AMINU WALI BASHIR

Performance of aerogel as a thermal insulation material towards a sustainable design of residential buildings for tropical climates

Original Version

Dissertation submitted to the Polytechnic School of the Universidade de São Paulo, to obtain the title of Masters in Science

Area of Concentration: Civil and Urban Construction Engineering

Supervisor: Prof. Dr. Brenda Chaves Coelho Leite

São Paulo
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DEDICATION

I dedicate this work to my parents, Alh. Bashir, Haj. Maryam & Haj. Fatima, and my siblings, Raji, Rabi, Dahiru, Hauwa & Ahmad for their endless support throughout the development of this project. A special dedication to the last member of my family, Isa, whom we lost recently after a brief illness, I pray and hope he is in a better place.

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I am highly indebted to my sponsors, The Nigerian Petroleum Technology Development Fund, for their financial support throughout this work and for the opportunity to witness my biggest dream turn into reality. Words cannot express my deep appreciation, I can only say thank you and hope that the fund continues to inspire lives.

I wish to also express my sincere gratitude to my parents and siblings for their never-ending support and unconditional love. Space does not permit the acknowledgment of all the assistance and inspiration I had, but I would like to express my greatest gratitude to my colleagues, friends, and all those that supported me directly or indirectly in the accomplishment of this work. I say a big thank you to you all and may God continue to give us the strength and ability to break new grounds.

Title: Performance of aerogel as a thermal insulation material towards a sustainable design of residential buildings for tropical climates

ABSTRACT

The building sector accounts for nearly 40% of global energy consumption with an anticipation of a continuous increase in the coming decades. Energy efficiency measures through the adoption of thermal insulation materials are tools that could crash the peak demand for energy in buildings while improving their thermal comfort. Aerogel is then considered to be the most effective material for insulation, owing to its unique thermal properties. This research presents a study on the performance of aerogel as a thermal insulation material towards a sustainable design of residential buildings for tropical climates of Lagos, Nigeria, and Belém-Pará, Brazil. The aim was to examine its performance in terms of thermal comfort improvement and energy consumption reduction against the conventional materials utilized in constructing residential buildings in the selected locations. A residential building design comparable to both selected locations was selected and modeled with common conventional materials utilized in the selected locations as base variants. Then the models were later modified by including aerogel blanket on various surfaces of the models. Major parameters that influence indoor environmental quality were measured through building energy simulations and the results obtained in both cities were compared to standard recommended values. Also, their corresponding energy consumption and tariff charges are reported. Results showed that in Lagos, the proposed insulation material had the highest influence when inserted in the attic and floor slabs of the designed model, while in Belém, the insulation material had the highest significance when inserted on the external façades. In terms of thermal comfort improvement, it can be concluded that aerogel had more significance in Lagos than in Belém, while concerning energy consumption reduction, the insulation material had more influence in Belém than in Lagos. Aerogel demonstrated significant potential for both thermal comfort improvement and energy consumption reduction in both selected locations. However, further research may be necessary to effectively conclude the performance of the proposed insulation material in the selected locations. The findings in this study provide a stepping-stone for the design and construction of efficient & sustainable residential buildings for tropical climates in Nigeria and Brazil.

Keywords: Aerogels. Energy consumption. Energy efficiency. Thermal insulation materials. Building energy simulation.

Título: O desempenho do aerogel como material isolante térmico em projetos sustentáveis de edifícios residenciais em climas tropicais

RESUMO

O setor de construção civil é responsável por cerca de 40% do consumo da energia global, com a expectativa de um aumento progressivo nas próximas décadas. Medidas de eficiência energética através da adoção de materiais de isolamento térmico são ferramentas que podem diminuir o pico de demanda por energia nos edifícios e, ao mesmo tempo, melhorar seu conforto térmico. O aerogel é então considerado o material mais eficaz para o isolamento, devido às suas propriedades térmicas únicas. Esta pesquisa apresenta um estudo sobre o desempenho do aerogel como material de isolamento térmico para um projeto sustentável de edifícios residenciais para climas tropicais de Lagos, Nigéria e Belém-Pará, Brasil. O objetivo é examinar seu desempenho em termos de melhoria do conforto térmico e a redução do consumo de energia em comparação aos materiais convencionais utilizados na construção de edifícios residenciais nos locais selecionados. Um projeto de edifício residencial comparável aos dois locais selecionados foi escolhido e modelado com materiais convencionais comuns utilizados nos locais selecionados como variantes base. Em seguida, os modelos foram modificados por incluir o aerogel em várias superfícies dos modelos. Os principais parâmetros que influenciam a qualidade ambiental interior foram medidos por meio de simulações de energia de edifícios e os resultados obtidos em ambas as cidades foram comparados aos valores recomendados padrão. Além disso, são relatados seus correspondentes consumos de energia e os custos de energia. Os resultados mostraram que, em Lagos, o material de isolamento proposto teve a maior influência quando foi inserido no sótão e nas lajes do modelo projetado, enquanto em Belém, o material de isolamento teve a maior significância quando foi inserido nas fachadas externas. Em termos de melhoria do conforto térmico, pode-se concluir que o aerogel teve mais significado em Lagos do que em Belém, enquanto que, com respeito à redução do consumo de energia, o material de isolamento teve mais influência em Belém do que em Lagos. O aerogel demonstrou um potencial significativo tanto para a melhoria do conforto térmico quanto para a redução do consumo de energia em ambos os locais selecionados. No entanto, mais pesquisas podem ser necessárias para concluir efetivamente o desempenho do material de isolamento proposto nos locais selecionados. Os resultados deste estudo fornecem uma guia para a construção de edifícios residenciais eficientes e sustentáveis para climas tropicais na Nigéria e no Brasil.

Palavras-chave: Aerogels. Consumo de energia. Eficiência energética. Materiais de isolamento térmico. Simulação de energia de edifícios.

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LIST OF ABBREVIATIONS

ASHRAE - American Society of Heating, Refrigerating, and Air-Conditioning Engineers

AVG – Average

CLI - Cooling Load Intensity

EN – European Standard

FF – First Floor

GF – Ground Floor

HVAC - Heating, Ventilation, and Air Conditioning

h – Hours

IEA – International Energy Agency

Max – Maximum

Min – Minimum

NETL - National Energy Technology Laboratory

RHrecommended – Recommended Relative Humidity (%)

SSA - Sub-Saharan Africa

Trecommended – Recommended Temperature (°C)

ZN - Zone

LIST OF SYMBOLS

CO_2 – Carbon dioxide

T_{od} - Outdoor Air Drybulb Temperature (°C)

T_m - Mean Air Temperature (°C)

RH - Air Relative Humidity (%)

T_o - Operative Temperature (°C)

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1. INTRODUCTION

Global energy consumption has elevated nearly twice its average growth since 2010, with an estimate of about 8.92 Gtoe/year and a prediction of up to 60% increase by the end of 2020. This increase can be linked to the global economic growth coupled with the unusual heating and cooling demand recorded in recent years since electricity demand alone represented more than 50% of this growth. On the other hand, energy-related CO_2 emission also hiked to about 33.1 Gt as of 2018, with the power sector responsible for nearly two-thirds of the emission increase (Allouhi et al., 2015; IEA (2018), 2018; Ong, Mahlia, & Masjuki, 2011).

