elements, the internal spatial organization, the external aesthetic and the identities. Furthermore, the works contain many charts, graphs, and data for the analysis which is necessary to use appropriate strategies to achieve human comfort within a building. This approach called Bioclimatic design which refers to as “passive mode” design, being passively responsive to the local climate to improve thermal comfort without the inclusion of any active engineering environmental system. *Figure.9.*

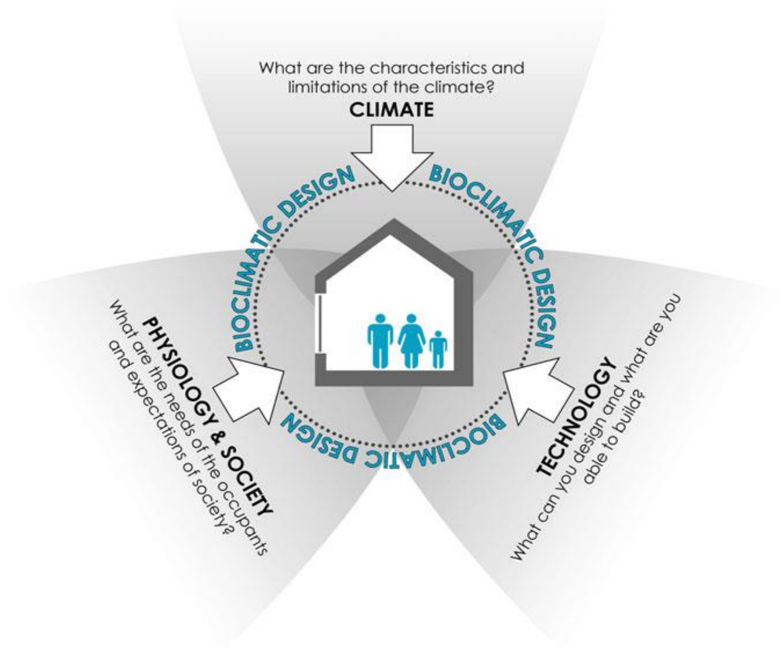


Figure 9. The three basic constituents of bioclimatic design (Košir, 2019)

This approach contains a set of methods and principles used to capitalize on the advantages of climatic conditions surrounding the buildings, making use of the physical–environmental parameters (daily exterior temperature, solar radiation, and wind speed) and the building design parameters (building form, transparency, orientation, thermal–physical material properties and urban Canyon). *Figure.10.* These principles provide thermal and visual comfort with less energy consumption, through cooling, heating, day-lighting and ventilation strategies. (Guedes and Cantuaria, 2019).

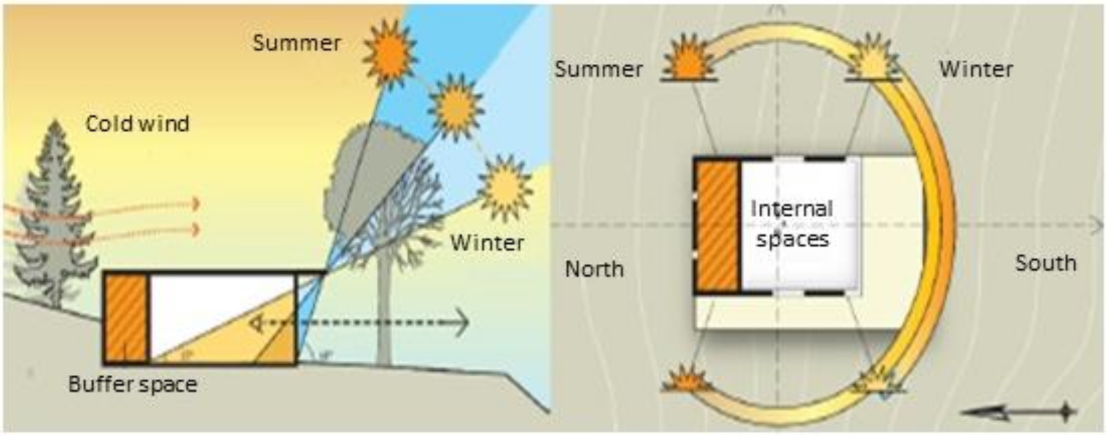
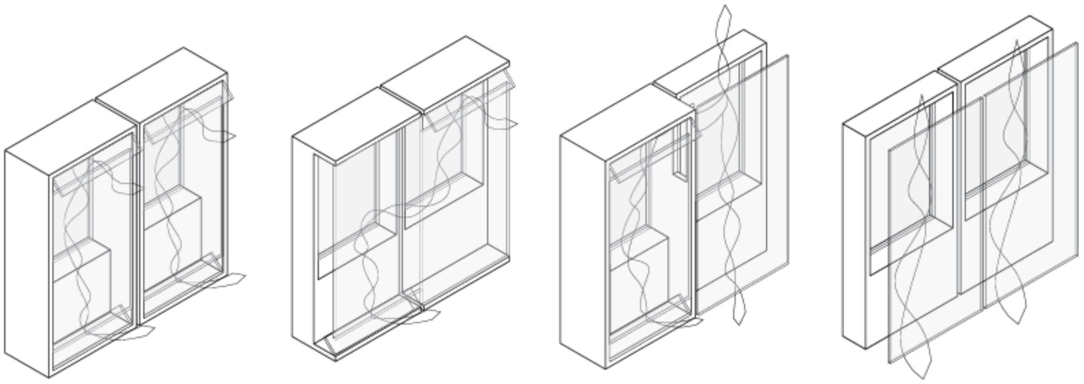


Figure 10. The different design principles of the bioclimatic concept (Misse, A. 2011)

1.3.2 Building facade and energy design performance

The term façade generally refers to the external side of the wall or the frontal part of a building (Sandak et al., 2019). Building façades define the characteristics of the architecture; the structures and the identities, as well as, it is a separator between the exterior and the sheltered environment. Throughout history, the façade's design, functions, and integrated elements have been changed responding to the growing technological abilities and the people's new lifestyle (Herzog et al., 2012). Furthermore, facing the challenge of climate change and to perform hight building energy efficiency; the prevailing trend in the façade is its increasing complexity of the design requirements, more and more facade technologies being developed to increase the user's comfort level with low energy consumption (Knaack et al., 2007). The main three general facade design trends are classified by (Aksamija, 2013); the first, is the small-scale methods that developed to improve facade performance at the micro-level, it includes the coatings, the advanced glazing technologies, and the smart materials such as the Phase change material (PCM). The second consists of large-scale innovations including the double-skin facades and all its various typologies (Box window, Corridor, Shaft box, and Multistory façade) as it is illustrated in *Figure.11.* The third trend is to integrate alternative energy sources into the building façade such as the solar collectors, the photovoltaic cells (PV), Wind powers, as well as the dynamically controlled façade.



(a) Box-window (b) Corridor facade (c) Shaft-box (d) Multistory

Figure 11. Double skin facade classifications (Knaack et al., 2007).

All these facade design trends must fulfill many functions, providing views to the outside, resisting wind loads, supporting its dead load weight, allowing daylight to interior spaces, blocking unwanted solar heat gain, protecting occupants from outside noise and temperature extremes, and resisting air and water penetration (Aksamija, 2009). *Figure.12.* Additionally, The facade becomes an integral part of the concept for adaptation of the building to the climate conditions, thus the facade should behave as an energy-efficient passive or active mechanical system, that can respond and adapt its properties and components with the immediate environment and the climatic conditions. Furthermore, the most common external factors associated with climate-adaptive façades are solar radiation together and outdoor temperature. Because these factors have a direct impact on thermal, visual comfort, and on the energy performance of buildings (Aelenei et al., 2016).

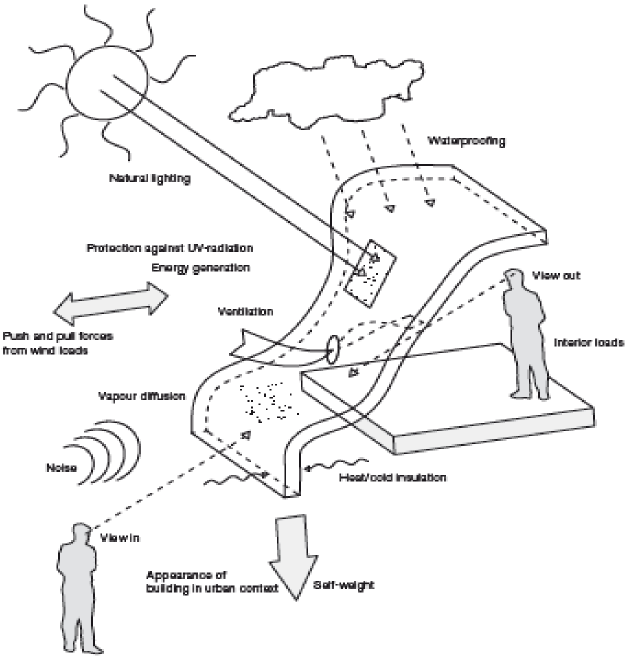


Figure 12. High-performance facade requirements (Knaack et al., 2007).

Moreover, many other research studies revealed that the internal room climate of buildings is determined to a great extent by the facade elements and its orientation, the proportion of the window area, solar screening design, and constructional wall material.

The orientation of a building determines its exposure to sunlight, Strategies for controlling solar heat gain depending on the building’s orientation. As it is revealed by (Givoni, 1994) the choice of the orientation depends on many considerations that affect the indoor environment; the potential of solar penetration, and the wind directions. (Al-Anzi and Khattab, 2010) also have reported that in a BWh climate during the peak months the large glazing area orientated to the SE and SW achieves higher demands on total cooling loads compared to new proposed building design that has more facades oriented to the North, and South directions. Furthermore, heat loss and gain are often associated with the external wall structure and materials, which makes its selection an important factor in designing high thermal performance facades, it is one of the most effective energy conservation measures for cooling and heating in buildings. Therefore, determining and selecting the optimum wall structure is the main research field of many engineering investigations. (Bolattürk, 2008), revealed that considerable energy savings for heating or air-conditioning can be obtained by the limit transmission loads to/from the buildings. In this study, the optimum insulation thicknesses on external walls of buildings were calculated based on both annual heating and cooling loads in Turkey's warmest zone. Also, (Aldawi et al., 2013), estimated the total ongoing heating and cooling energy requirements for four (4) house wall system, the new house wall systems have shown significantly higher energy efficiency in comparison with the conventional house wall system for all Australian climate conditions. The conventional wall is typically composed of brick veneer, air cavity, insulation foil, and timber frame, while the new proposed system contains polystyrene insulation, reinforced concrete, the design differs on changing the insulation position from inside to outside. Additionally, (Bevilacqua et al., 2019) Investegrated the efficiency of the Trombe wall in the yearly building energy requirements in warm and cold climates, the results revealed that the configurations of; the external glass properties, vents geometry, position and the schedule for the activation of the ventilation strategies have to be designed in terms of the climatic context to obtain best results for both summer and winter periods.

Furthermore, Windows parameters are also an important element of the facade design, they are often arranged for admission of the airflow, direct and indirect sunlight, and to provide views. Therefore, window design optimization for thermal and daylight performance is important in achieving energy conservation and increasing overall efficiency. When choosing fenestration materials, specific properties should be considered; the windows to wall ratio (WWR), the properties of glass such as U-values, SHGC, and visual transmittance. (AlAnzi et al., 2009) in this study, applied a detailed parametric analysis indicates that the effect of building shape on total building energy use depends on primarily three factors, the relative compactness (RC), the window-to-wall ratio (WWR), and glazing type defined by its solar heat gain coefficient, (SHGC). (Rathi, 2012) provides a method that optimizes the thermal and daylight performance based on the fenestration parameters to achieve the overall efficiency of buildings. The results revealed 10-15% reductions in the total energy use of office buildings with an increase in overall. Furthermore, (Feng et al., 2017) studied the influence of different glazing percentages (WWR) in the different orientations on energy consumption for nearly zero energy building (NEZEB) in the severe cold area using energy plus software for the simulation. The results showed that the WWR has a greater impact on the orientation east and west compared to the south and the north respectively, as well as the most energy-efficient WWR for NZEB in East, and West orientations is between 10%-15%, south WWR is between 10%-22.5%, north WWR should be appropriately reduced taking into consideration the lighting and ventilation conditions.

Moreover, The amount of incident solar radiation (insolation) admitted through the glazed surfaces in the facade may show severe thermal and visual discomfort issues, to avoid excessive solar gain and reduce energy consumption it is necessary to adopt suitable shading device design, this strategy can help in overcoming the penalties of heat loss in winter and excessive heat gain in summer. The protection of a facade from direct solar radiation induces an important reduction of the solar energy absorbed. A shaded facade will then only have to sustain the diffuse and reflected radiations as it is revealed by (Capeluto, 2003), this study investigated the impact of the Solar Collection Envelope (SCE), this concept is used for the generation of the self-shading envelope. The simulation results reveal that for all the orientations there is an important improvement in the energy performance of the building when designing according to the self-shading envelope. Similar results can be also obtained for vertical facades using high-performance low-emissivity windows. The combination of the building self-shading geometry and internal blinds provide the best solution, particularly for east and west orientations. Furthermore, (Valladares-Rendón et al., 2017) Reviewed the literature about energy savings by solar control techniques and optimal building orientation for the strategic placement of façade shading systems, The results showed that the cases that integrate this passive strategy have effectively lowered the insolation and achieved potential energy savings of 4.64% to 76.57%. The strategies selected for six cases were suitable for subtropical and temperate zones. The most recommended solutions were complex designs of facade self-shadings and shading devices; their strategic placements and accurate designs can further improve the building efficiency.(Planas et al., 2018) Analyzed different façade types of office buildings in the Mediterranean climate, this study affirmed that the decisive parameter that affects cooling demand is the incident solar radiation. This confirms that climates with high solar radiation and relatively high temperatures, the design of facades with a low overall solar factor is crucial to properly control the air conditioning demand.

Moreover, In the study context, also many research has been conducted to improve building energy performance.(Berghout et al., 2014) have demonstrated the relationship between the amount of energy absorbed by the wall and the interior temperature, which is closely related to the orientation, also it has been found that for the Algerian hot and dry climate, the energy requirements for air-conditioning depend on the orientation and, during the summer period electricity consumption is higher, especially for the East and West orientations which should be avoided in the building design, contrary to the South and North orientations. (Hamdani et al., 2012) addressed the envelope impact on the interior temperature of a building in the desert climate in Algeria. Three main feature has been analyzed; the orientation, the thermal inertia, and the thermal insulation, it has been concluded that: the most effective measure to achieve better results is the thermal insulation, however, the orientation of thermally isolated external walls doesn't have a considerable impact on the interior temperature. Thermal inertia of buildings may thus generate thermal comfort. It was revealed that adequate use of stone thermal inertia is essential to achieve better building thermal comfort. Also, (Matari, 2015) In this study three wall types are analyzed in terms of interior temperature variations in the hot and dry climate; these materials are consist of an adobe wall, concrete block, and hollow brick. it has been concluded that double brick walls and single adobe walls are significantly more efficient compared to single concrete block walls. Besides, Adobe is a local product that requires less polluting emissions during its production. Furthermore, (Khadraoui M A et al., 2018) investigated the thermal behaviors of four different facade typologies of office buildings; ventilated facade, curtain wall, earthen brick, and double skin facade, in Biskra city in Algeria, assessing both the surface temperature and the operative temperature through a field measurement and a dynamic simulation. It has been found that the earthen brick facade system was more efficient followed by the ventilated facade, while the curtain wall system and the double-skin facade that includes steel exterior layer have a negative effect. Furthermore, (Latreche Sihem and Sriti Leila, 2018) examined the influence of constructive choices on the ambient and surface temperature, air velocity, and humidity. 15 variates were investigated including conventional wall systems; hollow brick, hollow concrete block, and standard concrete block, the variations were applied for the wall dimensions and structure. This experiment has shown that a judicious choice of materials can positively influence the inner thermal comfort, as well as the double hollow brick wall system that includes the air cavity was the best variant.

Additionally, in hot and dry climate the intense solar radiation the excess solar gains and high outside temperatures, especially in summer, resulting in indoor discomfort. Minimizing the glazed surfaces is always a recommended passive solution for these areas. (ZEMMOURI, 2005) examined a method based on daylight availability to determine window size alternatives providing optimum conditions in terms of visual comfort and heat transfer. The findings show that glass type represents a basic parameter to be considered to achieve good indoor climatic and lighting conditions with minimal energy consumption. (Zekraoui, 2017) studied the optimal choice of the window parameters in Algerian hot and dry climate, including the window to wall ratio (25%,50%, 75%,100%) and different glazing type. As a recommendation, this study stated that the optimal ratio for East, West directions in terms of building energy consumption should be between 20-40% to avoid overheating. Additionally, (Badeche and Bouchahm, 2020) Demonstrated that optimizing fenestration parameters including the orientation, the window to wall ratio, the thermal conductivity of both the glass and the frame, the solar heat gain coefficient (SHGC), can reduce energy loads in office buildings for the three major climatic regions of Algeria (the Mediterranean, semi-arid, and arid), and the importance of each paramtres vaired depending on the climatic conditions; shading devices has greater affect on the energy load of the office especially in the hot and dry climate. Also, (Bourbia, 2016) investigated the impact of the kinematic shading strategies and solar control for the hot and dry climate in Algeria, This paper presents initial findings of ongoing research about design optimization of the dynamic shading facades using the parametric design tool. It has been found that the dynamic shading system contributes to a significant reduction in energy consumption reaching 43%.

Throughout reviewing the literature, to help in formulating the research main problem and aim, it is noteworthy that: first, The building sector in Algeria, partially the residential buildings are the most energy consumer of the final energy consumption, which produced from natural resources; Natural gas was the main produced and consumed primary energy. Sustainable thinking and high building energy performance design should be promoted in the country. Secondly, the building facade design is an important contributor to save energy and provide thermal, visual comfort, and indoor air quality for the occupants in the indoor environment, These aspects impact human health, activity, and production. Additionally, Many façade design trends and technologies have been developed and tested, and it has been proved that the facade components are the main impacting parameters of building energy efficiency, including the window to wall ration, wall structure and materials, the shading system, and the orientation. Although, in Algerian hot and dry climate which represent 89% of the country, most of the studies dealing with the topic in a fragmented way, no holistic optimization approach that deals with the facade parameters and its impact on the comfort level of the occupants have been applied, also almost of the research when dealing with the facade design, the studies are applied for the office buildings. Strict guidelines of the facade design in this context are missing for the residential buildings. However, this gap in the body of knowledge was identified and is being pursued in this research to be bridged.

1.3 Research problem

The thesis attempts to find a solution by finding answers to these research questions:

- Do current, residential social housing in Algeria provide indoor comfort of occupants, which meets the building energy efficiency standard?
- Since the building facade is the most contributor element to the energy efficiency of buildings. How a design guideline can be developed to enhance the building energy-efficiency in terms of thermal comfort indoor air quality, and visual comfort?
- What is the optimal façade design interaction between all the facade components to find the optimum thermal comfort, visual comfort, indoor air quality with less energy consumption?
- What are the main decisive comfort levels/aspect to define the optimal solutions for the facade design?
- What are the possible executable techniques for local builders/ context that can be developed for optimizing the building facade design in Algeria?

1.4 Research objectives

The main aim of this research is to present an optimization approach for the building facade design and to develop generic facade guidelines for the residential building in the hot and dry climate of Algeria, that seeks to provide occupants thermal, visual comfort and indoor air quality with minimum energy use. To fulfill this aim, the following objectives have set:

1. Review current literature on the building facade research and applications to define the main impacting parameters on the inhabitants’ comfort and energy consumption.
2. Diagnose the current situation of the existing social housing in Algeria in terms of building energy efficiency.

3. Investigate and find the optimal interaction between the several facade components design, to balance thermal, visual comfort, and indoor air quality with less energy consumption.
4. Define the most important aspects of comfort which are related to high building energy efficiency in the study context.
5. Develop design guidelines for the building facade in a hot and dry climate to provide high building energy efficiency with easily executable techniques for local builders/ context.
6. Determine recommendations considering the responsive facade design for helping the designers/architects to improve the energy performance in a hot arid climate in the early stage of designing.

1.5 Research hypothesis

Balancing thermal comfort, visual comfort, and indoor air quality (IDQ) by optimizing the building facade design parameters passively can further improve building energy efficiency in Algerian hot and dry climate.

1.6 Conceptual analysis

To concretize the concepts of the hypothesis and to fulfill the thesis's main goal; the conceptual analysis of this study is determined; it present on the one hand the facade design strategies and parameters and the other hand the building energy performance concept. they are transformed into observable and measurable indicators. All these variables are defined based on the literature, and the problematic of the study context. *Figure.13.*

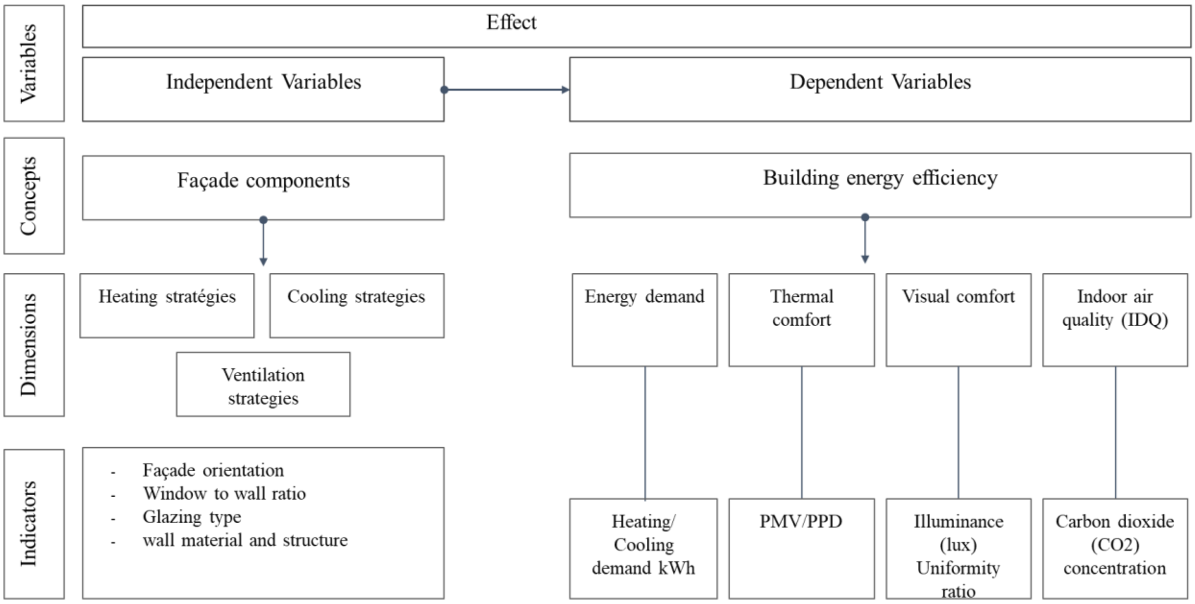


Figure 13. Conceptual framework of the research study

1.7 Scope and limitations:

This study is focused on investigating the possibilities of optimizing the building facade design to improve building energy efficiency. The study is limited to the residential building in the Algerian hot and dry climate. Although, some of the findings may be generalized. Furthermore, the multiobjective optimization methodology can be applied in different contexts and different building types. Moreover, Facade load-bearing and acoustic comfort through the facade materials are not investigated in this study.

2. RESEARCH METHODOLOGY OVERVIEW

The research methodology of this work is applied research its goal is to solve a real problem, it is deductive using quantitative and experimental methods. it is based on a quantitative evaluation using a thermal dynamic simulation through the free and open-source VI-Suite, it is a plugin that uses some built functionalities of Blender 3D software to control the external applications Energy plus and Radiance to conduct energy and thermal performance simulation, artificial and natural lighting analysis, advanced natural ventilation network creation, glare analysis, and wind rose generation.. (Southall and Biljecki, 2017),(Sousa, 2012),(Crawley et al., 2000), (Ward, 1994). *Figure.14.* Shows the main interface of the decision-making tool.

The Excel decision-making support tool was used to compare the results and to make the decision on selecting the optimum models.

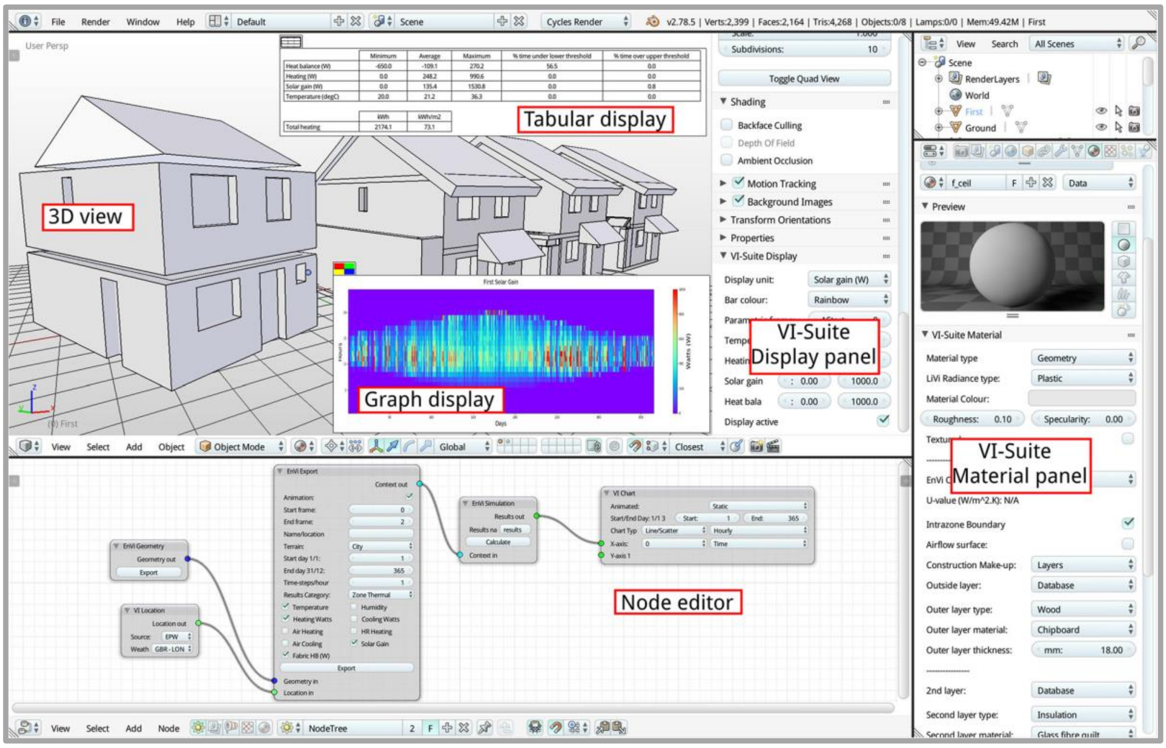


Figure 14. The main interface of the decision-making tool blender 3D and the plug-in Vi-suite (Southall and Biljecki, 2017)

This methodology comprises four main parts. Namely, they are in order; the research outline and scientific background. Validating the modeling, and the accuracy of the dynamic simulation. Study case analysis and diagnosis of the existing building in terms of energy efficiency. Multi-objective optimizing for indoor comfort performance and energy efficiency in the study context. Finally applying the combined optimum results.

2.1 First part: research scientific background

A theoretical analysis of the current literature in this topic worldwide and the study context is analyzed, all revolving on the building facade performance design, its main impacting parameters, and the design trends. The main goal is to determine the main parameters that will be used in the optimization approach for the study context.

2.2 Second part: Modeling and simulation validation

The validation methodology is carried out in a full apartment located in Biskra city-Algeria in a hot and dry climate. First, a data logger Mi-sol, Model: WS-HP3001-8MZ was used by installing five (5) sensors in the apartment to obtain the field measurements data of dry bulb temperature and humidity, it is conducted from (25th to 29th July 2019). Secondly, a dynamic simulation with VI-Suite add on Blender 3D was affected for the same apartment using the same meteorological data of the mentioned days. Finally, the comparison between the field measurement results and the dynamic simulation is applied to determine the simulation process accuracy.

