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The analysis of occupants' thermal comfort in a residential building in Tangier, Morocco

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Bioclimatic design is currently one of the most important steps in passive building design adapted to outdoor climatic conditions. However, the Moroccan Thermal Building Regulations (RTCM) primarily focus on the building envelope and its energy performance, often overlooking occupant comfort. To address this gap, a bioclimatic analysis of the Mediterranean climate in Tangier was conducted to determine the percentage of thermal comfort naturally provided by this climate and to identify suitable passive strategies for buildings in the region. The results indicate that Tangier's climate can provide up to 28% thermal comfort. Consequently, the most effective passive strategies for buildings in Tangier include shading techniques, high thermal mass, internal heat gains, and direct passive heating. Furthermore, implementing these strategies can enhance occupant comfort by 6% and reduce the building's energy demand by 11.74%.

Keywords: *bioclimatic design; building thermal regulation; energy performance; Mediterranean climate; thermal comfort; passive strategies.*

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1. Introduction

The design and construction of passive or near-passive buildings [1] are currently one of the main challenges facing the scientific community. The creation of energy self-sufficient buildings offers a crucial solution to a number of current challenges, such as climate change [2], greenhouse gas emissions [3, 4], the growing demand for energy and the transition to sustainable energy sources [5].

According to estimates from the International Energy Agency, most countries are not immune to the effects of climate change. Furthermore, by 2050, three–quarters of the world's population will be moving from rural areas to cities. Hence, the need to implement a series of strategies to meet the increased energy needs arising from this spatial mobility.

In the building sector, and among the solutions and alternatives that are being studied by scientists today, we find passive strategies such as: the use of ecological materials [6, 7], and bioclimatic design strategies [8,9]. However, few studies have focused on exploiting the building's external environment in bioclimatic architecture as a preliminary step to determine the characteristics and strategies appropriate for both the site and the building.

In reviewing previous research, particular attention has been paid to a number of notable contributions in the field of bioclimatic design. Agugliaro et al. [10] examined several bioclimatic architecture construction strategies for different climatic zones in order to achieve high levels of thermal comfort and energy efficiency, which revealed that the application of bioclimatic architecture requires the consideration of thermal comfort offered by the climate in the vicinity of the building. To this end, several tools have been used to determine thermal comfort. For example, Mahoney and Evans [11] developed an analytical tool in the form of calculation sheets to be filled in based on meteorological data for the site under study. In addition, Givoni [12] has developed a bioclimatic diagram divided into 14 zones, each requiring the application of an appropriate active or passive strategy, enabling design choices to be directed towards more appropriate solutions. However, this tool requires an assessment of the weather conditions outside the building. If outside the comfort zone, bioclimatic architectural strategies are proposed, such as internal heating gains, passive solar heating, solar protection, conventional heating, active solar heating, cooling by high thermal mass, humidification, cooling by high thermal mass with night-time renovation, cooling by evaporation, cooling by mechanical and natural ventilation, air conditioning and conventional dehumidification.

A concrete example of the application of these concepts was seen in the in-depth study carried out by Charai et al. [13] who attempted a bioclimatic design analysis to improve the thermal comfort level inside a building located on the university campus in the city of Oujda in Morocco. The study showed that the Oujda climate provided only 20% of the comfort, whereas the application of the main bioclimatic design strategies reduced the building's heating and cooling requirements by 9.5% and 45.6% respectively.

Following on from this work, and bearing in mind that indoor thermal comfort is closely dependent on outdoor conditions, the aim of this study is to carry out a bioclimatic analysis of the city of Tangiers in Morocco. This analysis will be based on the PMV (Predicted Mean Vote)/PPD (Predicted Percentage of Dissatisfied) methods, with the aim of proposing specific recommendations for the construction of passive buildings in this locality, thus contributing to a more personalized and effective approach to the design of energy-efficient buildings in the region. These recommendations will then be applied to a residential building meeting the requirements of the RTCM in order to quantify their impact on the indoor comfort and on energy demand. We also assess the feasibility of combining the recommendations of the bioclimatic analysis with the requirements of the RTCM for a given climate zone.

The paper is organized as follows. Section 2 deals with a detailed discussion of the problem, so as to present a description of the building and climate studied, as well as in a comparison of energy performance with the RTCM, and a review of the state of thermal comfort. Section 3 is devoted to a bioclimatic analysis of the climate of Tangier, Morocco, in order to propose passive strategies adapted to the buildings constructed in this city. Section 4 then examines the impact of applying the bioclimatic analysis recommendations on the energy demand and thermal comfort levels of the building concerned. Finally, the results of the work are presented in Section 5.

2. Methods and materials

2.1. Problematic description

The implementation of the Thermal Regulations for Buildings in Morocco (RTCM) [14] in 2014 marked a significant step forward in the search for energy-efficient solutions. However, despite these regulations, the reality on the ground reveals a discrepancy between the standards imposed by the RTCM and the actual level of thermal comfort achieved in most buildings constructed in compliance with its requirements.

The RTCM, in its current form, is based mainly on two distinct approaches. The prescriptive approach sets standard values for the transmission coefficient of the various walls in the building envelope. The second approach, known as performance-based, focuses on determining the building's maximum heating and cooling energy requirements. Although these approaches are useful, they have their limitations, particularly in terms of tailoring solutions to the specific weather conditions of each locality.