The overall energy consumption in regions like the US, EU, and other fast-developing countries (Brazil, Russia, India, China, and South Africa) differs significantly. An estimate carried out between 1990 – 2010 showed that, while the consumption increase was moderate in the US and EU, a huge difference in the developing (BRIC) countries was seen, where a compelling increase was recorded in every sector. This is mainly due to rural-urban migrations and industrialization among other factors, causing an increase in the population and infrastructural development and consequently raising energy demand (Berardi, 2017).

A projection of energy demand or consumption over the next century may be inherently uncertain, but reports from the National Energy Technology Laboratory (NETL) and other studies give some idea of the likely explosion of global energy consumption, where demands are predicted to overtake the population growth in some decades to come (Allouhi et al., 2015; Ong et al., 2011; “World Population and Energy Demand Growth,” 2011). As the world’s population increases, there is also an increasing demand for sustainable and affordable energy. Therefore, urgent steps must be taken to meet these demands in the coming years, since recent studies concluded that a rapid continuous increase is certain. With this, attention towards energy and environmental issues has grown and many policies have been refined globally (Ng, Jelle, Sandberg, Gao, & Wallevik, 2015). Alternatives like renewables and energy efficiency are tools with huge potentials in this regard and although their percentage share is steadily growing, combining the two and with the consideration of socio-economic factors can aid the world’s fossil fuel - clean energy transition process, thereby aiding the CO_2 emission cut target (Allouhi et al., 2015).

Energy consumption through different sectors also varies across countries. While transportation consumes the most energy in the US, the building sector is seen to consume the most in the EU countries and a large part of Africa, as for China, its industrial sector had the highest consumption followed by the building sector. Abu-Madi and Rayyan also concluded that residential buildings alone consume almost 40% of the total energy in the Arabian countries and these figures have increased significantly in the past few years, considering the rapid economic evolution and urbanization seen in the region, which led to more energy demand (Berardi, 2017; Geng et al., 2017).

However, based on a global survey, the building sector was recorded to cover a sizable part of the global energy consumption (about 40%), and these values are predicted to be in an increasing lane as well. The main drivers are projected to be population increase, economic growth among others (Allouhi et al., 2015; Geoff Zeiss, 2015). This consumption can also be attributed to different influences in buildings, like building element's specific heat capacity, their thermal conductivity, standards of the Heating, Ventilation, and Air Conditioning (HVAC) system and coupled with regions' weather variation and occupants' pattern in energy utilization (Delzendeh, Wu, Lee, & Zhou, 2017; Schiavoni, D'Alessandro, Bianchi, & Asdrubali, 2016).

Depending on the region, weather variation, and building type, space heating & cooling consume majorly the energy in most buildings together with other uses like lighting, water heating, electrical appliances, etc. In the US for instance, most use of energy goes to space heating and electrical appliances while in countries like Nigeria, space cooling dominates the energy use in buildings. Furthermore, extreme temperatures were recorded in many parts of the world in recent years as more heating and cooling demands were experienced (Akande, Fabiyi, & Mark, 2015; Berardi, 2017; IEA (2018), 2018).

As one sector that consumes a vast amount of energy that is majorly to provide thermal comfort, the building sector could contribute to lower its energy consumption through proper and effective energy efficiency measures. This is often regarded as the largest means of reducing energy demand particularly in buildings and with respect to harmful emissions (IEA (2018), 2018; Ng et al., 2015; Yang, Yan, & Lam, 2014). Energy efficiency in buildings through the adoption of various insulation strategies is among the best practices for thermal comfort improvement and energy saving. Effective insulation conserves energy and requires less energy for space cooling in summer and less heat to keep the building warm in winter. Therefore, energy-efficient buildings with low negative environmental impact could significantly aid energy savings while improving occupants' comfort (Schiavoni et al., 2016).

An acceptable thermal resistance of the building envelope is an effective way to lower the energy needs in buildings, but thicker layers of conventional insulation materials are generally required to obtain high thermal resistance values, which ends up in heavier constructions or smaller spaces. Hence, innovative and highly insulating materials with remarkable thermal properties are increasingly considered globally, for instance, foam glass, rock/glass wool, polystyrene foam, polyurethane foam, silica/aerogels, and many other materials (Jelle, 2011; Schiavoni et al., 2016). However, aerogel, as studied by (Berardi, 2018; Buratti & Moretti, 2012; Ebert, 2011; Ihara, Jelle, Gao, & Gustavsen, 2015; Jelle, Baetens, & Gustavsen, 2015; Lakatos, 2017; Liu, Wang, & Deng, 2016; Riffat & Qiu, 2013) among others, can be concluded as the optimal insulation solution and maybe the most assured option when compared to other insulation materials. A very rare distinction with aerogel is that it can be produced in various forms, thus enabling a wide range of possible applications.

Although there are various articles on the application of aerogel in buildings in many parts of the world, most recent studies carried out are concentrated on either existing building retrofits, glazing system improvement, or concrete and renders enhancement (Berardi, 2018). However, with the significant advancement in technology and building energy performance tools over the past years, the construction industry around the world is adopting new strategies. Energy organizations, policymakers, and other stakeholders across different countries are enforcing the application of building codes & standards via building performance designs & simulations throughout the life cycle of construction projects. This enables the complete evaluation of the performance of buildings while simplifying the decision making between professionals involved right from the inception of construction projects. Therefore, this highlights the importance of expanding the methodology of exploring the performance of aerogel through pre-construction designs and simulations, especially in regions where its potentials are yet to be explored.

In this research, a study on the performance of aerogel as a thermal insulation material in residential buildings for tropical climates of Nigeria and Brazil is presented. The aim was to examine its performance in terms of thermal comfort improvement and energy consumption reduction against the conventional materials utilized in constructing residential buildings in the two selected locations. The findings from this study could serve as a base reference for designing sustainable and energy-efficient residential buildings in the selected locations. The rest of this report is structured as follows; the next section (chapter 2) spells out the aim and objectives of the research, chapter 3 looks at the energy situation in sub-Saharan African countries and Nigeria, stating some expected future developments in the region. Chapter 4 gives an overview of aerogel material; its classification, synthesis processes, and some of its properties & performance in buildings. The materials and methods carried out in this research are presented in chapter 5, while discussions of the simulation results are in chapter 6. Conclusions were drawn in chapter 7.

