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# Passive systems for energy savings of buildings in tropical climate

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### Abstract

Passive systems and bioclimatic architecture principles applied to modern architecture are able to reduce the energy demand of the building sector, and to meet the Nearly Zero-Energy Building goals. The aim of this research is to reduce the discomfort time of buildings located in tropical climate, by using passive systems taken from vernacular architecture and bioclimatic modern buildings. For this purpose, a model building has been designed, meeting the tropical climate requirements. Energy simulation has been done to compare the thermal behavior and thermal comfort conditions of the model building, under different passive systems cases: thermal mass, solar protections, crossed ventilation, and dehumidification. The results reveal that a combination between high thermal inertia with nocturnal ventilation, the use of solar protections on the north facade, dehumidification, and the use of thermal insulation in the roof is fundamental for achieving the thermal comfort in buildings located in tropical weather.

Keywords: *Energy simulation, bioclimatic strategy, passive design, thermal comfort, office building.*

## 1. Introduction

Building sector consumes 40% of the final energy consumption (Economidou 2011). Half of this energy consumption is due to the use of active systems for heating and cooling (Meijer et al. 2009). For these reasons, the greatest energy savings potential is associated to the building sector, and to the reduction of the energy demand from heating and cooling systems (Economidou 2011). To reduce buildings energy consumption, it is created the concept Nearly Zero-Energy Building (NZEB). This concept has become part of the energy policies of many countries, to make possible the reduction of emissions of $CO_2$ generated by the building sector (COM 2011; Crawley et al. 2009). Passive systems and bioclimatic architecture principles applied to modern architecture are able to reduce the energy demand of the building sector, and to significantly contribute to the NZEB goals. These strategies were broadly used in vernacular architecture (Manzano-Agugliaro et al. 2015). However, the major part of contemporary architecture does not use them. Most of modern buildings are not designed in adaptation to their climatic conditions and, therefore, they require active systems for achieving the indoor thermal comfort.

The aim of this paper is to reduce the number of hours not meeting thermal comfort criteria of buildings located in tropical climate. This is done by using passive systems taken from vernacular architecture and bioclimatic modern buildings. For this purpose, this paper analyses the thermal behavior of a model building that incorporates different cooling passive systems, by using energy simulation. The building is located in Goiânia, a city of the interior of Brazil, with tropical climate (Aw according to Köppen). This research is part of an initiative that aims to build a prototype with the NZEB concept, named Model House, to realize experimental researches about thermal comfort and energy efficiency.


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## 2. Passive systems for tropical climate

### 2.1 The climatic conditions of the location

The analyzed building in the simulation is hypothetically located in Goiânia, the capital of the State of Goiás, Brazil (Latitude -16.7º, Longitude -49.3, Elevation 741 m). The region of Goiás is within the Tropical savanna climate area (Aw), according to Köppen climate classification (Kottek et al. 2006). This climate is characterized by two main seasons: wet -from October to April- and dry -May to September- (Tab. 1). In Goiânia, the predominant winds are; north (16% of the time), south east (16% of the time), east (14% of the time), and north west (13% of the time).

**Tab. 1: Climatic conditions of Goiânia, Brazil (World Climates 2016).**

| Month | Average Air temperature* | Relative humidity* | Daily solar radiation | | |
|---|---|---|---|---|---|
| | | | Roof | South Facade | North Facade |
| | ºC | % | kWh/m²·d | kWh/m²·d | kWh/m²·d |
| January | 23.8 | 75 | 5.13 | 1.03 | - |
| February | 23.8 | 76 | 4.67 | 0,14 | 0,27 |
| March | 23.9 | 74 | 4.69 | - | 1,10 |
| April | 23.6 | 71 | 5.50 | - | 3,00 |
| May | 22.1 | 65 | 4.66 | - | 3,77 |
| June | 20.7 | 60 | 4.47 | - | 4,36 |
| July | 22.9 | 53 | 4.67 | - | 4,25 |
| August | 24.6 | 47 | 5.04 | - | 3,29 |
| September | 24.6 | 53 | 5.68 | - | 1,96 |
| October | 24.6 | 65 | 4.74 | 0,14 | 0,35 |
| November | 24.0 | 73 | 5.58 | 0,88 | - |
| December | 23.5 | 76 | 4.58 | 1,18 | - |

**Climatological average (1961-1990)*

In this latitude, the North facade is exposed to winter insolation. For this reason, it should be well protected from solar radiation and should have a reduced glass surface (Fernandes 2006). The south facade can have a wider glass surface, but still requires solar protections in summer period, when solar radiation can reach it. Along all the year, the roof is the part of the building which receives the highest solar radiation (Tab.1).