In this context, our study proposes a thermal comfort analysis of a building that meets the requirements of the RTCM, located in the city of Tangiers. This study is carried out in the form of a numerical simulation using TRNSYS software. However, the study will help to identify potential gaps in compliance with the RTCM in terms of thermal comfort, while paving the way for specific, customized recommendations for improving the thermal comfort and energy efficiency of buildings in the region through bioclimatic design.

2.2. Description of the studied building

The studied building is a two floors residential oriented due south. The study concerns only the ground floor, which is 3m high with an area of $85.5\,\mathrm{m}^2$. The distribution of space within the floor is illustrated in Figure 1, while the composition of the envelope is detailed in Table 1.

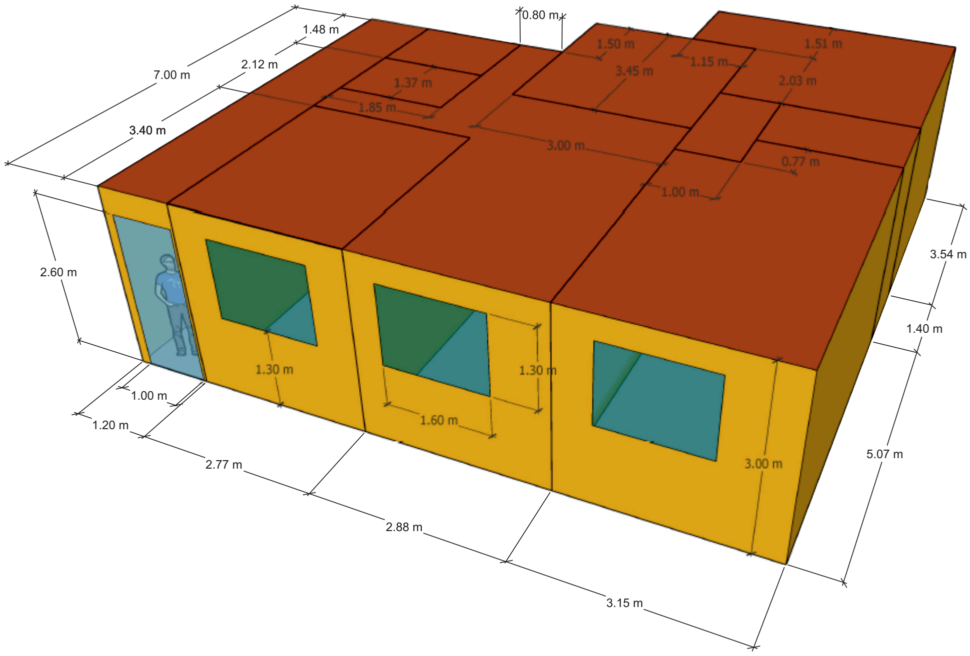

Fig. 1. Plan of the studied building.

Table 1. Envelope materials and their thermophysical properties.

Envelope components	Materials	Thickness (cm)	Thermal conductivity (KJ/h m K)	Density (kg/m^3)	Thermal capacity (kJ/(kg K))
Ground	Hard stone	15	7.94	2400	0.8
	Cement mortar	3	4.68	1900	1
	Polyurethane	3	0.108	35	0.83
	Heavy concrete	10	7.2	2450	1
	Cement mortar	5	4.68	1900	1
	Tiles	1	4.68	2300	0.84
High floor	Gypsum plaster	1	2.016	1315	1
	Concrete slabs	12	9	2500	1
	Cement mortar	5	4.68	1900	1
	Polyurethane	6	0.108	35	0.83
	Cement mortar	2	4.68	1900	1
	Tiles	1	4.68	2300	0.84
Interior wall	Cement mortar	2	4.68	1900	1
	Hollow brick	10	0.684	918	0.74
	Cement mortar	2	4.68	1900	1
Exterior wall	Cement mortar	2	4.68	1900	1
	Hollow brick	10	0.684	918	0.74
	Polystyrene	6	0.141	25	1.38
	Air gap	5	0.216	1	1.22
	Hollow brick	10	0.684	918	0.74
	External plaster	1	4.15	1700	1

— Glazing: Single glazing: $U = 5.69\,\mathrm{W/m^2\,K}$, $g = 0.82$.
— The window/wall ratio (WWR): 9.53%.
— Building orientation: due south.

2.3. Overview of Tangier's climate

Tangier is a Moroccan city in the far north of the country. The climate is Mediterranean, with hot, sunny summers and mild, rainy winters. Figure 2 shows the annual temperature distribution, relative humidity variations, solar radiation and wind speed.