2. AIM AND OBJECTIVES

This research aims to explore the performance of aerogel through design models & computational building energy simulations, to unveil its potentials as a thermal insulation material towards a sustainable design of residential buildings and the study was carried out in tropical climates of Lagos, Nigeria, and Belém-Para, Brazil.

To achieve this, the research explored and identified:

a) The energy situation and the global energy consumption with an emphasis in sub-Saharan Africa and particularly in Nigeria;
b) The building energy effect of aerogel material as compared to the conventional materials utilized in constructing residential buildings in Nigeria and Brazil;
c) The perfect surface of the building the proposed insulation material can best be applied to in each selected location;
d) How the proposed insulation material can improve thermal comfort and minimize energy demand/usage in buildings.

3. ENERGY IN THE SUB-SAHARAN AFRICA AND NIGERIA

3.1 Sub-Saharan Africa

It is often said that an improved energy system leads to a more comfortable and healthy life, while its absence can adversely affect the social and economic development of any nation. This is, unfortunately, the case today in Africa, especially in the sub-Saharan region (SSA), as the unbalanced and unrealized energy resources in the region makes it difficult to cover the energy need of the populace (International Energy Agency, 2014; Ouedraogo, 2017).

African countries including Angola, Nigeria, and South Africa among others are well-known major energy producers and the reserve for numerous energy resources sufficient enough to serve the whole continent and even beyond. Even with that, these countries face huge difficulties in accessing power, and not only that, they are also associated with poor economic growth, rapid population increase. In addition, there is a high pollution rate caused by the continued use of solid biomass and other non-renewable energy sources that generates a dreadful effect on human health and the environment (Hanif, 2018; International Energy Agency, 2014). Nigeria alongside other countries like the Central African Republic and Angola suffers the most inadequate electricity supply in the region (see Figure 3. 1). The energy situation in general and electricity availability, in particular, is approximately very low in the SSA, and despite its renewable capabilities, the latest renewable energy makes up a significantly low percentage of its energy mix, less than 2% (International Energy Agency, 2014; Ouedraogo, 2017).

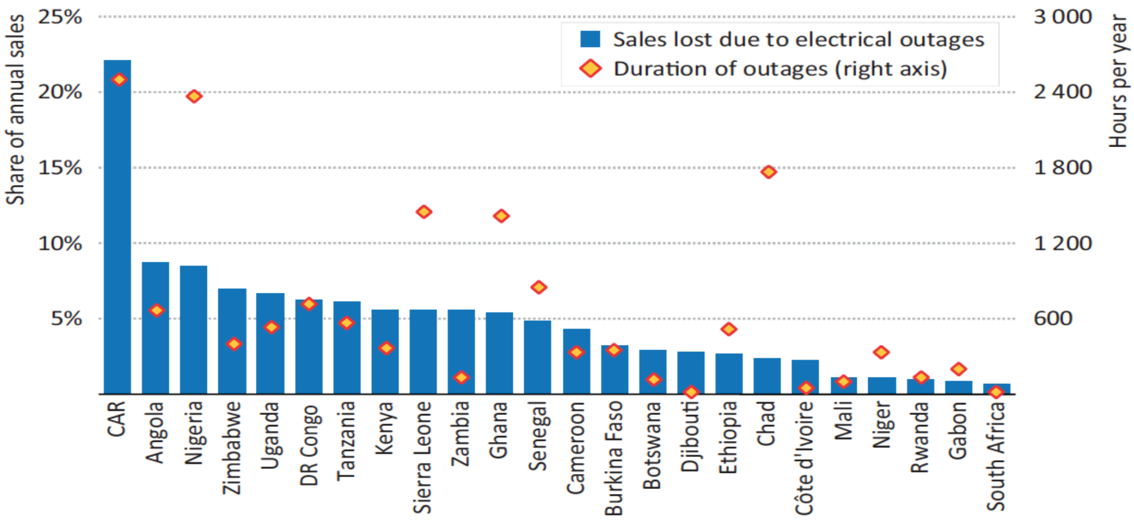

Figure 3. 1: Power outage and its effect on businesses in some SSA countries
Source: (International Energy Agency, 2014)

Since non-renewable energy is cheaper and more readily available than clean and renewable alternatives, these countries opt-in for them. Moreover, there are more primary issues to deal with in the region like; economic growth, food insecurity, poverty among others. Thus, environmental outcomes were considered secondary and consequently causing a high annual death rate since a huge percentage of the populace rely on energy sources like solid biomass for cooking and other domestic usages (Hanif, 2018; Ouedraogo, 2017). However, this is seen to change recently, especially in the urban areas as infrastructural patterns, energy efficiency, and climate change insight among other factors grew significantly, thereby reducing the health risk associated with pollution (International Energy Agency, 2014).

Africa's primary energy demand as of 2014 was estimated at around 752 million tons of oil equivalent (Mtoe). The SSA's demand alone was estimated at 570 Mtoe, with Nigeria and South Africa responsible for about 40% of the total demand. Electricity demand was recorded around 605 terawatt-hours (TWh) with north Africa alone taking almost 40% of the total demand, as for the SSA, the demand estimate was around 352 (TWh) (International Energy Agency, 2014; Ouedraogo, 2017).