### 2.2 Bioclimatic strategies

According to this climate conditions, the thermal comfort is achieved during 27.4% of the year (Fig. 1). The rest of the year, the recommended bioclimatic strategies are:

- Solar heating (15% of the year).
- Thermal inertia for heating (13.4% of the year).
- Ventilation (13.8% of the year).
- Night ventilation (10.1% of the year).
- Thermal inertia for cooling (10.1% of the year).
- Evaporative cooling (10.1% of the year).

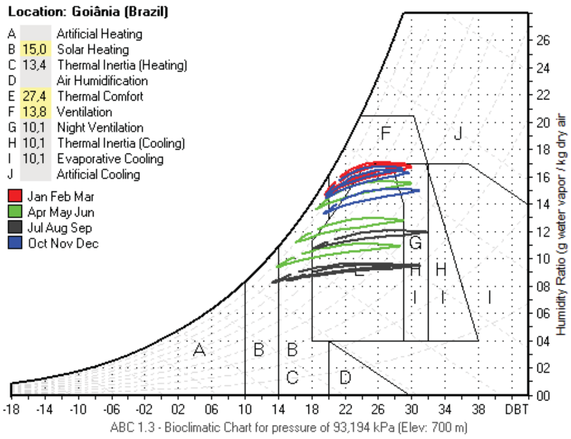


**Fig. 1: Architectural bioclimatic classification according to psychometric abacus. Source: Roriz (1992).**

The bioclimatic strategies for tropical climate are identified, selected, and applied to the building model. They are presented in Tab. 2.

**Tab. 2: Bioclimatic strategies for tropical climate, based on Manzano-Agugliaro et al. (2015).**

| Bioclimatic strategy | Temperature | Relative Humidity | Operation | Architectural implementation |
|---|---|---|---|---|
| 1. Solar protection | >20ºC | - | Avoiding heat gains through solar radiation. Avoiding temperature increases to remain in the comfort zone. Protection is focused on all building openings but can also be generally applied to the building envelope. | • Pergolas with deciduous vegetation<br>• Porches<br>• Awnings<br>• Interior store<br>• Exterior (sunblind) blinds<br>• Exterior brise soleils. |
| 2. Cooling through a high thermal mass | 20-35 °C | - | The thermal mass of the building envelope that receives and subsequently transmits radiation to the interior with a phase difference to achieve climate uniformity throughout the day. | • Capacitive materials help to create a phase difference in the daily energy transmission and temper the intensity. Nocturnal dissipation by the facade and roof is necessary.<br>• It is ideal to place a mobile daytime protection device to avoid gains and promote nocturnal dissipation |
| | From 24 ° C | 80–50% | | |
| | Up to 35 °C | 30% | | |
| 3. Cooling by high thermal mass with nocturnal renovation | 20 °C- 44 °C | - | Creating a phase difference between the effect of the daytime and night time outside temperatures to conduct a nocturnal renovation It is effective when the climate exhibits significant thermal differences between the day and night periods. | • The building envelope should comprise capacitive materials that transmit energy with the largest phase difference possible (approximately 12 h) with some damping.<br>• At night, dissipation and renovation should be conducted through openings, patios and roofs. |
| | 44 °C | 5% | | |
| | 31.5 °C | 32% | | |
| | 24 °C | 80% | | |
| 4. Cooling through natural ventilation | 20 °C - 31.5 °C | 95% - 20% | A greater thermal sensation is achieved while the indoor air is simultaneously cleaned. | • Cross-ventilation from north to south facades or dominant winds<br>• The chimney effect<br>• A solar chamber<br>• Subterranean ventilation<br>• Wind towers<br>• Evaporative towers<br>• Vertical spaces within a building<br>• Patios |
| | From 31.5 °C | 50% | | |
| | Up to 26.5 °C | 95% | | |
| 5. Conventional dehumidification | > 25 °C | > 80% | The objective is to incorporate strategies to absorb water from the environment in order to achieve the comfort zone. | By using absorbent salts and saline cells and requires complementation with other strategies. |
| 6. Thermal insulation in the roof | - | - | Avoid heat gains from solar radiation (perpendicular to the roof in tropical latitude) | Incorporation of thermal insulation in the roof. |

