# The Future of Responsive Facade for Multi-Storey Residential Buildings in Tropical Climates

Paloma Suzan Marques de Souza[1], Juan Vallejo[1]*, Joana Carla Soares Gonçalves[2], Rosa Schiano-Phan[1]

1: University of Westminster, London, United Kingdom;
2: Architectural Association School of Architecture, London, United Kingdom

Joana.Goncalves@aaschool.ac.uk

## 1. Abstract

The design study seeks to comprehend the principles and elements of a Responsive Facade and how they affect user comfort and energy efficiency for space cooling in multi-story residential buildings in extreme hot conditions. The research is based on precedent studies, occupant behavior, and a critical analysis of challenges in existing building facades, having a tropical hot and dry city in Brazil as case study. It identifies the different factors that interfere in the internal thermal conditions and building performance to build passive strategies that will optimize facade design proposal and energy saving. As a result, a facade was proposed with ceramic being the main material to make perforated and opaque panels that function as a second layer of shade and permeable envelope that moves in response to the sun or under occupant's control. The impact on the internal conditions is seen in a reduction of 4°C of the internal resultant temperature , leading to a reduction of energy demand for space cooling of 44% .

Keywords - responsive facades, multi-storey residential building, tropical climate user comfort, energy efficiency.

## 2. Introduction

The facade is one of the main features of a building that promotes internal comfort and building performance, particularly in tropical regions. This has become an increasingly important feature to address as temperatures rise due to climate change. Attia, Shady (2016) describes adaptive facades as building envelopes that can adjust based on atmospheric conditions changes as hourly, daily, seasonal, or annual. The word "adaptive" means the ability to react or take advantage of outside weather conditions to fulfil productivity and, more essentially, to successfully meet the inhabitant's comfort. In addition to thermal comfort improvements, it also reduces energy consumption by lowering the demand for active systems to cope with the weather.
Therefore, the design study seeks to understand the principles and elements of a responsive façade for multi-storey residential buildings in tropical dry climates, as well as how they affect occupant thermal comfort and energy consumption. The research is based on a literature review, climate analysis and computational thermodynamic analysis using TAS software to incorporate potential passive strategies into the design concept, followed by an occupant's behaviour survey with families living in tropical climates and a façade analysis, with the city of Cuiaba, in Brazil, as the context of a typical middle-class case study building.

A great number of Brazilian cities have experienced in the last two decades a high demand for residential space, with multi-storey buildings dominating the construction market, but with little or no design attention paid to the climatic conditions, leading to inadequate treatment of the facades. The verticalization of buildings and densification of these cities are responses to the rise of land prices coupled with the cheapening of construction. The city selected for this analytical-design investigation is Cuiabá, Mato Grosso – Brazil, which is characterized as a Tropical Savanna Climate Aw (dry climate), according to Koppen classification. Temperatures can rise above 30°C all year, with temperatures reaching 35°C and greater during the drought season, which lasts from June to September. According to IPCC RCP, mean max temperatures in 2050 can reach up to 37°C if no action is taken to reduce overall ghg emissions in the country. In such climatic conditions there is a high demand for natural ventilation, shading, evaporative cooling, thermal mass and night ventilation, with air-conditioning maybe needed in the most extreme heating hours. In this context,

the design study tackles the following research question: What passive strategies are required to achieve thermal comfort and energy savings in multi-story residential buildings, in a dry tropical climate, and what is the associated optimum responsive facade design guidelines?

## 3. Research Methods

In order to comprehend the principles required to attain comfort inside buildings, literature research and climate analysis was made to comprehend the best façade strategies for tropical climates, how the façade can impact the thermal comfort of the occupants and their energy consumption, and to highlight the challenges and potential solutions. Additionally, an analytical and thermodynamic analysis using TAS software of a base case building was also conducted as part of the background study to provide a reference for the development of the design guidelines and proposal. Prior to the design-analytical phase, a questionnaire was distributed to families in tropical climate cities in Brazil, to better understand occupant attitudes towards the use of passive and active systems and to develop a criteria to optimize active cooling operation based on realistic occupant behaviour. Second, the facade of an existing building in a tropical hot and dry climate in Brazil was analytically examined to see how a façade not designed for a tropical climate can compromise thermal comfort and energy performance.

