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Optimization of the Air-Conditioning Energy Performance and Daylight Performance of A Residential Building According to the Bioclimatic Design Principles: An Application to the Moroccan Mediterranean

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Abstract

The bioclimatic architecture concept refers to an approach that takes into account the various characteristics of a building environment to make it more comfortable for its occupants. This work aims to improve the passive design parameters of an air-conditioned residential building located in the north of Morocco, in accordance with bioclimatic principles. The bioclimatic chart diagram is used to select the passive design measures that are the most appropriate for the north Morocco climate characteristics. Then, a set of design parameters are selected for more delimitation in the optimization study. The optimization problem is multi-objective and aims to find the design solution that simultaneously includes the best air-conditioning energy performance and daylight performance. The obtained results showed that the multi-objective optimum design solution is characterized by massive walls and roof, exterior insulation, double window glazing type, and a high summer ventilation rate. Also, a small glazing area with a large sun-shading covering is needed for the east facade. Ultimately, the building performance analysis revealed that the optimum bioclimatic design solution fully meets the requirements established by the Moroccan Building Thermal Regulation (MBTR), leading to an energy performance improvement of about 52%.

1. Introduction

In Morocco, the demand for primary energy increases every year by 6%, while the national electricity demand increases by 7.5% (MEMSD, 2012). This trend is due to the rapid population growth coupled with the increasing rate of urbanization and improvement in the standard of living. The heating and cooling systems are responsible, in addition to the cooking energy for over 70% of the building sector's energy bill (AMEE, 2014). Therefore, the reduction of energy consumption in all sectors, including the building sector, presents a major challenge for Morocco, which depends on energy imports for more than 90% of its supply (MEMSD, 2019).

Morocco has set the objective of achieving an energy saving of 15% by 2030 compared to 2010 (AMEE, 2010a). In this context, improving the performance of the building envelope undeniably offers a means of saving energy. The Moroccan Building Thermal Regulation has been instituted to provide the guidelines to integrate energy efficiency measures into new building constructions. The aim is to reduce energy consumption in the building sector and contribute to reducing the country's overall energy bill. To achieve this result, building designers have suggested to consider the building site environment to present a design adapted to the specificities of the environment (Ochedi & Taki, 2022). This approach represents the substance of bioclimatic architecture (Katafygiotou & Serghides, 2015). Jamaludin et al. (2014) suggested that the implantation of bioclimatic design strategies not only reduces energy use but, more importantly, provides comfort for the occupants. M.W. Akram et al., (2021) considered that the bioclimatic design is one of the best attempts for improving energy saving and cost-effectiveness in buildings. It leads, on one hand, to exploit the characteristics of the local climate to maintain a pleasant indoor temperature with less need for the air-conditioning systems. On the other hand, promoting the use of natural daylight for lighting purposes contributes not only to reducing energy consumption but also enhances the visual comfort of the occupants (Elaouzy & El Fadar, 2022b; Boukli Hacene & Chabane Sari, 2020).

Nomenclature

ASHRAE	American Society of Heating, Refrigerating and Air‑Air-conditioning
ACS	Air conditioning system
COP	Coefficient of performance
DGI	Daylight glare index
EER	Energy efficiency ratio (%)
$E_{H/C}$	Energy demand for heating and cooling (kWh)
LEC	Lighting energy consumption (kWh)
MBTR	Moroccan building thermal regulation
Q_C	Cooling loads (J)
Q_H	Heating loads (J)
$X_1 \ldots X_n$	Design parameter 1…. Design parameter n
WWR	Window-to-wall ratio (%)
η_{LEC}	Lighting energy-saving (%)
MR/P	Metabolic rate/Person A

In recent years, several studies have explored the impact of bioclimatic design measures to enhance the building's energy efficiency performance in different climates worldwide. For instance, Gong et al., (2012) conducted a study to select the optimal combination of bioclimatic design measures in 25 representative cities in China. The investigation was limited to seven design measures. The results showed that the optimal combination of the bioclimatic design measures could greatly reduce annual thermal loads and even replace air-conditioning systems in winter for areas with high solar radiation, such as Lhasa city. Hamdaoui et al., (2018) analyzed the impact of different design measures on the energy efficiency of an office building in different climate zones of Morocco. The set of design measures included the thermal mass and insulation of the building envelope components, natural ventilation, window shading, and window glazing type and area, and solar protection. The authors found that the energy efficiency measures could reduce the heating/cooling loads between 20% and 56% depending on the climate zone. Ali-Toudert & Weidhaus, (2017) defined and delineated the most efficient passive design measures for minimizing heating and cooling energy in a residential building located in the Mediterranean and Saharan climate zones. Belkacem et al., (2017) conducted an optimization study to enhance the energy performance of a pilot bioclimatic house located in Algiers (Algeria). The findings revealed that applying bioclimatic design measures, such as the increase of South-facing window size, the use of night ventilation and shading devices, yields better thermal comfort in summer since it could decrease the cooling energy demand by 48.70%. More recently, Elaouzy & El Fadar, (2022b) have investigated the impact of five bioclimatic design measures on the energy demands of office buildings in different locations in the Mediterranean region. The optimization included the following design parameters: window-to-wall ratio (WWR), solar heat gain coefficient, sun shading with overhangs, thermal insulation, and natural ventilation. In another study (Elaouzy & El Fadar, 2022b), the same authors assessed the impact of different bioclimatic design strategies, namely green roofs and walls, shading solutions, natural ventilation, efficient glazing systems, building orientation, and Trombe walls, on the energy performance of a typical residential building in different climate zones of the world (arid, temperate, and cold climates). The findings proved that applying the appropriate design strategies to each climate zone strategy greatly reduces the energy demand and GHG emissions in all climates.