## 3. Building design

This research is part of an initiative that aims to build a prototype with the NZEB concept, named Model House. This building will be used to realize experimental researches about thermal comfort and energy efficiency. In this paper energy simulations will be carried out to quantify and compare the benefits of the proposed bioclimatic strategies and to improve the building design. Once built, the building will be monitored to validate experimentally the simulation results.

The Model House is designed according to bioclimatic criteria, based on the tropical climate conditions and latitude. These criteria take into consideration the optimum shape factor in plan and volume, window size, surface façade and roof color, solar protection, and indoor natural daylighting (Fig. 2).

Moreover, the building is designed for meeting both requirements; experimental research and office use. For this reason, the building has two identical office rooms; the first one will be the reference case, and the second one the case of study. Both rooms share a common patio. This patio has local vegetation ("Cerrado") and a fountain to generate shadow and evaporative cooling. The mobile facades allow the connection of the offices to the patio, depending on the experiment.

According to Olgyay (1963), the optimum shape in plan of a building in tropical climate is 1:1.7, with a range to 1:3. Therefore, the shape plan 1:2 of the designed office space is between this range.

The net floor area of each office is 32.80 $m^2$ (8.20 m x 4.00 m). The interior height is 2.70 m. The building facilities (toilette, kitchen and storage) are located separately, in the east and west part of the building.

The roof is designed for projecting shadow over the building. This double roof protects the building from temperature variations due to solar radiation.

The east and west facades are highly insulated. The north and south facades are removable to make possible the change of experiments. Prefabricated construction systems are used to make possible the removal of materials.

Windows are the 30% of the total facade, according to Rizki et al. (2016), who determined three optimum solutions of window size, orientation and wall reflectance with regard to various daylight metrics and lighting energy demand in simple buildings placed in the tropical climate. They determined that the most optimum solution is the combination of window-to-wall ratio 30%, wall reflectance of 0.8, and south orientation (in the North hemisphere).

**Fig. 2: General view of the Model House, a building designed with bioclimatic principles for experimental purposes in tropical climate.**

The building also meets the Brazilian habitability and construction regulations (NBR 9050/2004, NBR 15220/2003, NBR 15575/2013). According to these regulations (ABNT NBR 15220-3), the maximum overall heat transfer coefficient (or U-value) for facades is 2.2 $W/m^2 \cdot K$, for the roof is 2.0 $W/m^2 \cdot K$. The physical characteristics of the materials used are shown in Tab. 3. The U-values are calculated for each construction system, according to their construction materials.