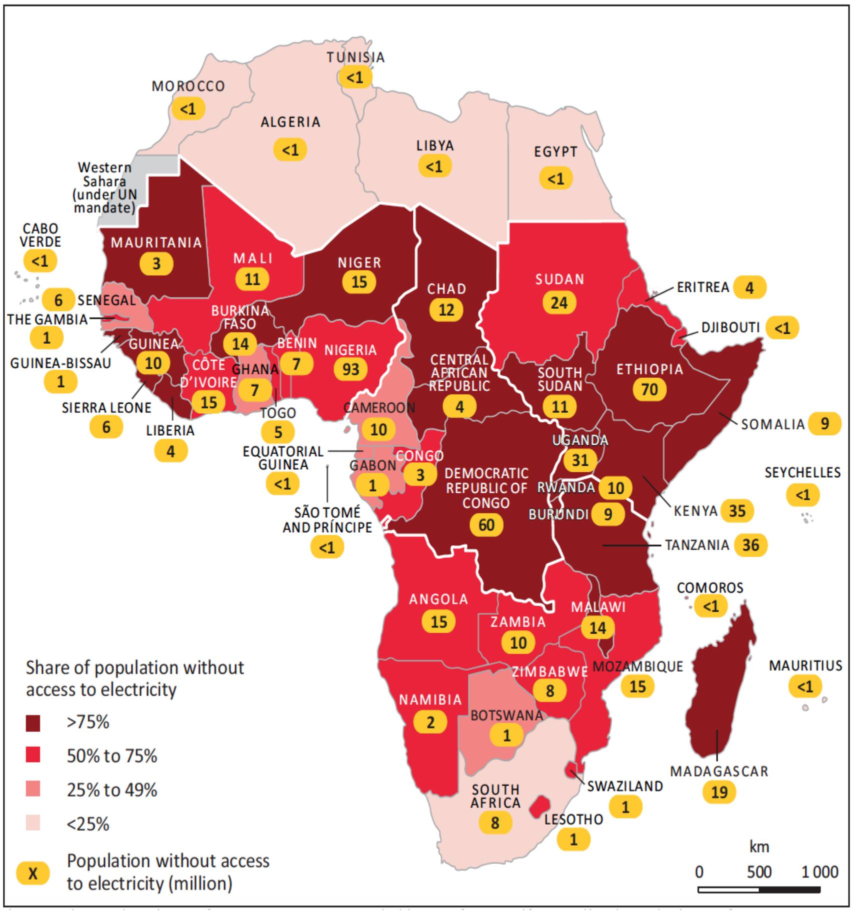

Figure 3. 2: Access to electricity in Africa
Source: (International Energy Agency, 2014)

Although nearly all North African populace has access to electricity, that is not the case in the SSA, as more than half a billion (about two-third of the population) experience difficulty in accessing affordable electricity (Figure 3. 2). This restriction can be attributed mainly to the lack of adequate energy infrastructure and poor maintenance strategies, since the little percentage with power access is still liable to outage recurrently, resulting in the use of back-up generators and other local alternative sources of energy (International Energy Agency, 2014; Ouedraogo, 2017).

On the positive side, energy reports reveal that the demands have doubled from the past decade in the region (SSA), primarily due to the rapid population growth, the appearance of new and modern industries, and urbanization. Nigeria, Ethiopia, and South Africa among other countries gained more access to electricity reaching about 32% in 2012 as compared to the 23% figure recorded since 2000. South Africa and Nigeria represent the regions' largest energy consumers, about 40% of the overall demand (International Energy Agency, 2014; Ouedraogo, 2017). Equally, Power reforms are being deliberated in most of the countries with a huge deployment of energy infrastructural projects.

African countries through large hydropower potentials and local & isolated energy frameworks can draw out up to 40% of its power generation in the coming decades, and realizing this is major step policymakers have to set in the region since it represents about 15% of the world's population but accounts for only about 5% of the global energy demand (International Energy Agency, 2014). Potentials like natural gas can also aid the regions' power dilemma, and its demand has been increasing over the years reaching almost 30 billion cubic meters (bcm). Higher demands were seen from Nigeria (more than 50% of the total demand) since Gas-fired plants are the main power generation mechanism in the country. Yet, the total volume of gas being flared alone if summed could electrify the whole region for years. Therefore with proper administration and frameworks in place, energy poverty through these potentials would have been a thing of the past in the SSA (International Energy Agency, 2014).

3.2 Nigeria

In the case of Nigeria, it is considered as one of the most important countries in the region since it has the largest population (about 200 million in 2018, Mwaniki, 2018), the largest economy of about $1.2 trillion in the Purchasing Power Parity's 2019 estimate (about 30% of SSA's total economy), substantial producer and a net exporter of crude oil in the SSA region, and for its reach in renewable energy resources ("Energy Subsidy. Reform SSA," 2013;

OECD/IEA, 2014). Despite all these capabilities, it was recorded to have had the least level of energy efficiency and is among the countries with the highest rate of power outage in Africa (see Figure 3. 1).

Energy failure and blackouts are common features in Nigeria because as of 2014, estimates have shown that more than 50% of the population is without access to electricity (Figure 3. 2). Although the pervasive use of back-up power generators significantly reduces this figure, since they often provide about 6 hours of electricity a day in some regions reaching about 12 – 15 hours of power supply in other regions. IEA's 2014 report on the SSA showed that Nigeria alone represented more than 70% of the electricity generated through back-up power generators in the SSA (Figure 3. 3). These failures and the inability of constant energy supply have been hindering business development and has affected the socio-economic growth of the nation. Almost 10% of trades are lost each year due to power outages, forcing consumers and businesses to utilize back-up power generators, thereby inflating expenditures and consequently increasing environmental pollution (Amaewhule, 2002; International Energy Agency, 2014).

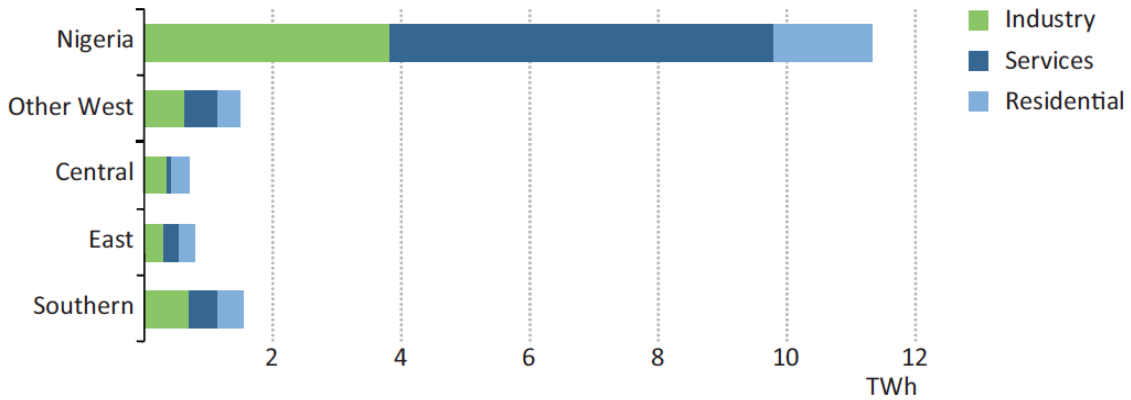

Figure 3. 3: Power generation through back-up generators by sector and sub-region, 2018
Source: (International Energy Agency, 2014)

Administrative concerns, sub-standard maintenance strategies on both transmission and distribution lines, political instability among others are the major causes of these complications. In addition, pipeline destruction and other ethnic crisis in the oil-producing region has crashed investment and production of crude oil (the country's primary source of economy) over the past years, where an estimated amount of nearly $5 million is being lost annually, funds enough to finance the electrification of the whole nation for years if properly utilized (International Energy Agency, 2014).