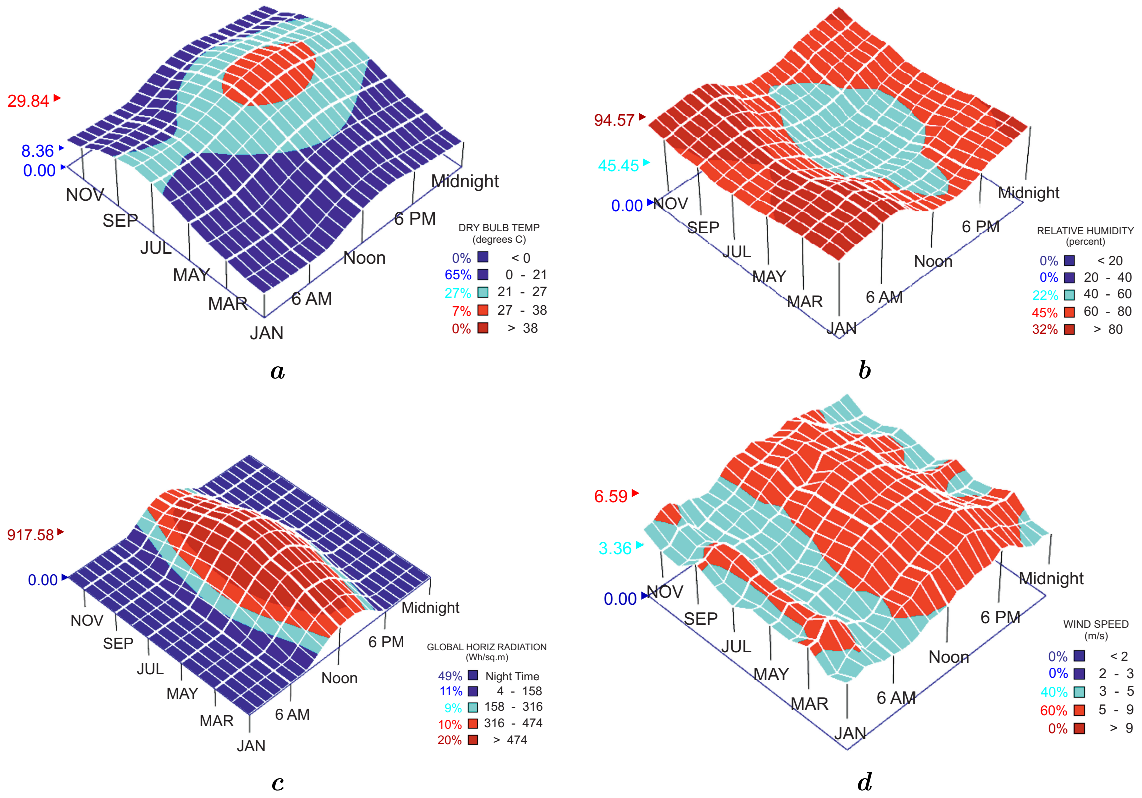

Fig. 2. Climatic data for Tangier city (***a***) Temperature (°C), (***b***) Relative humidity (%), (***c***) Solar radiation (Wh/m^2), (***d***) Wind speed (m/s) (Climate consultant 6.0).

2.4. Comparison of numerical results with the RTCM requirements

The results are compared between our numerical results based on the mathematical modeling described below and the requirements of the RTCM and the thermal comfort model based on the two indices PPD and PMV.

- Prescriptive approach:

For this approach, the calculation is based on the U thermal transmittance formulae (1)–(3):

$$U = \frac{1}{R_{\text{Tot}}}, \tag{1}$$

U and R_{Tot} are respectively the thermal transmittance ($\text{W/m}^2\,\text{K}$) and the total thermal resistance ($\text{m}^2\,\text{K/W}$). The total thermal resistance of an envelope wall is expressed:

$$R_{\text{Tot}} = R_{si} + \sum_{i=1}^{n} R_i + R_{se} = R_{si} + R_1 + \ldots + R_n + R_{se}, \tag{2}$$

$$R_i = \frac{e_i}{\lambda_i}, \tag{3}$$

R_{si} and R_{se} are the thermal resistance of internal and external surfaces respectively ($\text{m}^2\,\text{K/W}$). And R_i is the thermal resistance of the layer i the wall, expressed as a function of thickness $e\,(\text{m})$ and thermal conductivity λ ($\text{W/m\,K}$).

— [(1)] If the wall opens onto another unheated room, R_{si} applies on two sides.

— [(2)] A room is said to be open if the ratio of the total surface area of its permanent openings to the outside, to its volume, is equal to or greater than $0.005\,\text{m}^2/\text{m}^3$.

Table 2. Envelope materials and their thermophysical properties.

Wall facing	Outside An open passage An open room[2]	R_{si} ($\mathrm{m^2\,K/W}$)	$R_{se}^{(1)}$ ($\mathrm{m^2\,K/W}$)	$R_{si}+R_{se}$ ($\mathrm{m^2\,K/W}$)
Horizontal wall (angle of inclination $< 60^\circ$)	Ascending flow Descending flow	0.10 0.17	0.04 0.04	0.14 0.21
Horizontal wall (angle of inclination $\geqslant 60^\circ$)	********	0.13	0.04	0.17

• Performance-based approach:

For this approach, the calculation is based on the energy balance for each thermal zone of the building:

$$\Phi_{\text{Total}} = \Phi_{\text{Inf}} + \Phi_{\text{Vent}} + \Phi_{\text{Coup}} + \Phi_{\text{Wall,surf}} + \Phi_{\text{G,int}} + \Phi_{\text{Solar,glz}} + \Phi_{\text{Solar,sh}}, \tag{4}$$

where Φ_{Inf} is thermal gains through air infiltration, Φ_{Vent} is thermal gains through air ventilation, Φ_{Coup} is thermal gains due to coupling between thermal zones, $\Phi_{\text{Wall,surf}}$ is thermal gains due to air convection around walls, $\Phi_{\text{G,int}}$ is thermal gains due to internal gains, $\Phi_{\text{Solar,glz}}$ is thermal gains due to solar radiation passing through the windows, $\Phi_{\text{Solar,sh}}$ is thermal gains due to solar radiation absorbed by shading devices of the thermal zone.