2.3 Third part: Energy performance diagnosis of the existing social houses in Algeria

This part is based on a quantitative diagnosis of the energy performance of the building (DEP), which provides information on the amount of energy consumed in terms of heating and cooling together, with thermal comfort, daylight, and indoor air quality, using the dynamic simulation tool. The goal is to define the strengths and weaknesses of the building design in the study context to be optimized.

2.4 Fourth part: Multi-objective Optimization approach for high-performance facade design

After defining the main impacting parameters of the building facade based on the literature, as well as analyzing and defining the real problems of the case study. Multi-objective optimization is headed, by examining the impact of the different facade components on the building energy consumption, thermal comfort, visual comfort, and indoor air quality. The key components considered for the optimization are; the parameters of the opening, the wall structure, and the orientation. To fix the variables in this experience and to develop general guidelines for building facades design, the application of this optimization is carried out on a virtual model.

2.5 Fifth part: Optimum results application on existing residential building

In this part; the total convenient optimum interactions of the building facade components that provide the best energy efficiency were summarized and applied in the diagnosed existing buildings to compare the results of the energy consumption, the thermal comfort, the visual comfort, and the indoor air quality.

2.6 Research structure

In the below *Figure .15.* the research structure is demonstrated in a diagrammatic form.

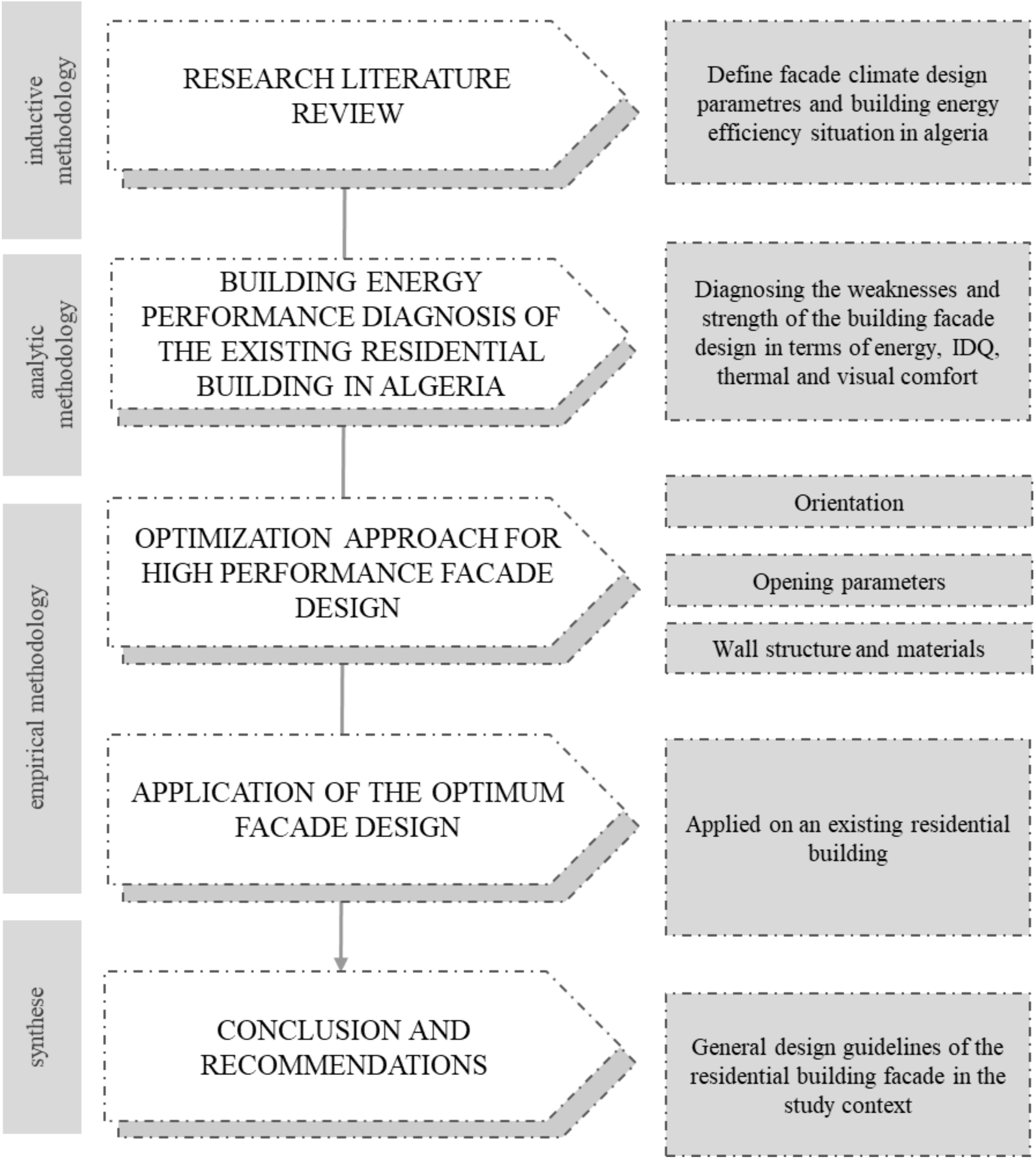


Figure 15. Research structure diagram for the topic

3. VALIDATION OF THE MODELING AND THE SIMULATION ACCURACY

Currently, in the building energy efficiency design field, predictive numerical modeling has been widely used. It is considered one of the most important decision-making tools in the environmental design process of any building type. These tools are helping to determine the appropriate passive design strategies, the Heating, ventilation, and air conditioning (HVAC) systems, as well as to analyze the building's thermal and energy performance. Thus, the research methodology is based on a virtual modeling and simulation process for applying analysis and the optimization approach. Verifying and validating the accuracy of theses process is necessary to determine the modeling and the programming errors which can occur in the thermal dynamic simulation.

3.1 Measurement and dynamic simulation tools

The validation methodology is carried out by comparing the thermal dynamic simulation results with the real field measurements; the simulation results are generated by the decision-making tools; Blender 3D software for modeling and building information has been included by the plugin VI-suite that controls the external application Energy Plus. Otherwise, The measurements data were collected by installing a data logger Mi-sol, Model: WS-HP3001-8MZ. *Figure.16.* This data logger provides field measurements data of dry bulb temperature and humidity levels. Table.1. shows the properties of the used data logger.

Table 1 Datalogger properties

Temperature range	Range: -40 - +60°C
	Accuracy: +/- 1˚C
	Resolution: 0.1˚C
Humidity range	Range: 10% - 99%
	Accuracy: +/- 5%

Figure 16. Data logger used for the Measurements collection (Author)

3.2 Case study location and climate

The study context is located in Algeria, in a Hot and dry climate region, because it represents the major part of the country 89 % depending on the Köppen-Geiger climate classification, this climate is characterized by very hot summers and mild winters. The city of Biskra was selected as a representative city of this climate, it is located in north-eastern of Algeria on the northern edge of the Sahara Desert at a latitude of 34°48' north and a longitude of 5°44' east, it rises to an altitude of 86 meters. *Figure.17.*

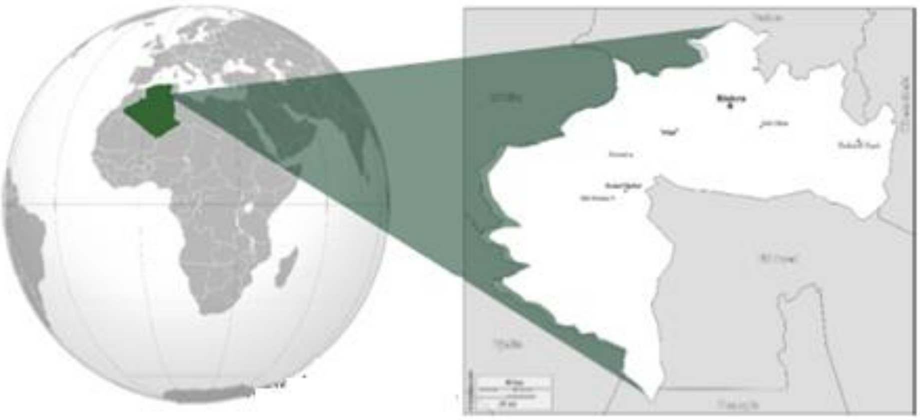
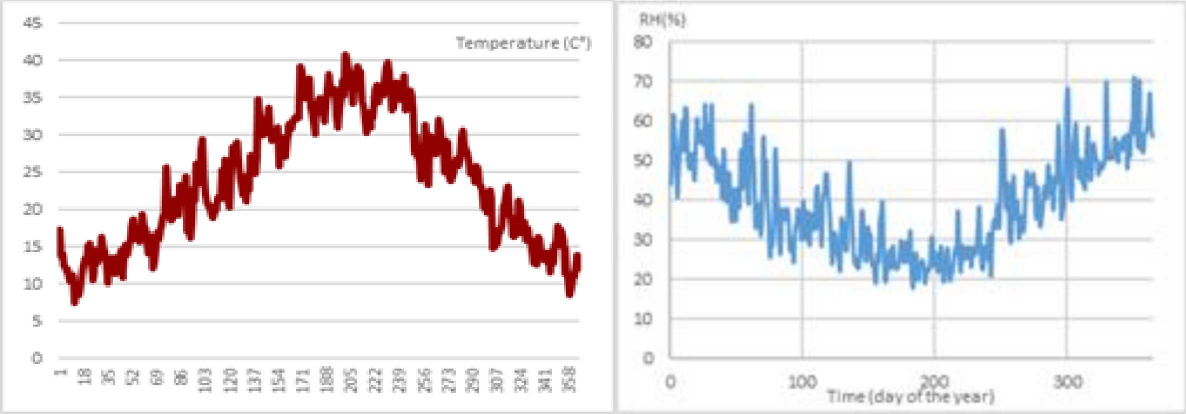


Figure 17. Location of the case study

Based on ‘Biskra’ climate station from the weather file ‘Meteonorm 7’, during the year the average temperatures in this city it is varied by 22.7 °C. The warmest month is July with an average temperature of 40.2 °C. Moreover, January has the lowest average temperature of the year at 16.7 °C. Furthermore, the highest relative humidity average is in December 60.7%, while July represents the lowest relative humidity average, it is 26.5%. *Figure.18.*



(a) Average outside temperature (b) Average outside humidity

Figure 18. Climatic data of the representative city (weather file Meteonorm 7')

Biskra city is characterized by different periodical and typological residential buildings. This city is classified by four periods: Traditional, colonial, independence, and contemporary building (SRITI, 2013). This study is focused on the contemporary Collective residential building type in Algeria called Social housing. *Figure. 19.* shows a typical residential building in the city.

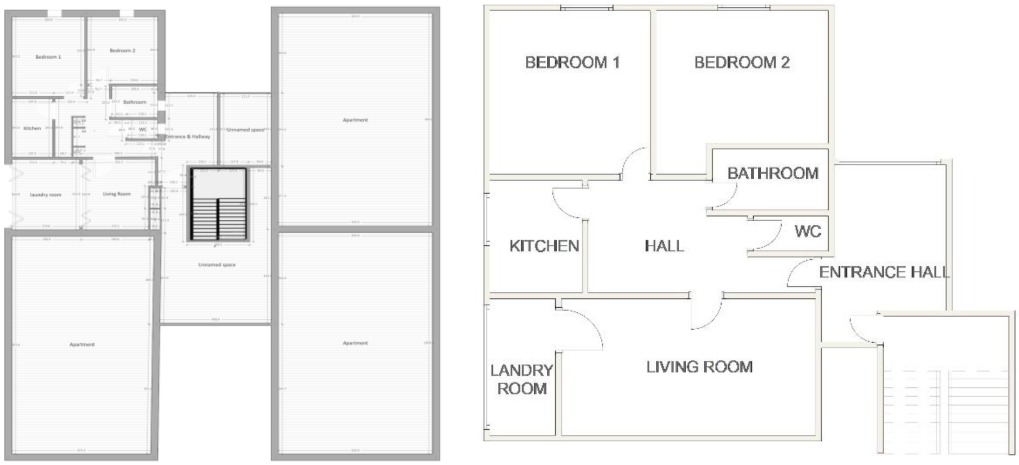
Figure 19. Contemporary residential building in Biskra, Algeria (Author)

3.3 Validation methodology process

The measurement was carried out in an apartment located in Biskra city-Algeria. It is located on the second floor of a collective house, the exposed facades of the selected apartment are oriented towards the Southe-East and South-West. The interior environment of this apartment did not have any internal heat gain due to the absence of any equipment and the occupants, besides the location, this was the main selection criterion of this apartment to obtain more thermal precise results. *Figure.20.*

Furthermore, the measurements were collected by installing five (5) sensors in the apartment (in the Living room, the two bedrooms, the kitchen, and the entrance hall). The process was conducted from (25th to 29th July 2019), these days represent the hottest days of the summer in this context.

Secondly, a thermal dynamic simulation with VI-Suite add on Blender 3D was affected for the same apartment using the same meteorological data of the mentioned days to generate dry-bulb temperature and humidity levels in the different zones. Finally, the comparison between the field measurement results and the dynamic simulation was applied to verify the agreement degree.



(a) plan of the floor (b) Plan of the apartment

Figure 20. illustration of the apartment position and plan (Author)

3.4 Validation results and discussion

The results in the entrance hall as it is illustrated in Figure.21. and Figure .22. shows excellent agreement between both simulation and measurement data in all the measured days, this is due to the façade configuration of the entrance hall that has an opening to the outside.

This means that the inputs of the simulation were nearly the same as the real build environment.

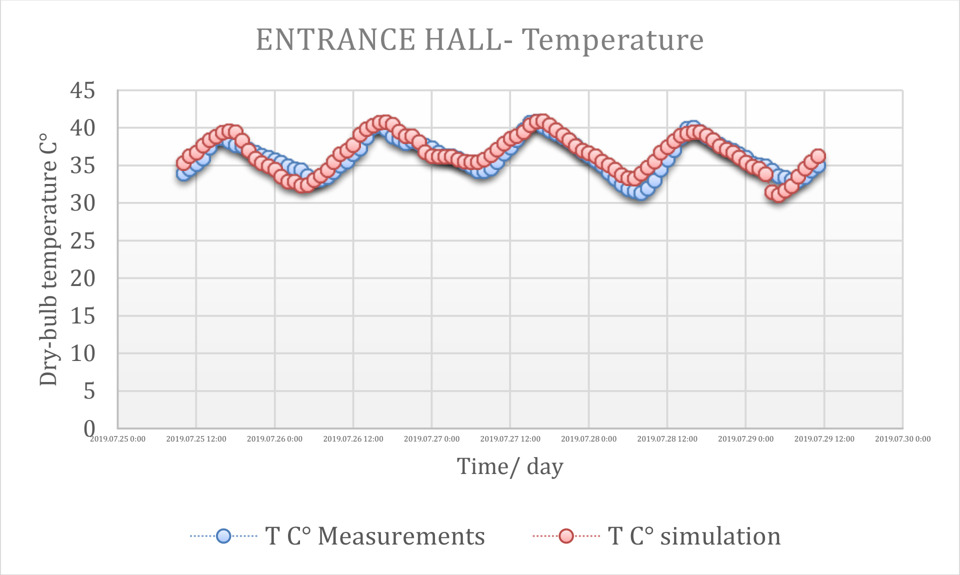


Figure 21. Comparison of the Dry-bulb temperature results in the entrance hall

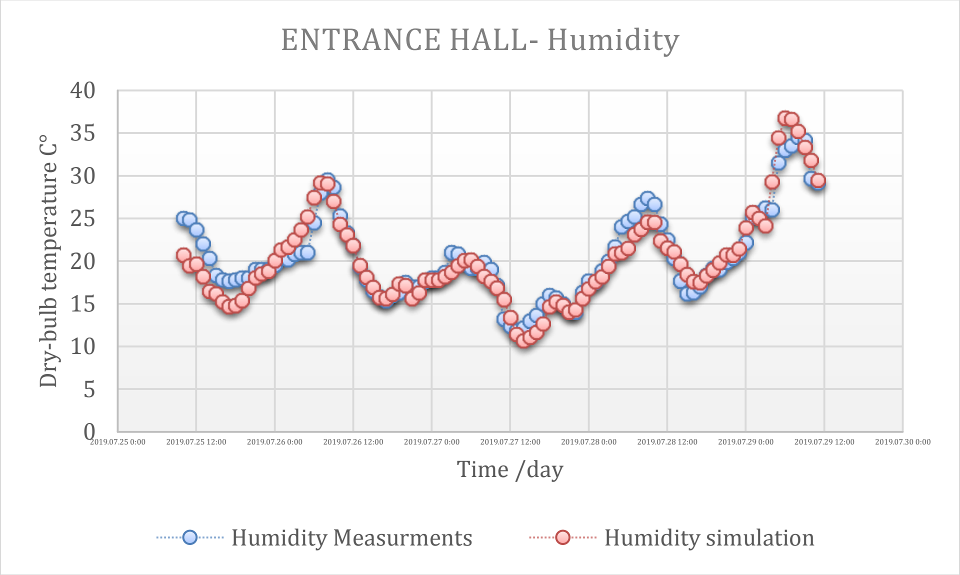


Figure 22. Comparison of the Humidity results in the entrance hall

The results of the bedroom n°1 as it is illustrated in *Figures 23, 24* .show that there is a difference in the dry-bulb temperature between the simulation and the measurements, the simulation data was higher than the measurements. However, the 1st-day a small difference was obtained because of the installation process of the sensors including; the opening of the doors by the installers which were not considered in the simulation, as well as their metabolic rate impacted the humidity levels. Whereas, the humidity shows a good agreement in the last 4 days.

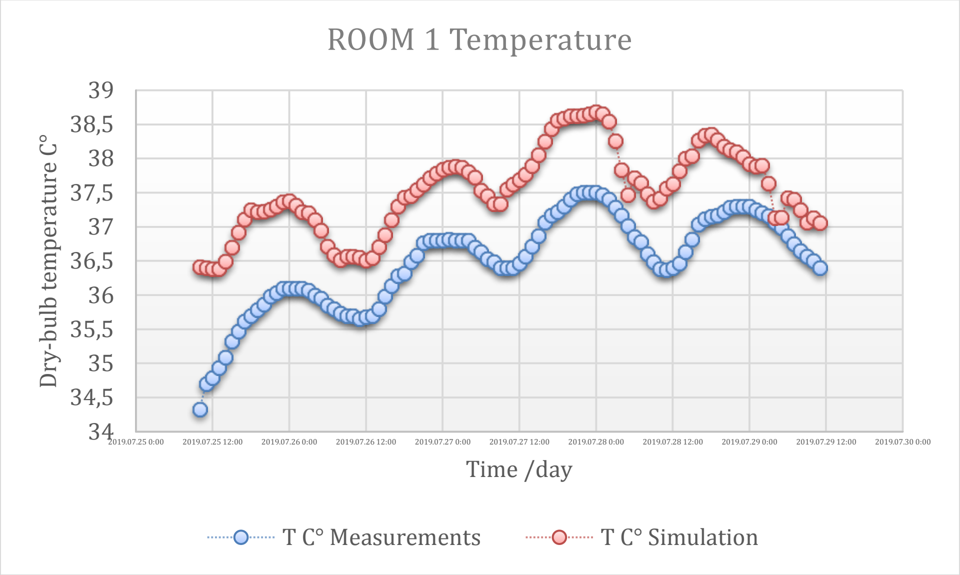


Figure 23. Comparison of the Dry-bulb temperature results in Bedroom n°1

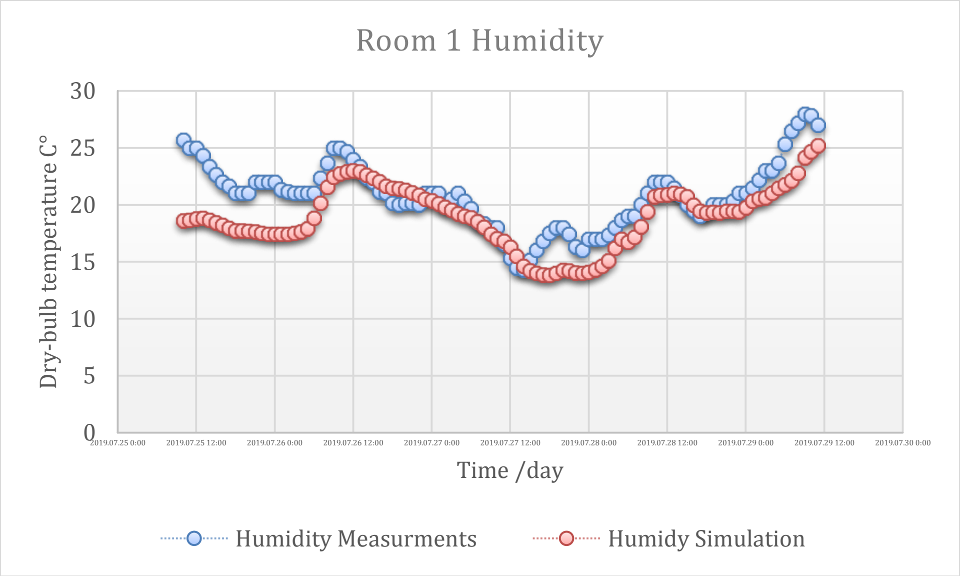


Figure 24. Comparison of the Humidity results in Bedroom n°1

The *Figures 25, 26* illustrate the results of the bedroom n°2, The same results have been obtained as the bedroom n°1 for the dry-bulb temperature, whereas, the fluctuation of the humidity in the simulation were slightly changed in the different days, which was not the same for the real case.

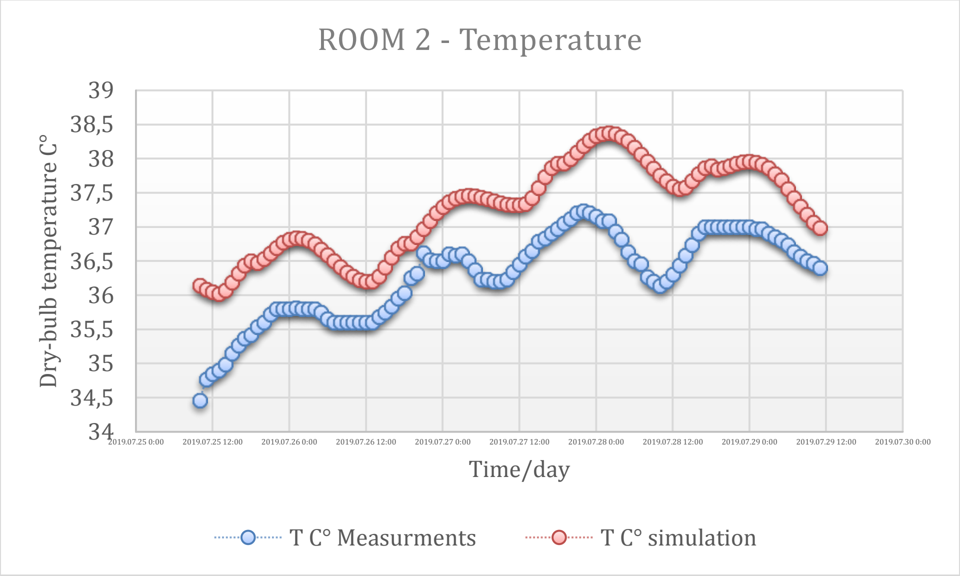


Figure 25. Comparison of the Dry-bulb temperature results in Bedroom n°2

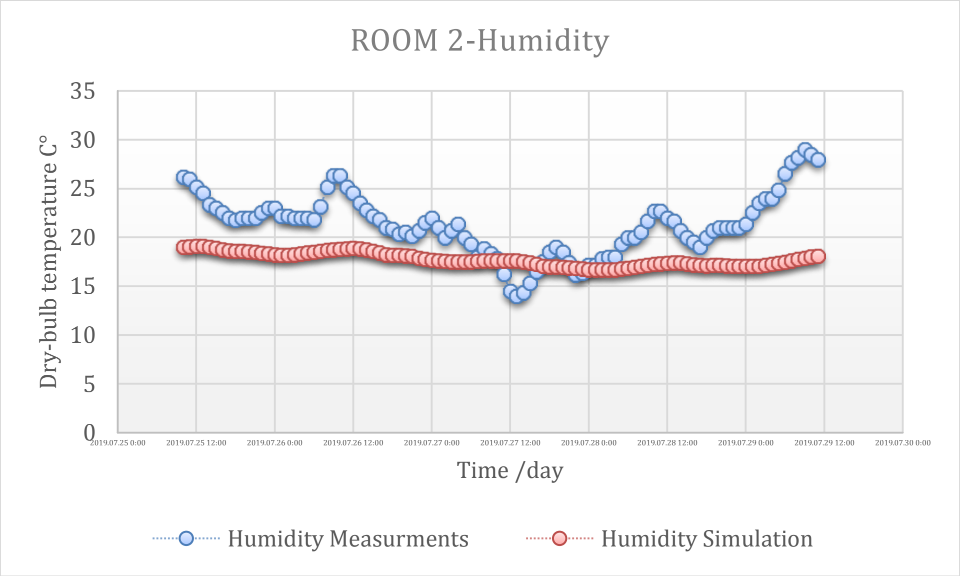


Figure 26. Comparison of the Humidity results in Bedroom n°2

Figures.27, 28 show the results of the kitchen, which illustrate a good agreement between both the thermal simulation and the measurement data for all the different days.

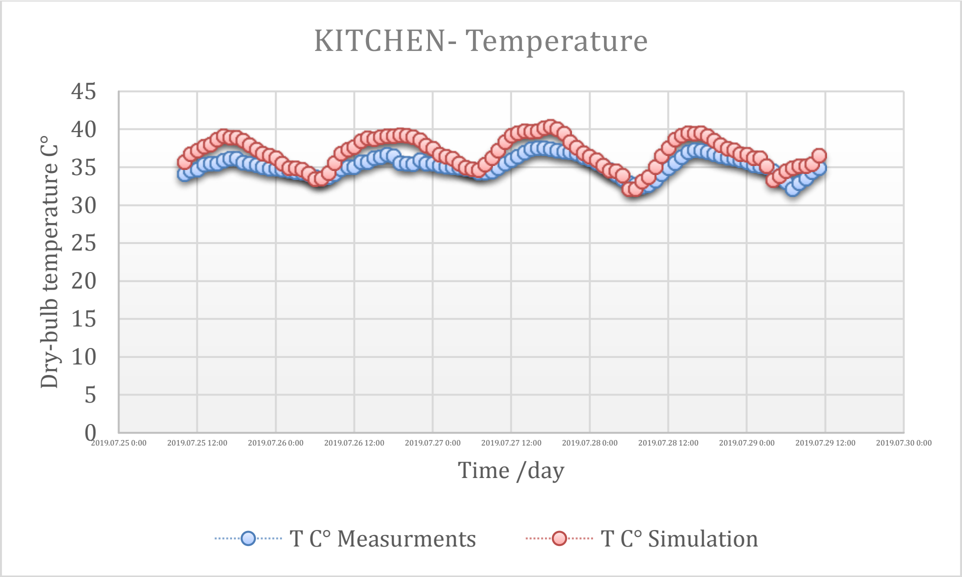


Figure 27. Comparison of the Dry-bulb temperature results in the Kitchen

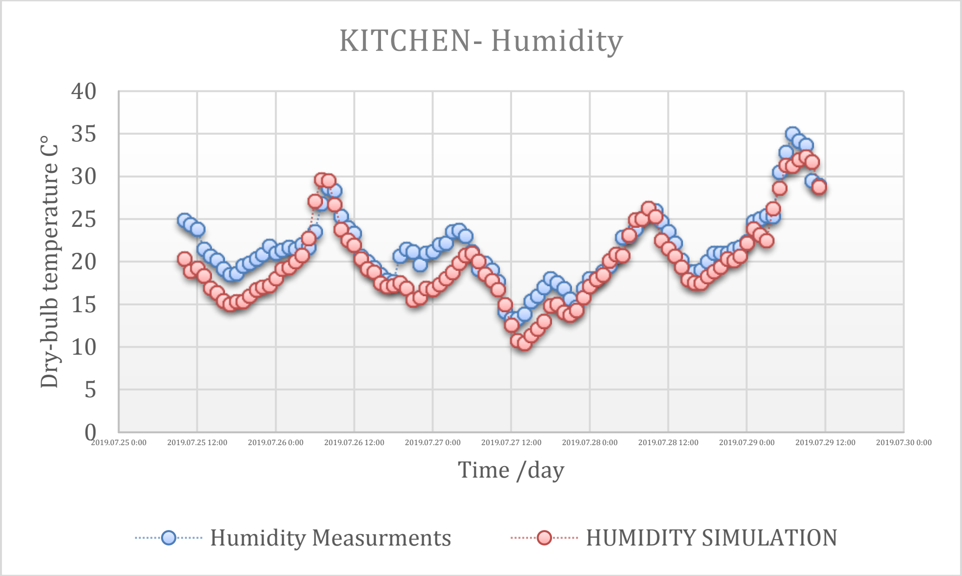


Figure 28. Comparison of the Humidity results in Kitchen

For the living room as it is illustrated in *Figures 29, 30* shows a good agreement in terms of temperature fluctuations, but there is a difference of 5 c° between the average temperature of the simulation and the measurements. However, the humidity level shows that the measurements were higher than the simulation.