As a result, outcomes and passive strategies for the design guidelines and proposal were established from the case study, and several façade scenarios were investigated as tested to find the best one for the climate that could promote better thermal comfort in the base-case building typology, for most of the day without the constant use of an active cooling system, thus reducing energy demand. As a final outcome, an optimized responsive façade was designed, which can be widely applied to new and existing buildings in tropical hot and dry conditions.

## 4. Occupants Survey

### *4.1 Questionnaire: Occupant's thermal preferences and behaviour towards the use of active cooling systems in Brazil*

The questionnaire was made and sent online to one occupant of the family and answered by 26 middle-class families from 11 states of Brazil characterized for the high temperatures throughout the year. The survey questions were based on the paper from Ramos, Greici, et al. (2021) comprising a total of 16 questions. Based on the findings, a family profile could be developed to identify people's behaviour patterns toward the use of air conditioning and fans in hot climate regions of Brazil; most families interviewed consisted of three people, and all of them are usually at home in the evening, but 65% of the time there is only one person at home in the morning and afternoon, indicating a 24-hour occupancy.

When it comes to the ideal temperature, the average range of answers ranges from 20°C to 26°C. However, the results also showed a preference for naturally ventilated space at home, with 76.9% preferring it over air-conditioned space (23.1%). It also demonstrates a tolerance for high temperatures and a preference for passive strategies over fans and air conditioning. When asked what the maximum acceptable temperature was without the AC, the responses ranged from 26°C to 30°C. Furthermore, 38.5% of families do not use the air conditioner on a weekly basis, and when they do, it is 84.6% of the time at night. In this case, this behaviour is related to more than just human adaptive ability; it is also related to a general concern about energy consumption; 84,6% of responses stated avoiding the use of AC due to the cost. Keeping an AC on all day is expensive, making it unaffordable for middle-class families. In terms of air conditioning costs, the thermostat setting is critical for energy savings. When asked what AC setpoint they usually use, the responses range from 16°C to 22°C. According to the Brazilian Association of Refrigeration, Air-conditioning, Ventilation, and Heating (ABRAVA), the best air-conditioning setpoint for energy savings is between 22°C and 24°C. According to their research, every degree decrease in the setpoint results in a 3.5% increase in energy consumption. In terms of fan use, 65% of interviewed families say they use it daily, and 50% have at least one fan at home, compared to 15% who say they have 1 and 26% between 2 to 3 AC units. They were also asked what the maximum temperature acceptable for using only

fans before introducing air conditioning; the answers ranged from 24°C to 35°C, indicating a high tolerance for heat before requiring the use of AC.

## 5. Analytical Studies

### *4.1 Case Study: Residential Tower Jardim Beira Rio, Cuiabá – Mt, Brazil.*

The building chosen is the Residencial Jardim Beira Rio, located in Cuiabá – Mt, Brazil (-15.65 N/-56.1 E). The assessed flat is on the tenth floor and has two facades exposed to the outside, the main one facing north-east is exposed to the morning mid-day sun. The flat layout can provide cross ventilation between rooms and the color of internal and external finish are bright, however, the facade does not have any shading element, and the walls and windows do not have any insulating material/feature to decrease thermal conductivity.

Figure 1: Residential towers Jardim Beira Rio, Cuiabá – MT – Building external perspective, balcony and living room.

For the dynamic thermal simulation, only the living room and bedroom 01, which face northeast, were analyzed. According to the questionnaire results, most people are normally at home in the evening, but only one person is at home 65% of the time in the morning and afternoon; thus, a 24-hour occupancy was used to examine how the flat will behave in the worst-case scenario when people are working from home. In terms of energy consumption, the analysis was performed with the air conditioning thermostat set to 24°C, as recommended by the Brazilian Association of Refrigeration, Air-conditioning, Ventilation, and Heating (ABRAVA). The table below shows other inputs.

*Table 1: Simulation Inputs*

| |
|---|
| Constructive Materials: Ceramic block walls, single glazing windows, door facing outside (aluminum frames and glass 4mm) |
| WWR: Bedrooms: Between 17% to 19% and Living Room: 21% |
| Not air conditioning was applied on thermal comfort analysis |
| Windows open all day for the thermal comfort analysis |
| 02 people per room |
| Bedroom Occupancy all day (24 hours) |
| Living Occupancy during daytime (12 hours) |
| The simulation was made in selected rooms on a typical day of the year with temperatures up to 35ºC (mean maximum average temperature of the year), and a clear sky. |

The thermal comfort simulation result graph below shows how the typical day acts during the hours without the usage of air conditioning, and how it influences the internal conditions of the flat. Peak hours of the day are between 1 and 3 p.m. when outdoor temperatures reach 35°C and the relative humidity drops to 20%. The hours with the lowest risk of overheating are early morning until 2 p.m., and late afternoon until 5 p.m., when radiation levels are lower. However, during peak hours, the temperature rises above comfortable levels.