The results of the present study are compared with the requirements of the two RTCM approaches. The city of Tangier belongs to the second climatic zone (Zone 2). In this zone, the performance-based approach imposes a maximum threshold for the building's heating and cooling requirements, while the prescriptive approach sets values of the thermal transmittance of the building's walls for a given ratio of glazed openings "U", as shown in Table 3.

Table 3. Comparison of the present study results with RTCM requirements.

Approach	Specifications	RTCM	Our work
Performance approach	Annual energy requirements ($\mathrm{kWh/m^2\,year}$)	46	45.04
Prescriptive approach (WWR = 9.53%)	$U_{\text{Exterior wall}}$ ($\mathrm{W/m^2\,K}$)	$\leqslant 0.80$	0.277
	$U_{\text{High floor}}$ ($\mathrm{W/m^2\,K}$)	$\leqslant 0.75$	0.435
	$U_{\text{Floor on ground}}$ ($\mathrm{W/m^2\,K}$)	NE	0.773
	U_{Glazing} ($\mathrm{W/m^2\,K}$)	$\leqslant 5.80$	5.69

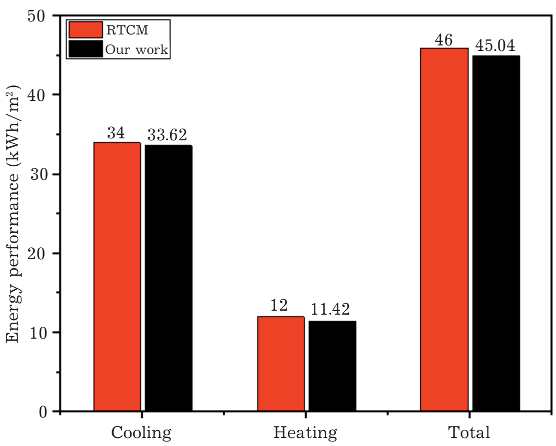

Fig. 3. Comparison of the building's energy performance with RTCM requirements.

Figure 3 clearly shows that our numerical results are in good agreement with the specifications of the RTCM performance approach. In addition, and to test the reliability of our numerical calculations, a comparison of the energy requirements obtained by simulation with those required by the RTCM is carried out. To do this, the relative error (RE) is calculated using the formula (5),

$$\mathrm{RE}\,(\%) = \frac{|E_{\text{sim}} - E_{\text{real}}|}{E_{\text{real}}} \cdot 100\%, \tag{5}$$

where E_{real} and E_{sim} are the real energy consumption and the simulated energy consumption. So the real data is that of the RTCM.

Table 4. Validity of the numerical model.

Energy requirements	Heating	Cooling	Total
RE (%)	4.83%)	1.11%	2.08%

2.5. Thermal comfort study

To study the state of thermal comfort, we use the famous PMV and PPD comfort indices based on the ISO 7730 standard [15].

In order to estimate the state of indoor thermal comfort in a building, two indices are commonly used: the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD).

The PPD estimates the number of people dissatisfied with thermal conditions and can be calculated using the following formula (6):

$$\mathrm{PPD} = 100 - 95\big(-0.03353\,\mathrm{PMV}^4 - 0.2179\,\mathrm{PMV}^2\big). \tag{6}$$

The PMV is an index that estimates the average vote of a group of people on a scale of seven thermal sensations Table 5. It is expressed as

$$\begin{aligned}\mathrm{PMV} = \big(0.303\,e^{-0.036M} + 0.028\big) \times \big\{&(M-W) - 3.05\cdot 10^{-3}[5733 - 6.99(M-W) - P_\alpha] \\ &- 0.42(M-W) - 58.15] - 1.7\cdot 10^{-5} M(5867 - P_\alpha) - 0.0014M(34 - t_\alpha) - 3.96\cdot 10^{-8} f_{\mathrm{cl}} \\ &\times [(t_{\mathrm{cl}}+273)^4 - (\bar{t}_{\mathrm{r}}+273)^4] - f_{\mathrm{cl}} h_{\mathrm{c}}(t_{\mathrm{cl}} - t_\alpha)\big\},\end{aligned} \tag{7}$$

where M is the metabolic rate $(\mathrm{W/m^2})$, W is the effective mechanical power $(\mathrm{W/m^2})$, P_α is the water vapor partial pressure (P_a), t_α is the air temperature (K), f_{cl} is the ratio of surface area of the body with clothes to the surface area of the body without clothes, t_{cl} is the clothing surface temperature (K), t_r is the mean radiant temperature (K), h_c is the convective exchange coefficient $(\mathrm{W/m^2\,K})$.