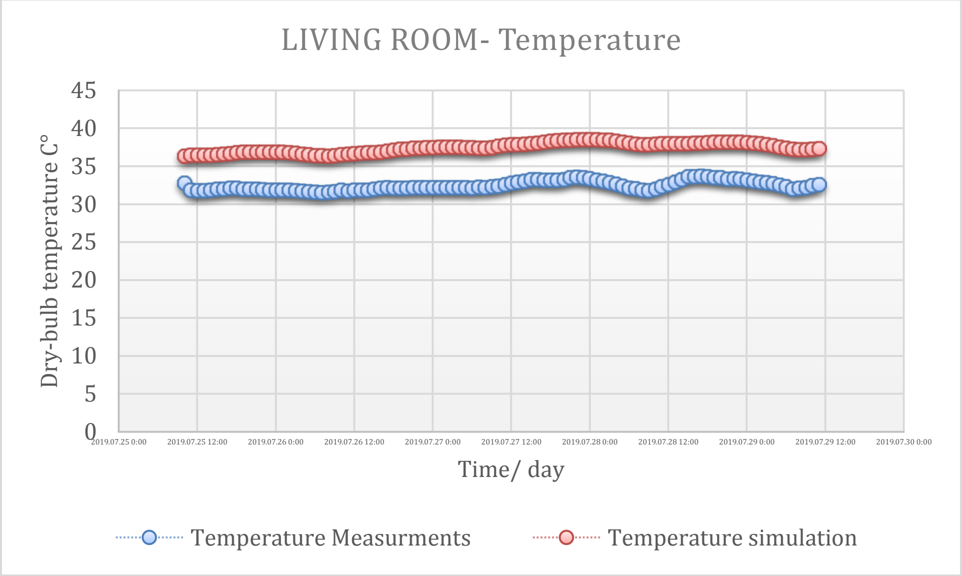


Figure 29. Comparison of the Dry-bulb temperature results in Living room

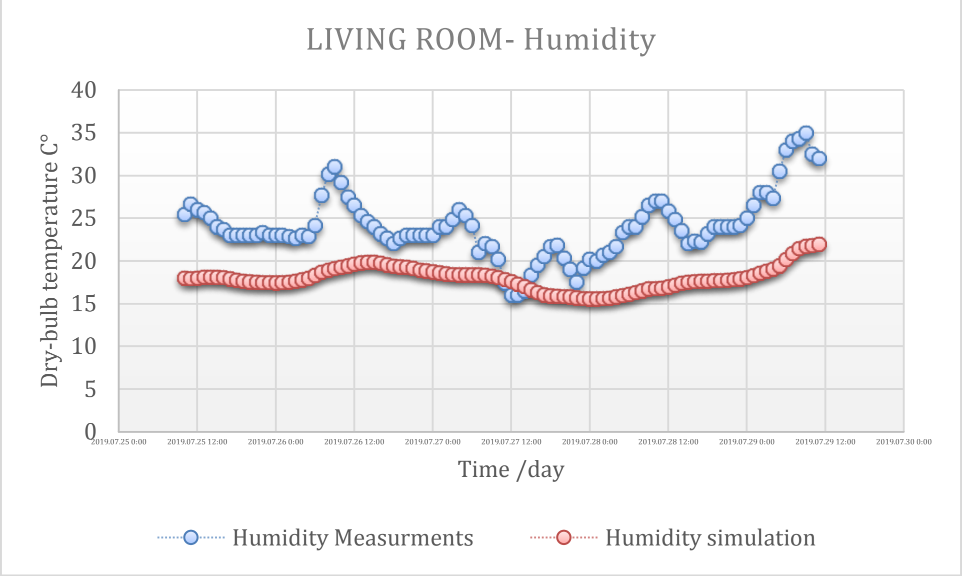


Figure 30. Comparison of the Humidity results in Living room

Generally, the results of the comparison between the field measurements data and the thermal simulation show variations in the agreement between both data, in the different zones of the apartment. Some zones have an excellent agreement and others have some differences. The recorded dry-bulb temperature in the simulation was always higher than the measurement data. The opposite of the humidity level, the measurements were higher. This is due to the missing inputs in the simulation, that are related to the occupant's behaviors of the other apartments in the building including; their numbers, the opening of the HVAC system, the windows/ doors closing and opening, time of occupancy…etc. The accurate prediction of all these parameters impacts the agreement degree between the measurements and the simulation results. Otherwise, since the agreement has been obtained in some zones in the apartment, that means the modeling method with Vi-suit add on Blender 3D is precise enough and it can be used to fulfill the research main goal, Therefore, all the other parameters in the other apartments in the building will be neglected and considered as fix variables in the research simulation methodology.

4. BUILDING ENERGY PERFORMANCE DIAGNOSIS OF THE EXISTING RESIDENTIAL BUILDING FACADE IN ALGERIA

In this section, an analysis of the current situation of the existing residential buildings in the study context in a hot and dry climate is presented to investigate the weakness and strength of the Algerian building design in terms of building energy efficiency. A referential building has been chosen, to carried out the diagnosis. Furthermore, to evaluate the energy consumption, thermal comfort, indoor air quality, as well as visual comfort the simulation with Energy plus and radiance software was used through Vi-suite add-on Blender 3D.

An existing building in Biskra city was selected as a referential model, it represents the most widely constructed building typology in the city based on the study of (TIBERMACINE, 2016). Also, This building reference is located in an urban area, the implementation is oriented within the axis North-east and South-west. This building is a multiple-dwelling unit, that contains 8 apartments and all the apartments have a similar spatial distribution; living room, two rooms, kitchen, laundry room, toilet, and bathroom. The total area of one apartment is 92.13 m², with a ceiling height of 2.70 m. *Figure.31. 32.*

Figure 31. a) Location of the building; b) Reference building model

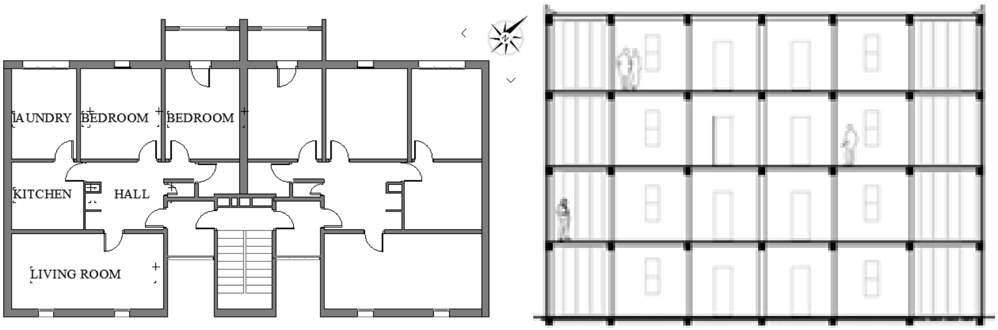


Figure 32. Plan and section of the social house reference

The materials applied for the facades are concrete blocks and plasterboard, the plaster is used for the coating. Currently, these materials are less used in the Algerian residential building factory, therefore the concrete blocks were replaced by double hollow brick in this study because it is the most commonly used in the last years. *Table.2.* shows the detailed thermal properties of the material used in the diagnosis based on the Algerian thermal regulation of residential buildings (D.T.R C 3-2).("12-DTR-C-3.2.pdf," n.d.)

Table 2 Conventional wall Thermal properties

Material (mm)	Conductivity(W/m-K)	Thickness (mm)	Specific Heat capacity (J/kg-K)	Density (kg/m3)
Cement Mortar	1.4	20	1080	2200
Hollow Brick	0.48	150	936	589
Air gap	0.026	50	1000	1
Hollow Brick	0.48	100	936	625
Plaster	0.35	20	936	875

4.1 Input data and boundary conditions for the simulation process

The current methodology is based on a quantitative diagnosis of the energy performance of the building (DEP), it provides information on the amount of energy consumed in terms of heating and cooling together, with thermal comfort, daylight, and indoor air quality. The diagnosis is carried out by using dynamic simulation with Blender 3D software for modeling, and building information has been included by the plugin VI-suite that controls the external applications Radiance, Energy Plus. *Figure.33.* shows the diagnosis process used in this study.

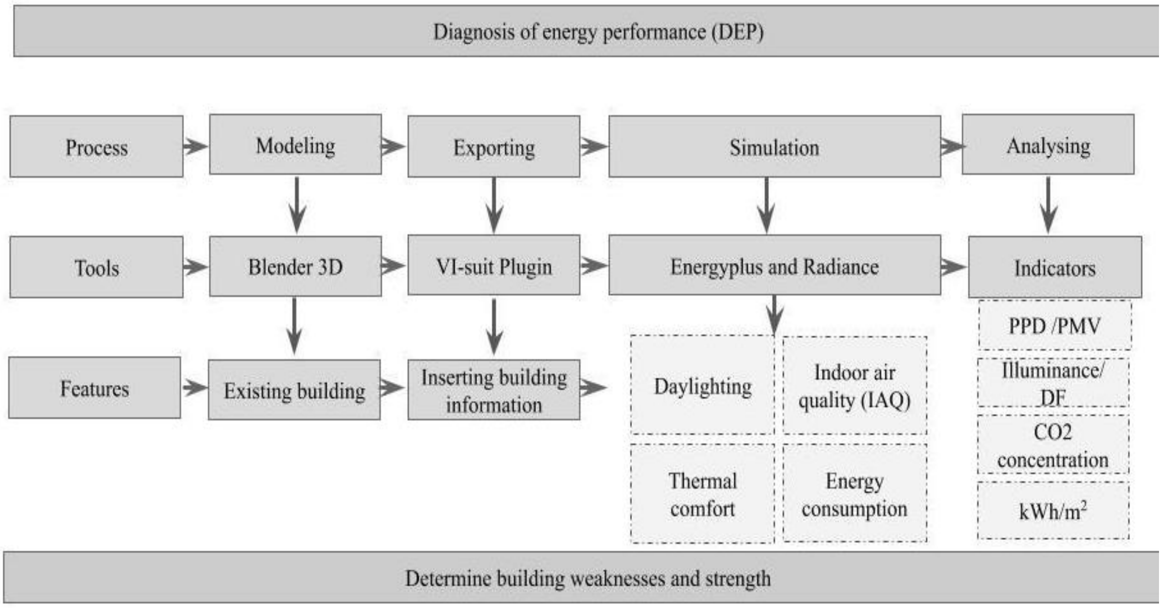


Figure 33. Diagnosis of energy performance process related to building facade components

The inputs of the climate data used in the simulation are based on ‘Biskra’ climate station from the weather file ‘Meteonorm 7’.

Before running the diagnosis a sunlit-time simulation is applied in the selected building, the aim is to define the worst apartment that has the highest level of solar gain. The results show that the most exposed apartment to solar radiation is the apartment on the fourth floor which oriented to the southwest. The exposure of this apartment during the day reached 70%, it is the maximum level compared to other facade orientations. *Figure.34.*

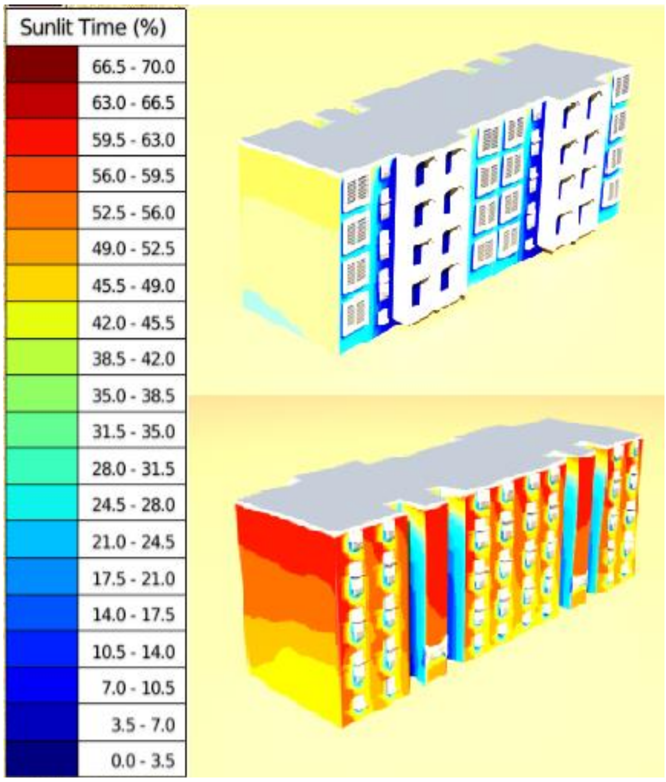


Figure 34. Sunlit time simulation results

The assessment of the energy consumption is conducted by insertion of the Heating, Ventilation, and Air conditioning system (HVAC); and it is applied in the upper apartment which is the most exposed in the selected block. The simulation period has been carried out in the whole year (from 01 January to 31 December). To analyze each space in the apartment, the building boundary is specified in sixteen (16) zones; six (6) zones with an HVAC system (hall, 2 bedrooms, living room, kitchen, and bathroom / WC) and eight (8) zones without HVAC (laundry, entrance and the seven (7) other apartments in the building), The analysis is carried out for the 6 zones that have an HVAC system. The balconies' setting was inserted as shading elements. Additionally, the building cooling-heating service system setting was inserted based on the Algerian Regulatory technical document, the cooling system turns on if the temperature is above 25 °C, while the heating system turns on when the temperature is less than 20 c °. The selected building is built during the eighties ('80s), thus the infiltration rate (ACH) was inserted 10.

Meanwhile, the analytical methodology adopted for thermal comfort is based upon the Fanger's model that includes Predicted Mean vote (PMV) and Predicted Percentage of Dissatisfied (PPD) (Fanger, 1972). PMV refers to the thermal sensation scale that includes seven (7) levels from (-3) to (+3) as follows; -3= Cold, -2 = Cool, -1= Slightly cool, 0= Neutre, 1= Slightly warm, 2= Warm, 3= Hot, while In extreme real weather conditions, PMV can be higher than +3 or lower than –3 (Mayer and Hoppe, 1987). The recommended accepted PPD and PMV range for thermal comfort is introduced by the International standard ISO 7730, five methods developed upon the Fanger comfort model. This standard proposed three categories called A, B, and C for Category A, PMV is comprised in the interval [-0.2, +0.2], PPD ≤ 6%; for Category B, in the interval [-0.5, +0.5], PPD ≤ 10%, and for Category C, in the interval [-0.7, +0.7], PPD ≤ 15%. (Carlucci, 2013). Thes PMV ranges have come from temperate climate countries, however, the occupants in warm climatic conditions have different heat endurance capabilities. Consequently, (Ole Fanger and Toftum, 2002) proposed an extension of the PMV model for the warm climate countries for non-air conditioning buildings, as a result, the extended thermal comfort range is between [-1, +1], PPD= 80 % of people which satisfied within this range. Finally, this range will be used for the analysis in the study context.

The potential of the simulation software has been used to calculate the PMV/PPD indices. In this phase of the analysis, 2 zones (living room, Room 1) in the upper apartment were specified to be analyzed, assuming two occupants and one occupant respectively, and no mechanical system has been applied in the zones.

Furthermore, the diagnosis is concerning also on the daylight comfort which is related to the window to wall ratio (WWR). Thus, two main factors have been used to assess the visual comfort performance; the illuminance levels that concerning the amount of light that falls on a surface per unit area, measured in lux (Lumen per square m²). Additionally, the light uniformity, which is usually defined as the ratio of the minimal illuminance over the area-weighted average illuminance, see equation (1).

$$U = E\,min \div E\,Average \qquad (1)$$

The analysis is applied for the living room and Room 1in two design days (21 December and 21 June) form the sunrise to the sunset for both days. The results are compared with the standard of Building Research Establishment Environment Assessment Method (BREEAM) that provides information about the required daylight, to ensure best practice in visual performance and comfort for building occupants. The recommended average daylight illuminance over interspace should be At least 100 lux for 3450 hours per year or more, and the minimum at the worst point At least 30 lux for 3450 hours per year or more, also the minimum area to comply should be 100%. Besides the daylight uniformity at least 0.3.

Finally, the analysis of the indoor air quality (IDQ) is focused on evaluating the amount of the carbon dioxide (CO2) concentration, which considered one of the indicators of the air quality within the indoor environment, The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard determined the optimal level of the CO2 concentration which should be ≥1000 ppm.

The analysis has been set up in two zones (the living and the Room 1), assuming 2 occupants in the Livingroom and 1 occupant in the Room 1, and the windows opening/closing was set up based on a normal family house activities. Those are open on weekdays between 7.20 am to 7.30 am and from 16.20 to 16.30, as well as the unoccupancy time is defined between 7:30 to 16;20. On the weekends, it is assumed that the occupants are staying all the time in the apartment and the windows are opened between (07:20 am to 07:30 am, 12:00 pm to 12:10 pm, and 16:20 to 16:30.).

4.2 Simulation results evaluation and discussion

4.2.1 Energy consumption evaluation

The simulation results of the energy consumption showed that 89% of the total energy consumption was used on cooling, while 11 % was used on heating. *Figure.35.*

The comparison of the energy consumed in heating and cooling shows a variation in each different zone, this is due to the zone's position in the apartment, the different surface areas that have direct contact with the outside and its orientation.

The bathroom has the highest cooling energy consumption, followed by the kitchen, the living room, the hall, Room1, Room2 which includes the balcony has less consumed energy. The cooling consumption in the bathroom reached 287.19 kW/m^2, it has direct contact with the entrance hall that has a fully glazed façade which increased the greenhouse effect in the entrance hall and impacts directly the bathroom. In the kitchen, the assumed energy is 183.16 kWh/m^2, the main façade of this zone is oriented to the south-west which has a higher solar gain. The living room has 173.01 kWh/m ^{2}, it has 2 facades one oriented to the south-east, and the other is oriented to the south-west. The cooling consumption in the hall reached 172.37 kWh/m^2 because it is surrounded by the different spaces, during the day the heat is accumulated, which means there is no effective air circulation. The bedrooms are both oriented to the north-west façade but the energy consumption in Room1is higher than Room2, 158.09 kW/m2, 155.29 kW/m^2 respectively, this is revealed that the balcony as a shading element has an impact on minimizing the solar heat gain, therefore the energy consumption. For the heating consumption, the kitchen has the highest heating energy consumption 49.49 kWh/m^2, followed by the Room 1; 23.02 kWh/m^2, and the Room 2; 22.92 kWh/m2, the bathroom 19.53 kWh/m^2, the hall 18.61 kWh/m^2, and the living room that has less heating consumption 8.96 kWh/m^2. The heating and cooling consumption show reversed results according to orientation and solar gain; the more exposed zone to solar gain, the less heating, and more cooling it consumes. *Figure.36*.

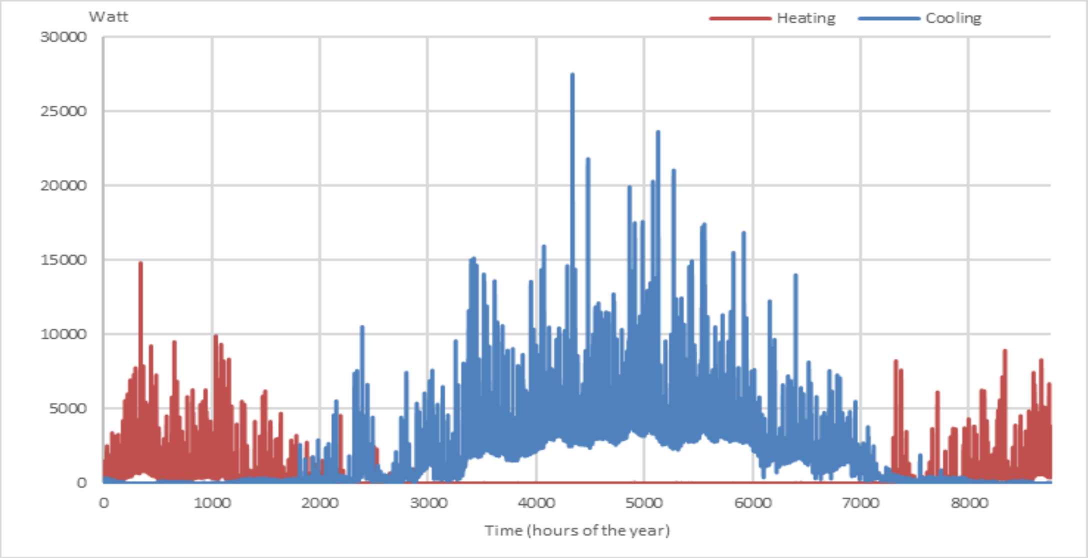


Figure 35. The energy consumption of the upper apartment in a whole year.

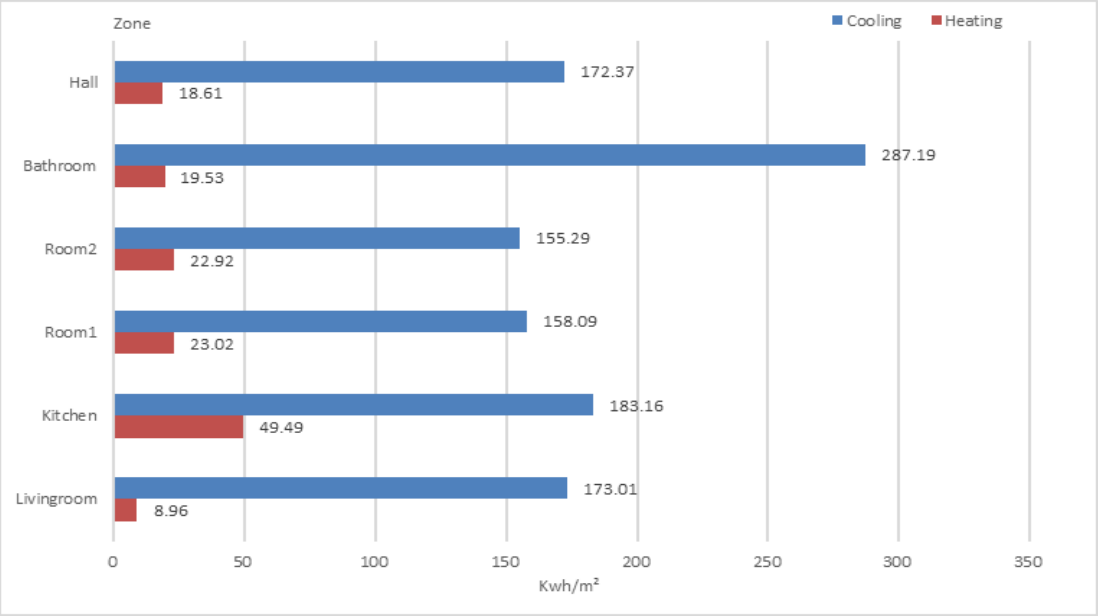
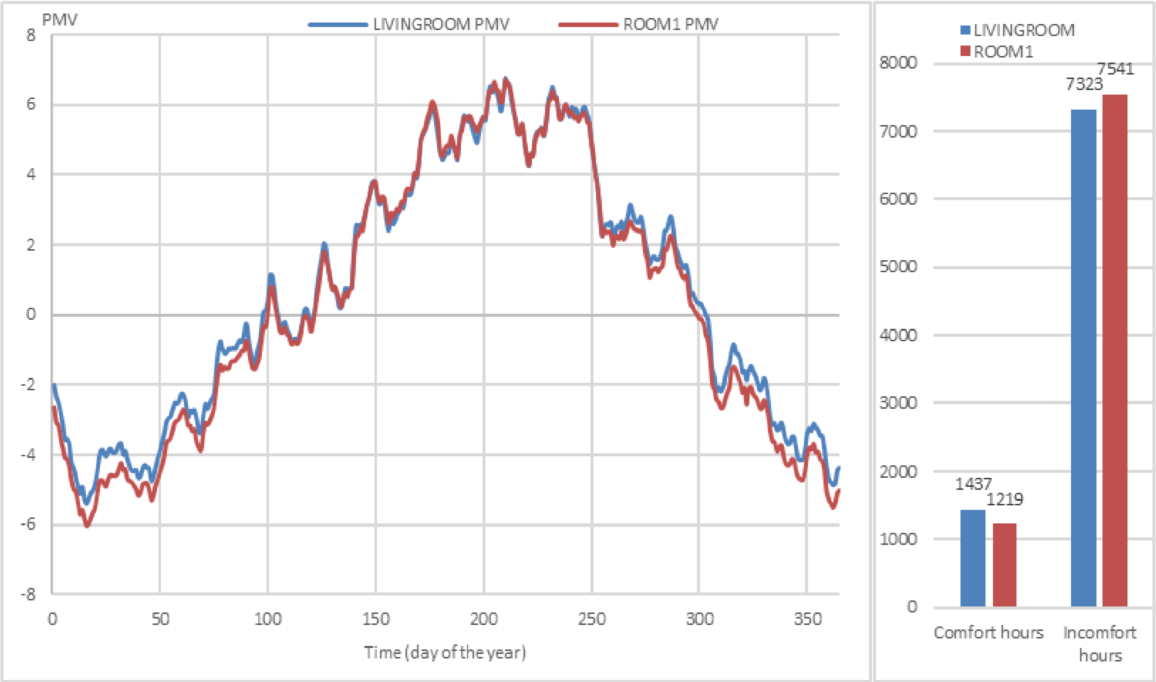


Figure 36. The cooling and heating consumption of all the simulated zones

4.2.2 Thermal comfort analysis

The diagnosis of thermal comfort is also applied in the living room and the Room1. The resulting analysis of the PMV/PPD indices for the given zones shows that; based on the PMV people are feeling very hot almost all the summer period (June, July, August), in the winter (January, February, and December) they are feeling cold to very be cold, the feelings are approached the comfort zone in some days of the mouths (March, April, May, and October). Furthermore, the comfort hours for the whole year are reached 1437 Hours and 1219 Hours for the living room and Room 1 respectively. The comfort range is defined between -1< PMV <+1, and the feelings above this range are uncomfortable, the discomfort hours are attained 7323 Hours in the living room and 7541 Hours in room 1, *Figure.37.* Illustrate the scale of occupant's sensation from very cold feelings +6 to very hot -6, while zero expresses neutral feelings.