*Figure 2: Plan for thermal comfort analysis.*

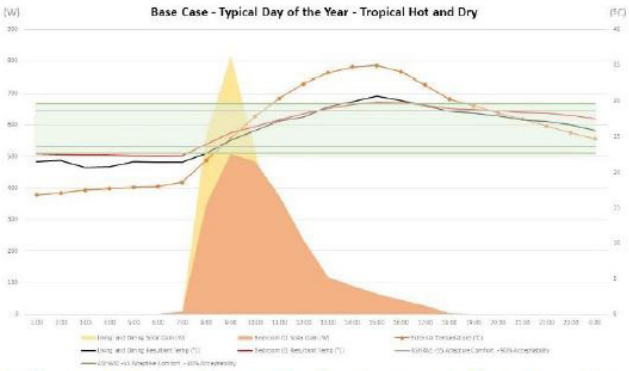


*Figure 3: Thermal Simulation for the case. Chart derived from TAS*

The annual cooling loads demonstrate a high energy demand, even using a reasonable thermostat setting, which can be assumed to be related to the poor envelope characteristics that doesn't provide any solar control strategy to cope the weather.

*Table 2: Cooling Loads – Residencial Beira Rio*

| Setpoint | Annual Cooling Loads |
|---|---|
| 24ºC | 330,59 kWh/m² |

### *5.1 Outcomes and Parameters for the design proposal*

Based on studies results, limitations were identified that can interfere with the internal comfort inside the flat and which served as parameters to be optimized for the design proposal, for example, the absence of shading elements on the facades to control the solar gains, and the use of single glazed windows can result in an easy heat transfer between the external temperature and internal spaces. Furthermore, the external wall construction could also be improved to reduce thermal conductivity. Also, the small balcony has no adequate depth ratio to act as a shading feature on the facade and allows free solar gain into the internal space. About the apertures, the optimal Window-to-Wall Ratio (WWR) of the rooms was also lower than what has been suggested by ASHRAE-90.1-2013 to be between 0.30 and 0.45 for all sorts of climates and buildings. As a result, there is a high demand for active cooling systems like air conditioning, which, when paired with a poor envelope condition, can have a significant influence on energy usage. As a result, the strategies for a better façade design are as follows.

- External Wall

In terms of materiality, ceramic is the most used material due to its cultural significance in the Brazilian building environment and its high thermal mass properties, that decrease the time of the heat to travel through the wall to the inside space. Ceramic and concrete walls are the traditional building materials used in Brazil's tropical regions. Both materials have a high thermal mass, which is ideal for this climate because they can store heat during the day and reduce heat transfers. However, it is necessary to improve their ability to respond to climate change and perform better by employing it in more elaborate ways than just block, plaster, and finishing. A possible solution is to use insulation between the blocks, which increases the u-value and allows the wall to perform better, and for the design proposal, the following improved external walls were used for the simulation.

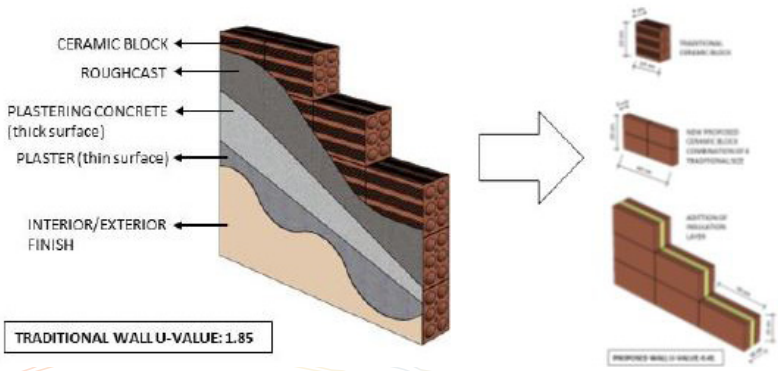


*Figure 4: Ceramic block wall scheme.*

As illustrated in the image, the scheme represents an arrangement of a ceramic block wall by adding an insulation layer. The U-value improves significantly from 1.85 W/m²K to 0.41 W/m²K with a 6 cm insulation of polyurethane foam layer and two ceramic blocks of 5 cm thickness each.