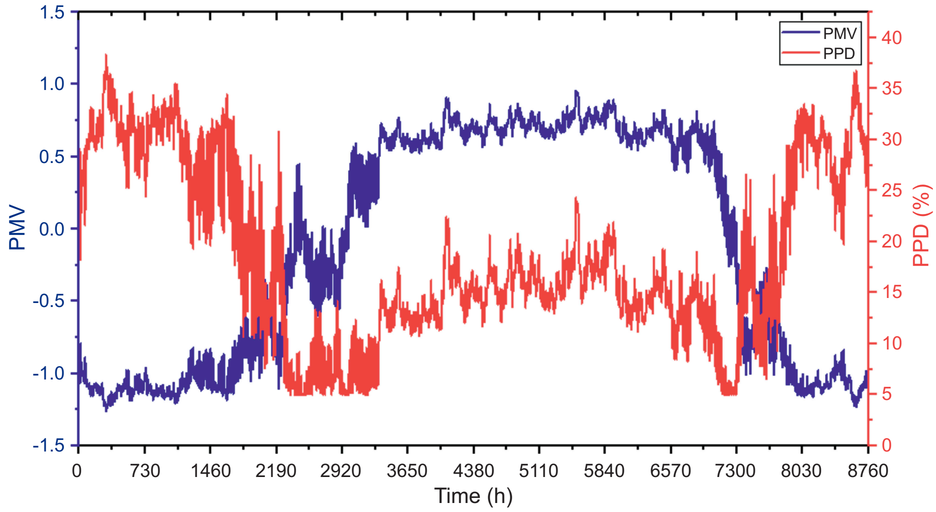

Fig. 4. PMV-PPD graph of thermal comfort in room 1.

Figure 4 shows the variations in the PMV and PPD comfort indices in room 1 on the ground floor. Careful reading of this graph and based on the data in Table 5, in the worst case, more than 36% of occupants are dissatisfied with the state of comfort inside the building, even though it is an RTCM building. In fact, improving the building's interior comfort is conditional on the recommendations of a bioclimatic analysis of the climate in the city of Tangier.

Table 5. The comfort zone based on PMV index values.

PMV	−3	−2	−1	0	+1	+2	+3
Thermal Perception	Cold	Cool	Slightly cool	Neutral (Comfortable)	Slightly warm	Warm	Hot

3. Bioclimatic analysis of Tangier climate

In this step, we will try to find bioclimatic design strategies adapted to the buildings constructed in the city of Tangier. In fact, the bioclimatic analysis of a given region climate is a very important step, since it enables optimum use of changes in the external climate in order to minimize cooling and heating requirements.

For the city of Tangier and according to Figures 5–7, using the California energy code, the percentage of thermal comfort is estimated at 20%, while winter and summer discomfort are estimated at 62% and 18% respectively. It should be noted that the state of comfort can vary according to the standard used, as shown in Table 6. For the ASHRAE 2005 standard, comfort increases to 28%. Whereas for the ASHRAE 55 standard, comfort increases to 28%.

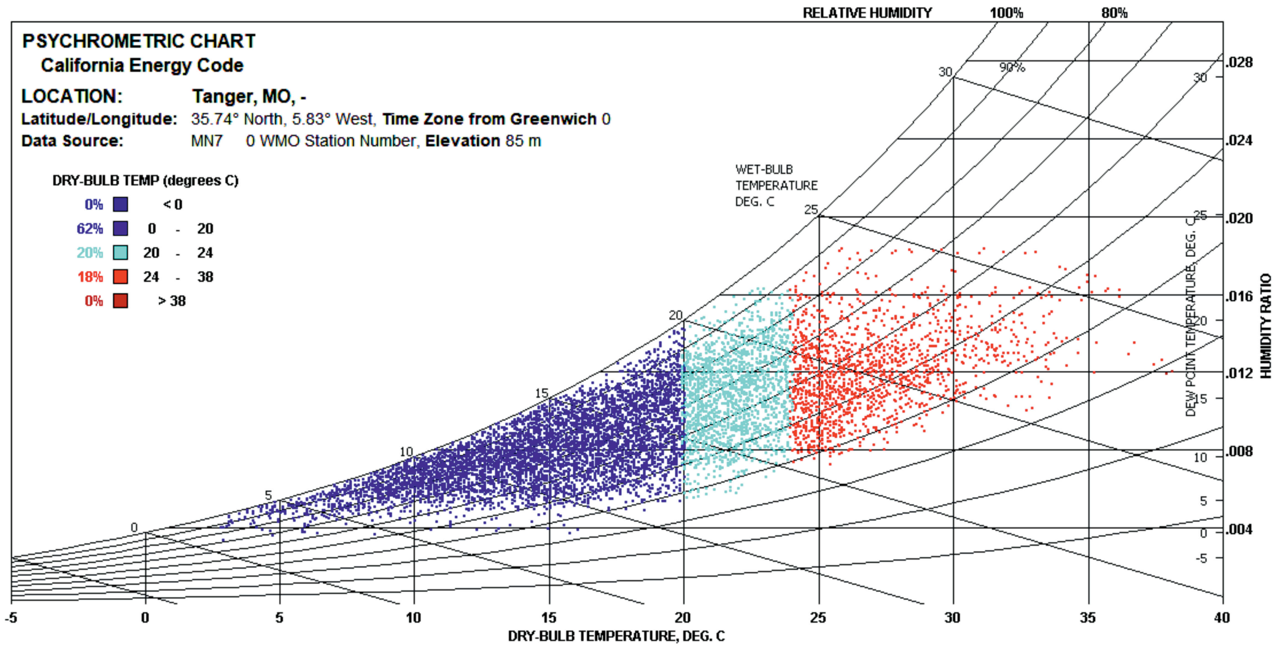

Fig. 5. Comfort levels as a function of outdoor temperature in Tangier according to California Energy Code (Climate consultant 6.0).