However, in recent years, Nigeria, alongside other most SSA countries have initiated energy policies and intentions to boost the energy situation in the region. For example, the disclosure of various schemes by the Nigerian government like the adoption of minimum energy performance frameworks for appliances and industrial equipment, the renovation and modernization of the country's crude oil refineries to enhance production, distribution & export, and the plans to electrify 99% of the country by the end of 2030. The government has also introduced an energy expansion plan called the 'Electric Power Reform Act' hoping to increase the grid capacity from the 5,000 MW seen today to about 25,000 MW, latest by the end of 2030, through interventions like the power investment loan acquired from China's Import-Export Bank, among others (Gujba, Mulugetta, & Azapagic, 2011; International Energy Agency, 2014).

Expected future developments in Africa indicate that the population expands rapidly, with a higher occurrence in the SSA region, where growth projections meet 850 million by 2040 to reach almost 2 billion people, representing one-fifth of the world's population. Also, the highest growth rates are anticipated to come from the west as countries like Nigeria are seen to have more than 90% population increase in the next two decades to come, becoming among the topmost populous nations in the world (International Energy Agency, 2014).

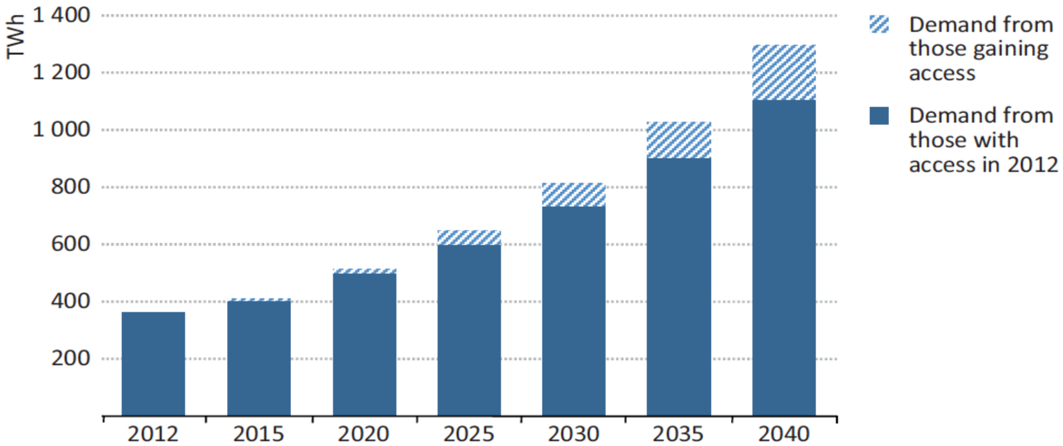

Figure 3. 4: Electricity demand in sub-Saharan Africa through 2040
Source: (International Energy Agency, 2014)

Electricity is also anticipated to be in the rising lane as rates are expected to triple from the current figure reaching almost 1300 TWh by 2040 (see Figure 3. 4) with residential, industrial, and services demand anticipated to represent the highest percentages. As should be expected, Nigeria principally and alongside other east African countries covers the largest share of these increased demands. Specifically, Nigeria's electricity demand sees more than a

90% increase reaching almost 300 TWh by 2040, representing about 30% of SSA's total demand. Furthermore, 44% of SSA's power generation is also predicted to come from renewables made up of Solar, wind, hydro, geothermal & biomass by 2040, meaning cleaner energy is likely to prevail in many parts of the region (International Energy Agency, 2014).

Looking at the current and future projections of population and energy layout registered, it is clear that African countries, especially in the SSA need to explore various alternatives to cleaner and more sustainable energy sources in the coming years to meet up with the fast-growing demands. Alternatives like the implementation of new and modern energy efficiency policies, exploration and utilization of renewable energy sources available, creation of small and or off-grid power transmission stations, the incorporation of energy-efficient measures into the construction standard, etc. The use of insulation materials should highly be given more consideration globally, but especially in African countries like Nigeria, considering the anticipated increase in its population and the lack of adequate/constant supply of clean and affordable electricity. This will not only aid in satisfying the increasing demand but will also improve internal comfort and sustainability to the energy mix.

4. AEROGELS

Aerogel, also known as “frozen smoke” is a synthetic porous ultralight material derived from gels, where the liquid component of the gel is replaced with a gas constrained in nanoscale cavities. First discovered in the 1930s by Dr. Kistler, aerogel, although made from gel, they are rigid and dry materials and do not appear like a gel in their physical form. They can be prepared using several based materials such as alumina, chromium, tin oxide, carbon, and silica and are used to improve the thermal resistance of buildings and other industrial applications (Baetens, Jelle, & Gustavsen, 2011; Buratti & Moretti, 2012; Cuce, Cuce, Wood, & Riffat, 2014; Gurav, Jung, Park, Kang, & Nadargi, 2010; Huang & Niu, 2015a; Maleki, 2016; Nocentini, Achard, & Biwole, 2018; Nosrati & Berardi, 2018; Riffat & Qiu, 2013; Thapliyal & Singh, 2014; Wong, Kaymak, Brunner, & Koebel, 2014).

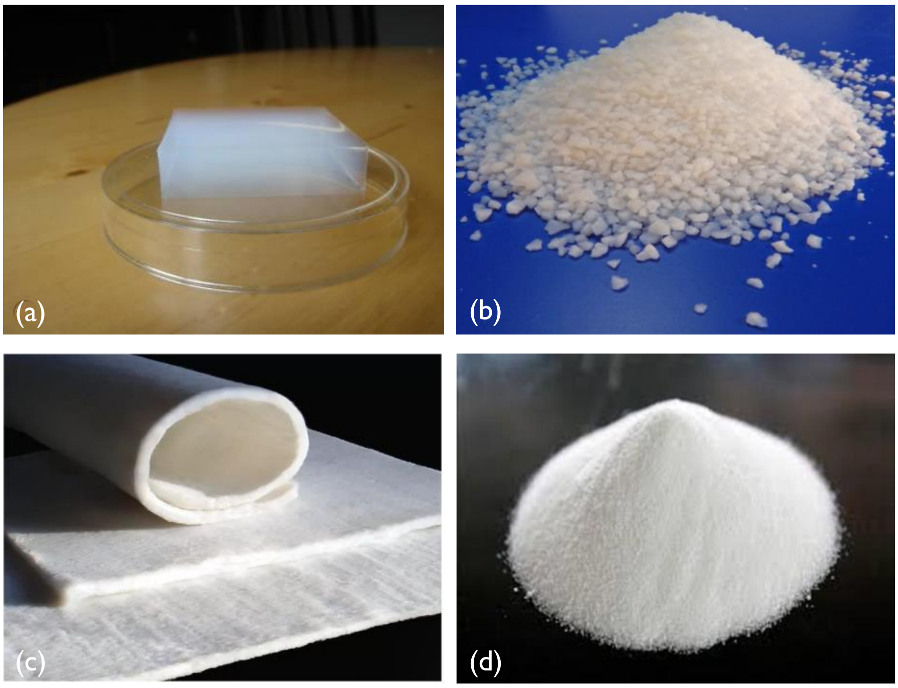

Figure 4. 1: Aerogel classification: (a) Monolithic (b) Granules (c) Blanket/Board (d) Powder
Source: (WorthPoint; Aerogel UK; Aspen; BlogBeats)

They can be classified based on the synthesis procedure into the end product as;

a) Monolithic aerogel: larger pieces (>1 cm) of homogeneous aerogels;
b) Divided materials: random small pieces of aerogel beads such as granules <1 cm or powdered form <1 mm;
c) Composite materials: homogeneous or heterogeneous aerogel-based materials that contain additives that can be incorporated either into the gel matrix during aerogel

synthesis or a second separate phase or by a subsequent compounding (see Figure 4. 1) (Koebel, Rigacci, & Achard, 2012).