**Tab. 3: Physical characteristics of the materials used in the building envelope.**

| Part of the building | Construction system | U-value [W $m^{-2}$ $K^{-1}$] | Material | Thickness [cm] |
|---|---|---|---|---|
| Roof | Insulated roof | 0.441<2.0 | Gravel | 6 |
| | | | XPS | 6 |
| | | | Asphalt membrane | 1 |
| | | | Cement mortar | 2 |
| | | | Concrete slap & beams | 30 |
| | | | Plaster coating | 1.5 |
| | Non-insulated roof | 1.980<2.0 | Gravel | 6 |
| | | | Asphalt membrane | 1 |
| | | | Cement mortar | 2 |
| | | | Concrete slab & beams | 30 |
| | | | Plaster coating | 1.5 |
| | Highly insulated roof | 0.248<2.0 | Gravel | 6 |
| | | | XPS | 12 |
| | | | Asphalt membrane | 1 |
| | | | Cement mortar | 2 |
| | | | Concrete slap & beams | 30 |
| | | | Plaster coating | 1.5 |
| South & North Facade | Concrete panel* | 2.777>2.2 | Mortar coating | 2 |
| | | | Precast concrete panel | 10 |
| | | | Plasterboard | 1.5 |
| | Ceramic brick | 2.175<2.2 | Mortar coating | 2 |
| | | | Ceramic Brick | 11.5 |
| | | | Plasterboard | 1.5 |
| East & West Facade | Timbered facade | 0.172<2.2 | Plywood | 2 |
| | | | Mineral wool | 10 |
| | | | Glass wool | 12 |
| | | | Plasterboard | 1.5 |
| Windows | Window | 5.689 | Wooden frame, simple glass | - |
| Doors | Door | 3.280 | Wood | 4.5 |
| Floor | Non-insulated floor | 4.351 | Reinforced concrete | 10 |
| | | | Cement mortar | 2 |
| | | | Ceramic tile | 1 |

*Used in the four facades in experiment #3.*

The space type for both offices is defined by regulation EN 16798, as well as the occupancy schedule. This means that it is stablished 17 $m^2$/person, or 2 people in each office space. The occupancy will be distributed from 8-12 AM and 1-7 PM.

No heating or cooling device is simulated, only free floating temperatures, because bioclimatic strategies are evaluated.

## 4. Energy simulation experiments

The thermal behavior of the Model House is simulated before its construction. This simulation is done with Energyplus software, by using Opens Studio (Fig. 3). The simulation results will be validated with the monitoring of temperature, humidity, and air flow in the constructed building. The experiments will take place under hot and humid, and hot and dry weather conditions for the tropical climate. The experiments held in the building model are:

- **Solar protection:** Comparison of a window with solar protection (horizontal brise soleils) versus a window with no solar protection (Fig. 3).
- **Cooling through a high thermal mass:** Comparison of two different materials in the facade; high thermal mass (concrete panel) versus low thermal mass material (ceramic brick), and different wall resistance (Tab. 3).
- **Cooling through a high thermal mass with nocturnal renovation**: Comparison of the use of night ventilation and no ventilation, with concrete panel in the four facades (Tab. 3).
- **Cooling through natural ventilation:** The effect of ventilation in the thermal comfort, comparing a ventilated office by using infiltrations through the window area (4 renovations per hour) and a no ventilated office.
- **Conventional dehumidification:** The use of absorbent salts for decreasing the humidity of the air of the test office (simulated by using a HVAC Dehumidifier) compared to a non-dehumidified office.
- **Thermal insulation in the roof** (Fig. 3): Comparison of the effect of thermal insulation in the roof without solar protection, comparing a roof with and without insulation (Tab. 3).

**Fig. 3: Views of the office building (Model House) energy simulation done with SketchUp and Open Studio. From left to right: Solar protections, Cooling through natural ventilation, Thermal insulation in the roof.**

Because of the latitude, the North facade receives solar radiation mainly in the winter season (Tab. 1). For this reason, the experiment #1 “Solar protections” will be done during solstice of June.

June is the month with wider thermal lag, reaching the coolest temperatures of the year during the night (Tab. 1). For this reason, winter solstice (the week around June 21st) is the selected period for the experiment #2 “Cooling by high thermal”.

The same experiment will be done with and without nocturnal renovation #3 “Cooling through a high thermal mass with nocturnal renovation”. Previous simulation with AnalisisBio (Albano 2013), points out this month as the optimum to reach the Nearly Zero Energy consumption.

The experiment #4 “Cooling through natural ventilation” will be done in both, dry and wet season. For this reason, the driest month, September, and the more humid month, December, are selected (Tab. 1).

December is the month with higher requirements of thermal comfort, due to the high relative humidity combined with the high air temperature (Tab. 1). This discomfort can be corrected by using natural ventilation (Albano 2016). It is in December, during the wet season, when will be done the experiment #5 “Conventional dehumidification”.