From the literature cited above, it appears that the utility of applying bioclimatic design strategies for improving the air-conditioning energy performance of buildings has been extensively investigated and proved. Nevertheless, it is important to consider the daylight performance factor in bioclimatic building design. On one hand, the exploitation of sunlight for lighting may enhance the visual comfort criteria and reduce the need for artificial lighting, leading to more energy savings (Yu & Su, 2015; Košir et al., 2018). On the other hand, the undesirable heat gains from the sunlight could negatively affect the air-conditioning energy performance of the building, especially during the hot season. Thus, finding the best compromise between daylight exploitation and air-conditioning usage is essential to enhance the total performance of the building. Košir et al., (2018) applied a set of bioclimatic design measures to delineate the appropriate envelope configuration of a modular office building for heating, cooling and lighting energy performance. The study was limited to five design parameters, including the building orientation, window-to-wall ratio, window distribution, window glazing type, and envelope thermal transmittance. The results obtained indicated a substantial impact of artificial lighting on the total energy use. Méndez Echenagucia et al., (2015) conducted a multi-objective study to minimize the energy needed for heating, cooling, and lighting of office buildings located in different cities in Europe. The authors focused on the window design parameters and the thickness of the walls. The approach followed in the previous studies is interesting, but it presents a fundamental weakness. In fact, the set of the design measures under investigation had been chosen hypothetically by the authors. This approach might not lead to defining the most adaptable bioclimatic design measures to the climatic characteristics of the chosen location. In this regard, using a specific tool called bioclimatic charts leads to assessing, initially, the potential effect of several bioclimatic active and passive design measures depending on the outdoor climate conditions and the thermal comfort requirements (Givoni, 1992). The recommendations of the bioclimatic charts are presented in the form of general orientations. Thus, they should be the subject of delimitation and dimensioning with respect to the features of the building case study under investigation (Elaouzy & El Fadar, 2022b; Ali-Toudert & Weidhaus, 2017; Ameur et al., 2020).

2. Aims of Work

From the literature review above, a few multi-objective studies have combined both air-conditioning energy performance and daylight performance, but they do not cover the Moroccan climate zones (Košir et al., 2018; Méndez Echenagucia et al., 2015; Aydın et al., 2015). This work aims to optimize the bioclimatic building design of an air-conditioned residential building located in the Moroccan Mediterranean climate zone, using a multi-objective optimization approach. This consists of providing the best building design for simultaneously enhancing the air-conditioning energy performance and the daylight performance. Unlike other studies on the subject (Košir et al., 2018; Méndez Echenagucia et al., 2015; Aydın et al., 2015), the bioclimatic design measures under investigation are not chosen completely hypothetically, but in a selective manner in order to define the design measures most adapted to the considered climate zone. The bioclimatic chart tool is employed for this purpose. Aside from that, the findings of this study, as well as those of the authors' previous study on the case of a free-running residential building (Ameur et al., 2020), should provide an integral assessment of the bioclimatic architecture application in the Moroccan Mediterranean climate.

3. Approach and Framework of the Study

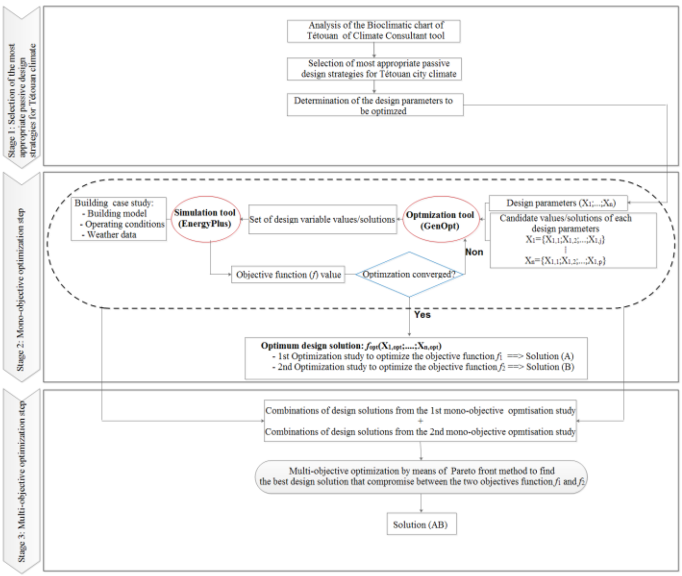

Fig. 1 *Flowchart of the adopted methodology*

The study is carried out in three main stages, as is shown in the Fig. 1. Stage one consists of defining the most adapted bioclimatic design measures to the climate of north Morocco through the bioclimatic chart. In stage two, the selected design measures are applied to a residential building case study. To do this, two separate simulation-based optimization studies are carried out: the first consists of delineating the design measures that improve the air-conditioning energy performance and the second has the objective to improve the building daylight performance. The simulation-based optimization method leads to defining the best design solution amongst a large number of possible solutions (candidate solutions), and it consists of coupling an optimization algorithm with the building thermal simulation tool. In this study, the optimization calculations are carried out via a coupling between EnergyPlus and GenOpt (Wetter, 2011).

Stage three consists of defining the best design solution combining air-conditioning energy performance and daylight performance. These two objective functions are often contradictory and working to pull the design in opposite directions. For example, the large glazed area allows the transmission of an important amount of natural light into the building and consequently enhances the daylight performance, but it may lead to an increase of the cooling loads during the hot season, which means a poor level of building air-conditioning energy performance. The optimum multi-objective solution is selected among the set of Pareto front candidate solutions by means the utopia point criterion method (Nguyen, Reiter, & Rigo, 2014). This method consists of selecting the Pareto front solution that is located at the shortest distance to the utopia point. Utopia point is an imaginary ideal solution where the both objective functions achieve their best values. Finally, the air-conditioning energy performance and daylight energy performance obtained from the optimum design solution are presented and discussed.

4. Climatic Analysis

4.1 Characteristics of the Climate of Northern Morocco

The study is performed under the climate conditions of northern Morocco and specifically in Tétouan city (35.58° N, 5.33° W). This city belongs to climate zone 2 in Morocco. The climate zoning was established for an easy and efficient application of the Moroccan Building Thermal Regulation (MBTR) (AMEE, 2010b; AMEE, 2016). Tétouan city is characterized by a hot-summer Mediterranean climate (Csa) according to the Köppen-Geiger climate classification (Peel, Finlayson, & McMahon, 2007). The winter is humid, not very harsh, but rainy and moderately cold. The monthly mean temperature varies between 13.5°C (January) and 26°C (August), while the monthly global solar radiation on a horizontal surface varies between 89 kWh/m2 (January) and 243 kW/m2 (July) (Meteotest, 2014).