- Second Layer Envelope

To deal with hot, dry weather, the building's design is also essential. The shading mechanisms, which help regulate heat transfer between the internal and external temperatures, are one of the most popular facade features in those harsh climates. Therefore, the second layer envelope is proposed as a shading device, having the ceramic also used as a perforated screen panel as a reinterpretation of the "cobogó" blocks, an architectural element used as a perforated element for dividers and facades of buildings. It was introduced in Brazil in the 1920s, as a legacy of Arab culture, based on the mashrabiya (built-in wood). The reason for its introduction in Brazil was the need to create architectural solutions that allowed ventilation and lighting of the spaces, while also ensuring privacy. The cobogó has become an iconic and characteristic element of modern Brazilian architecture, being used in various architectural projects as a form of cultural expression and national identity.

*Figure 5: Ceramic Panels for Shades and Double-Skin Façade. .*

Moreover, ceramic can be reused and recycled. Its property can act as a heat mitigator for its dense material, a high capacity for storing heat during the day and radiate at night, and, when not highly treated, is porous enough to absorb moisture, ideal for the dry climate.

- Window Apertures

According to ASHRAE 90.1-2013, the optimal window-to-wall ratio (WWR) for all climates and buildings is between 0.30 and 0.45. A minimum of 35% of WWR was used for each room in the design studies. In terms of window aperture, the design proposal maximized the openable window aperture for improved airflow. The two sided slider pane is a common window design that obstructs 50% of the openable aperture. As previously discussed, natural ventilation can be critical to improving thermal comfort in a hot climate. Thus, for rooms where cross-ventilation is not commonly available, such as bedrooms, it is critical to provide as much airflow as possible; thus, more than the WWR, the openable value is also critical.

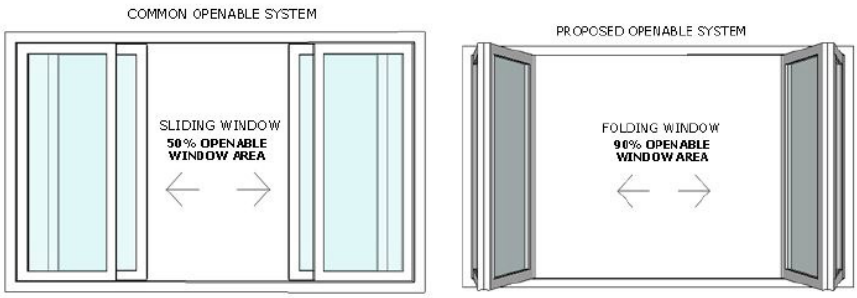


*Figure 6: Openable window aperture scheme.*

### *5.2 Façade Design and Simulation Results*

Scenarios were created to simulate various levels of intervention to the facade for thermal comfort analysis. For the thermal simulations, a 2050 future weather file and the improved wall construction was used as a base case; from there, external facade features ranging from minor interventions that only used passive strategies to more complex interventions that included active systems were assessed. This way, the limits of passive strategies for maintaining indoor thermal comfort in the tropical hot and dry climate could be identified, as well as the best scenario strategy.