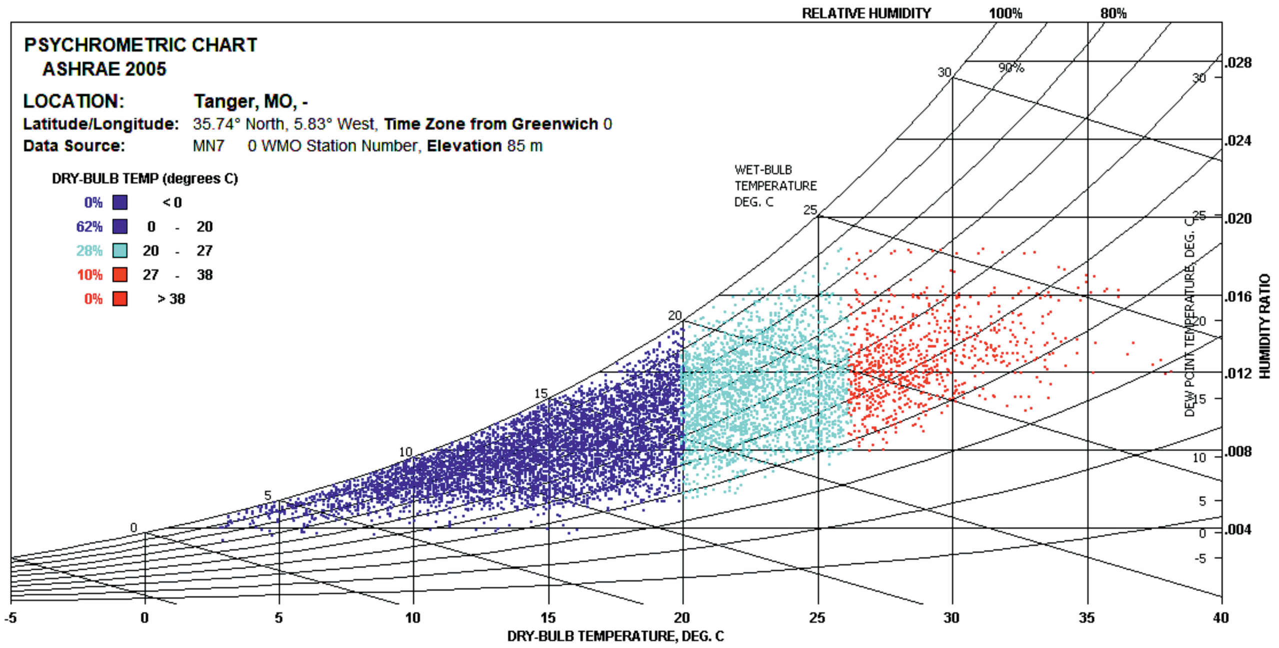

Fig. 6. Comfort levels as a function of outdoor temperature in Tangier according ASHRAE2005 (Climate consultant 6.0).

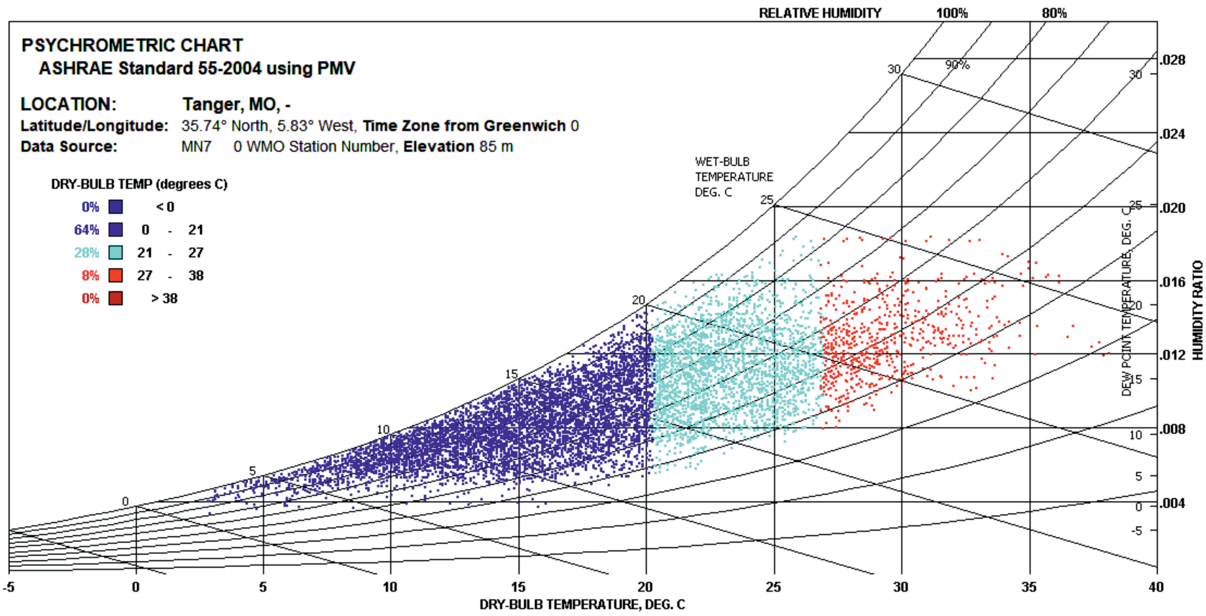

Fig. 7. Comfort levels as a function of outdoor temperature in Tangier according ASHRAE55 (Climate consultant 6.0).

Table 6. Thermal comfort in Tangier according to the three standards.