4.2 Bioclimatic Chart Analysis

The study is started by interpreting the bioclimatic chart outputs to define the most effective passive design measures for Tétouan climate zone. For this purpose, the Climate Consultant 6 software developed by the UCLA group company has been used in this study (UCLA, 2018). This software is an easy-to-use tool to calculate the relative potential of the application of each bioclimatic design measures (passive and active) to improve indoor thermal comfort. It can use different thermal comfort models. In this study, the ASHRAE Handbook of Fundamentals Comfort Model 2005 is used, which is closer to the MBTR standards in terms of the range of thermal comfort temperature (Ameur et al., 2020). Only passive design measures are considered in this study.

The outputs of the Climate Consultant tool are depicted in Fig. 2. The results show that the comfort period, without using any bioclimatic measures, could last up to 2176 hours, which presents 24.8% of the one-year period. The exploitation of the internal heat gains during the cold period could extend the comfort period by 42.9%.

The incident solar radiation could further reduce the need for heating by 21.2% when it is exploited for a massive building envelope (i.e. high thermal mass), compared to 14.1% when it is exploited for a lightweight building envelope (i.e. low thermal mass). In summer, a solar shading system could have a significant effect on the reduction of artificial cooling as it may extend the comfort period by 15.7%. Additionally, natural ventilation should present lower benefits, however it is still significant (+9.8% to the yearly comfort period). The outcomes of the bioclimatic chart also show that the impact of the high thermal mass is more important when it is combined with the night ventilation strategy (+8.2% to the yearly comfort period) compared to the case without night ventilation (+5.9% to the yearly comfort period). The effect of the wind protection systems is negligible. In conclusion, the bioclimatic passive design measures that are worthy to be considered are summarized as follows: (i) Internal heat gain (ii) Solar heat gain (iii) High thermal mass of building envelope (iv) Summer night natural ventilation and (v) windows shading system. The selection of the passive bioclimatic design measures which are the most effective in enhancing the thermal comfort of the building in Tétouan was done based on the outdoor climate data only. Thus, the projection of these strategies on a specific building case study involves further specifications and needs to be clearly delineated.

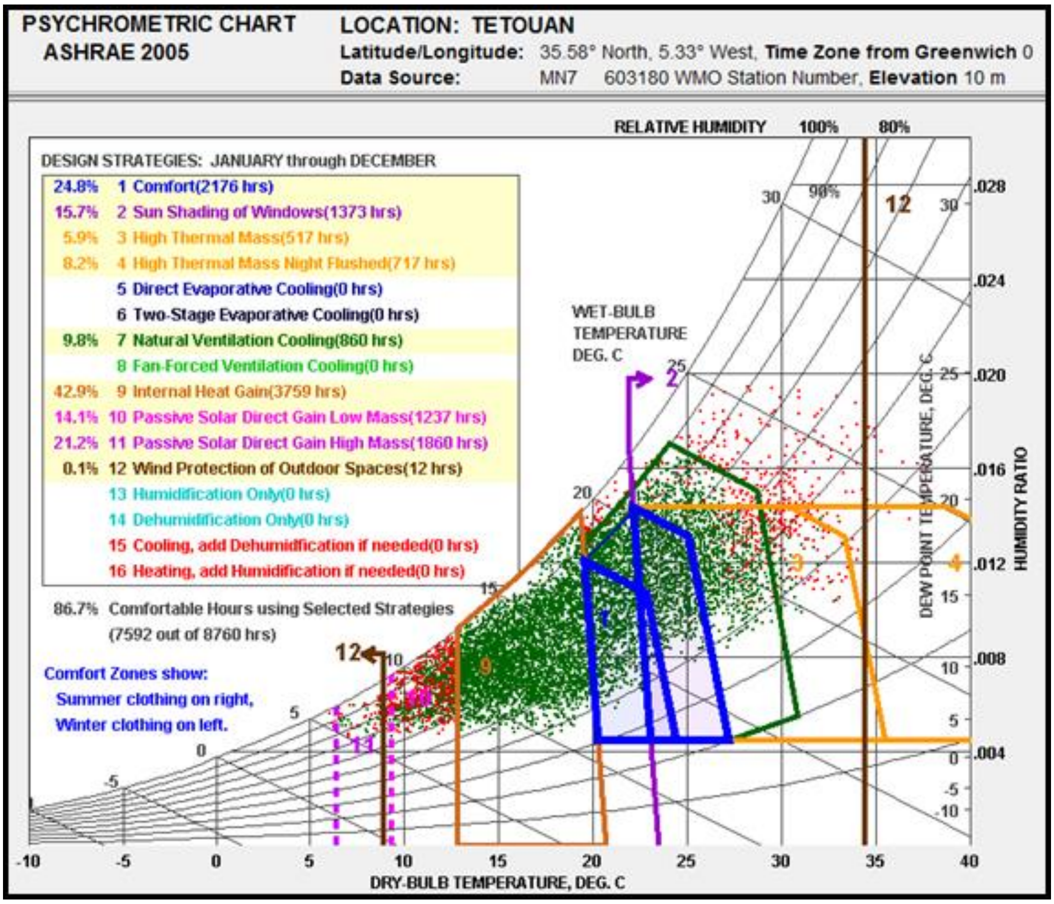

Fig. 2 *Potentials of the bioclimatic passive design strategies for Tétouan (Obtained by Climate Consultant 6)*

5. Case Study Description

5.1 Reference Building and Operating Conditions

In this paper, a prototype of a residential building inspired by the architecture of modern Moroccan houses is considered (Guechchati, Moussaoui, & Mezrhab, 2012). The building is designed as a single-story with a total living area of 100 m^2 (10m× 10m), and a ceiling height of 3 m. A schematic of the building is shown in Fig. 3.