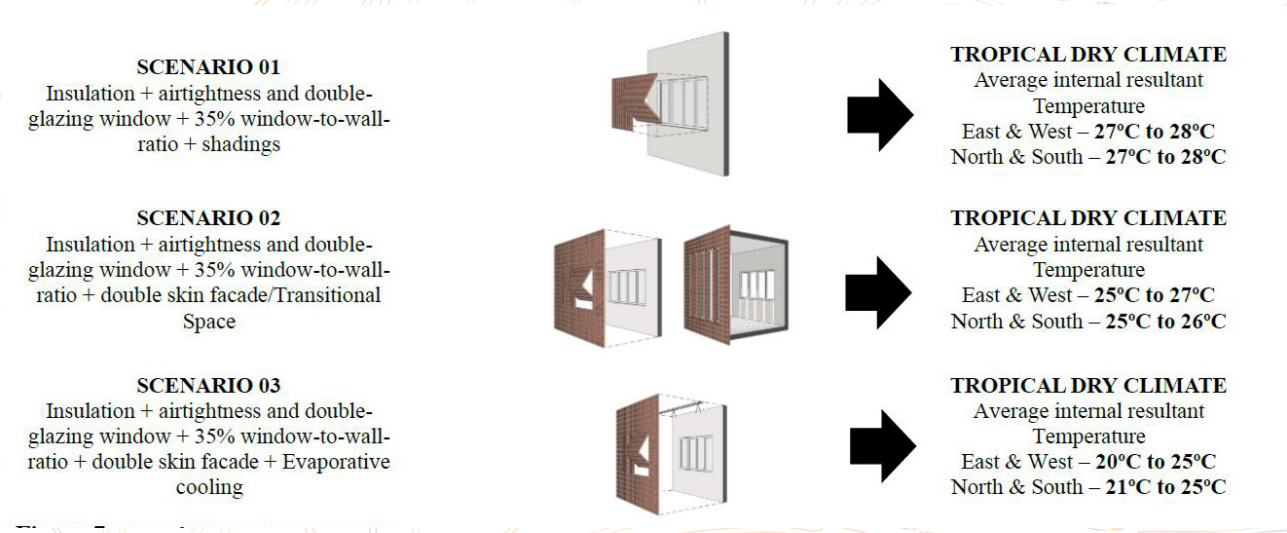


*Figure 7: Facade intervention scenarios.*

The double-skin façade, together with natural ventilation, reduces the internal temperature by 2°C from scenario 01 to 02, placing it into the comfort zone. In light of the dry climate and temperatures that can reach 35°C or more all year, a third scenario can be realised by installing evaporative cooling in the double-skin façade, which cools the air before it enters the flat and helps to improve air quality by providing moisture. Scenario 02, on the other hand, is the best scenario for the climate because it does not employ any active cooling equipment. When compared to the current building case study, the optimised design reduced 4°C, allowing the inside temperature to remain in the comfort zone for the most of the day.

Figure 8 also demonstrates that through envelope improvements and the implementation of passive strategies, it is possible to achieve and maintain thermal comfort for the majority of the day. This holds true even when considering future weather projections for 2050, which anticipate a rise in temperatures. Therefore, it is evident that with the appropriate measures in place, thermal comfort can be effectively managed and sustained in the face of changing climatic conditions.

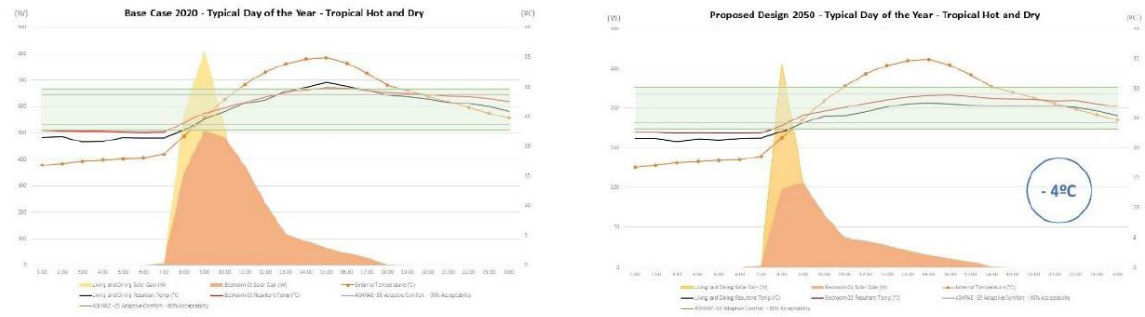


*Figure 8: Thermal Simulation results comparison – left side, base case thermal result – right side, best scenario – double-skin façade, future climate projection (2050).. Residencial Jardim Beira Rio. Chart derived from TAS software.*

The facade proposal is divided into three configurations, each of them includes a double-skin envelope consisting of a series of panels that are movable and perforated in front of windows and balconies and fixed and opaque when in front of walls. The proposed shadings' typology was based on the sun-path of city Cuiabá, Brazil (15°35'56"S/56°06'01"O), to optimize shading efficiency according to the orientation and can be both automated and controlled by the occupant. Based on the climate analysis and study results, the facade proposal adhered to the parameters described in the previous topic, which were deemed necessary for a better responsive facade design that can provide indoor comfort for users while also assisting in the reduction of energy consumption in daily life.