Standard	Comfort temperature intervals	Below comfort level	Thermal comfort	Above comfort level
California Energy Code	[20°C, 24°C]	62%	20%	18%
ASHRAE 2005	[20°C, 27°C]	62%	28%	10%
ASHRAE 55	[21°C, 27°C]	64%	28%	8%

A simple comparison of the average temperatures recorded in summer and winter with the comfort intervals shows that there is large thermal discomfort, especially in winter. That is why the city of Tangier needs as much heating as cooling.

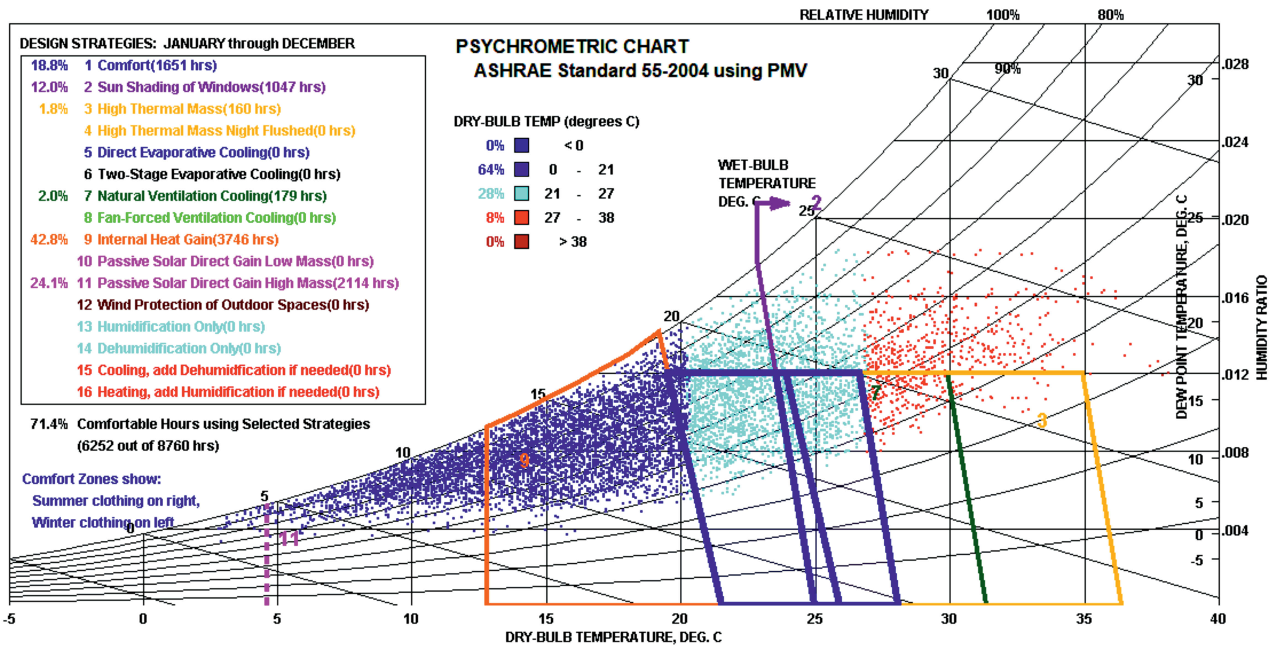

Fig. 8. Passive strategies appropriate to Tangier climate using the PMV/PPD method (Climate consultant 6.0) [16].

To increase thermal comfort. Bioclimatic building design strategies are used. To do this, based on the PMV/PPD standard, and using Climate 6.0 software for a clothing factor of 1 in winter and 0.5 in summer and with a metabolic rate of 1.2. Figure 8 shows a psychometric map indicating the different passive strategies appropriate to the city of Tangier climate. According to this map, direct passive heating by solar radiation contributes by up to 24.1% to the improvement in thermal comfort hours, a technique that can be achieved by using a good glazing system with an adequate wall/window ratio. In addition, a shading system for fenestration improves comfort by 12%. Internal thermal gains represent the most remarkable strategy, with a comfort improvement of up to 42.8%. However, the effect of natural ventilation and the thermal mass of the building envelope remain very limited, offering an improvement of only 2% and 1.8% respectively. These passive strategies are the most recommended for a passive building in Tangier.

4. Application of bioclimatic analysis recommendations

In this section, we will assess the impact of applying the bioclimatic design strategies recommended previously.

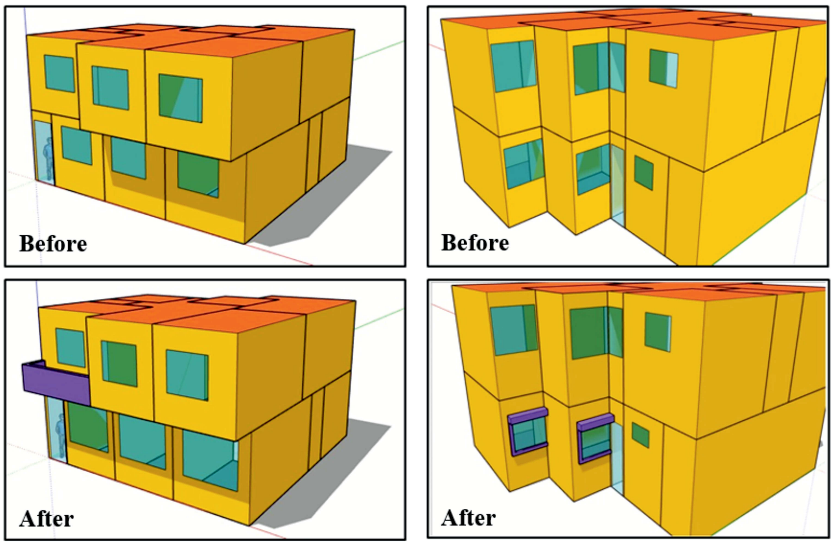

Fig. 9. The building before and after the application of bioclimatic design strategies.