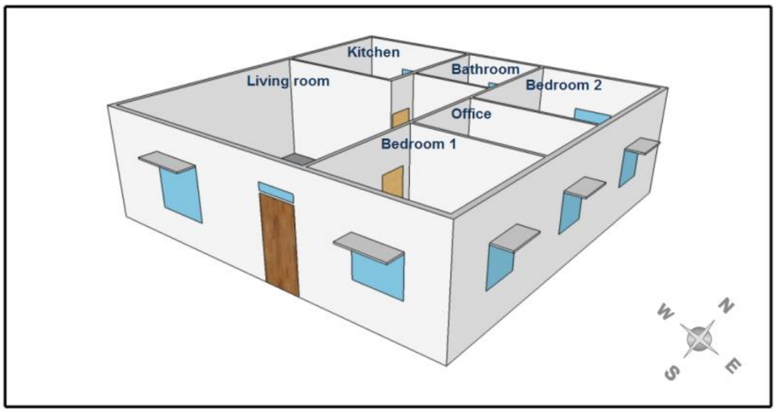

Fig. 1 *Sketch of the building*

There are six zones including living room (Zone 1), bedroom 1 (Zone 2), office (Zone 3), bedroom 2 (Zone 4), bathroom (Zone 5) and kitchen (Zone 6). Three facades are fenestrated (South, North and East). All windows are equipped with a movable exterior blind to limit excessive heat gain during the summer and an excessive daylight illuminance level. Moreover, the South and East facades, that receive a higher level of solar radiation, are equipped with fixed overhangs for better protection. More general details about building characteristics are presented in Table 1.

The amount of natural light transmitted into the building depends on many factors such as; the daylight illuminance level, windows size, glazing type and shading factor. Thus, to ensure the indoor visual comfort standards, an auxiliary artificial lighting system is turned on whenever the illuminance in the zone goes below the required level. For efficient use of artificial lighting during the daytime, a four-level dimmable electric lighting system with a power density of 5 W/m^2 is installed in each zone. The activation of the artificial lighting during the daytime is "On" if the value of the illuminance indicator of the zone's control points is below the level recommended by the Moroccan Agency for Energy Efficiency (Table 1) (AMEE, 2015a).

Table 1 *General building design details*

Building design parameters	Value/description
U-value floor	1 (W / m^2. °C)
U-value of interior walls	1.75 (W / m^2. °C)
U-value internal /External doors	2.8 (W / m^2. °C) / 2 (W / m^2. °C)
Glazed area for the north facade	10%
Recommended illuminance level by zone	Zone 1: 300 lux; Zone 2: 300 lux; Zone 3: 300 lux; Zone 4: 300 lux ; Zone 6: 500 lux (AMEE, 2015a)
Movable blind activation conditions	If Indoor temperature (Tint) >25 °C If Daylight Glare Index (DGI) >22 (Piccolo & Simone, 2009)
Air infiltration rate	0.6 ACH (minimum rate)

The building is considered to be occupied regularly by a family of four people. The details of human occupancy, lighting, and electric equipment are summarized in Appendix A (AMEE, 2016; Sghiouri et al., 2018). The indoor temperature is set to be controlled between 20-26 °C through an Air-Conditioning System (ACS) during the occupied time. The ACS has a Coefficient of Performance (COP) when used in cooling mode and an Energy Efficiency Ratio (EER) when used in heating mode.

5.2 Objective Functions Assessment

The air-conditioning energy performance of the building is estimated through the value of energy demand for heating and cooling (EH/C):

$$E_{H/C} = \frac{Q_H}{EER} + \frac{Q_C}{COP} \tag{1}$$

In EnergyPlus, the module Zone HVAC: "Ideal Loads Air System" is used to generate the thermal loads for heating QH and cooling QC. The air-conditioning energy performance is better when the EH/C is lower and vice versa.

For the building daylight performance, it is estimated through the Lighting Energy Consumption (LEC). As was mentioned in Section 4.1, the artificial lighting is activated during the daytime to meet the minimum illuminance level, whenever the amount of natural light is insufficient. Thus, the daylight performance is higher as the lighting energy consumption is lower and vice-versa. The value of LEC is generated by EnergyPlus as an output.

5.3 Presentation of Design Parameters and Their Ranges of Variation

The chosen design parameters (Xi) correspond to the bioclimatic passive design measures that were selected through the bioclimatic chart tool in section 3.2. Furthermore, a set of possible values or solutions is specified for each design parameter for the optimization study: Xi= {Xi, 1, Xi, 2, Xi,j}. The corresponding building design parameters for the bioclimatic design measures are depicted in Table 2. Also, in the same table, the candidate solutions (or candidate values) for each design parameter have been presented.

A detailed description of different wall, roof and windows glazing types scenarios are reported in Table 1B and Table 2B in the Appendix B. The thermo-physical properties of the construction materials were taken from the BINAYATE software library developed by the Moroccan Agency for Energy Efficiency (AMEE, 2015b).

Table 2 - *Design parameters and their ranges of variation*

Bioclimatic design measure	**Design parameter**	**Values /solutions**
Internal heat gain + Solar radiation gain + High thermal mass	Wall type (X_1)	Wall 1 (medium-massive wall with exterior insulation) Wall 2 (medium-massive wall with interior insulation) Wall 3 (high-massive wall with exterior insulation) Wall 4 (high-massive wall with interior insulation)
	Roof type (X_2)	Roof 1 (medium-massive / exterior insulation) Roof 2 (medium-massive / interior insulation) Roof 3 (high-massive / exterior insulation) Roof 4 (high-massive / interior insulation)
	Glazed area_South facade (X_3) Glazed area _East facade (X_4)	from 10% to 40% from 10% to 40 %
	Windows glazing type (X_5)	Simple glazing Double glazing Triple glazing
Windows shading system	Overhang depth_South facade (X_6) Overhang depth_East facade (X_7)	from 0.1 m to 1.1 m from 0.1 m to 1.1 m
Summer night natural ventilation	Opening area for summer natural night ventilation in each zone (X_8)	from 0.2 m^2 to 1 m^2