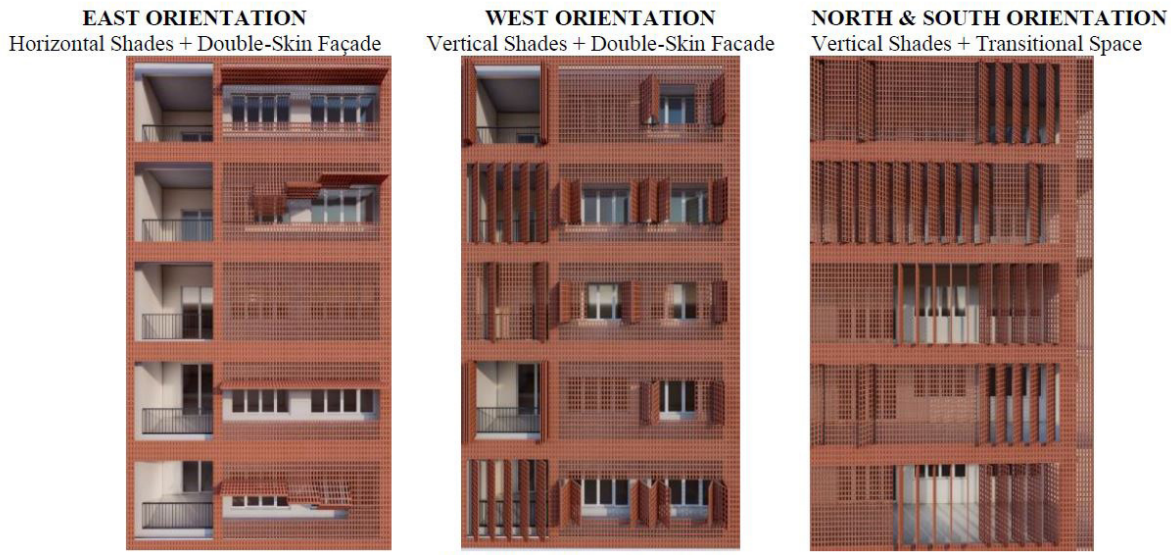


*Figure 9: Design Facade Design*

Horizontal shading was used on the east façade due to the high sun altitude from 51° to 77° when sun reaches 28°C.

The dynamic operation folds up and becomes a horizontal shade in front of the bedroom windows. However, shade was not required on the balcony; simply having the proper balcony depth ratio according to the sun's altitude can act as a shading device for the living room.

Vertical shades were required on the West facade due to the lower sun altitude from 1° to 4° when the temperature can get higher than 30°C. In this case, the shades in front of the bedroom windows fold horizontally, allowing for greater sun and daylight control. In contrast to the East, a proper balcony depth alone would not suffice; thus, vertical shades were also inserted in a different operating system; they can rotate on their axes and be completely moved to the sides, not obstructing the view.

During the day, the north and south facades are the most exposed to the sun. A different approach was required in this case. To control the amount of sunlight inside the flat, a combination of horizontal and vertical shades would be preferable for these orientations. As a result, a transitory space (either a corridor or a common balcony) was used to investigate the benefits of this larger space between the envelope and indoor.

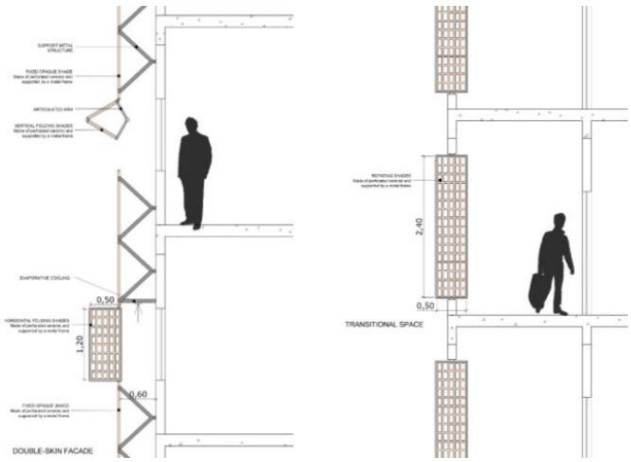


*Figure 10: Double-Skin Facade section – Horizontal and vertical shade*

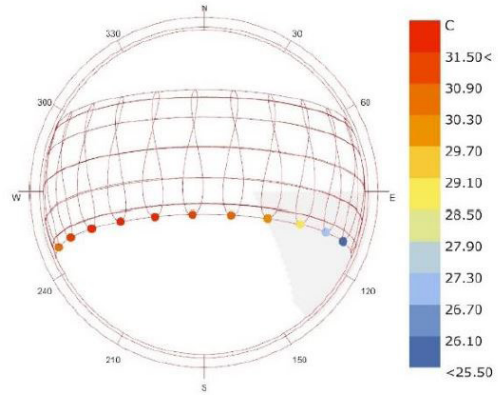


*Figure 11: Sun-Path, Summer Solstice 21DEC. Cuiabá – detail and Transitional Space and rotating shade. MT.*