Moreover, the PPD indicates that more than 90% of people are not satisfied almost all the summer and winter periods, while in March and April it varied between 10 % to 70% for both the living room and Room1. *Figure.38.*



(a) The PMV scale *(b) the comfort/ discomfort hours -1< PMV <+1*

Figure 37. The indices PMV for the living room

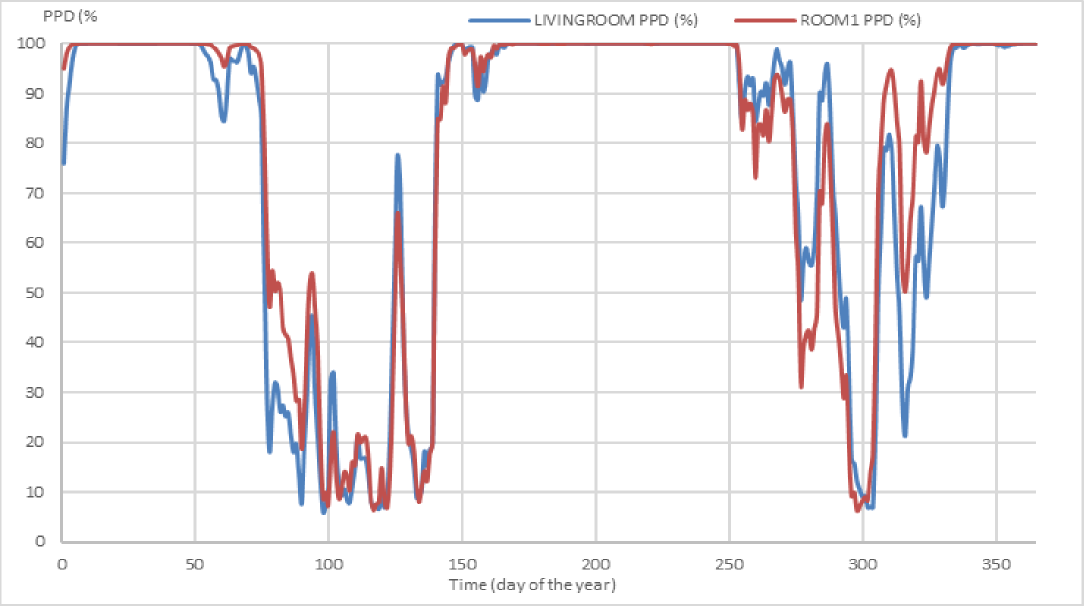
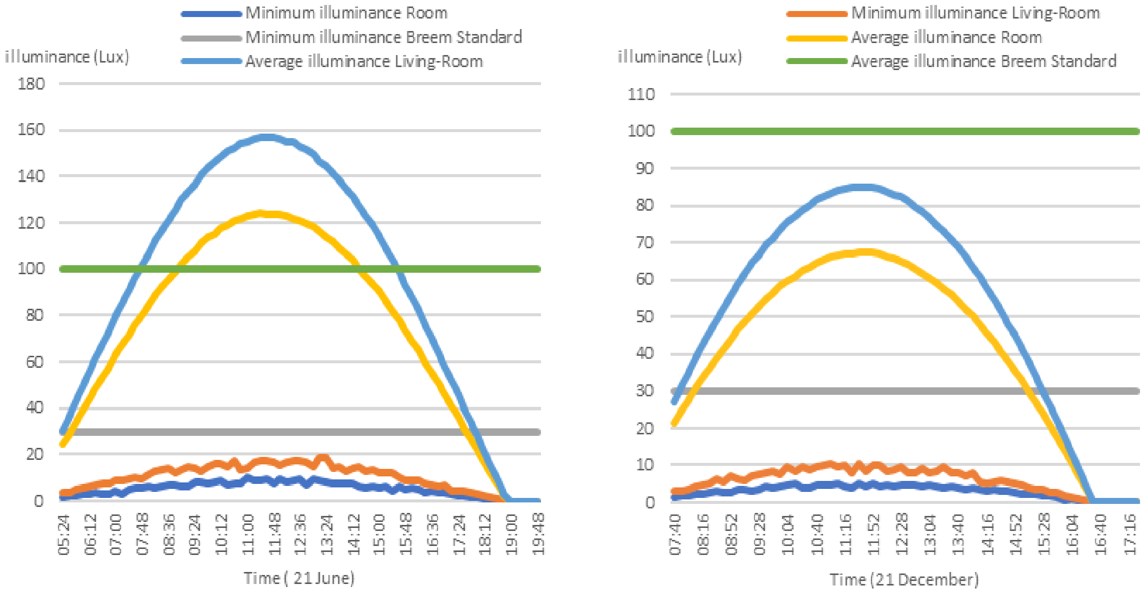


Figure 38. PPD results for the living room and Room 1

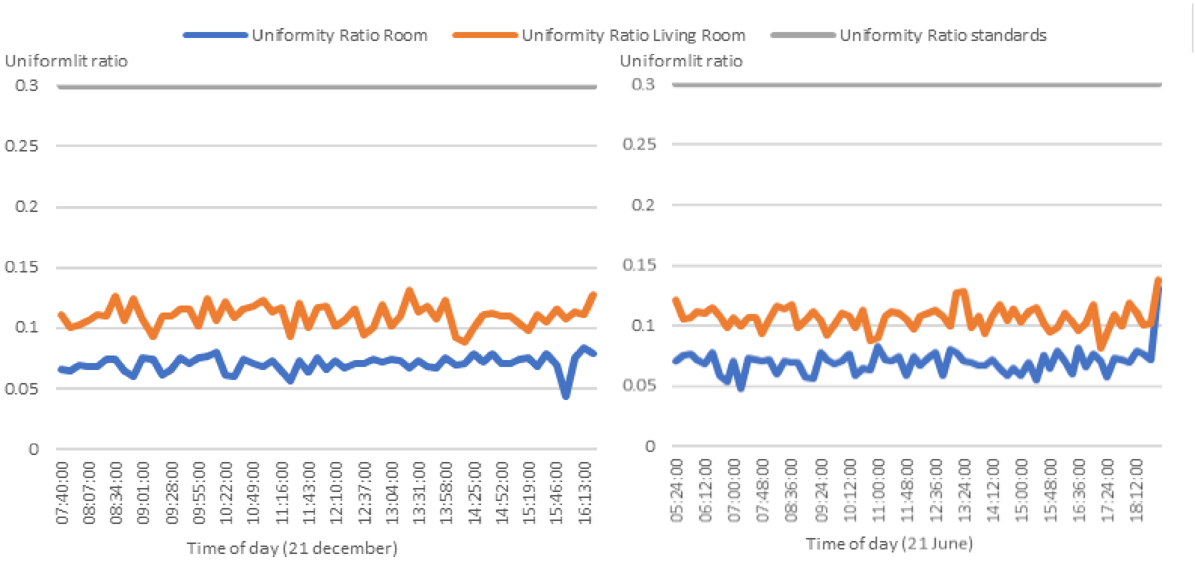
4.2.3 *Daylighting availability analysis*

The daylight analysis which carried out in the Room 1 and the living room in winter and in summer shows that the minimum illuminance for the living room reached maximum 20 lux in the summer and 10 lux in the winter, and the Room 1 reached in the summer 10 lux, while in the winter 5 lux, both zones have less than the minimum illuminance required by the BREEAM standard which is 30 lux at the worst point. Meanwhile, the optimal average daylight illuminance in the BREEAM standard is 100 lux, both zones have more illuminance levels than the standard, in summer, the living room reached 160 lux and the Room 1 reached 125 lux, while in winter both zones have less than the standard illuminance, the living room 87.5 lux, and the Room 1 62.5 lux. *Figure.39.* In addition, the results revealed that there is a uniformity problem in the zones as is illustrated in the graphs of *Figure.40.* which indicates that the uniformity of both zones in summer and winter is less than the uniformity value (0.3) which is required by the BREEAM standard.



illuminance in the winter (December), (a) illuminance in the summer (June)

Figure 39. Daylight illuminance comparison between bream standard and the Living room and Room 1



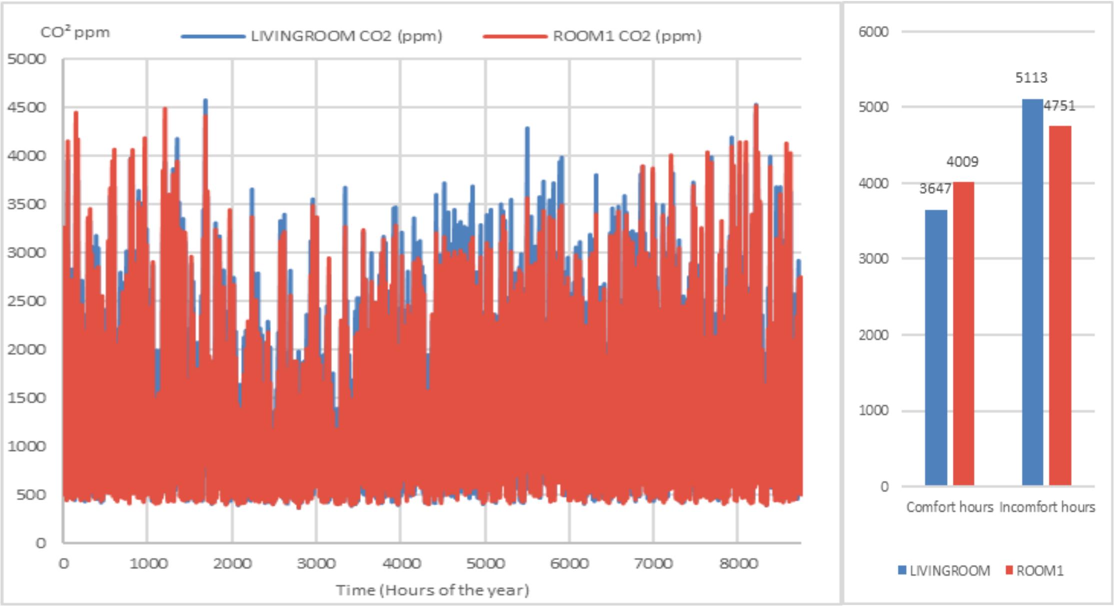
(a) uniformity in June, *(b) uniformity in December*

Figure 40. Daylight uniformity comparison between bream standard and the Living room and Room 1 results

4.2.4 Indoor air quality analysis

The CO2 concentration analysis is applied in Room 1 and the living room and the results are compared with the ASHRAE standard (American Society of Heating, Refrigerating, and Air-Conditioning Engineers), that determined the optimal level 1000 ppm of CO2 concentration. The results show that the living room has higher CO2 concentration levels than Room 1. The levels are varied between 500 to 4000 PPM as a maximum level for the whole year.

A reduction of the CO2 concentration is presented during windows were open, it reached 1000 to 2500 ppm, while when the windows were closed, the concentration exceeded the recommended value of 1000 ppm as it is indicated by the ASHRAE standard. Fig.8 illustrate the variation of the CO2 concentration in the whole year. The best hours of CO2 concentration is reached 3647 Hours and 4009 Hours in the living room and the room1 respectively in the whole year, while the CO2 concentration that is above the standard 1000 ppm is reached 5113 Hours and 4751 Hours in the living room and the room1. *Figure.41.* shows the CO2 concentration in the whole year together with the hours of comfort/discomfort.



(a) CO2 concentration in the whole year, (b) CO2 ≥1000 ppm

Figure 41. The CO2 concentration in the living room and Room 1 for the whole year.

4.2.5 Synthesis of the building energy diagnosis

The building energy diagnosis results generally are negative, and the residential building in the study context has not complied with the building energy design standards, there are many weaknesses in terms of building energy consumption, thermal comfort, visual comfort, and indoor air quality.

This study revealed that further design strategies are needed including; materials with high thermal performance to maintain the thermal comfort, the window configuration with its orientation, and accurate design that responds to the climate to ensure the best practice in visual performance and minimize the penetration of direct solar irradiation. Furthermore, accurate ventilation should be integrated to improve indoor air quality (IDQ). In this study, it can be concluded also that during the early design stage, these needed strategies should be considered especially for the hottest period which represents the longer period in the year (89% of cooling consumption is estimated).

5. AN OPTIMIZATION APPROACH FOR HIGH-PERFORMANCE BUILDING FACADE DESIGN

This section will present the optimization approach to explore reducing energy consumption and increasing thermal comfort performance, daylighting, and indoor air quality, through investigating different passive strategies of the building facade design; the wall structure, the opening dimensions, and the glazing type. as it is illustrated in *Figure.42.* that shows the simulation protocol of the optimization approach.

The optimazation approaches are supported by a dynamic simulation with the plug-in VI-suite that controls the external application Radiance and Energy Plus software. In addition, the Excel decision support tool was used to analyze and evaluate the optimization process.

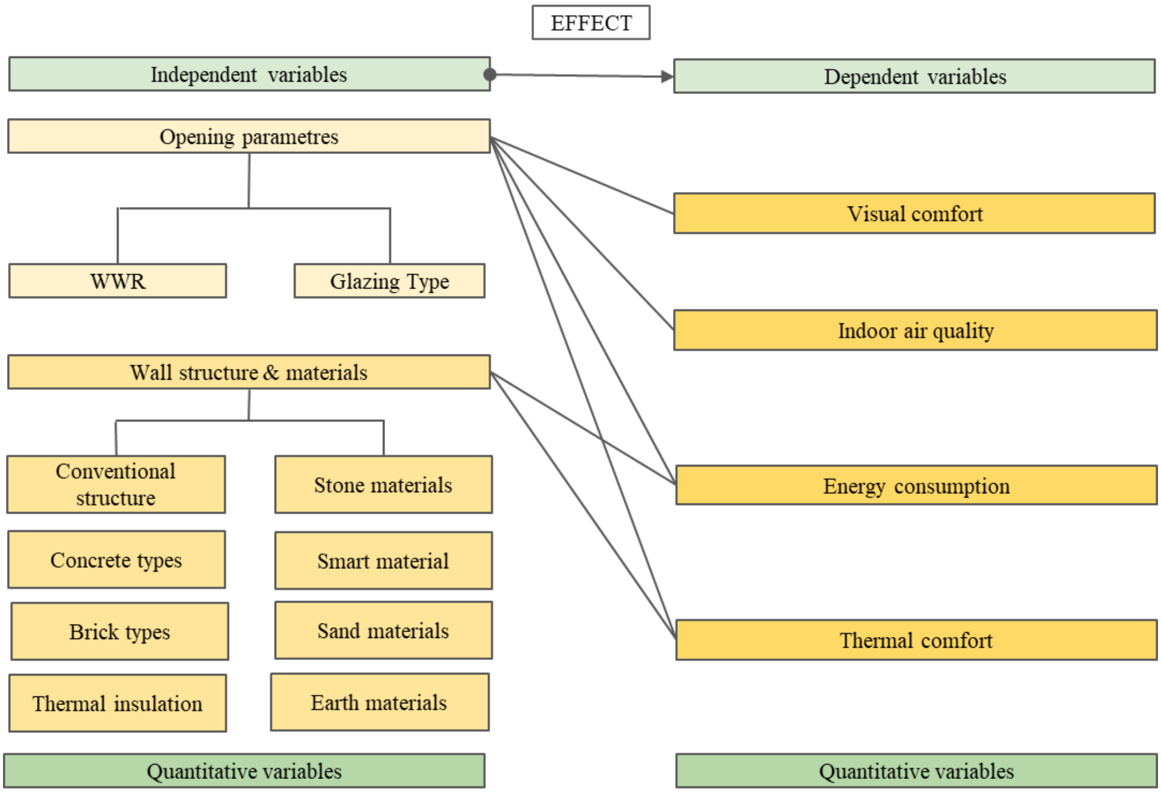


Figure 42. Simulation protocol for the optimization approach

To fulfill the research's main goal; as well as to have accurate control of the different dependent and independent variables of the simulation protocol, a virtual model has been designed based on standard room dimensions (3.00 m × 3.00 m × 4.30 m). All the different scenarios are applied in this model. *Figure.43.*

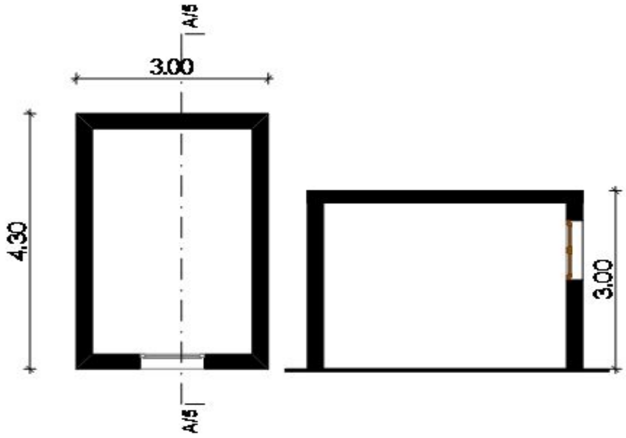
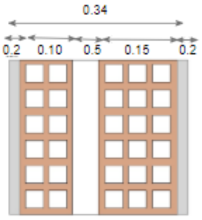


Figure 43. Virtual model

5.1 An optimization approach for the conventional wall structure

After creating the base model. The first step in the optimization process was choosing alternative materials and structures that have the potential of optimizing the thermal performance of the existing wall structure of the Algerian residential building. *Table.3.* shows the conventional wall structure and the materials used. Then, all the selected scenarios have been simulated, and the simulation results have been compared with the base model, the Excel tool was used for comparing the results with the base model.

Table 3. Conventional wall structure and materials

Wall layers	Shema	Image of the material
Cement mortar (0.2cm) Hollow brick (15 cm) Air gap (0.5cm) Hollow brick (5 cm) Plaster (0.2 cm)		

In this investigation, the wall structure and materials are changed; the overall obtained thickness of the wall is proposed to be (44 cm), adding (10 cm) between the two layers of the hollow brick, as well as proposing other materials to replace the air gap. All these materials are selected based on; their thermal characteristics, Ecological aspect, Availability aspect. And smart material. *Figure.44.*

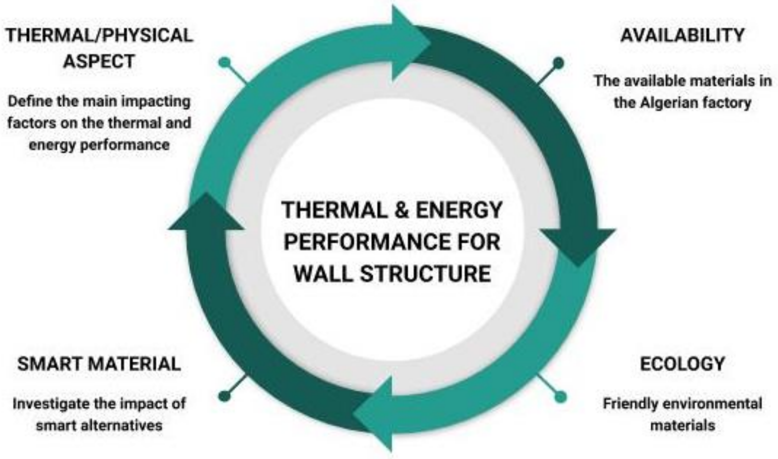


Figure 44. Selection criteria for the wall structure alternatives

As a result, these materials are including; various Brick types, Concrete, Stone, Sand, Phase change material (PCM),Earth materials and thermals insulations. The materials which are currently used and the potential to be used are systemized in *Table.4.* All the thermal characteristics (Conductivity, Density, Specific Heat) are defined based on (ASHRAE standard, Algerian thermal regulations).

Table 4. Thermal and physical properties of the investigated alternative wall material

	Thickness (m)	Conductivity	Density (Kg/m)	Specific heat
Solid Brick	0.15	1.00	1800.00	936.00
Honeycomb Brick	0.15	0.27	1700.00	1000.00
Unfired Clay Brick	0.15	0.90	2500.00	1426.00
Common Earth	0.15	1.28	1460.00	879.00
Rammed Earth	0.15	1.25	1540.00	1260.00
Hempcrete	0.15	0.09	330.00	2100.00
Sand Material	0.15	0.20	1500.00	700.00
Sandstone Block	0.15	1.83	2200.00	712.00
Limestone Block	0.15	1.30	2180.00	720.00
stone block	0.15	1.90	2350.00	792.00
Tuff Material	0.15	0.40	1400.00	800.00
Gravel	0.15	1.28	1460.00	879.00
Aerated Concrete Block	0.15	0.24	750.00	1000.00

Inner Concrete Block	0.15	0.51	1400.00	1000.00
M02 150mm Lightweight Concrete Block	0.15	0.49	512.00	880.00
M14 150mm Heavyweight Concrete Block	0.15	1.95	2240.00	900.00
Screed (Cement Mortar)	0.15	0.41	1200.00	2100.00
Expanded polystyrene (EPS)	0.15	0.04	15.00	1000.00
(PCM): DuPont Energain	0.15	0.16	850.00	2500.00
Rockwool	0.15	0.04	300.00	1000.00

5.1.1 Energy demand and thermal performance simulation results & discussion

The first step of the analysis is to compare the impact of the different wall structures on the cooling and heating demand. The various alternative materials are tested and compared to the base model (conventional wall structure), using a thermal dynamic simulation tool Energy Plus which is controlled by the Vi-suite Plug-in that uses the free open source Blend 3D. All the obtained results of the colling and heating demand are illustrated in *Figure.45. and 46.* The results showed that for both heating and cooling demand, the Rockwool and the Expanded polystyrene (EPS) are the best in terms of energy demand.

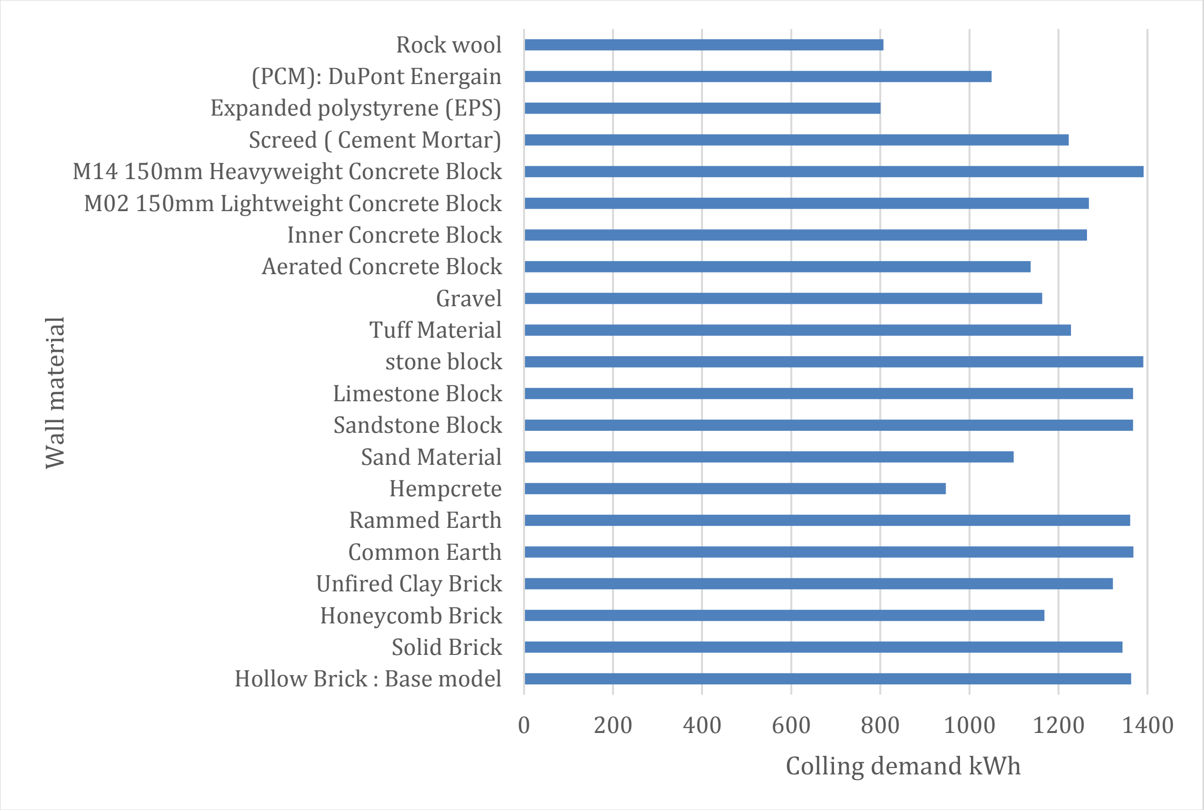


Figure 45. Cooling demand comparison for the different wall materials

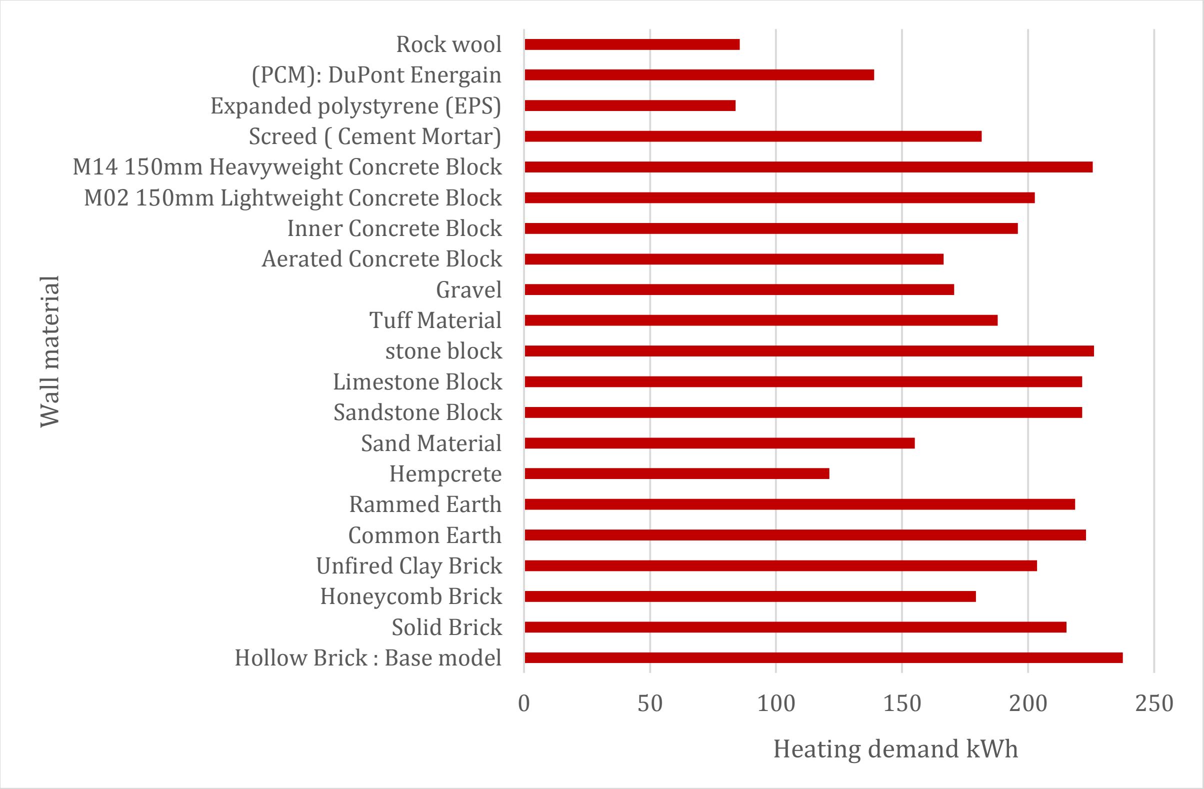


Figure 46. Heating demand comparison for the different wall materials

The analytical methodology adopted for thermal comfort is based upon the model of Fanger (PMV/PPD) that is described in the previous chapter. Using the potential of Energy plus software. In this study, the thermal comfort is categorized into the best comfort hours, and the unacceptable comfort hours, all compared in terms of the occupancy hours during the whole year (8760h), the Comfort range is determined in this context between (25 °C and 30 °C) which is represented in the scale (-1≥ PMV≤+1).