6. Results and Discussion

6.1 Optimization Results

Two independent simulation-optimization studies were carried out to find the optimum values (or solutions) of the design parameters, allowing the best air-conditioning energy performance and the best daylight performance of the building. These objective functions are assessed by means of the heating/cooling energy consumption and lighting energy consumption indicators, respectively. The simulation-based optimization studies were carried out by coupling EnergyPlus and GenOpt. Regarding the optimization problem nature with continuous and discrete independent design variables, the hybrid Generalized Pattern Search Particle Swarm Optimization with Constriction Coefficient Hooke–Jeeves (GPSPSOCCHJ) algorithm (Wetter, 2011) was used in this study as it is recommended by Ali et al., (2013). Then, the Pareto front method was employed to solve the multi-objective optimization problem (Machairas, Tsangrassoulis, & Axarli, 2014). The Pareto front solutions, also called non-dominated solutions, correspond to every solution which it is not possible to improve one objective function without worsening another (Anagnostopoulos & Mamanis, 2010).

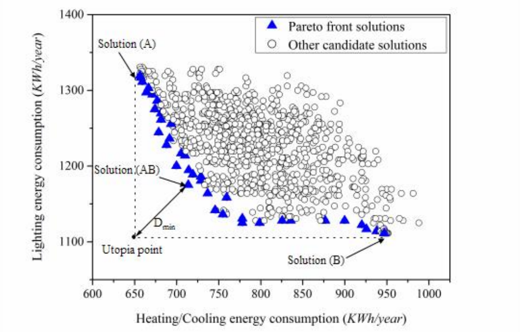

Fig. 4 *Pareto front diagram and optimal design solutions illustration*

The set of Pareto front solutions is depicted in Fig. 4. Solution (A) refers to the optimal design solution for best air-conditioning energy performance (i.e. Lower $E_{H/C}$ at 656 kWh/year), while Solution (B) refers to the optimal design solution for best daylight performance (i.e. lower LEC at 1111 kWh/year). The intermediate Solution (AB) between the two Solutions (A) and (B) is selected as the closest solution to the utopia point solution, as shown in Fig. 4 (Nguyen et al., 2014). The utopia point solution is an imaginary solution corresponding to the minimum of $E_{H/C}$ and LEC (Fig. 4). The optimum design parameters corresponding to the Solutions (A), (B) and (AB) are presented in Table 3.

Table 3 *Optimum design Parameters for Solution (A), Solution (B) and la Solution (AB). (Note that X1/ X2: walls/roof types; X3/ X4: south/east glazed area; X5: glazing type; X6/ X7: south/east overhangs depth; X8: Opening area for summer natural night ventilation)*

	X1	X2	X3 / X4	X5	X6 / X7	X8
Solution (A)	Wall 3	Roof 3	13% / 10%	Triple glazing	1.1 m / 1.1 m	1 m2
Solution (B)	Wall 1	Roof 2	40% / 40%	Simple glazing	0.1 m / 0.6 m	1 m2
Solution (AB)	Wall 3	Roof 3	40% / 14.4%	Double glazing	0.6 m / 0.85 m	1 m2

6.1.1 Design Solution (A)

The results showed that the massive walls and roof with exterior insulation are suitable to achieve the best air-conditioning energy performance of the building (i.e. Solution (A)). The outcomes of the bioclimatic chart of Tétouan highlighted the importance of the thermal mass of the building envelope. On this basis, two scenarios with respect to the thickness of the thermal mass layer (stone) were investigated in the optimization study. As a result, the higher thickness of the thermal mass layer (30 cm) was selected to be optimal for enhancing the air-conditioning energy performance of the building. Tétouan city is characterized by a hot-summer Mediterranean climate where the need for cooling is more dominant. During the hot season days, and as the outdoor temperature begins to increase in the morning, the thermal mass stores the heat. This prevents the increase of the indoor temperature during the daytime and consequently limits the need for artificial cooling. Besides that, the building's thermal mass allows storing the excessive internal and solar gains during the cold season daytime and restores it during the night-time.

As for the exterior insulation, it leads to taking full advantage of the thermal inertia capacity (i.e. thermal mass) of the envelope. Moreover, the single outside insulation also proved more effective than the single inside insulation to reduce the cooling and heating energy loads according to the findings of Al-Sanea & Zedan, (2011).

Small triple glazed windows were also found effective for enhancing the air-conditioning energy performance. The optimum glazed area of the East facade is slightly smaller than that of the South facade. This is because the East facade is exposed to much more solar radiation during the hot season, which risks overheating. The optimal length of the shading devices was found to correspond to its maximum possible value (1.1 m) for both East and West-facing walls, which leads to avoiding the high intensity of solar radiation during the hot season. Night natural ventilation is a free and an efficient technique to reduce cooling energy consumption during the hot season. Ventilation allows buildings to bring out the released heat from the envelope and bring in the fresh air from the outside. The importance of this technique has been supported by the outcomes of the optimization study. Within a range of variation from 0.2 m2 to 1 m2, the optimum value of the opening area for summer natural night ventilation in each zone is 1 m2. In the study conducted by Elaouzy & El Fadar, (2022b) on bioclimatic building design in the Mediterranean region, the authors concluded that night ventilation is strongly recommended to improve the summer energy performance of the buildings in the north of Morocco. The authors used the window open rate as an indicator to assess the potential use of night ventilation. Within a range of 0% to 100%, the rate of 75% was selected optimally to improve the summer energy performance of the building.

6.1.2 Design Solution (B)

Solution (B) refers to the best design solution for daylight performance. As was expected, using a large glazed area is necessary to achieve the best daylight performance in the building.

Moreover, the single-glazing type is selected for windows because it has a higher capacity to transmit natural light, and consequently reduce the need for artificial lighting. In fact, the visible transmittance coefficient of the single glazing is the highest compared to the double and triple glazing types. The window shading systems lead to better exploitation of daylight and solar radiation to provide natural light and heat. For the range of 0.1m to 1.1m, the optimization study showed that a minimum length of the windows overhang is suitable for the South-exposed facade, while the medium length is optimal for the East-façade.