The monolithic aerogel products are rarely available as their synthesis process is time-consuming and cost-intensive (Ihara et al., 2015; Koebel et al., 2012), commercially available ones are silica aerogel, aerogel granules, aerogel enhanced renders and boards, etc. However, the most widely used product is the silica aerogel, for its preparation is easier and more reliable.

Aerogel preparation consists of three main steps:

a) Sol-gel preparation: - Where the gel is prepared by a sol-gel process through dissolving the solid components of the gel in liquid agglomerate to form a consistent three-dimensional network throughout the solution;
b) Gel aging: - Where the fragile gel is aged in its mother solution to become stiffer and stronger, while a relatively stronger porous solid is created by trapping the solvent inside the pores and;
c) Gel drying: - Where the liquid inside the gel network is replaced by air (Baetens et al., 2011; Nosrati & Berardi, 2018).

A simplified production reaction of the most common silica aerogel for insulation purposes is shown in equation 1 (Baetens et al., 2011; Nosrati & Berardi, 2018):

$$Si(OCH_3)_4 + 2H_2O \leftrightarrow SiO2 + 4CH_3OH \qquad (1)$$

Aerogel's drying process is strenuous because of the strong surface tension forces between the solid part of the pores and the inner liquid since cracking and shrinkage of the gel network occurs due to capillary pulls. Three drying processes are commonly used, Supercritical drying, ambient pressure drying, and freeze-drying (Baetens et al., 2011; Gurav et al., 2010; Nosrati & Berardi, 2018). The rare interconnected internal formation of SiO_2 chains with distributed air-filled pores gives rise to the unique properties of silica aerogels, plus very low thermal conductivity, low density, low refractive index, and low dielectric constant (Nosrati & Berardi, 2018; Riffat & Qiu, 2013). The main properties of the most common aerogel are summarized in Table 4. 1.

Aerogel-enhanced materials with thermal conductivity of less than 0.02 W/m·K are considered as super-insulation materials because the thermal conductivity is less than free air (0.026 W/m·K at ambient temperature) while other insulating materials like mineral wool or polyurethane and polymer foams are between 0.03 W/m·K and 0.05 W/m·K (Nosrati & Berardi, 2018).

Property	**Value**
Density	3-350 kg/m^3 (most common~100)
Primary particle diameter	2-4 nm
Pore diameter	1-100 nm (~20 nm on average)
Surface area	600-1000 m^2/g
Porosity	85-99.9% (typical ~95%)
Tensile strength	16 kPa
Thermal conductivity	0.01-0.02 W/m·K
Thermal tolerance temperature	500 ˚C (m.p1>1200)
Longitudinal sound speed	100 – 300 m/s
Coefficient of linear expansion	2.0-4.0 × 10 $^{-6}$ 1/˚C

Table 4. 1: Some outstanding properties of silica aerogels
Source: (Nosrati & Berardi, 2018)

Although not within the scope of this study, it is important to state that the high cost of aerogel material limits its wide application especially in the construction sector, however, various studies are being carried out by researchers and energy organizations on how this can be reduced while maintaining/improving its unique thermal properties (Ibrahim, Biwole, Achard, Wurtz, & Ansart, 2015). Aerogels synthesized with other insulating or non-insulating materials are being studied based on the end application required, some of these studies are discussed below;

Silica aerogel was used between an innovative glazing system and was examined by (Buratti & Moretti, 2012) for energy saving in buildings. The author constructed 14 mm thick of float & low-e glasses and granular & monolithic aerogel samples in compliance with EN 410/2011. The optical characteristics of the samples were measured, to estimate the light transmittance, solar factor, color rendering index, and thermal transmittance. Based on the author's examination, monolithic aerogel glazing showed the best performance compared to the granular system, both for light transmittance, thermal insulation. The outcome of the experiment displayed a favorable form of aerogel window compared to the conventional ones used in buildings in the region (Buratti & Moretti, 2012).

Another study was carried out by (Zhang, Ye, & Wang, 2017) with Zirconia fibers and a quasi-layered microstructure constructed using vacuum squeeze molding. The effects of inorganic binder content on the microstructure and room-temperature thermal and mechanical properties of fibrous zirconia ceramics samples were examined. Then, Al_2O_3–SiO_2 aerogel was transfused into fibrous porous ceramics and the microstructures. Thermal and mechanical properties of combined Al_2O_3–SiO_2 aerogel/porous zirconia composites were also studied. Results showed that the Al_2O_3–SiO_2 aerogel/porous zirconia composites exhibited higher compressive strength of up to 1.22 MPa and low thermal conductivity of about 0.049 (W/m·K). The study provided an efficient way to prepare high-temperature thermal insulation materials using the composite (Zhang et al., 2017).

The role of lightweight aggregates on the hygrothermal and mechanical performance of cementitious aerogel-based renders was implied by (de Fátima Júlio, Soares, Ilharco, Flores-Colen, & de Brito, 2016). The lightweight aggregates replaced silica sand, with a binder-aggregate volume ratio of 1:4 which comprises of cement-fly ash (50 wt%) binder, with 60 vol% subcritical silica-based aerogel, 20 vol% granular expanded cork, 15 vol% expanded clay, and 5 vol% perlite. Aggregate produced a lightweight of ~652 $kg.m^{-3}$, thermal conductivity of 0.084 $W.m^{-1}.K^{-1}$, with acceptable mechanical strength and good deformation capacity. The comparison of these renders' properties with the molecular and pore structure of the aggregates proved to be extremely useful to improve their overall performance (de Fátima Júlio et al., 2016).