The results show that all the alternatives provide better thermal comfort than the base model. As well as the aerated concrete block has more comfort hours that the other alternatives. *Figure.47.*

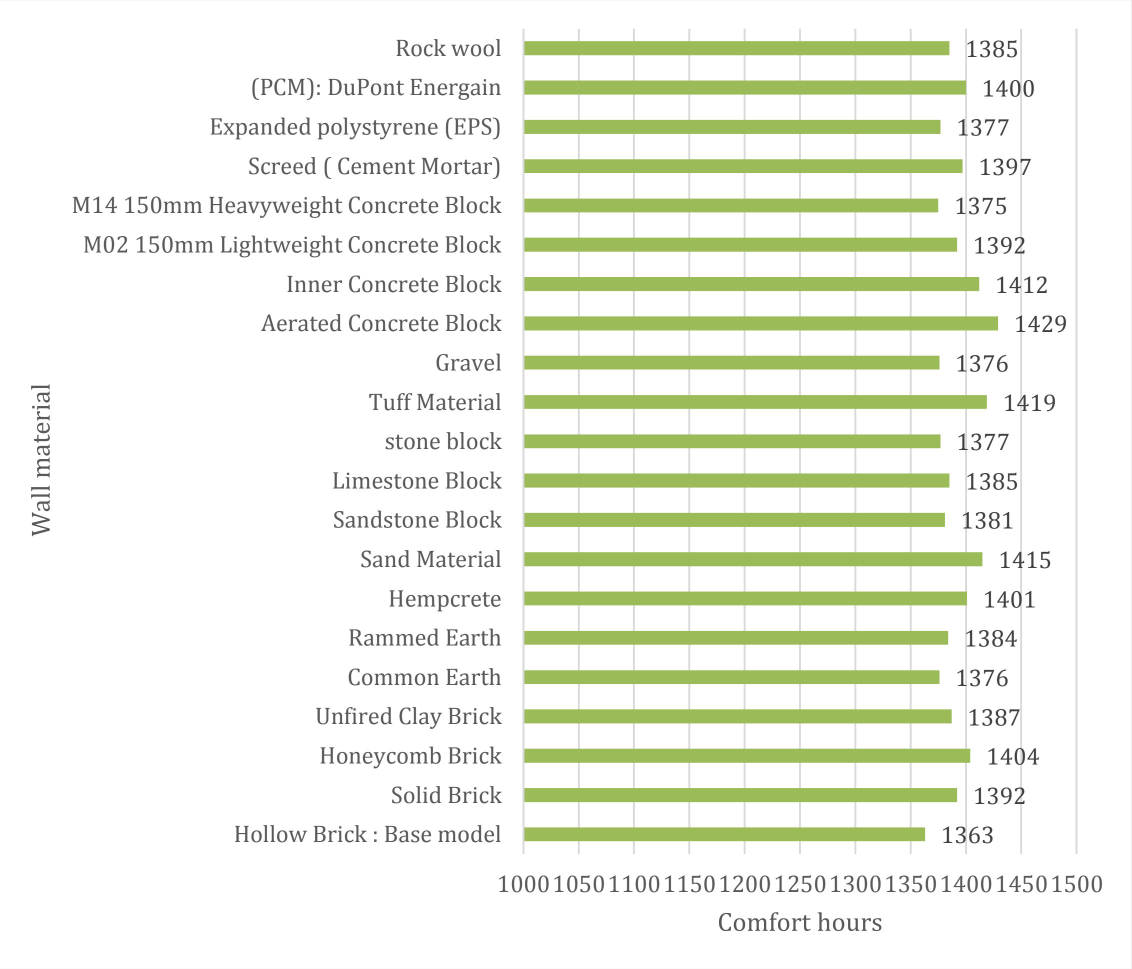


Figure 47. The best thermal comfort hours during the year (8760h) (-1≥ PMV≤+1).

For the unacceptable comfort hours, the results show that the heavyweight concrete block, Earth and Gravel, Stone block, and the Expanded polystyrene (EPS) have the highest unacceptable comfort hours in the year. *Figure.48.*

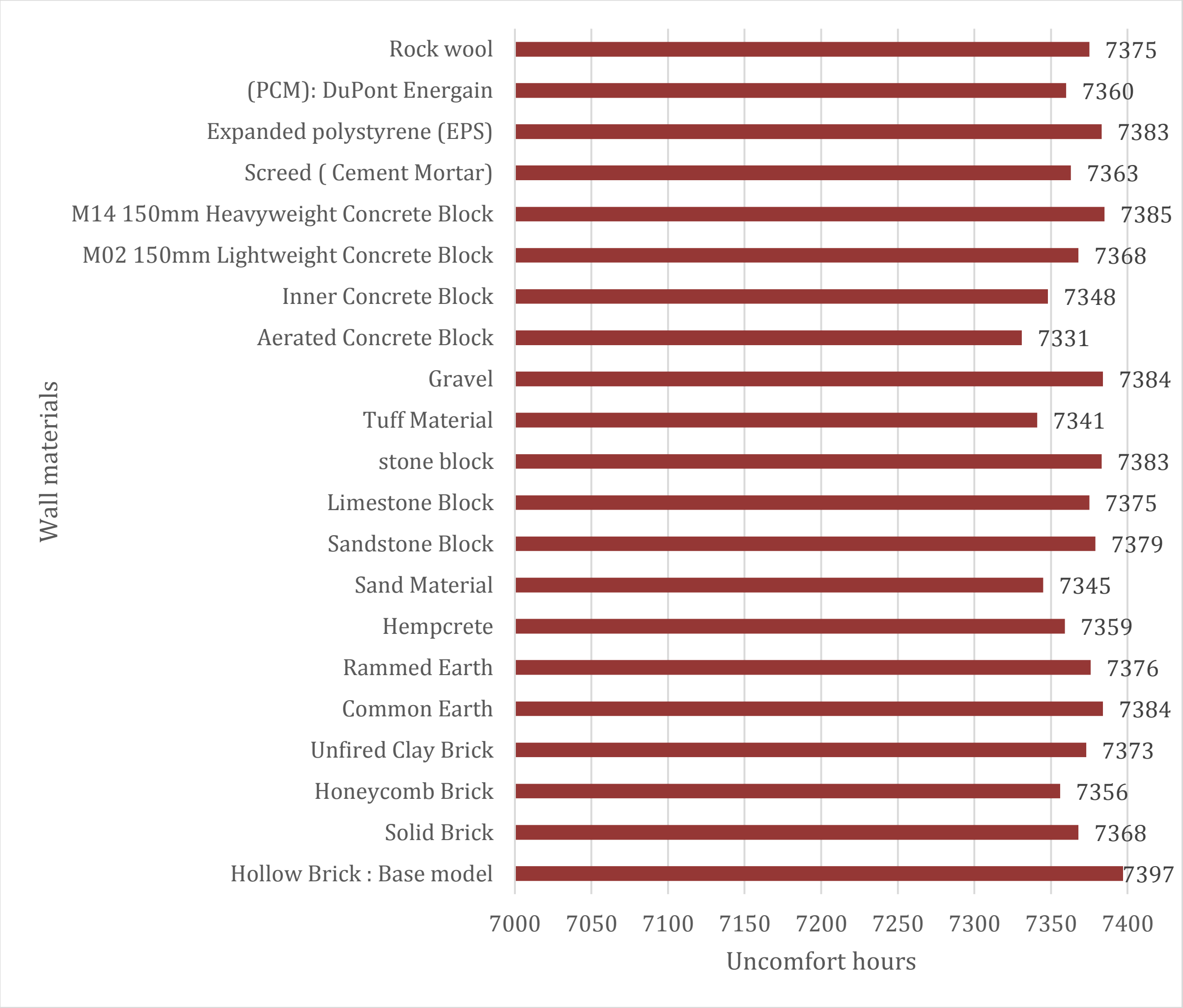


Figure 48. The unacceptable thermal comfort hours during the year (8760h)

The synthesis of the previous findings shows that the best material in terms of Energy demand did not provide the best thermal comfort hours. This contradiction is due to the thermal properties of the wall materials, as it is illustrated in *Table.5*. Similarity /unsimilarity of the color's degrees indicate the thermal relationship between the whole aspects; Thermal mass, Specific heat, Density, saved energy demand, and the optimize thermal comfort. *Figure.49.*

The analysis revealed that conductivity was the main influential parameter on the energy demand; the material that has the lowest thermal conductivity provides the highest heating and cooling energy saving. However, Thermal mass, Density, and specific heat proprieties of the materials did not provide a prediction for the material's thermal performance during the steady-state analysis.

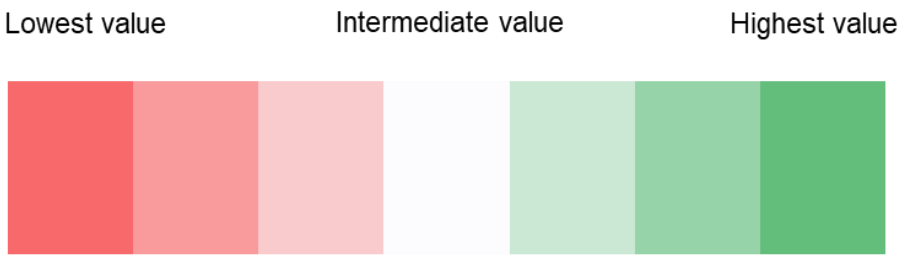


Figure 49. Colors degree indices for the thermal properties analysis

Table 5 Correlation between the material thermal properties and energy/thermal performance

Materials	Saved Heating	Saved Cooling	thermal comfort	Conductivity	density	specific heat	Thermal mass
Solid Brick	9.45	-7.41	11.38	1	1800	936	3032640
Honeycomb Brick	24.56	-19.47	6.91	0.27	1700	1000	3060000
Unfired Clay Brick	14.35	-8.91	8.77	0.9	2500	1426	6417000
Common Earth	6.17	-5.7	11.47	1.28	1460	879	2310012
Rammed Earth	8.01	-6.21	10.79	1.25	1540	1260	3492720
Hempcrete	49	-34.73	-1.77	0.09	330	2100	1247400
Sand Material	34.73	-24.22	5.06	0.2	1500	700	1247400
Sandstone Block	6.81	-5.78	11.38	1.83	2200	712	1890000
Limestone Block	6.81	-5.78	11.21	1.3	2180	720	2825280
stone block	4.84	-4.17	11.47	1.9	2350	792	3350160

Tuff Material	20.91	-15.39	11.3	0.4	1400	800	2016000
Gravel	28.17	-19.81	11.47	1.28	1460	879	2310012
Aerated Concrete Block	29.97	-21.59	8.43	0.24	750	1000	1350000
Inner Concrete Block	17.53	-12.91	11.72	0.51	1400	1000	2520000
M02 150mm Lightweight Concrete Block	14.7	-12.6	10.29	0.49	512	880	811008
M14 150mm Heavyweight Concrete Block	5.03	-4.15	11.05	1.95	2240	900	3628800
Screed (Cement Mortar)	23.57	-15.7	7.42	0.41	1200	2100	4536000
Expanded polystyrene (EPS)	64.67	-44.83	-9.02	0.04	15	1000	27000
(PCM): DuPont Energain	41.56	-27.63	2.78	0.16	850	2500	3825000
Rockwool	63.99	-44.38	-8.09	0.04	300	1000	540000

Figure.50. and 51. illustrate the above explication by a direct correlation between the conductivity and the energy demand; as well as the thermal mass and the thermal comfort.

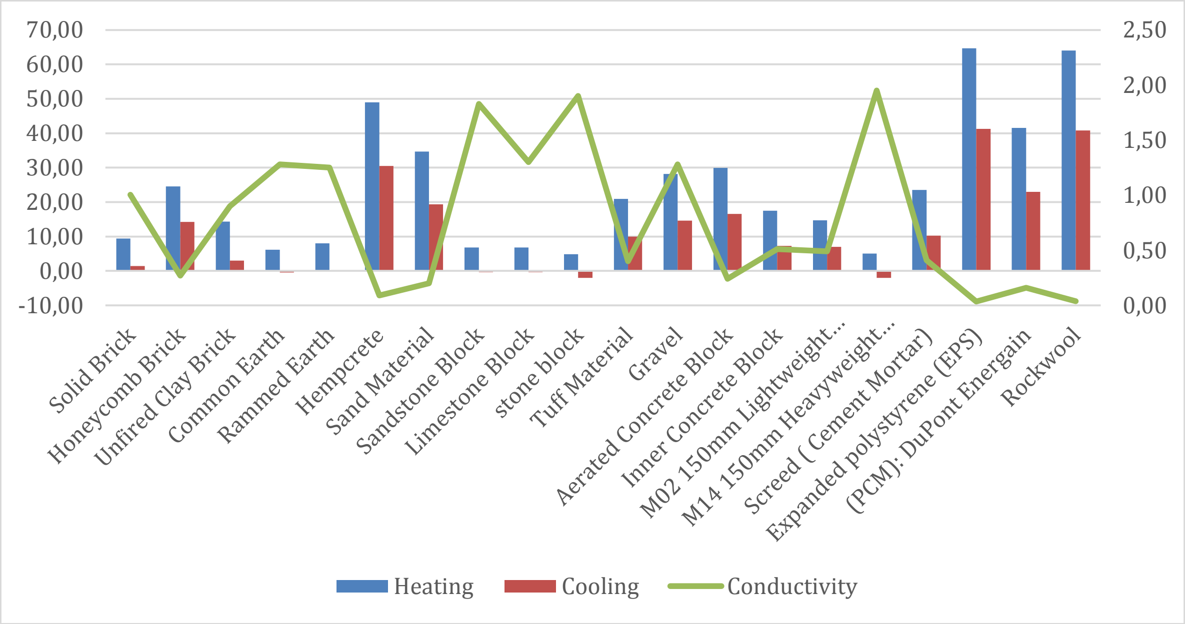


Figure 50. Correlation between the thermal mass and the thermal comfort

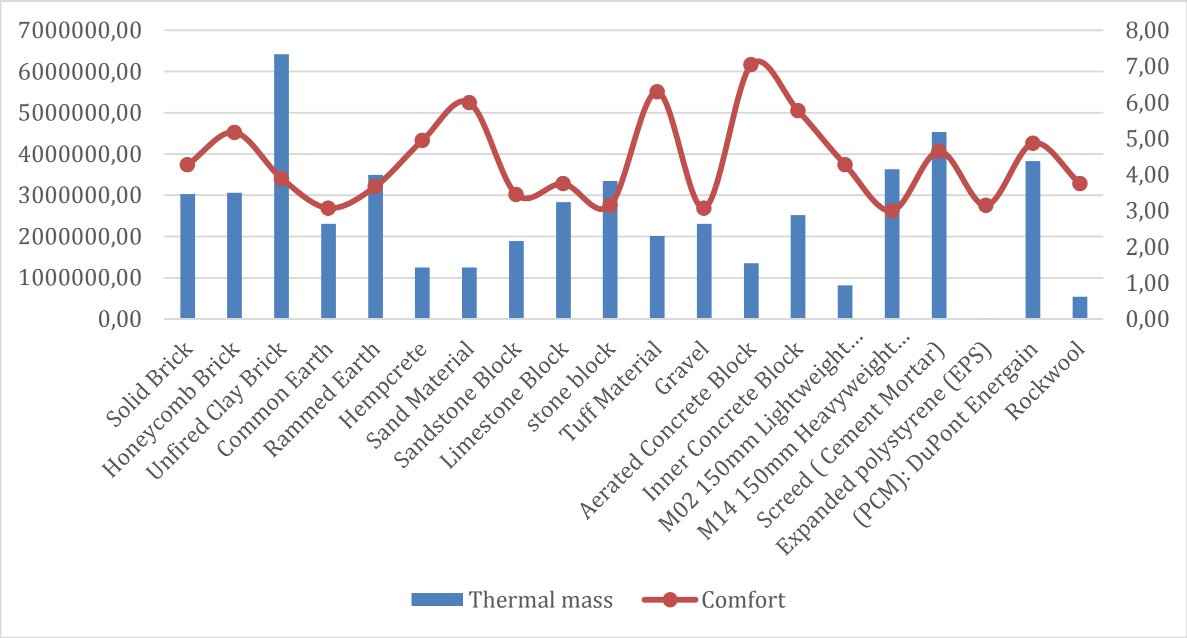


Figure 51. Correlation between the thermal conductivity and the energy demand

5.1.2 *Performance analysis of the different wall materials*

The performance analysis of the alternative wall materials is applied based on a comparison with the base model regarding the energy performance, and thermal comfort aspects in an interactive method.

The Rockwool insolation shows a significant reduction of the cooling energy demand reached 64 %, the heating demand 41%. Approximately the same results for the Expanded polystyrene (EPS) isolation. Followed by the Hempcrete; 49 % of cooling reduction, 31 % of heating demand reduction, the smart material PCM shows a reduction of 42 % of cooling demand, while, 23 % of heating demand. Furthermore, The different types of brick material results represent a variation on the reduction of the colling demand between 1 %, and 14 %, while the heating between 10% and 26%. Also, the Sand materials; the energy-reduced is between 10 %, 19% for cooling, 21%, 35% for heating. The concrete blocs' impact on the cooling demand is estimated between 10%, 16%. while for heating between 5%, 30%. Earth and Stone’s materials present a minimal reduction in the energy demand compared to the other alternatives, while it has the best increase in thermal comfort. Otherwise, Due to the severe climatic conditions in the hottest period, the thermal comfort is slightly optimized in the whole year for all the investigated wall materials, instead of the heavyweight concrete, the stone block, the Limestone, sandstone block, and the earth which have a negative impact on the thermal comfort and was the worst in terms of energy demand. *Figure.52.* illustrated the interactive performance comparison between the three evaluated aspects (Thermal comfort, Heating, and Cooling demand).

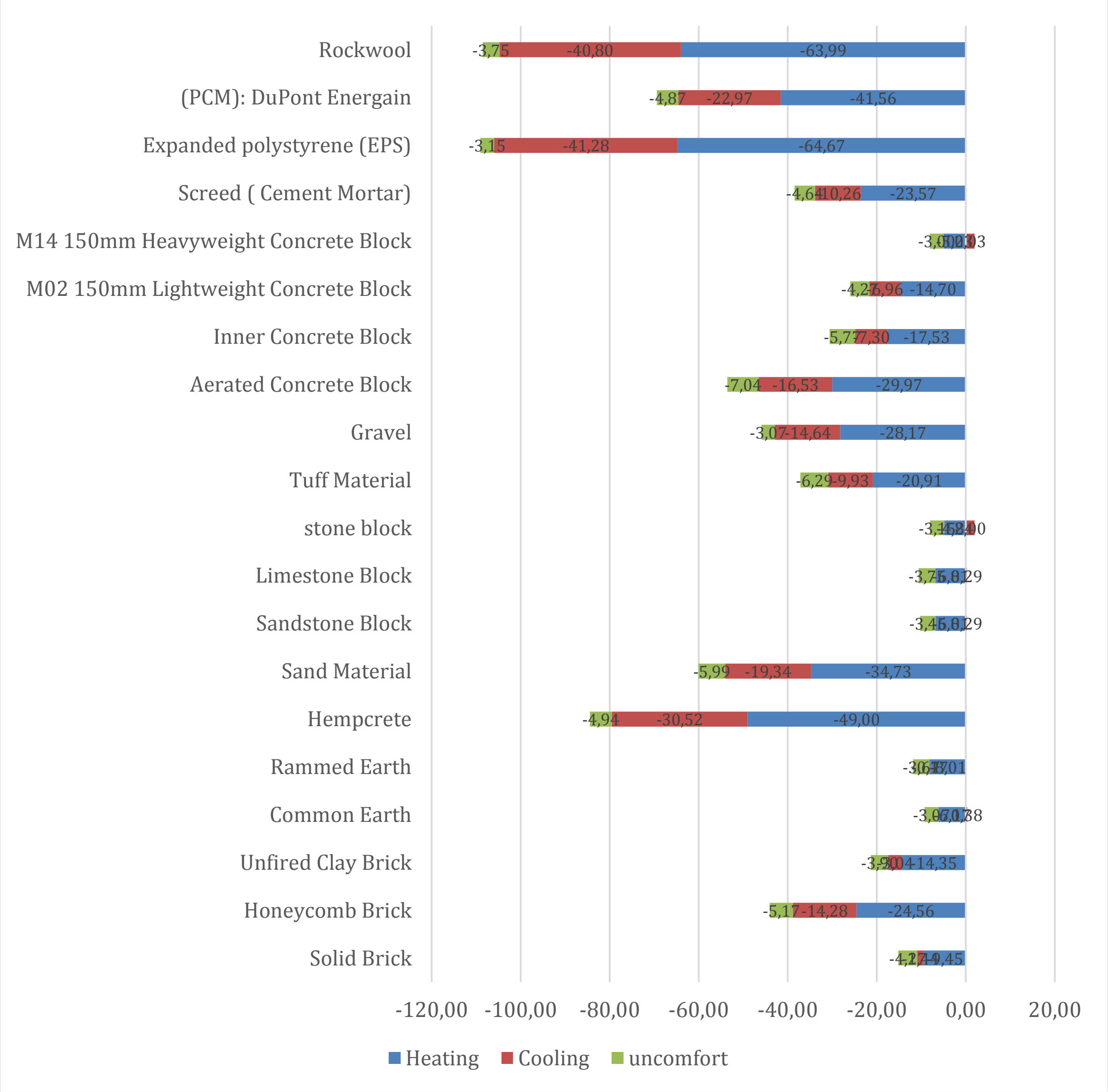


Figure 52. Interactive performance comparison between the different wall materials

5.1.3 Optimum material determination

The investigated alternatives showed contradictory results, in terms of thermal comfort and energy demand aspects. To determine the optimum material, this section presents a crucial step of the optimization approach, a virtual digital value from one to five was assumed to classify the importance of the aspects. Since cooling, energy demand represents 89% of the overall energy needed, while heating represents only 11% in the study context, the priority aspect has been determined as follows respectively; Cooling demand, Thermal comfort, Heating demand.

*Table.6.*illustrate the classification of the analyzed aspects, with the percentage of the energy Savion for each alternative.

Table 6 The percentage of reduction and increased energy consumption and thermal comfort in all scenarios.

	Cooling	Heating	Thermal comfort
Numerical values	5	1	4
Hollow Brick: Base model	Base variable	Base variable	Base variable
Solid Brick	-13.69	-7.41	11.38
Honeycomb Brick	-28.09	-19.47	6.91
Unfired Clay Brick	-18.36	-8.91	8.77
Common Earth	-10.56	-5.70	11.47
Rammed Earth	-12.31	-6.21	10.79
Hempcrete	-51.39	-34.73	-1.77
Sand Material	-37.78	-24.22	5.06
Sandstone Block	-11.17	-5.78	11.38
Limestone Block	-11.17	-5.78	11.21
stone block	-9.29	-4.17	11.47
Tuff Material	-24.61	-15.39	11.30
Gravel	-31.53	-19.81	11.47

Aerated Concrete Block	-33.24	-21.59	8.43
Inner Concrete Block	-21.38	-12.91	11.72
M02 150mm Lightweight Concrete Block	-18.69	-12.60	10.29
M14 150mm Heavyweight Concrete Block	-9.48	-4.15	11.05
Screed (Cement Mortar)	-27.15	-15.70	7.42
Expanded polystyrene (EPS)	-66.32	-44.83	-9.02
(PCM): DuPont Energain	-44.30	-27.63	2.78
Cavity wall insul 0.15mm	-65.67	-44.38	-8.09

As it is illustrated in *Figure.53.* EPS and Rockwool (0.15cm) was the best alternative nearly 283 points (P) are obtained, followed by Hempcrete 221 P, PCM 176 P, Sand 155 P, Aerated concrete block 141 P, Honeycomb brick 117 P, Gravel 114 P. The reset of the material obtained less than 100 points. It is assumed to be the worst alternatives.

Finally, since the Rockwool is more ecologic material than the EPS isolation. Thus, Rockwool is the best alternative for this investigation.

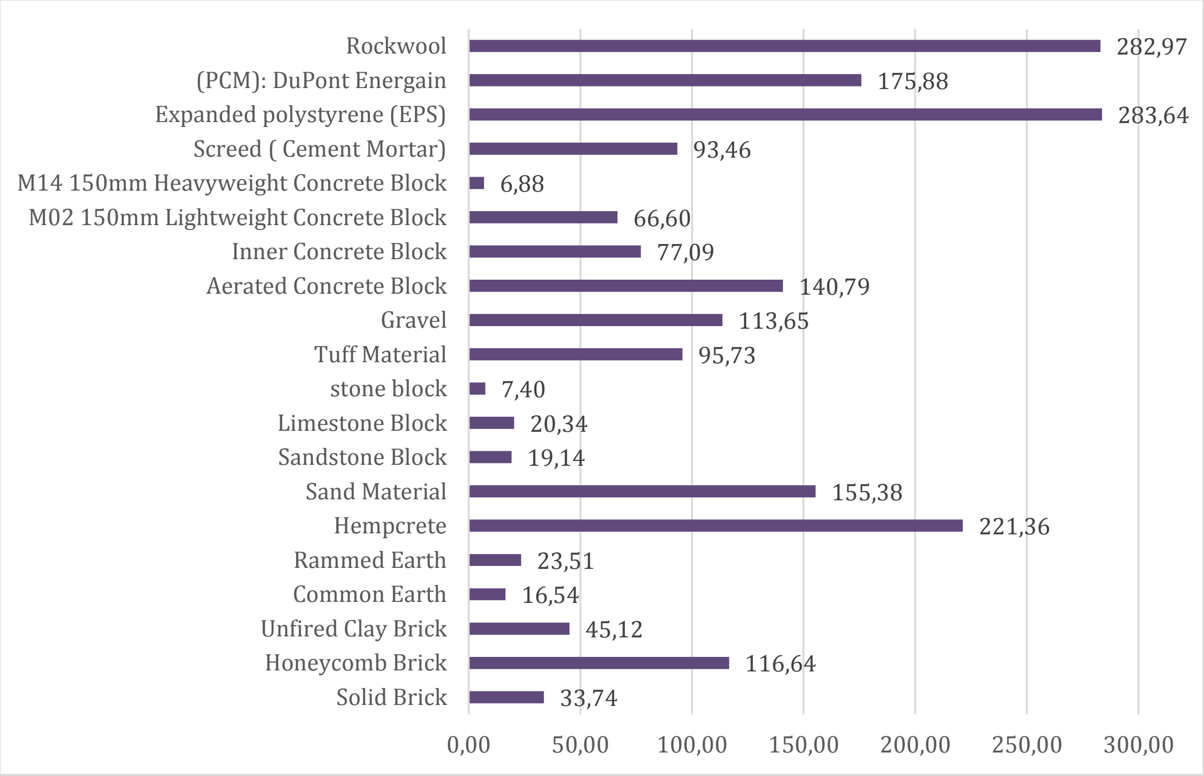


Figure 53.Performance classification of the selected materials

5.2 An optimization approach for the Opening parameters

Windows configurations in the building facade distinguish the energy use and visual comfort patterns in buildings; they provide an internal environment for lighting transmission and allow visual communication with outdoors for the occupants of the building, the airflow, direct and indirect sunlight. In hot and dry climates, it is hard to combine these functions in a balanced way. Additionally, the building design is becoming more dynamic and complex in this severe climate regions, the design of the openings, which is the main source of the heat gain, becomes more complex to provide visual comfort and thermal comfort with less energy consumption. A more detailed and comprehensive analysis of the different design factors for windows is required. Furthermore, the Window to wall ratio (WWR) is an important factor that impacts the heat transmission, solar gains in winter, and the solar penetration in summer. As it is illustrated in the research literature review, in hot and dry regions (20% to 40%) is determined as the best WWR for this climate zone in terms of energy consumption to avoid overheating.

In this step of the optimization approach, presents an evaluation of the Opening parameters and the facade orientations impact on the building energy demand, thermal comfort, daylight availability, and indoor air quality (IDQ) in an interactive method to improve these aspects.

Besides, it defines the main decisive aspects that have the potential to determine the best window dimensions and glazing material type for each orientation. The window to wall ratios (WWR) 20 %, 25%, 30%, 35%, 40%, and 3 different glazing types are investigated; Single pane glazing (SG) which is widely applied in the residential building in Algeria, then it is compared with the Double pane glazing (DG), and the Tripe pane glazing (TG) as alternative solutions. All the properties of the applied glazing are summarized in Table.7. The overall investigated scenarios in this step are 120.