6.1.3 Design Solution (AB)

Turning now to Solution (AB) refers to the best trade-off between air-conditioning energy performance and daylight performance. The high thermal mass combined with exterior insulation was selected as the best composition for the walls and roof. The optimal glazed area for the South-exposed facade is much wider compared to the East-exposed facade of about 7.6 m^2. The optimum overall WWR considering all facades of the building is about 17%. This result is still in line with the results of Košir et al., (2018) who concluded that a WWR value of below 30% is recommended to ensure a better compromise between heating, cooling, and lighting energy performance.

As for the length of the window shading system, the results showed that the overhang length of the South-exposed facade should be shorter compared to those of the East facade by about 0.25m. The optimum values of WWR and overhang length mean that the maximum exploitation of natural light is allowed from the South-facing wall without the risk of having an undesirable impact from the excessive incidental solar radiation during the hot season. As for the windows type, the double-glazing type was found to be the optimal solution to guarantee a better compromise between air-conditioning energy performance and daylight performance. This glazing type has a balanced capacity to transmit heat and light regarding the single glazing and triple glazing types (see Table 2B).

6.2 Building Performance Analysis of The Optimum Design Solution

To give a more detailed analysis of the obtained results, in this section the monthly air-conditioning energy performance and daylight performance of the optimum design solution “Solution (AB)” is presented and compared to those obtained for the Solutions (A) and (B).

6.2.1 Air-Conditioning Energy Performance Analysis

- **Monthly Assessment of Air-Conditioning Energy Performance**

Fig. 5 depicts the monthly heating and cooling energy demand of the Solutions (AB), (A) and (B). This consumption refers to the energy needed to maintain the indoor building temperature between 20 - 26 °C.

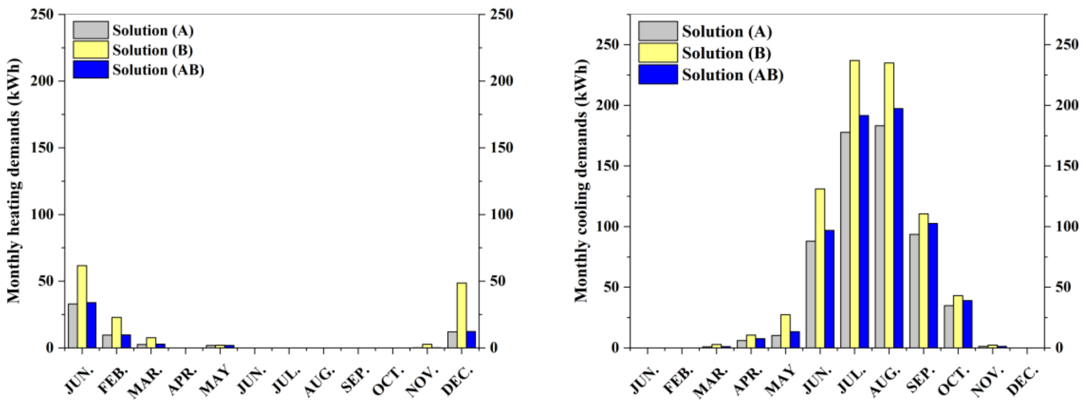

Fig. 5 *Monthly heating and cooling demands for Solution (A), Solution (B) and Solution (AB)*

It can be seen from Fig. 5 that the space cooling demand is more dominant throughout the year for the three solutions, which means that the building prototype has difficulty resisting summer high temperatures. Reviewing the data of the Solution (AB), the maximum monthly cooling energy consumption is up to 197 kWh (registered in August), while the maximum monthly heating energy consumption does not exceed 33 kWh (registered in January). The heating demand is only necessary for a short period of time and is mainly concentrated in three months of the year: December, January, and February. In terms of cooling energy demand, it begins to rise from March and peaks in July/August. The remarkable increase in the cooling energy demand from May to June suggests that the building design is more vulnerable to the high outside temperature even with the advantages of the night ventilation strategy. This trend keeps going up in July and August, which means that combining such bioclimatic design measures as high thermal mass, exterior insulation, and night ventilation is not enough to mitigate the peak cooling energy demand in Tétouan.

The total air-conditioning energy demand for the optimum design Solution (AB) is up to 711 kWh. This value is only 8.5% higher compared to the performance shown by the best design solution for air-conditioning energy performance (i.e., Solution (A).

- **Checking the Compliance of the Performance of the Optimum Design Solutions against MBTR Requirements**

The MBTR, which came into effect in 2015, aims to define the minimum requirements for residential and tertiary buildings (AMEE, 2013). The first version of these regulations was limited to the building air-conditioning energy performance by defining the minimum heating and cooling energy requirements for each Moroccan climate zone.

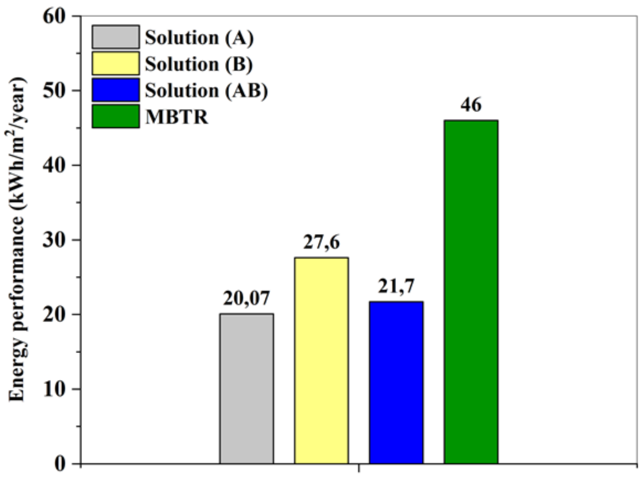

Fig. 6 *Monthly Comparison of the energy performances of the design Solutions (A), (B) and (AB) with the MBTR requirements*

Nevertheless, it is necessary to check the compliance of air-conditioning performance of the obtained design solutions with the thermal regulation requirements. It can be noticed from Fig. 6 that the application of the bioclimatic architecture approach resulted in a significant reduction in heating and cooling energy requirements compared to the MBTR limits. The annual heating and cooling energy demands of the Solution (AB), which refers to the best compromise between air-conditioning energy performance and daylight performance, is lower by about 52% in comparison to the maximum level allowed by the MBTR. The corresponding value for Solution (A) exceeds 56%. Moreover, the heating/cooling energy demand for Solution (B), which refers to the daylight performance, is higher compared to Solutions (A) and (AB). However, it is still well beyond the MBTR limits.