Finally, the experiment #6 “Thermal insulation in the roof” will be done during both solstices and the equinox in September, to test the differences in solar radiation along the key moments of the year (Tab. 4).

**Tab. 4: Experimentation cases and timing.**

| Bioclimatic strategy to be tested | Reference Case A | Evaluated Case B | Period of time of the experiment |
|---|---|---|---|
| 1. Solar protection in the north facade | No solar protection | Brise-soleils | 14th – 28th June |
| 2. Cooling through a high thermal mass | Ceramic brick | Concrete facade | 14th – 28th June |
| 3. Cooling by high thermal mass with nocturnal renovation | No nocturnal ventilation | Nocturnal ventilation | 14th – 28th June |
| 4. Cooling through natural ventilation<br>4.1. Dry season<br>4.2. Wet season | No Ventilation | All day ventilation | • Dry season: 1st-15th September.<br>• Wet season: 14th – 28th December |
| 5. Conventional dehumidification | No dehumidification | HVAC Dehumidifier | 14th – 28th December |
| 6. Thermal insulation in the roof<br>6.1. Solstice in June<br>6.2. Solstice in December<br>6.3. Equinox in September | No insulation | Insulation | 14th – 28th June<br>14th – 28th December<br>14th – 28th September |

## 5. Results

The thermal behavior of each office is evaluated by using the number of hours of discomfort in the office per the period of the experiment. Fig. 4 shows the "Time Not Comfortable" based on the ASHRAE Standard 55 Adaptive Comfort model, within the 80% acceptability limits. The ASHRAE Standard 55 Adaptive model is especially suited for naturally ventilated buildings with no mechanical cooling systems, and occupants have better control over their thermal comfort. More details about the requirements and features of the method are explained elsewhere (ASHRAE 2010). For the dehumidification case 5, the Fanger's Comfort model has been used instead, to be able to consider the effect of humidity on human comfort. The results are presented for the period of 2 weeks, during the time of occupation.

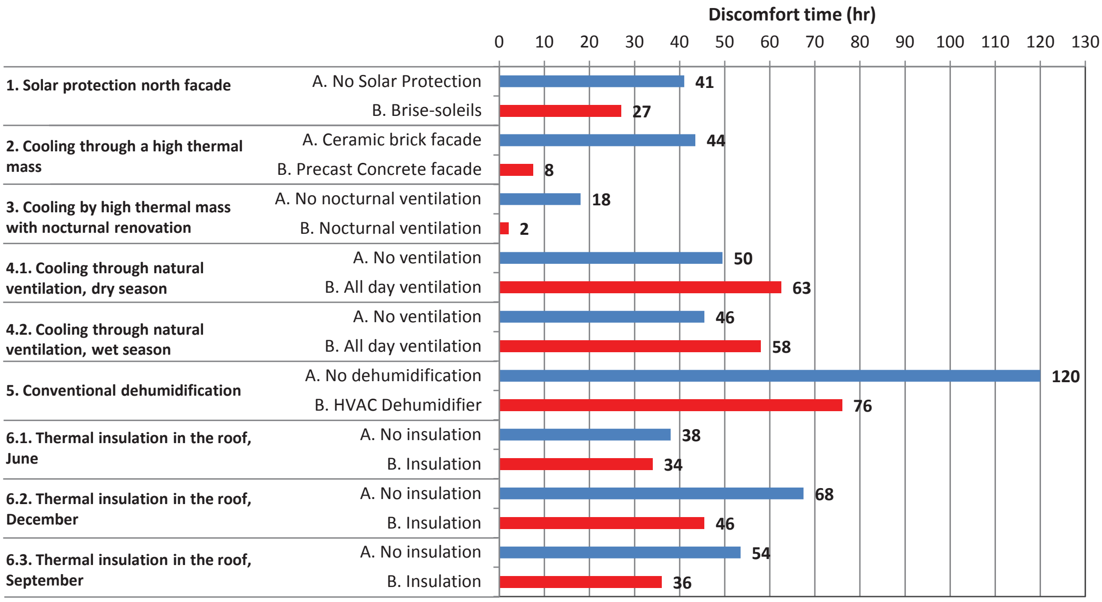


**Fig. 4: Time Not Meeting the ASHRAE55 Adaptive Comfort Model with 80% Acceptability Limits during Occupied Hours. Units: hr.**

The graphics of temperature, humidity, occupation, and air change rate for the selected period and each experiment are presented in Fig. 5: Outdoor temperature (black), indoor temperature in reference office (dark blue), test office (light blue), and occupation or ACH (pink dotted lines).