Table 7 Glazing Properties

Glazing type	Clear 3mm
Optical Data Type	SpectralAverage
Thickness	0.003
Solar Transmittance at Normal Incidence	0.837
Front Side Solar Reflectance at Normal Incidence	0.075
Back Side Solar Reflectance at Normal Incidence	0.075
Visible Transmittance at Normal Incidence	0.898
Front Side Visible Reflectance at Normal Incidence	0.081
Back Side Visible Reflectance at Normal Incidence	0.081
Infrared Transmittance at Normal Incidence	0
Front Side Infrared Hemispherical Emissivity	0.84
Back Side Infrared Hemispherical Emissivity	0.84
Conductivity	0.9
Dirt Correction Factor for Solar and Visible Transmittance	1
Solar Diffusing	No
Gaz type	Air
Thickness	0.014

5.2.1 Simulation results of the energy demand; the impact of orientations, WWR, Glazing type

The first evaluation is applied with a Single pane glazing as a fixed variable, and the variant variables are the orientation and the WWR. as it is illustrated in *Figures 54 and 55*. For cooling demand in all over the orientations the more the percentage of the window is high, the cooling demand is increased. Otherwise, the highest cooling energy demand is reached when the facade orientation has faced the South-West (SW), followed by the South-East (SE), South (S), West (W), East (E), North-West (NW), North-East (NE), North (N) which has the minimum cooling demand.

Moreover, The South facade window is the best orientation in terms of Heating demand, and it has approximately the same demand as the South-East, and the South-West, followed by the West, the South, The Nouth-West, The North-East, The North. As a result, generally, the orientations that have the best results on the cooling demand, are the worst on the heating demand. For the WWR, facing the orientations; South-West, South-East, East, and West, the high WWR the less heating is needed, due to the high heat gain that impacted by the amount of the solar radiation in these orientations. While at the south orientation, the WWR had no impact on the heating demand, the differences are almost nominal between the different WWR. However, N orientation, NE, NW the heating demand is higher when the WWR is increased.

Figure 54. Different WWR and orientations impact on cooling demand; case SG

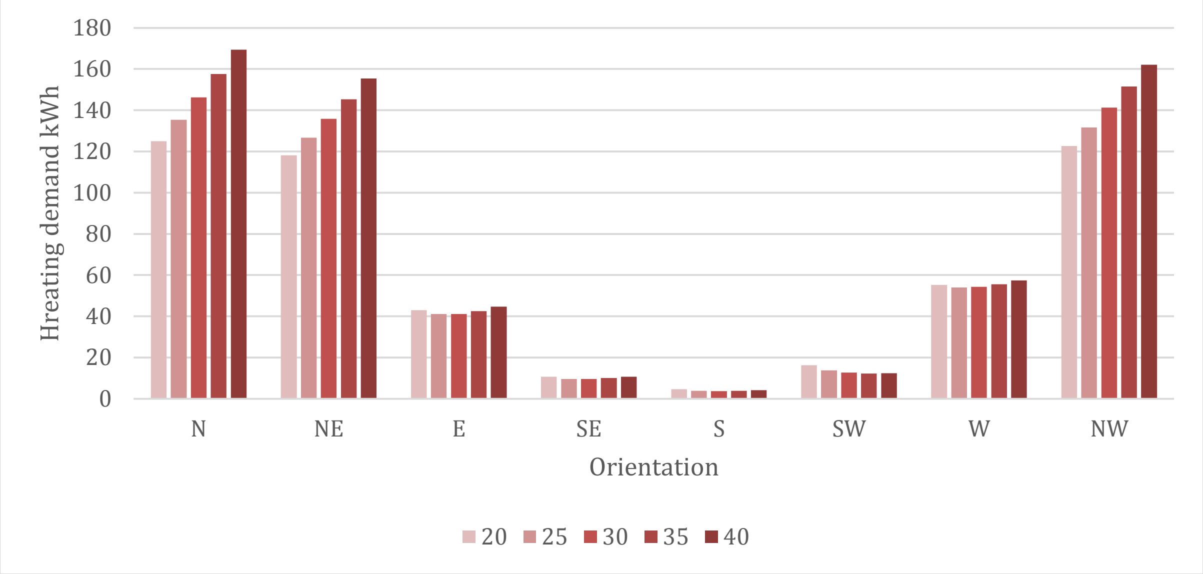


Figure 55.Different WWR and orientations impact on heating demand; case SG

Furthermore, the Simple pane glazing (SG) is compared with the two glazing type proposed in this study; double-pane glazing DG, and Triple pane glazing TG. The overall results revealed that applying DG or, TG decreases both cooling and heating demand compared with the SG, while the TG was the best alternative. Moreover, the glazing type efficiency is impacted by the orientations. For colling demand; the glazing type had a nominal impact in the North orientation, while in the S, SW, SE orientations the reduction was higher followed by E, W, NW, and NE. The results are illustrated in *Figures 56 and 57*.

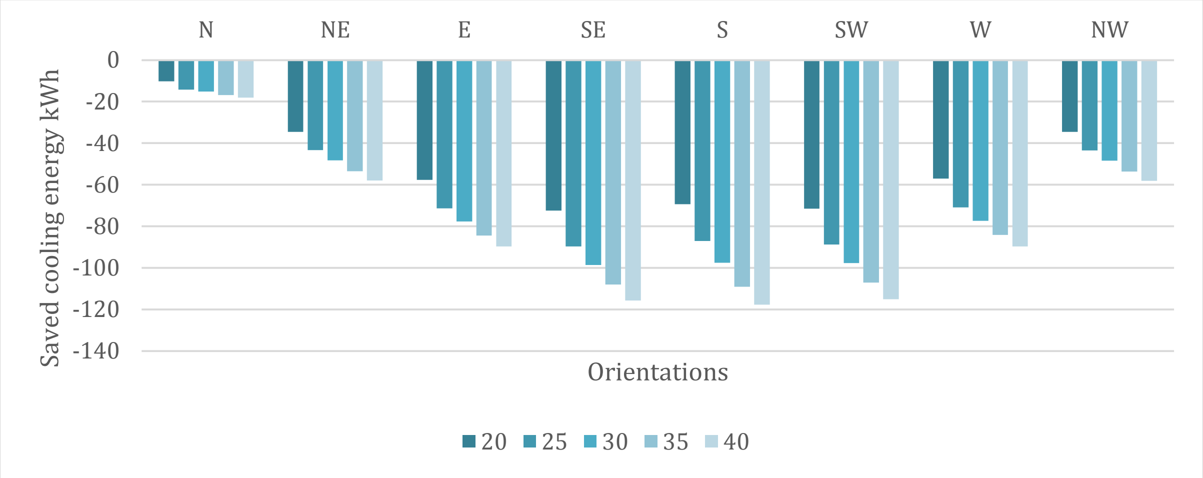


Figure 56. The cooling demand after the application DG

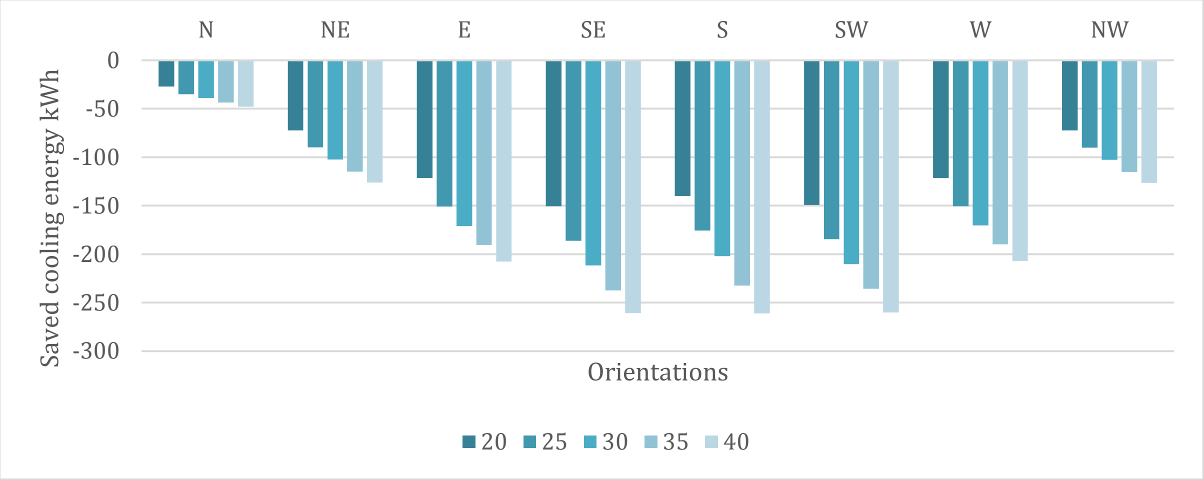


Figure 57. The cooling demand after the application TG

The opposite results are obtained for the heating demand; the glazing type had a nominal impact in the S, SE, and SW orientations, while the N the heating was significantly reduced flowed by the NW, NE, W, E orientations. *Figures 58. And 59.*

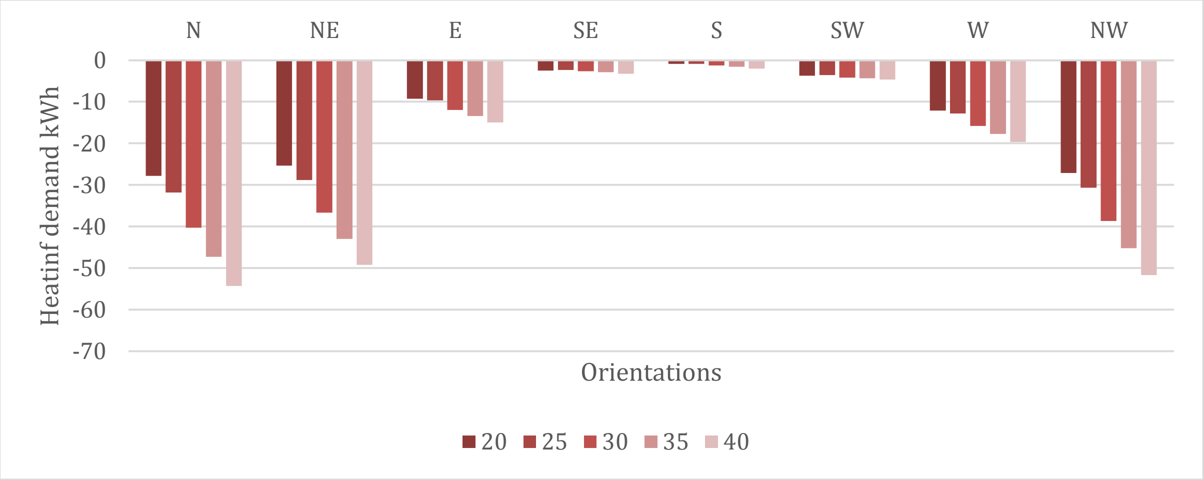


Figure 58. The heating demand after the application DG

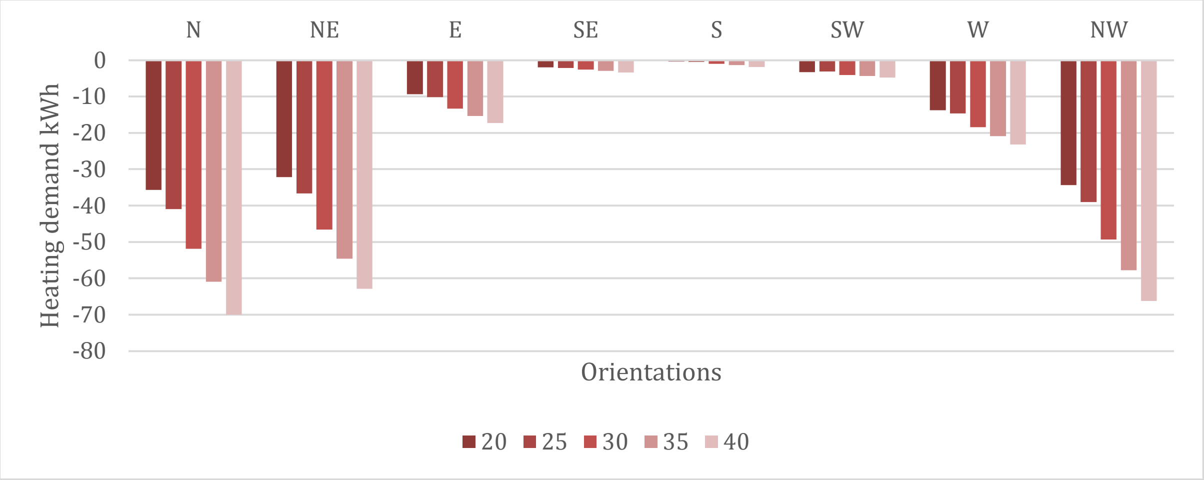


Figure 59. The heating demand after the application TG

5.2.2 *Simulation results of the thermal comfort; the impact of orientations, WWR, Glazing*

A comparison of thermal comfort for the different WWR and orientations when applying SG is illustrated in *Figure.60.* the results show that the S orientation provides the best results in terms of comfort hours in the whole year (8760h) which are between the $-1 \geq PMV \leq +1$, followed by the SE, SW, N, W, NE, NW, E which represent the highest comfort hours in the year.

Furthermore, The WWR has a nominal impact on the thermal comfort hours in all the orientations, instead of the South that represents a significant reduction in thermal comfort when the WWR is higher. The comparison between the thermal comfort hours and the WWR in the orientations N, NE, NW indicate that since the WWR is higher the comfort hours are reduced, the inverse for the orientations SE, SW, W.

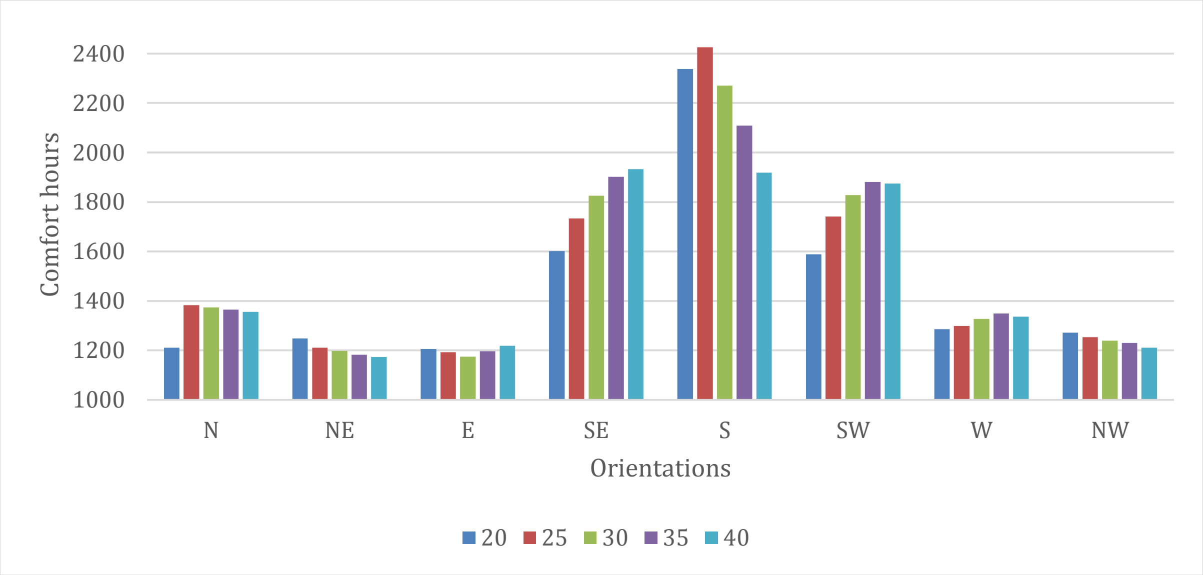


Figure 60. Comfort hours during the whole year (8670): case SG

After applying the double and triple pane glazing as is illustrated in *Figures.61. and 62*. The results show that the comfort hours has been increased depend on the orientation and the WWR. However, the glazing type improves nominally the thermal comfort in all the orientations.

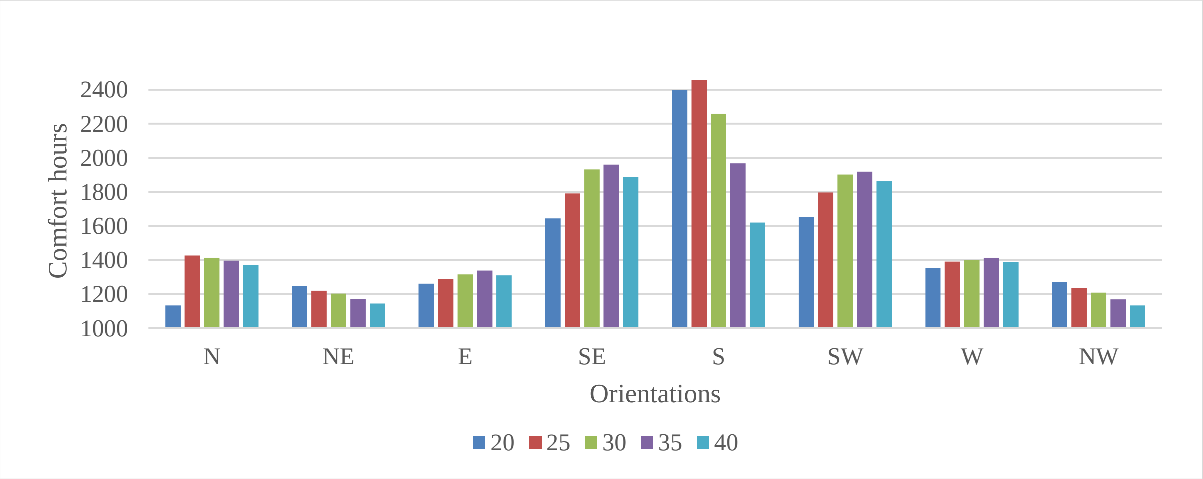


Figure 61. Comfort hours during the whole year (8670): case DG

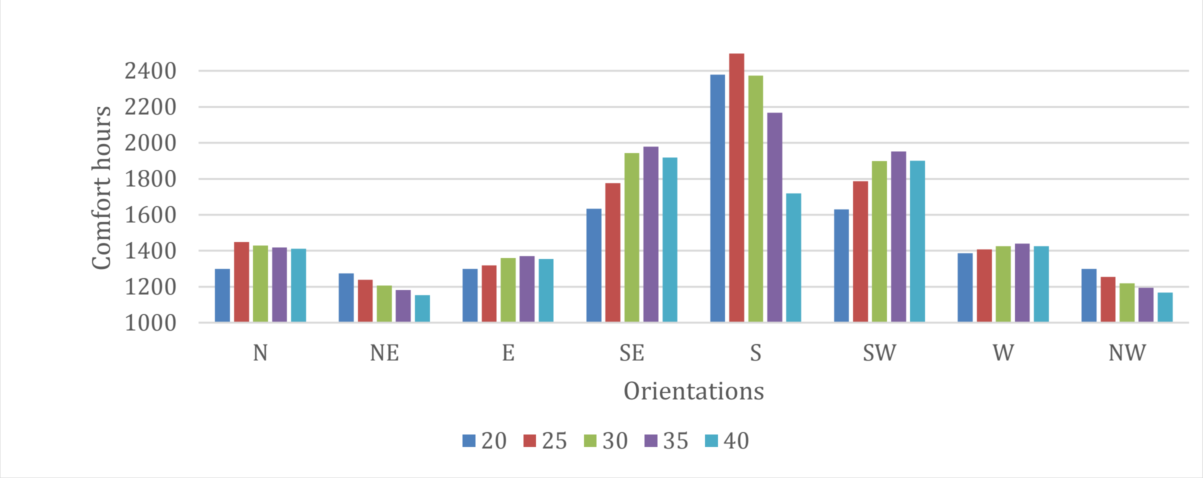


Figure 62. Comfort hours during the whole year (8670): case TG

5.2.3 Simulation results of the Daylight availability; the impact of orientations, WWR, Glazing

Daylighting studies in buildings play a major role in indoor environmental investigation and can be conducted at the early stages of building design to ensure best practice in visual performance, comfort, health for building occupants. Window parameters significantly effects daylighting performance. The objective of this step is to investigate the impact of the window's orientation, glazing type, and WWR on visual comfort. The empirical methodology has been used to fulfill this aim through a lighting simulation using Vi-suite add on Blender 3D software that controls the external application Radiance. To simulate the daylight availability; illuminance (lux) levels are evaluated in the virtual room. This factor indicates the total luminous flux incident on a surface, per unit area. It is a measure of how much the incident light illuminates the surface.

Figure.63. Illustrate the illuminance levels in the whole year, it indicates the hours in which 100 lux or more is provided naturally in the zone. The results revealed that the E orientation provides more daylight availability followed by W, NE, SE, SW, NW, S, N. Furthermore, The hight the WWR the high daylight availability is provided, WWR of 40% is the best for all the orientations.

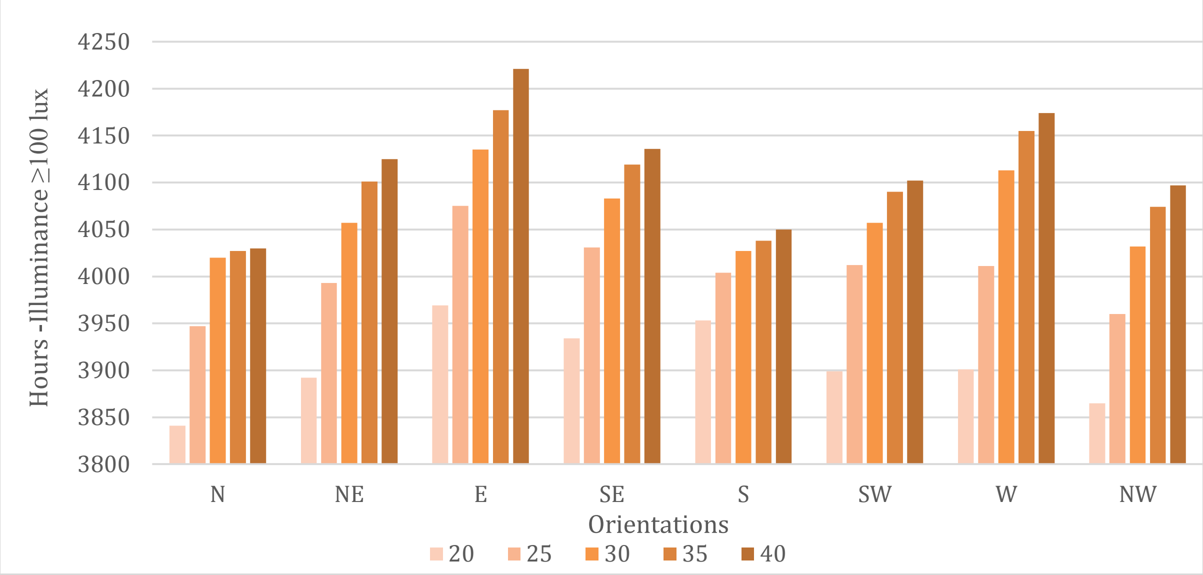


Figure 63. Daylight availability comparison between the different WWR and orientation: Case SG

*Figure64. and 65.*iIllustrate the glazing type impact on the illuminance levels in the whole year (8760 h). The results show that increasing the number of glazing panes minimizes slightly the daylight availability. The simple pane glazing shows the best results in terms of Ilumunance (lux) levels compared to the SG and TG.

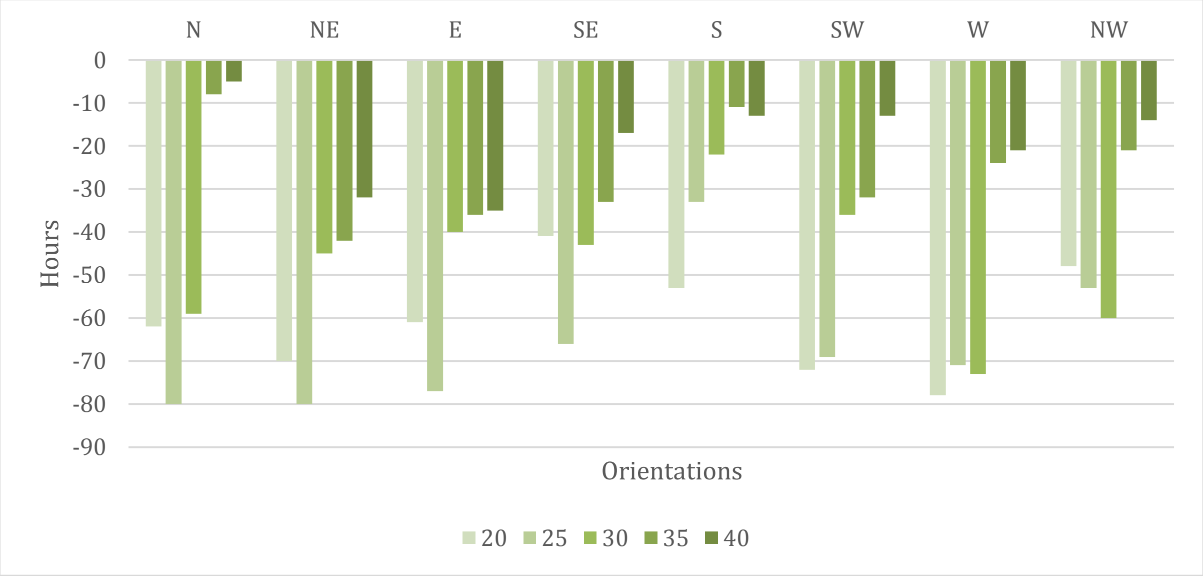


Figure 64. Daylight availability comparison between the SG and DG

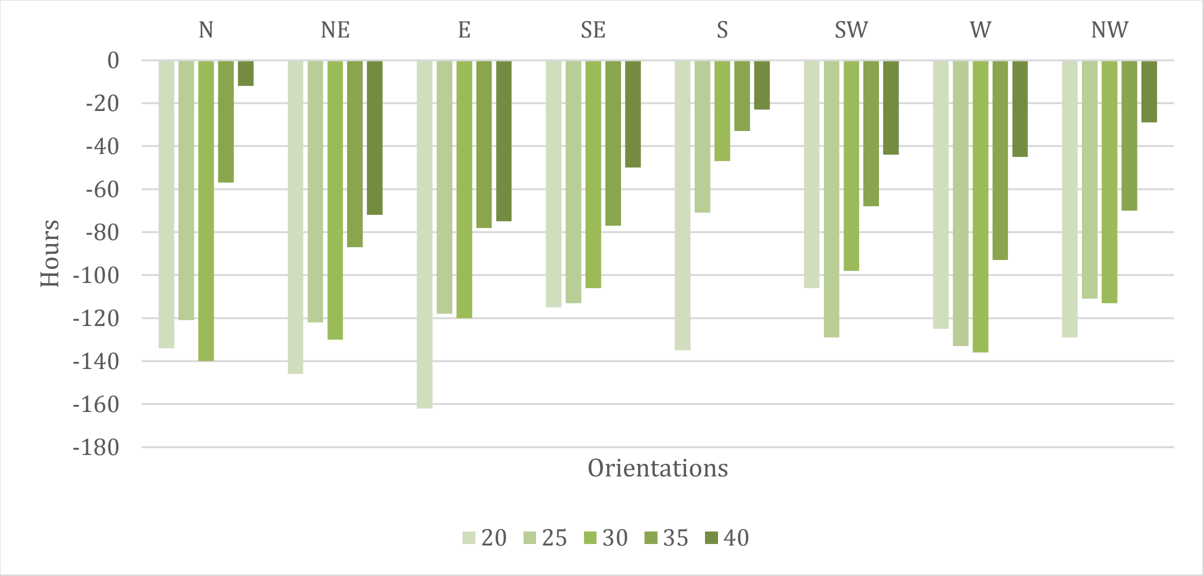


Figure 65. Daylight availability comparison between the SG and TG

5.2.4 Simulation results of the carbon dioxide (CO2) level

The building façade design plays an important role in providing effective ventilation configuration and strategies, to provide efficient Indoor Air Quality (IQA), which usually expressed by the Carbon Dioxide (CO2) concentration in the space and the air ventilation rate. The connection between indoor air quality and indoor CO2 concentration originates from the fact that high CO2 concentrations reduce our cognitive performance, health, comfort, and productivity. The recommended level of the CO2 concentration in the indoor space should be ≤ 1000 ppm as it is defined by ASHRAE.