6.2.2 Daylight Performance Analysis

The daylight performance of the multi-objective optimum design solution is highlighted through the interpretation of the contribution of sunlight to reduce the need for artificial lighting to meet the required illuminance level.

To this end, the resultant lighting energy consumption by means of two lighting controls is compared. The first one consists of dimmable lighting control, as was actually considered in the optimization study, and the second one consists of a hypothetical non-dimmable lighting control where the artificial lighting is always on at full power during the occupied period. Fig. 7 presents the monthly value of lighting energy consumption (LEC) with and without dimmable lighting control for the solution (AB), as well as for the solutions (A) and (B). The percentage of lighting energy-saving (η_{LEC}), achieved by using daylight-responsive lighting control, is also presented. Obviously, the value of η_{LEC} is higher as the amount of natural light transmitted is increased, and vice-versa.

It is seen that the maximum benefit of sunlight is achieved during the cold season, when the η_{LEC} is more important. During this period, the sun's position is lower. Consequently, the amount of light transmitted through the South-facing windows is more important. Focusing on the Solution (AB), combining the air-conditioning energy performance and daylight performance, it is recorded that the monthly value of the η_{LEC} is greater than 20% for the period from November to April. Conversely, the worst daylight performance occurs during the hot season when the η_{LEC} reaches its minimal level. The η_{LEC} varies within the range of 18% to 15% for the period from May to October. Therefore, the result is explained, in addition to the sun elevation factor, by the rise of the overheating risk, which involves using the movable blind to limit the incident solar radiation. On an annual basis, the results reveal that the solution (AB) reduces the need for artificial lighting to meet the required illuminance level by 19%. Whereas, this value is lower only by 4% compared to the daylight performance presented by the solution (B), which corresponds to the best design solution for daylight performance.

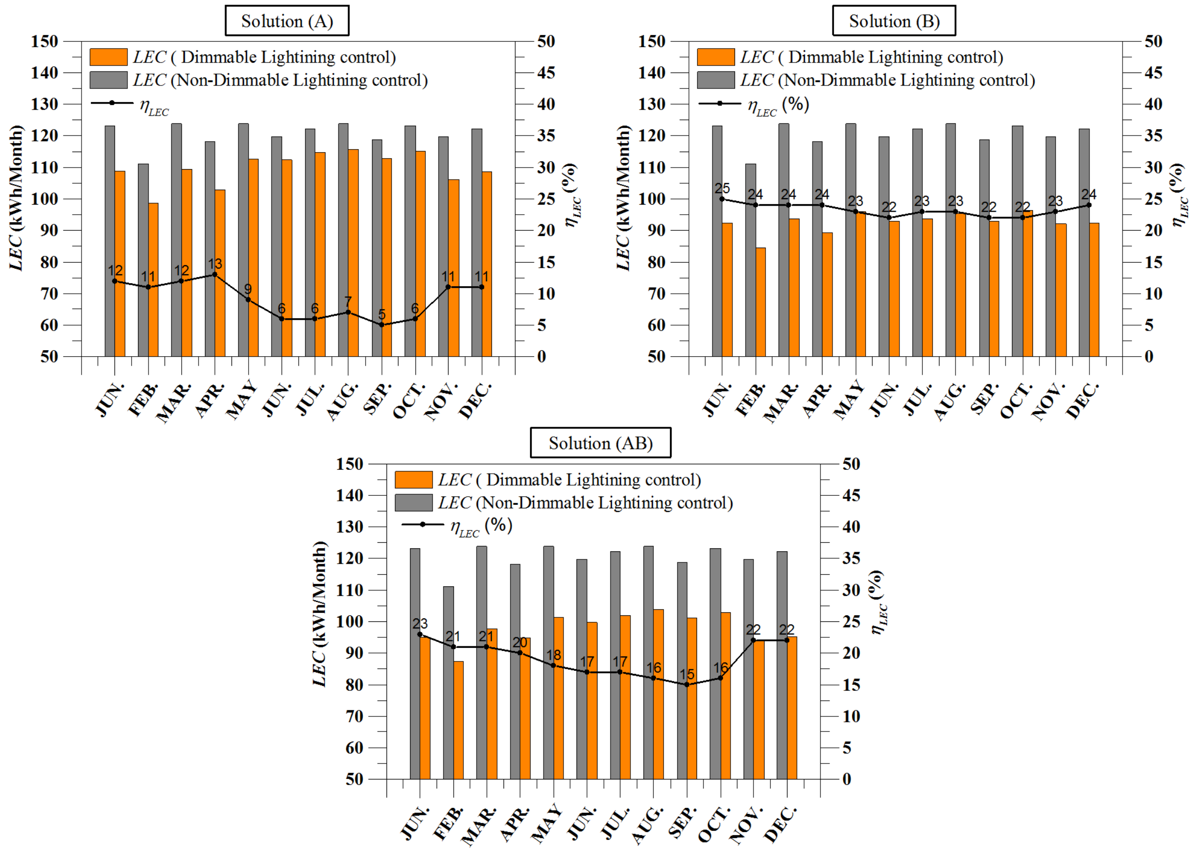

Fig. 7 *Monthly daylight performance of Solutions (AB), (A) and (B). Comparison of the lighting energy consumption (LEC) with and without dimmable lighting control*

7. Conclusion

The work presented a multi-objective optimization study of the passive bioclimatic design parameters of an air-conditioning residential building located in the north of Morocco. The optimization was based on a set of the most adapted bioclimatic design measures to the Moroccan Mediterranean climate and aimed to simultaneously improve the air-conditioning energy performance and daylight performance of the building. The set of bioclimatic design measures included: (i) reinforcement of the thermal mass of the envelope; (ii) exploitation of the internal heat gains and (iii) passive solar heat gains for heating; (iv) sun shading of windows; and (v) summer natural ventilation.