Huang & Niu in 2015 examined a super-insulating glazing system formed by two layers of conventional single clear glass panes and a layer of silica aerogel filled in between. The thermal and optical parameters of several glazing samples were measured and an annual HVAC system energy analysis was also conducted based on the space cooling load simulation. The result indicated that in humid subtropical climates, the application of silica aerogel glazing system can reduce the annual space cooling load by around 4%, and for the envelope heat gain, the reduction could be around 60% in a typical commercial building. It was also found that the silica aerogel glazing system performed better if the internal heat source in a building took a small proportion of the total space cooling load (Huang & Niu, 2015b).

Mortar with SiO_2 aerogel particles was prepared and examined by(Liu et al., 2016). Density, mechanical properties, softening coefficient, autogenous shrinkage, antifreeze performance, and thermal conductivity properties were studied when the SiO_2 aerogel particle replacement ratio was at 10%, 20%, 30%, 40%, 50%, and 60%. The mortar, based on SiO2 aerogel particles showed a density of ~1.2 g/cm^3, compressive strength, and flexural tensile strength of ~2.15 MPa and ~0.45 MPa, thermal conductivity of ~0.1524 W/m.K at the aerogel content of 60 vol%. Based on the result obtained, the thermal conductivity was further studied when fiber, air-entraining agent, and powder were added into the mortar. The results showed that when the added materials were 0.2%, 0.05%, and 1% respectively, the thermal conductivity was the lowest (0.0859 W/m.K) (Liu et al., 2016).

5. MATERIALS AND METHODS

First, to represent the tropical climate regions, Lagos and Belém, which are located in the southwest of Nigeria and the north of Brazil, respectively were considered. The selected cities are both in the coastal region with similar climate conditions of high humidity and rainfall. Also, their temperatures are moderately high throughout the year, with little or no distinctive difference between summer and winter days (see Figure 5. 1). Furthermore, the architecture of buildings in both selected cities are similar, therefore, a single design was selected to represent the two locations: a residential building with thermal zones distributed on two floors. However, some of the materials utilized for construction vary significantly, thus, the designs were modeled using conventional materials utilized in each city as a base reference and later modified through the inclusion of aerogel material (aerogel blanket) to different surfaces of the models.

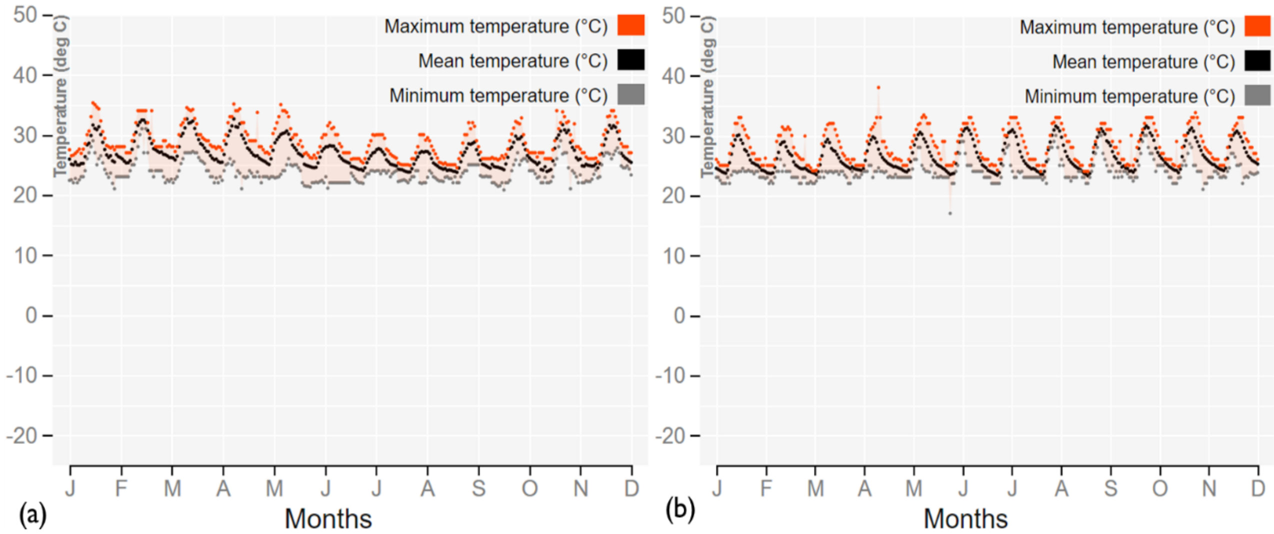

Figure 5. 1: Annual temperature variation: (a) Lagos, Nigeria (b) Belém-Pará, Brazil
Source: climaplus

Secondly, a whole building energy simulation was carried out with 'EnergyPlus' simulation program on the designed models, and the influence of including the insulation material to the different surfaces of the models in terms of thermal comfort improvement was analyzed with reference to the base variants (models with conventional materials). Then, an ideal loads HVAC system was introduced into the models to further examine the energy consumption reduction that could be attained from the utilization of the insulation material. The details of the procedures taken are highlighted in the following items:

5.1 Weather Data Selection

5.1.1 Nigeria

Nigeria's weather is characterized by a hot and dry climate in the far north with high temperatures (about 38 – 40℃) in some cities, especially during the summer season (from March-May). The south and the coastal region is majorly a tropical climate with high rainfall and humidity and with a temperature range almost constant throughout the year (about 22 – 33℃) (Encyclopedia Britannica, 2019). For this study, Lagos climate was considered; the city has a tropical climate (Aw, in consonance with the köppen climate classification) and lies on the southwestern coast of the country (longitude: 3.38° E, latitude: 6.52° N), with most of its land at ~6m above sea level. The temperature variation is almost constant throughout the year, with maximum values between 30 – 34℃ (see Figure 5. 1) ("climaplus," n.d.; Climate-Data.org, 2019b; Weather-Spark, 2019b).

For the simulations, Lagos's weather data was not available on the EnergyPlus database. In such situations, the consideration of nearby available weather or meteorological data to represent unavailable locations is recommended (ASHRAE Standard 55-2017, 2017; "Weather Data | EnergyPlus," n.d.). Therefore, the nearest station with available weather data was selected: Accra, Ghana; however, part of the weather file was incomplete and could not be used for the simulations. Thus, the next nearest station with complete weather data and a similar geographic location to the selected city was adopted for the simulation: Dakar weather station, Dakar-Senegal.

Dakar is characterized by a hot semi-arid climate (köppen climate classification: BSh) and lies on the westernmost coast of Senegal (longitude: 17.47° W, latitude: 14.72° N), with most of its land at ~11m above sea level. The maximum temperatures fall within 27 – 36℃ ("climaplus," n.d.), although Dakar's climate is warm and dry, it has an ocean-influenced climate, where the city is cooled almost throughout the year by the sea breezes. This makes it have a somewhat similar mean temperature with Lagos, hence its consideration for this study. However, to ensure that Lagos's climate condition was better captured, the obtained weather data (Dakar's weather file) was further modified to suit the selected city's average figures reported in ("climaplus," n.d.; Climate-Data.org, 2019b; Weather-Spark, 2019b) and (Nigerian Meteorological Agency, 2018).