Figure 9 shows the various passive strategies applied to the studied building:

- Shading is provided by the balcony on the main facade and by overhangs for the windows on the rear facade to prevent the passage of solar radiation, especially in summer.
- Thermal mass is increased using a new external wall envelope (cement mortar (1 cm) 8-hole hollow brick (7 cm) expanded polystyrene (12 cm) 12-hole hollow brick (15 cm) external plaster (1 cm)).
- Direct passive heating is achieved by making the following modifications:
  - For the south facade: use double glazing ($U_{\text{value}} = 1.27\,\text{W/m}^2\,\text{K}$) and increase the window/wall ratio to make the most of the sun's rays in winter.
  - For the rear facade (north and north-west): use double glazing with low transmission coefficient and solar factor values to avoid heat loss in winter.
- The building faces due south for optimum comfort.

The RTCM already takes into account a number of passive strategies as part of the application of its two prescriptive and performance-based approaches. The present work aims to increase the level of thermal comfort in order to approach that recommended by the psychometric map of Tangier city (ASHRAE Standard 55). Figure 10 shows the state of thermal comfort in the reference building (RTCM) and in the building after application of the strategies recommended by the bioclimatic analysis and the ASHRAE 55 standard. The results show that the application of these strategies improved thermal comfort by 6% and reduced energy demand by 11.74% (Figure 11).

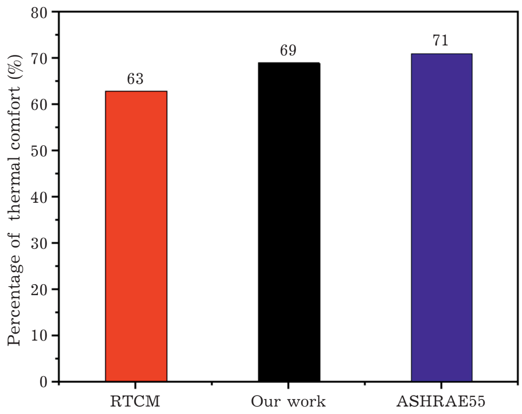

Fig. 10. Comfort in room 1.

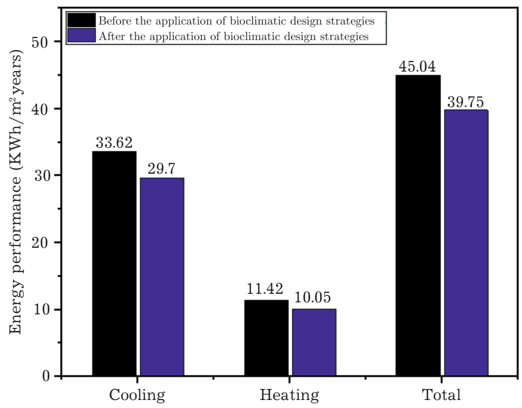

Fig. 11. Heating and cooling energy demand before and after the application of bioclimatic design strategies.

5. Conclusion

This work presents an investigation aimed at improving passive building construction in terms of occupant comfort by the example of Tangier City, Morocco. As a first step, an assessment of the comfort provided by the city's climate was carried out using the PMV/PPD method for three different standards: California Energy Code, ASHRAE 2005 and ASHRAE 55. The results show that Tangier's climate provides annual comfort in the order of 20%–28% according to the three standards mentioned above. Hence the need to improve thermal comfort levels by designing passive buildings. Psychometric maps generated using Climate 6.0 software show that the main passive strategies suitable for buildings in the city of Tangier are respectively: shading techniques, high thermal mass, internal thermal gains and direct passive heating. In order to verify the impact of these passive strategies on the comfort state inside a building located in Tangier, a numerical simulation using TRNSYS was carried out. The simulation results show that the application of appropriate bioclimatic design strategies can improve indoor comfort by 6% and reduce the building's energy demand by 11.74%.

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Аналіз теплового комфорту мешканців житлового будинку в Танжері, Марокко

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Біокліматичне проектування на даний час є одним з найважливіших кроків у проектуванні пасивних будівель, адаптованих до зовнішніх кліматичних умов. Проте, у марокканських теплових будівельних нормах (RTCM) враховуються лише огороджувальні конструкції будівлі та її енергетичні характеристики, без урахування комфорту мешканців. Щоб усунути цю прогалину, було проведено біокліматичний аналіз середземноморського клімату в Танжері, щоб визначити відсоток теплового комфорту, який природно забезпечується цим кліматом, і визначити відповідні пасивні стратегії для будівель у регіоні. Результати показують, що клімат Танжера може забезпечити рівень комфорту до 28%, а також що найбільшими відповідними пасивними стратегіями для будівель у Танжері будуть методи затінення, висока теплова маса, внутрішнє теплопостачання та пряме пасивне опалення. Крім того, поєднання цих стратегій може підвищити комфорт мешканців на 6% і знизити енерговитрати будівлі на 11.74%.

Ключові слова: *біокліматичне проектування; теплорегулювання будівлі; енергетичні характеристики; середземноморський клімат; тепловий комфорт; пасивні стратегії.*