The multi-objective optimization reveals the following recommendations:

- Balanced capacity of windows in terms of heat and light transmission.
- Massive envelope construction with exterior isolation.
- Small glazing area is needed for the East-exposed façade, versus wide glazing area for the South-exposed façade.
- Wide glazing area is allowed for the South-exposed façade.
- The East-exposed facade would require more shading compared to the South-exposed facade.
- Important summer night ventilation rate is needed.

The evaluation of air-conditioning energy performance of the optimum multi-objective design solution showed a significant improvement compared to the MBTR requirements. In relative terms, applying the optimum design solution might lead to an energy saving of 52% of the air-conditioning energy demand.

Concerning the daylight performance, it was concluded that the design features of the optimum design solution might reduce the need for artificial lighting to meet the required standards of visual comfort, by 19%.

The results reported here are encouraging to proceed with the application of the multi-objective bioclimatic design approach to new building construction not only in the North Moroccan region but also in the entire Mediterranean region. Besides, further studies are needed to explore other aspects of the bioclimatic design, such as its economic feasibility as well as its environmental footprint.

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Appendix A:

Table A1 *Internal heat gains generated by occupants (Presented by Metabolic rate by Person [MR/P])*

	Weekdays			Weekend		
Zones	Schedule	Nb of occupants	*MR/P*	Schedule	Nb of occupants	*MR / P*
Zone 1 Living & Dining room	07h – 08h	4	170 W	09h – 10h	4	170 W
	13h –14h	4	170 W	13h – 14h	4	170 W
	19h – 20h	4	170 W	20 h – 23h	4	170 W
	12h – 13h	3	100 W	15h – 18h	1	100 W
	18h –19h	3	100 W			
	08h – 11h	1	100 W			
	14h –17h	1	100 W			
	19h – 22h	1	100 W			
Zone 2 Bedroom 1	22h – 23h	2	100 W	08h – 09h	2	100 W
	23h – 07h	2	83W	14h – 17h	1	100 W
				23h – 08h	2	83 W
Zone 3 Office	20h – 22h	1	150 W	10h – 13h	1	150 W
Zone 4 Bedroom 2	20h – 22h	2	150 W	10h –13h	2	150 W
	22h – 23h	2	100 W	14h – 17h	2	100 W
	23h – 07h	2	83 W	23h – 09h	2	83 W
Zone 6 Kitchen	11h – 13h	1	209 W	08h – 09h	1	209 W
	17h – 19h	1	209 W	10h – 13h	1	209 W

Table A2 *Electrical equipment operating conditions*

	Weekdays			Weekend		
Zones	Schedule	Type of gains	Power	Schedule	Type of gains	Power
Zone 1 Living & Dining room	12h – 13h	TV	120 W	13h – 14h	TV	120 W
	18h – 22h	TV	120 W	20h – 23h	TV	120 W
	18h – 22h	Light	5 W/m^2	18h - 23h	Light	5 W/m^2
Zone 2 Bedroom 1	22h – 23h	Light	5 W/m^2			
Zone 3 Office	20h – 22h	Light	5 W/m^2	10h –12h	PC	200 W
	20h – 22h	PC	200 W			

Zone 4 Bedroom 2	20h – 22h 20h – 22h	Light PC	5 W/m^2 200 W	10h – 13h	PC	200 W
Zone 6 Kitchen	00h – 00h 10h – 11h 12h – 13h 18h – 19h 18h – 19h	Refrigerator Washing Kitchen Kitchen Light	100 W 2000 W 800 W 800 W 5 W/m^2	00h – 00h 10h – 11h 11h – 13h	Refrigerator Washing Kitchen	100 W 2000 W 800 W

Appendix B:

Table 1B *The scenarios components of exterior wall and roof*

Building component	Scenario	Description	Components and Thickness (cm)	U-value (W / m^2. °C)
Wall	WALL 1	Medium massive /exterior isolation	Solid brick (3 cm) Moroccan cork (5 cm) Stone (15 cm) Gypsum plaster (1,3 cm)	0,63
	WALL 2	Medium massive / interior isolation	Solid brick (3 cm) Stone (15 cm) Moroccan cork (5 cm) Gypsumplaster (1,3 cm)	0,63
	WALL 3	High massive/exterior insulation	Solid brick (3 cm) Moroccan cork (5 cm) Stone (30 cm) Gypsumplaster (1,3 cm)	0,60
	WALL 4	High massive/interior isolation	Solid brick (3 cm) Stone (30 cm) Moroccan cork (5 cm) Gypsumplaster (1,3 cm)	0,60
Roof	ROOF 1	Medium massive /exterior isolation	Ceramic (2 cm) Mortar (2 cm) Moroccan cork (5 cm) Solid slab (15 cm) Gypsumplaster (1,3 cm)	0,63
	ROOF 2	Medium massive /interior isolation	Ceramic (2 cm) Mortar (2 cm) Solid slab (15 cm) Moroccan cork (5 cm) Gypsumplaster (1,3 cm)	0,63
	ROOF 3	High massive/ exterior	Ceramic (2 cm)	0,61

	insulation	Mortar (2 cm) Moroccan cork (5 cm) Solid slab (30 cm) Gypsumplaster (1,3 cm)	
ROOF 4	High massive/ interior insulation	Ceramic (2 cm) Mortar (2 cm) Solid slab (30 cm) Moroccan cork (5 cm) Gypsumplaster (1,3 cm)	0,61

Table 2B *Thermo-physical properties of glazing types (Ameur et al., 2020)*

Type of glazing	Thermal transmittance coefficient (W/m².°C)	Solar transmittance coefficient	Visible transmittance coefficient
Simple glazing	5.75	0.87	0. 90
Double glazing	2.95	0.77	0.81
Triple glazing	2.00	0.70	0.74

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