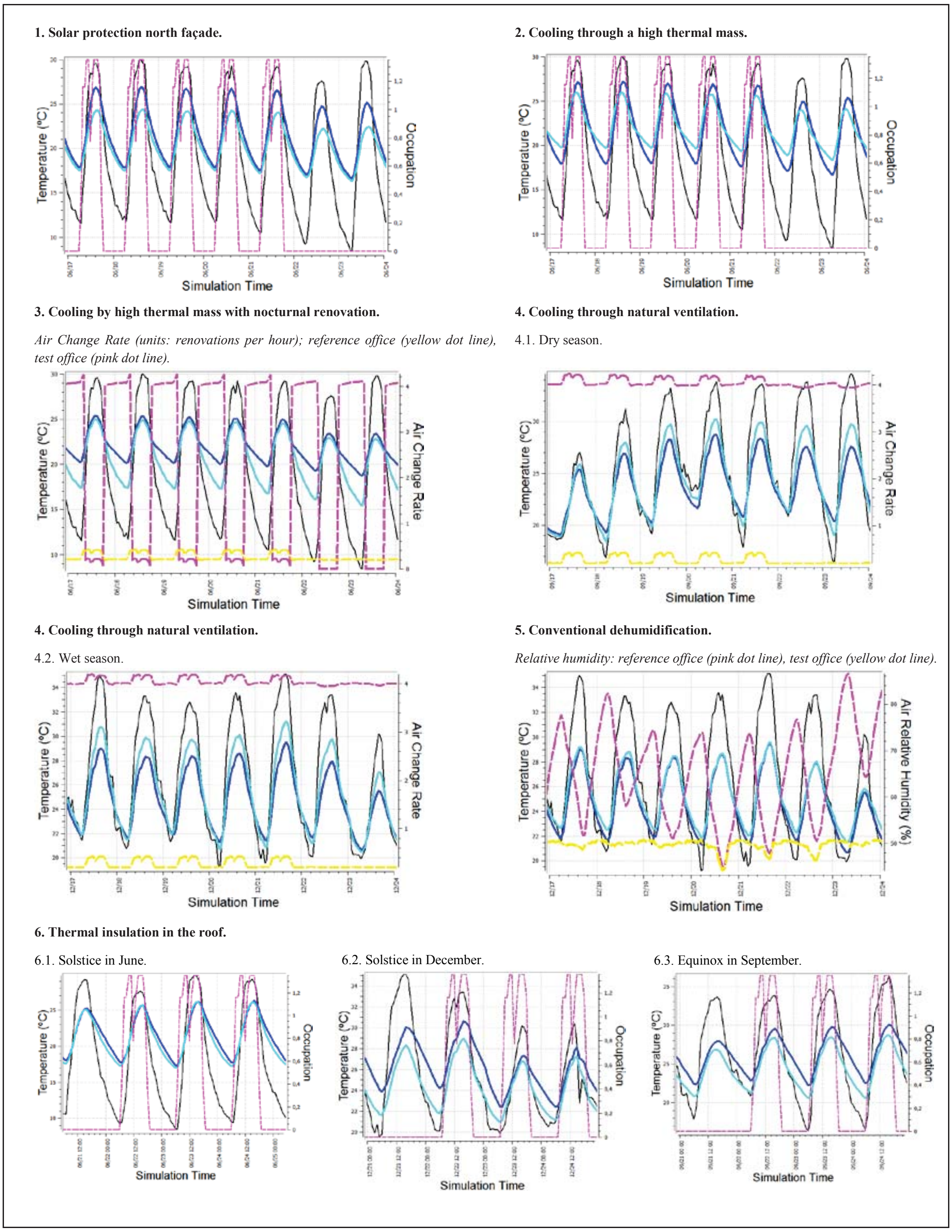


**Fig. 5: Results for each experiment in the selected period: outdoor temperature (black line), reference office (dark blue line), test office (light blue line), occupation or Air Changes Rate (pink dot line).**