In this step, the impact of WWR on the concentration of CO2 was assessed, the opening and closing of the opening are inserted based on a normal family house activities.*Figure.66.* illustrate the hours of the CO2 levels when they are ≤1000 ppm in the whole year. The results show that the hours that exceed the recommended value of CO2 concentration during the year decreased significantly when the WWR is higher. The WWR =40% is the best in providing better indoor air quality compared to the other alternatives. This is due to the higher ventilation rate that can be provided during the opening of a wider window surface.

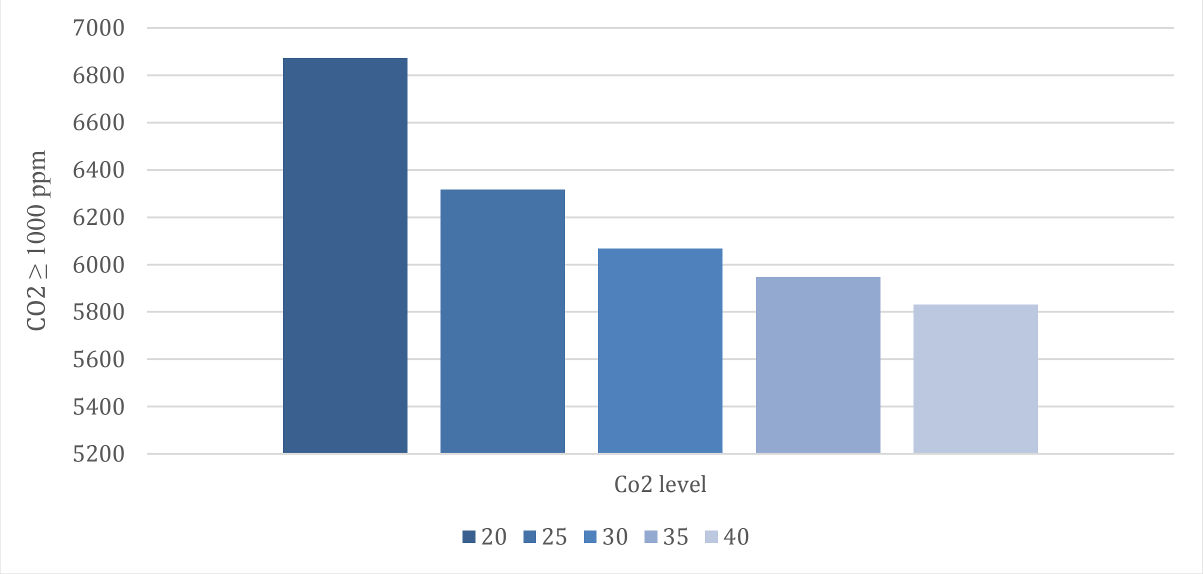


Figure 66. WWR impact on the CO2 level >1000 ppm during the whole year (8760h)

5.2.5 *Performance analysis of the best window parameters*

After analyzing the impact of the opening parameters, it was found that the effect of the WWR and glazing type varied depending on the orientation and the desired comfort; (daylight, thermal comfort, energy demand, and IDQ). Therefore, this section presents a holistic performance comparison between all the analyzed aspects. It is summarised in *Table.8.* which illustrates the results of the best WWR with the glazing type for each desired comfort. Thus, the WWR for providing better thermal comfort is 20% in N, NE. NW orientations, 35% in E, SE, SW, W. In the S 25% was the best. The WWR for the heating demand is 20% in N, NE. NW orientations, 35% in E, 30% in SE, 40% in SW and W orientations. The 3 pane glazing was the best for all the orientations, while the S orientation the simple pane glazing was optimal with 40% WWR. The cooling demand as it is revealed in the previous results, it is increased since the WWR is higher. At this end, 20% was the best alternative for all the orientations with 3 pane glazing. Otherwise, for the daylight availability and indoor air quality, when the WWR is higher these aspects are better provided. 40% of WWR was the best for all the orientations. The Figure illustrates all the obtained results

Table 8 The optimum WWT and glazing type for each aspect

		Thermal comfort H							
	WWR	N	NE	E	SE	S	SW	W	NW
TG	20	1478	1275	1300	1634	2380	1630	1386	1299
	25	1449	1238	1319	1776	2496	1787	1408	1254
	30	1430	1206	1359	1943	2374	1899	1425	1220
	35	1418	1181	1370	1979	2167	1952	1439	1194
	40	1412	1154	1355	1919	1720	1900	1426	1168
DG	WWR	Heating demand kWh							
	20	96.10498	91.73307	33.19468	7.98396	3.608888	12.4981	42.87786	94.68289
	25	99.18169	93.70474	29.38821	6.69218	2.837367	9.675221	39.44223	96.84438
	30	102.7308	96.2115	27.56001	6.51206	2.420521	8.079092	37.42023	99.72205
	35	106.8683	99.22353	27.29763	6.679795	2.127906	7.440422	36.50545	103.1631
	40	111.5119	102.6858	27.89395	7.05038	1.864942	7.208603	36.35548	107.0413
TG	20	87.84358	84.51907	33.05082	8.717704	4.295058	13.13009	41.37844	87.03976
	25	88.79841	84.53064	28.56535	6.858816	3.276879	10.01058	37.28385	87.1566
	30	90.19872	85.17091	26.05561	6.516458	2.762613	8.214975	34.6674	88.04776
	35	92.06218	86.26426	25.18613	6.631712	2.345361	7.405618	33.16598	89.4283
	40	94.46393	87.74081	25.2686	6.944211	2.009512	7.086394	32.52231	91.26189
	WWR	Cooling demand kWh							
TG	20	955.5847	1103.614	1287.801	1385.429	1307.689	1385.522	1291.244	1104.414
	25	1002.701	1187.934	1433.499	1550.905	1451.242	1550.091	1436.87	1189.106
	30	1049.612	1272.079	1580.588	1716.918	1596.582	1715.151	1583.188	1273.546
	35	1096.486	1355.938	1728.582	1883.228	1744.708	1880.964	1729.692	1357.682
	40	1143.373	1439.527	1876.846	2050.891	1901.427	2047.853	1876.224	1441.775
		Daylight availability lux							
SG	20	3841	3892	3969	3934	3953	3899	3901	3865
	25	3947	3993	4075	4031	4004	4012	4011	3960
	30	4020	4057	4135	4083	4027	4057	4113	4032
	35	4027	4101	4177	4119	4038	4090	4155	4074
	40	4030	4125	4221	4136	4050	4102	4174	4097

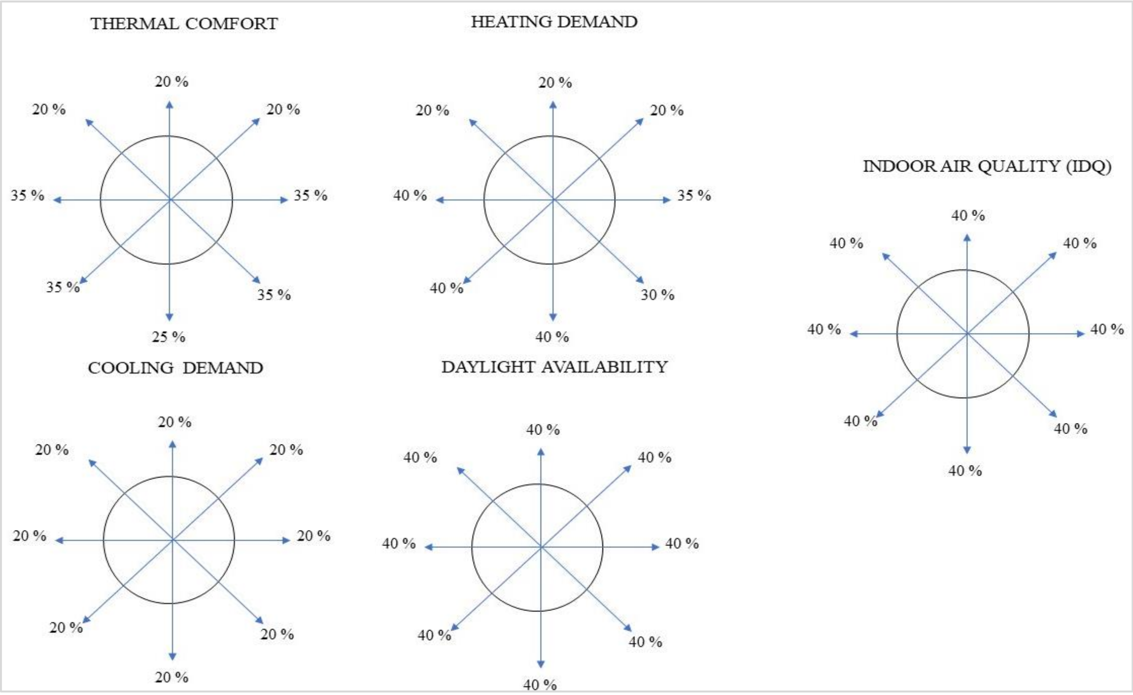


Figure 67. Optimal window to wall ratio for each orientation

5.2.6 Holistic comparison for optimum balance between the different indoor comfort's aspects

To determine the optimum opening design solution that has the potential to balance the different aspects (Thermal comfort, indoor air quality, daylight availability, heating, and cooling demand), a comparison between the different WWR and glazing types with a base model reference is applied in each orientation. The base model Opening parameters are defined based on the existing building design that was identified and diagnosed in the previous section, the WWR in the base model was 6% with single-pane glazing. The different results of the simulation of the base model are summarized in (*Appendix 1)*. These results are compared with the different alternatives. (*Appendix 2)* illustrate the comparison results that represent the percentage of increasing/ reduction of the thermal, visual comfort, energy demand, and IDQ.

Then, The obtained results were multiplied by the numerical values that define the aspect priority. *Table .9.* Shows the classification of each aspect.

The holistic comparison results are illustrated in *Table.10.* The green color indicates the solutions that gain the highest points. This means the best solutions. The results revealed that for all the orientations the 3 pane glazing was the best solution. The WWR in the N façade is found to be 25 % together with the S, SE, SW, NW, while NE, E, W the WWR 20 % is the best.

Table 9 The classification of the indoor comfort requirements in the study context

Comfort aspect	Numerical value
Thermal comfort	4
Indoor air quality	6
Daylight availability	3
Heating demand	2
Cooling demand	5

Table 10 Holistic comparison between the different aspects

WWR	Simple glazing pane							
	N	NE	E	SE	S	SW	W	NW
20	-27.4996	-93.6624	-118.051	31.60587	154.954	5.287128	-133.131	-98.5624
25	-43.8608	-134.562	-163.318	16.75524	128.488	3.062233	-172.743	-135.055
30	-79.3133	-192.615	-240.218	-37.031	18.90829	-48.2833	-232.21	-193.255
35	-129.148	-261.235	-318.456	-106.61	-104.725	-120.414	-308.629	-261.379
40	-180.258	-329.991	-397.969	-191.396	-240.231	-212.992	-398.012	-334.878
	Double glazing pane							

20	53.10279	-19.9247	-41.8932	92.68263	209.8937	71.60379	-50.3627	-21.004
25	51.65654	-40.8599	-64.9406	87.88442	186.1825	76.16447	-69.5251	-44.6658
30	33.96129	-78.913	-114.627	56.15636	76.42079	40.42128	-123.099	-89.3164
35	2.963528	-135.481	-183.322	-20.0627	-66.6621	-35.8545	-188.466	-146.645
40	-35.9748	-192.019	-270.023	-127.136	-230.071	-134.81	-271.672	-207.362

Triple glazing pane

20	81.92703	20.5915	-2.65477	121.6712	233.1238	101.0521	-4.70796	19.94811
25	90.6758	8.879261	-12.815	129.7702	236.2058	117.1185	-19.6084	4.477452
30	75.12032	-29.0998	-52.1095	113.3314	154.5884	92.67903	-62.1129	-33.589
35	54.75746	-71.9291	-112.374	49.50472	41.15888	37.71056	-118.692	-77.5244
40	31.32111	-120.129	-186.637	-44.8643	-132.353	-51.2119	-187.264	-124.334

6.2 Combination of the optimum Façade design solutions

Based on the presented multi-objective optimization approach results, the alternative design solutions for the building façade were chosen including; adding Rockwool (15 cm) to the conventional wall structure, the clear 3 pane glazing, and the WWR 20% for the orientations NE, E, W and 25% for the orientations S, SE, SW, NW. These solutions are providing a balanced design method between daylight availability, thermal comfort, IDQ, heating, and cooling demand, based on the defined priority.

Subsequently, these solutions are applied to the existing building façade, and the simulation results have been compared with the basic model.

The results of the thermal comfort show a significant increase in the number of comfort hours by 51.72 % in the living room, 97 % in the ROOM1, and ROOM2. *Figure.68.* shows the comparison per hour in the whole year (8760 h).

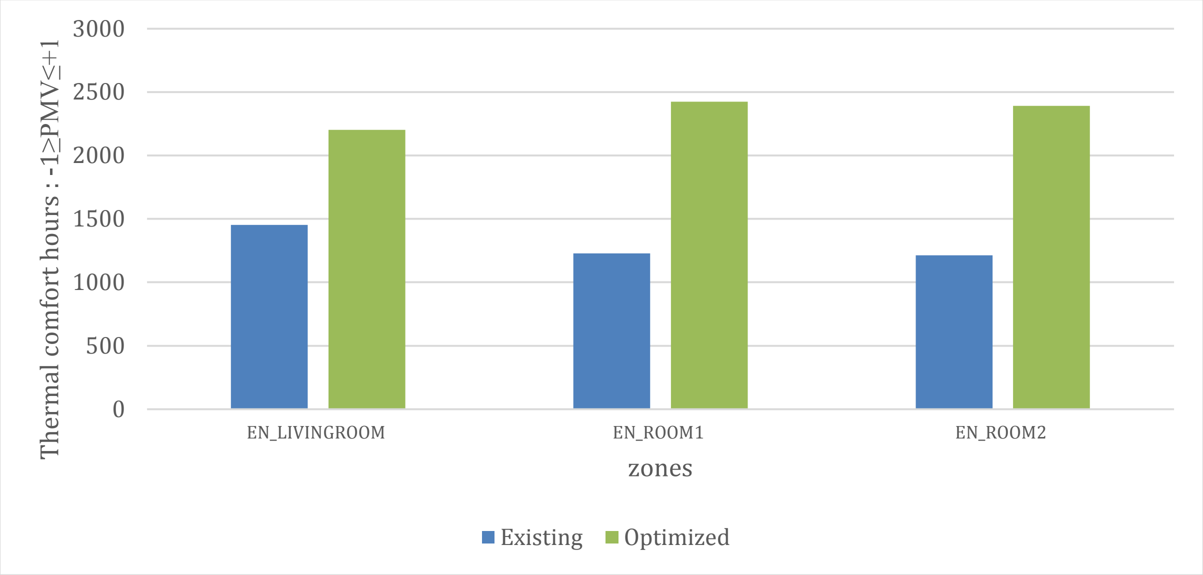


Figure 68. Thermal comfort comparison between the optimum facade and the existing building

The heating demand results of the improved model showed a reduction of 48% in the living room, 54% in the Kitchen, 46 % in the Room 2 that include the balconies, 52 % in the Room 2, 11 % in the Hall, and the bathroom 19%. *Figure.69.* illustrates the heating demand comparison between the different spaces.

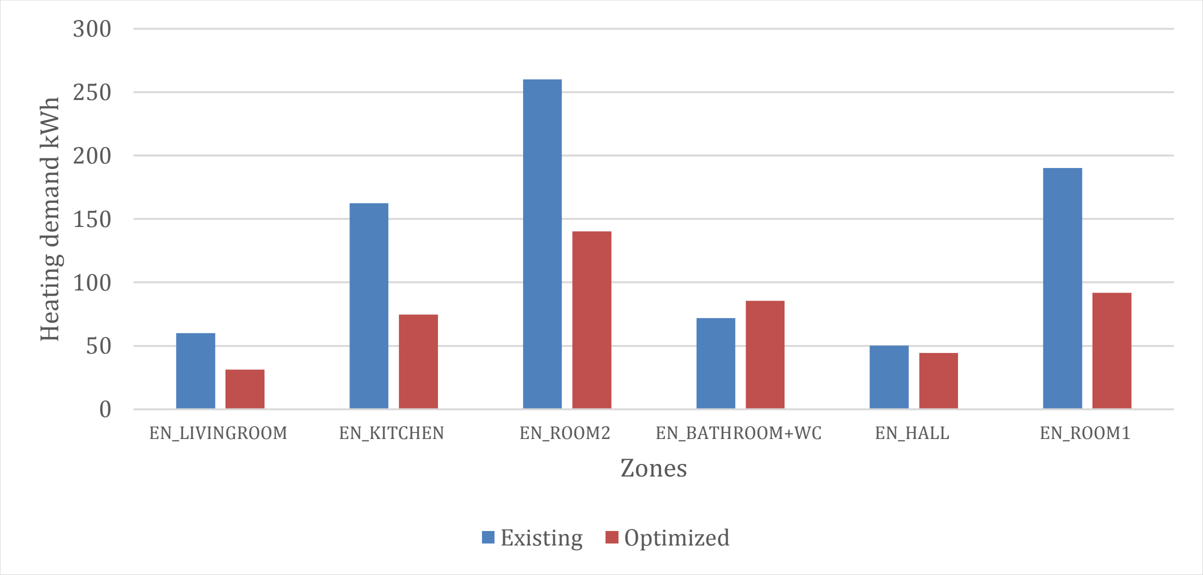


Figure 69. Heating demand comparison between the optimum facade and the existing model

The cooling demand results are increased nominally in the living room by 22%, Room2 that has a balcony 0.4%, Room1 6%, while in the Kitchen the cooling is reduced 17%, Bathroom 15%, and the Hall 10%.

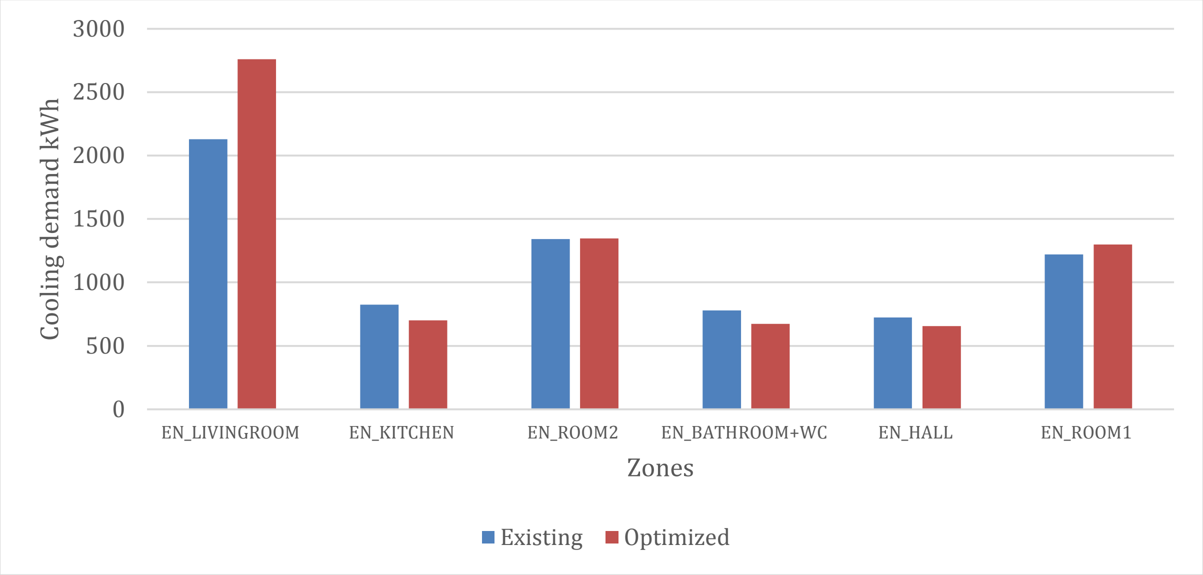


Figure 70. Cooling demand comparison between the optimum facade and the existing model

The indoor air quality has been optimized in the different spaces of the apartment, the Co2 concentration levels were reduced to 67% in the living room, 18% in the kitchen, in the Hall 39%. This means a good indicator of increasing the indoor air quality by a simple increase in the opening size. Which accelerates the air change in the indoor climate.

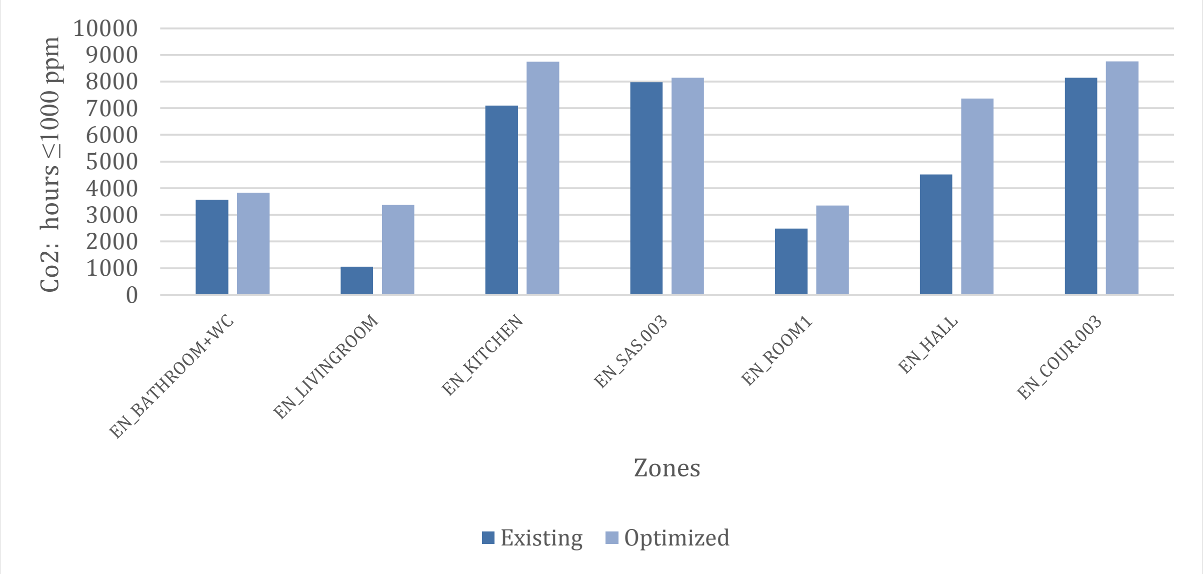


Figure 71. Carbon dioxide level ≤1000 pmm comparison

The daylight availability was increased significantly in the apartment. Tow main spaces (living room, and bedroom) are illustrated in Figure.72. which presents the comparison in terms of Illuminance level differences.

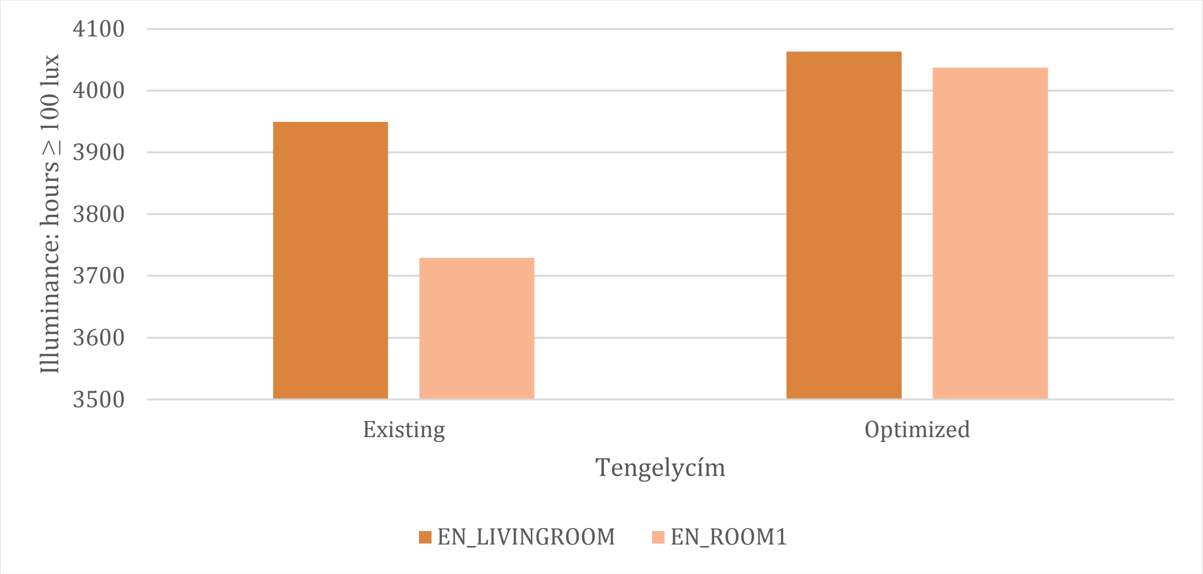


Figure 72. Daylight availability comparison

Furthermore, to ensure the best practice of visual comfort inside the spaces, more detailed and comprehensive analysis is applied, it is focused on assessing two main visual comfort factors; the illuminance and the light uniformity in two design days (21 December and 21 June). The analysis is based on the BREAM standard. Two main zones are compared; the existing living room (LR-E) and The optimized living room (LR-O), as well as the existing bedroom (R-E) and the optimized bedroom (R-O).

Figure.73. and 74. shows the comparison of average illuminance on 21 December and June, the results revealed a significant improvement on the illuminance levels that complies with the standard almost in the whole day in both design days.