### *5.2.2 Energy Performance of the proposal design*

A comparison of results from the base case and the proposal facade was made to see the impact of the improvements made on the envelope. The same 24 hour occupancy was used, with a thermostat set of 24°C. The results clearly show the impact of the envelope towards energy consumption. When comparing the base case results with the proposed facade, the cooling loads reduced by 44%.

*Table 3: Annual Cooling Loads for the proposal design and base case*

| **Annual Cooling Loads – Proposal Façade Design** | |
|---|---|
| **North-East** | 184,76 kWh/m² |
| **Annual Cooling Loads – Base Case** | |
| **North-East** | 330,59 kWh/m² |

### *5.2.2 Energy Performance of the proposal design*

The heat conduction of the exterior wall of both the living room and the bedroom was also investigated to demonstrate the effect of external shade and wall insulation. The graph below depicts an analysis of one external wall surface in each room, as well as a comparison of the basic case and the proposed façade design. The results show a significant reduction in conductive heat gains between the two scenarios, demonstrating the viability of the measures used to cope with the weather and offer better internal thermal comfort.

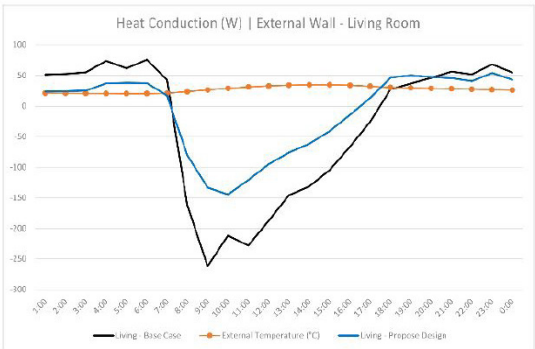


*Figure 12: Heat Conduction – Living Room*

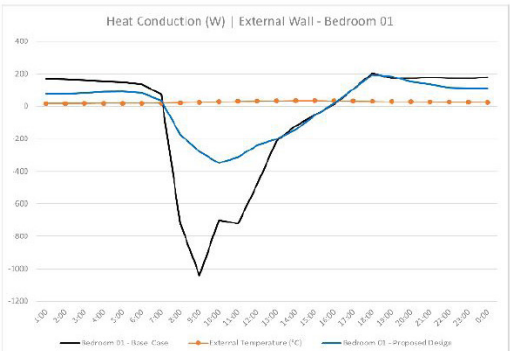


*Figure 13: Heat Conduction – Bedroom 01*

## 6. Discussion and Conclusion

As evidenced by the conducted studies, the implementation of a climate responsive building envelope plays a crucial role to improve user thermal comfort. In this research, this was achieved by reducing 4°C of the internal resultant temperature and contributing for energy savings of 44% by not demanding an extensive cooling load. The research findings underscore that the incorporation of shading elements, improvement of materiality and envelope construction, even when considering future climate projections (for 2050) is sufficient to maintain comfort with the same cooling demand. This emphasises the unquestionable importance of a well-designed envelope in achieving maximum occupants' thermal comfort. When contemplating its relevance in contemporary building construction in tropical and dry regions, the viability of this technique becomes clear.

By centering the architectural focus on creating a climate-responsive façade through passive strategies and harnessing the potential of locally available materials, such as ceramics with high thermal density, substantial improvements can be achieved. It is worth noting that these improvements can be attained without the need for drastic alterations to the original architectural layouts, but the integration of strategies that facilitate natural ventilation, such as cross ventilation, further enhances the overall effectiveness of these measures and keeping current market interests (due to no changes in the building form and plan layout).

In conclusion, the study emphasises the importance of the building envelope in improving user comfort and energy efficiency. The potential for enhanced building environments in tropical and dry climates becomes evident by proactively embracing passive design strategies and focusing on local materials. This method not only coincides with sustainability goals, but it also emphasises the balance of architectural creativity and environmental responsiveness.

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