## 6. Discussion

The more significant improvement performances were found in the following strategies:

- 1st: Cooling by high thermal mass with nocturnal renovation: 89% improvement.
- 2nd: Cooling through a high thermal mass: 83% improvement.
- 3rd: Solar protection on the north facade: 34% improvement (and even better, 52%, if we take the

90% acceptability limits.

- 4th: Thermal insulation in the roof during the Solstice of December and the Equinox of September: 33% improvement.

The implementation of materials with high thermal mass on the facade, such as the precast concrete panel, provided a more stable inner temperature in the office compared to the brick facade, despite the lower thermal transmittance of the concrete panel (Tab. 3). In the 2nd experiment, the thermal amplitude in the test office was 3 ºC lower than the reference office, reaching a maximum indoor air temperature between 1 ºC and 1.5 º lower than the reference office (Fig. 5). This temperature, together with the radiant mean temperature, yielded comfort conditions in most of the hours of occupation.

Night ventilation can help to decrease the day maximum air temperatures as long as there is high thermal mass in the building. In the 3rd experiment, a higher thermal mass was incorporated in the building by constructing the 4 facades with precast concrete panel. In this case, night ventilation was added. As a result, the maximum temperature was 1 ºC lower in the test office compared to the reference office. The minimum air temperature in the ventilated office decreased substantially during the night, a period with no occupation.

All day ventilation provided more hours of discomfort to the test office because it allowed the inlet of warm air from the hottest moment of the day. In both cases, dry hot and wet hot weather, the discomfort time in the ventilated office was around 26% higher than in the not ventilated office (Fig. 4). The maximum temperature in the ventilated office was around 2 ºC higher than in the non-ventilated office (experiments #4.1 and #4.2 in Fig. 5).

The use of horizontal brise soleils on the north facade was found to be an effective solar protection. The solar protection improved the temperature comfort during the afternoon, period with the maximum occupation. The maximum temperatures in the test office were 3 ºC lower than in the reference office (experiment #1, Fig. 5).

The incorporation of 12 cm of XPS in the roof, provided a significant improvement in the thermal comfort during the Solstice of December and the Equinox of September, when the solar radiation is more perpendicular to the roof, in tropical latitude (Tab. 1). In December, the maximum day temperature was around 2 ºC lower in the insulated roof office than in the non-insulated roof one.

The presence of a dehumidifier in the building simulation, maintaining the relative humidity below 50%, increases slightly the night minimum air temperatures (0.5 ºC), but helps achieving a 37% increase in thermal comfort hours, according to the Fanger's Comfort model, which takes into account, among others, the effect of the relative humidity in human comfort.

## 7. Conclusions

The use of passive systems in tropical climate contributes to reduce the discomfort time of buildings, in both wet and dry hot climate conditions. A combination between high thermal inertia with nocturnal ventilation, the use of solar protections on the north facade, dehumidification, and the use of thermal insulation in the roof is fundamental for achieving the thermal comfort in buildings located in tropical weather. However, the use of natural ventilation in the office has to be limited to the night, when it is effective due to the outdoor lower temperatures, but not to all the day. Daily crossed ventilation produce the increase of the maximum day temperatures in the office. For this reason, crossed ventilation can be only recommended when outdoor temperatures are below the maximum comfort temperature.

The implementation of these passive systems depends on the early stages of the design building process. This requires the knowledge of the architect and designers on bioclimatic strategies and passive systems. Technicians and designers need firstly to do a deep analysis of the climate and micro-climate conditions of the building site. Therefore, Nearly Zero Energy Buildings would require the implementation of passive systems in the design phase of new and renovated buildings and the spread of passive systems knowledge among technicians.

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