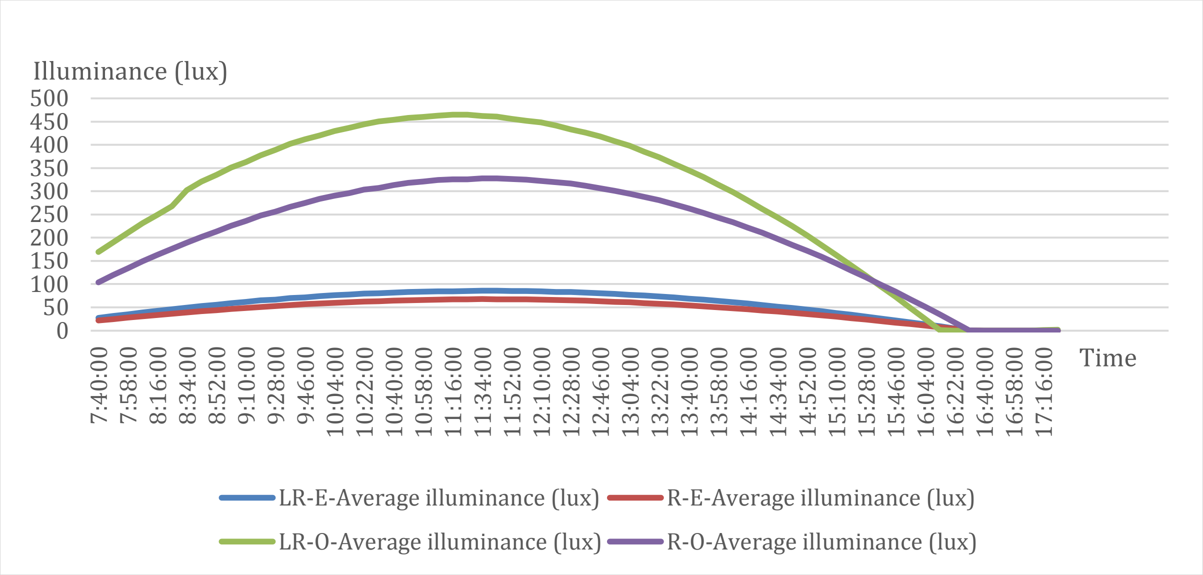


Figure 73. Average illuminance on 21 December

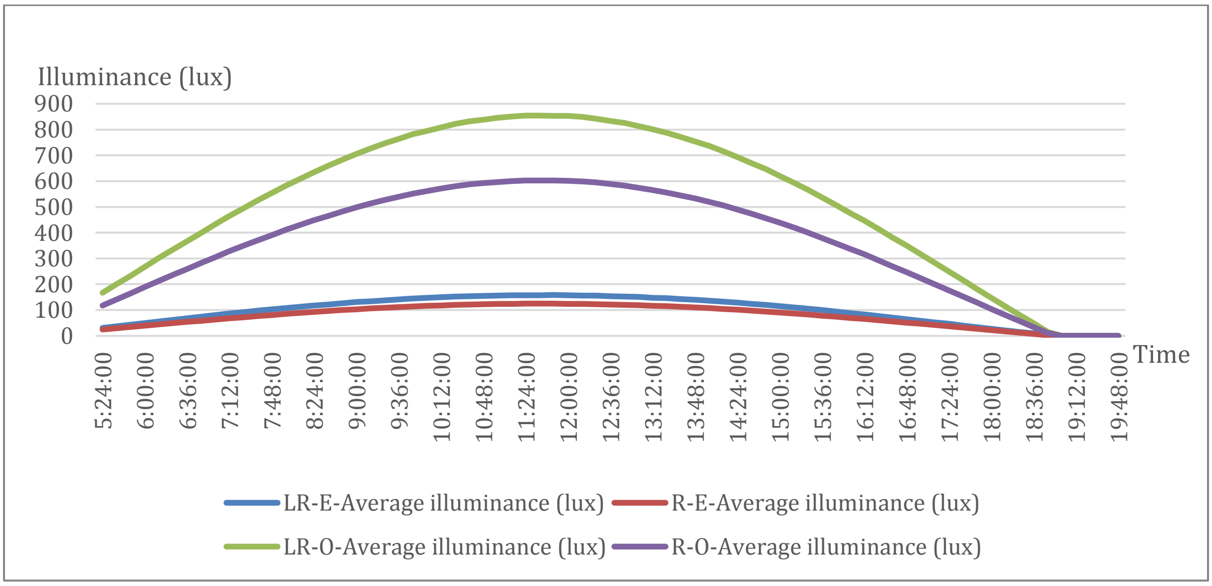


Figure 74. Average illuminance on 21 June

The area that complies the required average illuminance is also improved in both spaces to reach 100% in the both deisign days. *Figure 75. And 76.* Shows the results of the comparison between the difference zones in the two design days.

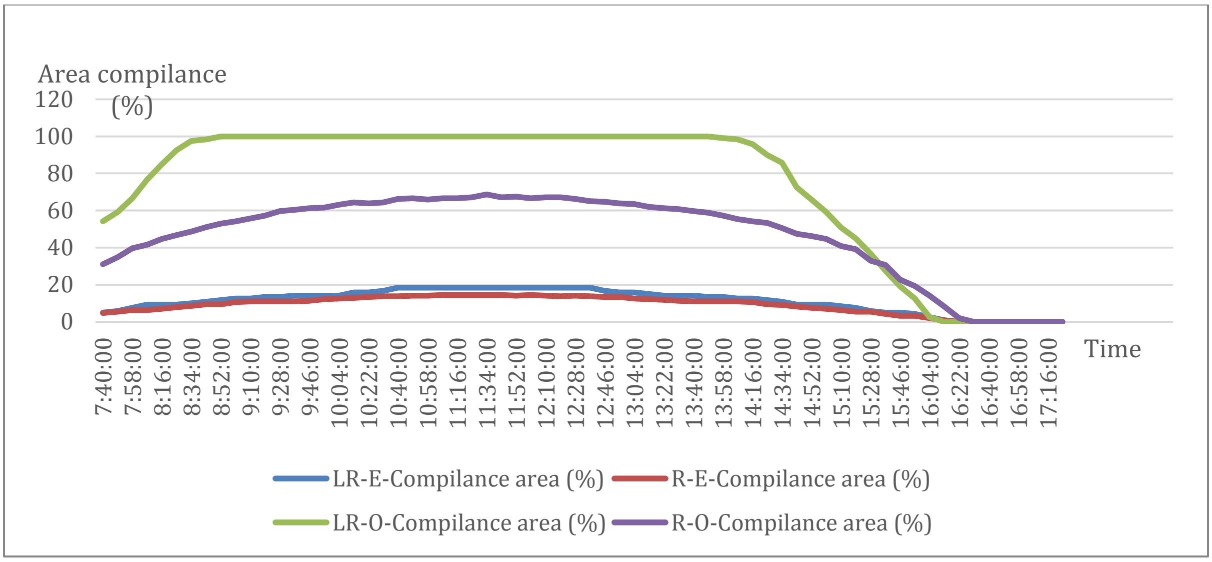


Figure 75. Compliance area with the required illuminance level on 21 December

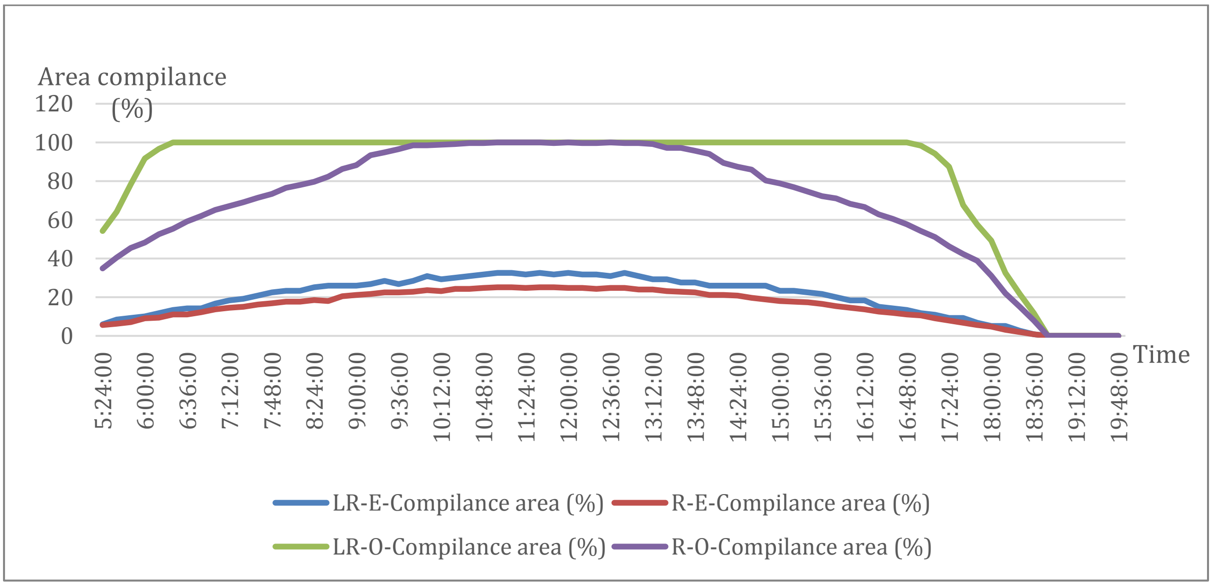


Figure 76. Compliance area with the required illuminance level on 21 June

Figure. 77. and 78. Illustrate the comparison results of the uniformity ratio, in the living room the uniformity has been improved to reach the required ratio 0.3 in bot design days, Additionally, the in the bedroom also it has been improved from 0.05 to 0.15 in December and 0.17 in June.

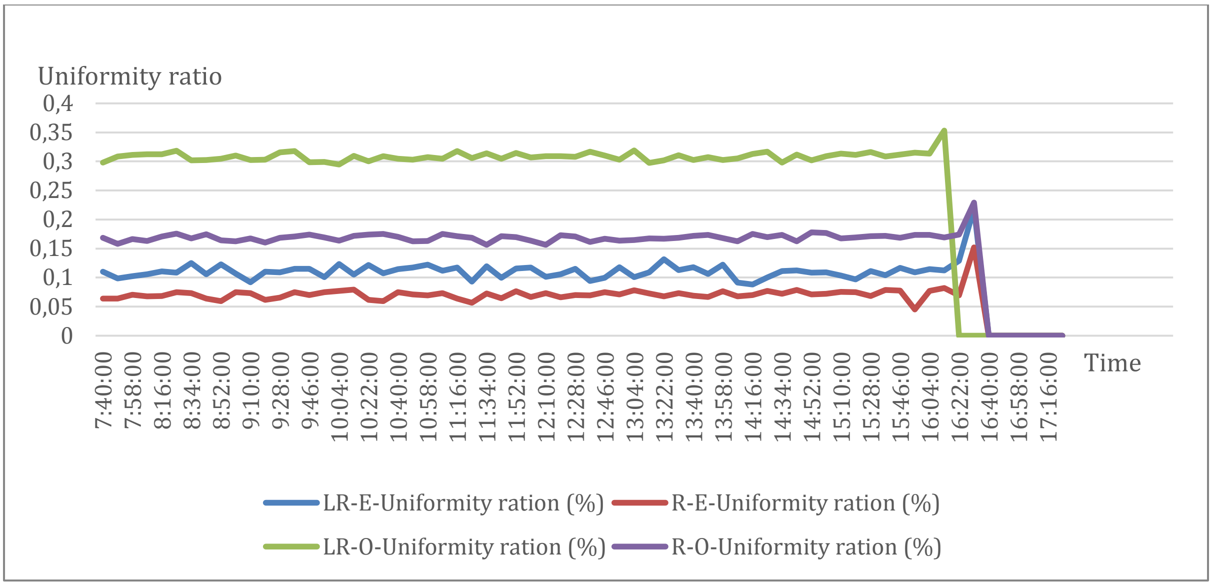


Figure 77. Uniformity ratio on 21 December

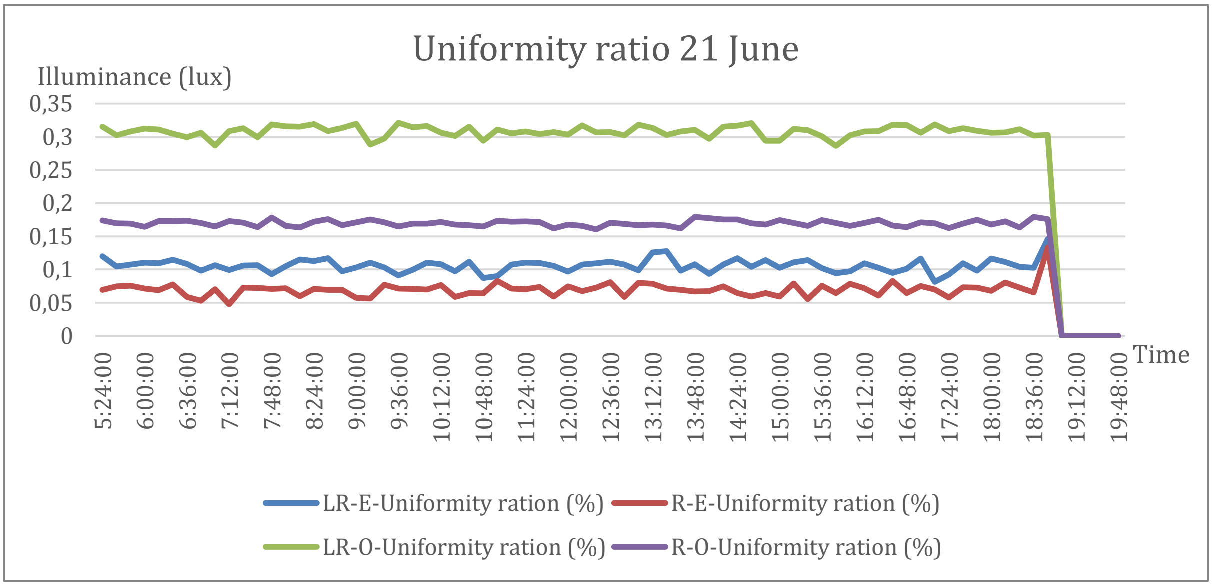


Figure 78. Uniformity ratio on 21 June

6. General conclusion & main finding

I have presented a holistic multi-optimization approach that can provide a structured method to define optimum design solutions for the high-performance façade design, and that can provide a balance between visual comfort, thermal comfort, energy demand, and indoor air quality through all the façade components. More precisely, the context of the optimization was in the hot and dry climate.

For all steps of the optimization, a dynamic simulation was carried out using Blender 3D software for modeling and building information has been included by the plugin VI-suite that controls the external applications (software) Radiance and Energy Plus.

1. The building façade is considered not only an interface between the interior and the exterior but also it acts as a skin that can provide a comfortable sheltered environment, therefore the first step of my study was the determination of the main Façade parameters that impact the thermal comfort, the energy demand, the visual comfort, and the indoor air quality, throughout a theoretical analytical methodology; I have found that the opening parameters together with the external wall structure and materials were the most related to the façade performance design.

2. The research methodology is based on a virtual modeling and simulation process. Thus, I have verified and validated the accuracy of theses process, to determine the modeling and the programming errors which can occur in the thermal dynamic

simulation through a comparison of a field Measurements and the simulation. I have found that The accurate inputs of all the parameters of the built environment impact the agreement degree between the measurements and the simulation results, including; the number of occupants and their behaviors, the HVAC system usage, the windows/ doors closing and opening, time of occupancy. Otherwise, since the agreement has been obtained in some zones in the apartment, the modeling method with Vi-suit add on Blender 3D was precise enough and it was used to fulfill the research main goal.

3. An analysis of the current situation of the existing residential buildings in the study context in a hot and dry climate is presented, the weakness and strength of the Algerian building design and standards in terms of building energy efficiency are determined. for the diagnosis, a referential building has been chosen. Furthermore, to evaluate the energy consumption, thermal comfort, indoor air quality, as well as visual comfort. the computational simulation Energy plus and radiance software were used. I have found that; the building energy diagnosis results generally were negative, and the residential building in the study context has not complied with the building energy design standards, there are many weaknesses in terms of building energy consumption, thermal comfort, visual comfort, and indoor air quality.

4. The optimization approach to reduce energy consumption and increase thermal comfort performance, daylighting and indoor air quality, through investigating different passive façade design strategies of the building facade design are applied by selecting different wall structures, opening dimensions (WWR), glazing type; For the facade wall structure, several materials have been selected based on the availability criteria, ecology, smart materials, and thermal/physical characteristics. The findings show that the best material that improves Energy demand was not the best on enhancing Thermal comfort. Besides, the analysis revealed that conductivity was the main influential parameter on the energy demand; the material that has the lowest thermal conductivity provides the highest heating and cooling energy saving. However, steady-state analysis of Thermal Mass, Density, and specific heat proprieties of the materials can not provide a precise prediction for the material's thermal performance. Thus, a dynamic simulation analysis is crucial to determine it.

5. For the openings, The impact of two main parameters have been investigated; the WWR (from 20 % to 40%) and the glazing type (Simple pane, Double pane, and Triple pane). The impact of these parameters together with the orientation has been evaluated in an interactive method to improve the building energy demand, thermal comfort, daylight availability, and indoor air quality (IDQ). I have found that the orientation and the glazing type and WWR have a significant impact on the cooling and heating demand but in an inverse manner; the orientations that provide the best heating demand were the worst for the cooling demand. Also, The comparison between the thermal comfort hours and the WWR in the orientations N, NE, NW indicate that since the WWR is higher the comfort hours are reduced, the contrary was obtained for the orientations SE, SW, W. Finally, the visual comfort and the indoor air quality was improved when the WWR was higher. Furthermore, the glazing type efficiency was impacted by the orientations. For colling demand; the glazing type had a nominal impact in the North orientation, while in the S, SW, SE orientations the reduction was higher followed by E, W, NW, and NE. The heating demand revealed inverse results.

6. The performance analysis of the impact of the different alternatives on the different comfort aspects revealed that each nominated type of comfort; (daylight, thermal comfort, energy demand, and IDQ) lead to a different window configuration (glazing type, WWR). The WWR that provides better thermal comfort in each orientation is as follows: 20% in N, NE. NW orientations, 35% in E, SE, SW, W. In the South, 25% was the best. And for the heating demand 20% in N, NE. NW orientations, 35% in E, 30% in SE, 40% in SW and W orientations. The 3 pane glazing was the best for all the orientations, while the South orientation the double-pane glazing was optimal with 40% WWR. The cooling demand increases as the WWR is higher, 20% was the best alternative for all the orientations with 3 pane glazing. Otherwise, for the daylight availability and indoor air quality, as soon as the WWR is higher these aspects offer better results. And for these aspects, 40% of WWR was the best for all the orientations.

7. The best design solutions in the study context were the clear 3 pane glazing for all orientations, and the WWR of 20% for the orientations NE, E, W, and 25% for the

orientations S, SE, SW, NW. These results are based on the classification of the desired indoor comfort as it follows; IDQ, Thermal comfort, Cooling demand, Daylight availability, and Heating demand

8. Comparing the existing residential building, the optimal combination of the façade design reduces 64 % of Heating demand, 3% of cooling demand, and improves 51 % of indoor air quality. The thermal and visual comfort hours have been increased by 35%, 6 % respectively.

List of publications

Energy design performance diagnosis for the existing Algerian residential building façade in the hot and dry climate

POLLACK PERIODICA: AN INTERNATIONAL JOURNAL FOR ENGINEERING AND INFORMATION SCIENCES

Optimizing the cooling energy consumption by the passive traditional façade strategies in a hot dry climate

POLLACK PERIODICA: AN INTERNATIONAL JOURNAL FOR ENGINEERING AND INFORMATION SCIENCES 14- 1 pp. 177-188. , 12 p. (2019)

Optimum window position in the building façade for high daylight performance: Empirical study in a hot and dry climate

POLLACK PERIODICA: AN INTERNATIONAL JOURNAL FOR ENGINEERING AND INFORMATION SCIENCES

Published in conference proceedings

The impact of the formal and constructive choices on the climatic performance of the facades.

1. 13th Miklós Iványi International PhD & DLA Symposium - Abstract Book: Architectural, Engineering and Information Sciences. Pécs, Hungary: Pollack Press, (2017) p. 110

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Evaluating the effect of incident direct solar radiation on building facades-case study Biskra-Algeria

2. Doctoral workshop: skill development in higher education and the labor market. University of pécs 25th -26th November 2017 Pécs Hungary

3. 14th Miklós Iványi International PhD & DLA Symposium - Abstract Book: Architectural, Engineering and Information Sciences. Pécs, Hungary: Pollack Press, (2018) paper 3.

[1] Adel Boumerzoug, [2] Messaouda Rais, [3] Leila Sriti

Thermal performance evaluation of the Algerian vernacular houses in the region of Ziban-Biskra: Hot and dry climate

4. 14th Miklós Iványi International PhD & DLA Symposium - Abstract Book: Architectural, Engineering and Information Sciences. Pécs, Hungary: Pollack Press, (2018) paper 63.

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Energy performance evaluation of the conventional wall materials applied on the Algerian residential building facade-Hot and dry climate

5. 8th international doctoral conference (IDK 2019) at the University of pécs- 24th -25th 2019, P92

Energy consumption and thermal comfort analysis of the existing residential building in Algerian hot and dry climate region

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6. 15th Miklós Iványi International PhD & DLA Symposium - Abstract Book : Architectural, Engineering and Information Sciences. Pécs, Hungary : Pollack Press, (2019). P 33

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Validation of a building environmental analysis tool based on real field measurements in a Hot and dry climate region

7. International conference of **Global Society for Research and Development (GSRD)-**Istanbul, Turkey, 20th - 21st November 2019.

Assessing the impact of local climate on the building energy design: case study Algeria-Egypt in hot and dry regions.

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Appendix 1: The results of energy demand, thermal comfort, daylight, and IDQ of the Base model

N	NE	E	SE	S	SW	W	NW
Comfort hours /h							
1386	1252	1354	1421	1764	1452	1396	1268
Heating energy demand / kWh							
91.16021022	91.67488	62.82858	43.11146	29.98852	47.39641	67.30448	93.38394
Cooling energy demand/ kWh							
829.3077	881.1064	912.7197	958.6385	931.7215	961.4138	915.2893	880.8315
Daylight availability / Illuminance (lux)							
3770	3814	3875	3877	3888	3809	3811	3809
Carbone dioxide concentration / PPM							
8760	8760	8760	8760	8760	8760	8760	8760

Appendix 2: Comparision between the base model and the proposed alternatives

	N	NE	E	SE	S	SW	W	NW
WWR	Thermal comfort %							
Simple pane glazing								
20	1.803752	-0.31949	-10.9306	12.73751	32.53968	9.435262	-7.87966	0.315457
25	-0.21645	-3.27476	-11.8907	21.95637	37.52834	19.90358	-7.02006	-1.18297
30	-0.93795	-4.39297	-13.2939	28.43068	28.68481	25.89532	-4.94269	-2.28707
35	-1.5873	-5.59105	-11.6691	33.8494	19.55782	29.54545	-3.36676	-2.99685
40	-2.23665	-6.3099	-10.0443	36.03096	8.786848	29.13223	-4.29799	-4.57413
Double pane glazing								
20	5.266955	-0.31949	-6.79468	15.69317	35.88435	13.70523	-3.08023	0.236593
25	2.958153	-2.63578	-4.87445	25.96763	39.3424	23.76033	-0.35817	-2.60252
30	1.948052	-3.91374	-2.8065	35.96059	28.00454	30.99174	0.358166	-4.653

35	0.793651	-6.46965	-1.10783	37.93103	11.56463	32.09366	1.217765	-7.80757
40	-1.0101	-8.54633	-3.24963	32.86418	-8.16327	28.30579	-0.50143	-10.5678
Triple pane glazing								
20	6.637807	1.837061	-3.98818	14.98944	34.92063	12.25895	-0.71633	2.444795
25	4.545455	-1.11821	-2.58493	24.98241	41.4966	23.07163	0.859599	-1.1041
30	3.174603	-3.67412	0.369276	36.73469	34.5805	30.78512	2.077364	-3.78549
35	2.308802	-5.67093	1.181684	39.26812	22.8458	34.43526	3.080229	-5.83596
40	1.875902	-7.82748	0.073855	35.04574	-2.49433	30.85399	2.148997	-7.88644

WWR	N	NE	E	SE	S	SW	W	NW
Heating demand %								
SG								
20	-37.09321469	-28.8948	31.69947	75.08561	84.60352	65.64377	17.99631	-31.4129
25	-48.47773766	-38.1939	34.60461	77.60581	87.20039	70.93039	19.6838	-41.0245
30	-60.36889263	-48.1501	34.58337	77.82503	87.51962	73.31441	19.30558	-51.3136
35	-72.82382212	-58.5912	32.40238	76.71402	87.17632	74.25548	17.53745	-62.2272
40	-85.84695699	-69.5463	28.96593	75.07656	86.38517	73.99743	14.701	-73.5865
DG								
20	-5.424259418	-0.06348	47.16628	81.48066	87.96577	73.6307	36.29271	-1.39098
25	-8.799321935	-2.2142	53.22478	84.47703	90.53849	79.58659	41.39732	-3.70561
30	-12.69263728	-4.9486	56.1346	84.89483	91.92851	82.95421	44.40158	-6.78716
35	-17.23133455	-8.23416	56.55221	84.50576	92.90426	84.30172	45.76074	-10.472
40	-22.32518536	-12.0108	55.60309	83.64616	93.78115	84.79082	45.98356	-14.6249
TG								
20	3.638242683	7.805639	47.39524	79.77869	85.67766	72.2973	38.52053	6.793644
25	2.590824306	7.793019	54.53446	84.0905	89.07289	78.87902	44.60421	6.668532
30	1.054730276	7.094598	58.52905	84.88463	90.78776	82.66752	48.4917	5.714234
35	-0.989435312	5.901966	59.91294	84.61729	92.17914	84.37515	50.72249	4.235885
40	-3.624077667	4.29133	59.78169	83.89242	93.29906	85.04867	51.67883	2.272393

WWR	N	NE	E	SE	S	SW	W	NW
Cooling demand %								
SG								
20	-19.0849	-33.9953	-54.8504	-60.6345	-55.7347	-60.0153	-54.7873	-34.1311
25	-25.5043	-45.3103	-73.5692	-81.1191	-74.4748	-80.3597	-73.4344	-45.5128

30	-31.8202	-56.4481	-92.1444	-101.346	-93.1958	-100.482	-91.8415	-56.6853
35	-38.0546	-67.3868	-110.527	-121.366	-112.311	-120.382	-109.997	-67.696
40	-44.1985	-78.1612	-128.639	-141.28	-132.267	-140.256	-127.896	-78.5554
DG								
20	-17.4159	-29.6791	-48.1697	-52.7072	-47.9495	-52.2286	-48.1637	-29.809
25	-23.5387	-40.2145	-65.7625	-71.8294	-65.2131	-71.2003	-65.6878	-40.3921
30	-29.6056	-50.6637	-83.4172	-90.8944	-82.5731	-90.107	-83.1491	-50.8703
35	-35.6468	-61.0153	-101.052	-109.928	-100.425	-109.023	-100.544	-61.2719
40	-41.6521	-71.2884	-118.599	-129.059	-119.432	-128.07	-117.848	-71.6212
TG								
20	-15.2268	-25.2532	-41.0949	-44.5205	-40.3519	-44.1129	-41.075	-25.3831
25	-20.9082	-34.8229	-57.058	-61.782	-55.7592	-61.2303	-56.9853	-34.9982
30	-26.5649	-44.3729	-73.1734	-79.0996	-71.3583	-78.3988	-72.9713	-44.5846
35	-32.217	-53.8904	-89.388	-96.4482	-87.2563	-95.6456	-88.9776	-54.1364
40	-37.8708	-63.3772	-105.632	-113.938	-104.077	-113.004	-104.987	-63.6834

WWR	N	NE	E	SE	S	SW	W	NW
Daylight availability								
SG								
20	1.883289	2.045097	2.425806	1.470209	1.671811	2.362825	2.361585	1.470202
25	4.69496	4.693235	5.16129	3.972143	2.983539	5.329483	5.247966	3.964295
30	6.6313	6.371264	6.709677	5.313387	3.575103	6.510895	7.924429	5.854555
35	6.816976	7.524908	7.793548	6.24194	3.858025	7.377264	9.026502	6.957207
40	6.896552	8.154169	8.929032	6.680423	4.166667	7.692308	9.525059	7.56104
DG								
20	0.238727	0.209754	0.851613	0.41269	0.308642	0.472565	0.314878	0.210029
25	2.572944	2.5957	3.174194	2.269796	2.134774	3.517984	3.384938	2.572854
30	5.066313	5.1914	5.677419	4.204282	3.009259	5.565765	6.008922	4.279338
35	6.604775	6.423702	6.864516	5.390766	3.575103	6.537149	8.396746	6.405881
40	6.763926	7.315155	8.025806	6.24194	3.832305	7.351011	8.974023	7.193489
TG								
20	-1.67109	-1.78291	-1.75484	-1.496	-1.80041	-0.42006	-0.91839	-1.91651
25	1.485411	1.494494	2.116129	1.057519	1.157407	1.942767	1.758069	1.050144

30	2.917772	2.962769	3.612903	2.579314	2.366255	3.938041	4.355812	2.887897
35	5.30504	5.243838	5.780645	4.255868	3.009259	5.592019	6.586198	5.119454
40	6.578249	6.266387	6.993548	5.390766	3.575103	6.537149	8.344267	6.799685

WWR	N	NE	E	SE	S	SW	W	NW
CO2 concentration %								
20	21.5411	21.5411	21.5411	21.5411	21.5411	21.5411	21.5411	21.5411
25	27.89954	27.89954	27.89954	27.89954	27.89954	27.89954	27.89954	27.89954
30	30.73059	30.73059	30.73059	30.73059	30.73059	30.73059	30.73059	30.73059
35	32.11187	32.11187	32.11187	32.11187	32.11187	32.11187	32.11187	32.11187
40	33.44749	33.44749	33.44749	33.44749	33.44749	33.44749	33.44749	33.44749