5.1.2 Brazil

Brazil's climate varies significantly but the country's weather is mostly tropical, with semiarid deserts and equatorial rainforests in the north and northeast to temperate coniferous forests in the south (CIA, 2019). For this research, the climate considered was from Belém weather station, Belém-Pará. Belém also has a tropical climate (köppen climate classification: Af) and it lies on the north coast of the country (longitude: 48.50° W, latitude: 1.46° S), with most of its land at ~15m above sea level. The city also has a high amount of rainfall and temperature variation is virtually constant throughout the year, with no distinctive difference between summer and winter days. Maximum values are between 32 – 34°C and it's hardly below 22°C or above 35°C all year round (see Figure 5. 1) (Climate-Data.org, 2019a; Weather-Spark, 2019a). Belém's weather station has complete weather data available on the EnergyPlus database and was used for the simulations.

5.2 Design and Modeling

The residential building selected to represent the two locations (with descriptions presented in Table 5. 1) was designed by UMD Design Plus, Nigeria, and has approved its utilization for this study, and to publish all images extracted from it. SketchUp and Open Studio modeling tools were used to create the models as shown in Figure 5. 2.

Description	Value
Total Building Area (Volume)	~ 455 m^2 (1135 m^3)
Number of floors	2 story: Ground Floor (GF) & First Floor (FF)
Floor-to-floor height	3m
Gross Wall Area	~ 293 m^2
Window Opening Area	~ 49 m^2
Net Conditioned Building Area	257.31 m^2
Unconditioned Building Area	197.74 m^2

Table 5. 1: Description of selected residential building
Source: Author

The designs were first modeled with common conventional materials utilized in each selected locations (with properties presented in Table 5. 2) as base variants (see Figure 5. 3 and Tables 5. 4 & 5. 5). Then they were later modified by including aerogel blanket (properties presented in Table 5. 2) to the external façades (variant 1), Internal façades (variant 2), and the

Attics and floor slabs (variant 3) of the models (see Figures 5. 4 & 5. 5 and Tables 5. 6 & 5. 7). Thermal zones where comfort is most likely required were considered for the insulation.

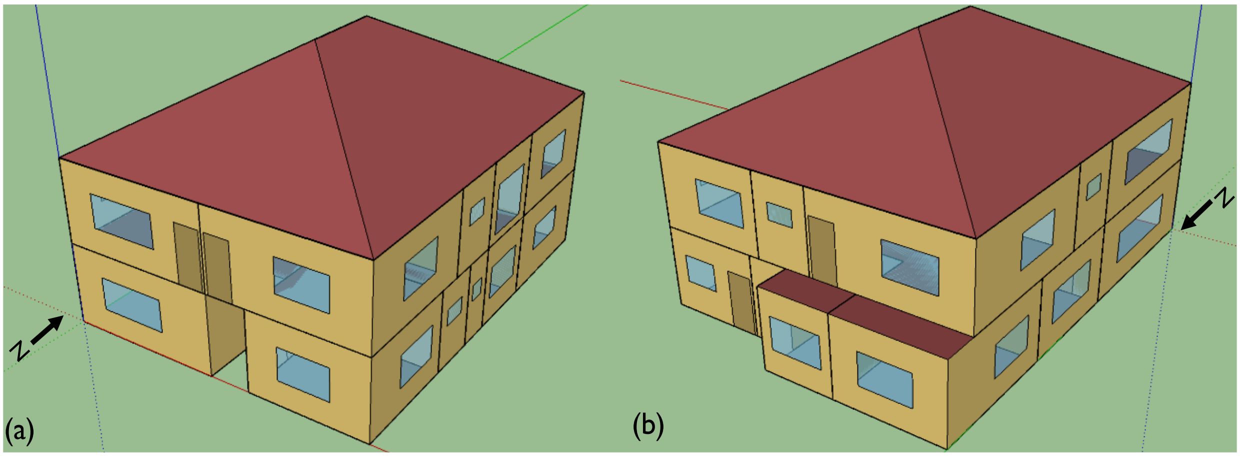

Figure 5. 2: A 3D view of the selected residential building models: (a) Approach-view (b) Rear-view
Source: Author

5.3 Construction Materials

To ensure optimum thermal comfort and stability of buildings, the thermal and mechanical properties of the materials used in their construction and their response to the effect of the climate are essential parameters. Heat gain and loss between spaces are seen to be affected by the materials contained in the elements of each space envelop, which in turn determines the energy consumption of the entire building. Therefore, materials used for the construction of elements, especially those exposed to solar radiation and wind should have sufficient resistance to these climate factors (Amasuomo, Atanda, & Baird, 2017; Olatunde, 2011).

For this study, popular construction materials used in Nigeria & Brazil and some of their thermal and mechanical properties are highlighted in Tables 5. 2 & 5. 3. Although there are materials like woods and ceramic tiles that are utilized in both locations, some materials like ceramic bricks and ceramic roof tiles are mostly used in Brazil while for Nigeria, concrete/sandcrete bricks and aluminum roof tiles are common materials for modern building constructions. However, there are other materials used in both locations but with different thermal and mechanical properties and or thicknesses as can be observed in Table 5. 2.

MATERIALS: MECHANICAL & THERMAL PROPERTIES					
Materials	**Roughness**	**Thickness (m)**	**Conductivity (W/mK)**	**Density (kg/m^3)**	**Specific Heat (J/kgK)**
Acrylic Texture*	Medium Rough	0.005	0.4	1300	1000
Wood (Doors)*	Medium Smooth	0.040	0.15	500	1340
Ceramics (Floor & Wall)*	Very Smooth	0.005	1.5	2000	920
Sandcrete Block 150**	Rough	0.150	0.481	1900	920
Sandcrete Block 230**	Rough	0.230	0.481	1950	920
Plain Plaster**	Smooth	0.025	1.2	1200	840
Mortar**	Smooth	0.015	1.6	2000	1000
Screed Coating**	Smooth	0.005	0.35	950	837
Concrete Slab**	Rough	0.150	1.75	2300	1000
Aluminum Roof Tile**	Medium Rough	0.005	45	7800	480
Gypsum Lining**	Smooth	0.020	0.35	950	837
Ceramic Block***	Rough	0.100	0.9	1500	920
Mortar***	Smooth	0.015	1.15	2000	1000
Plain plaster***	Smooth	0.025	1.15	2000	1000
Ceramics (Floor & Wall)***	Very Smooth	0.005	0.9	1500	920
Concrete Slab***	Rough	0.100	1.75	2300	1000
Ceramic Roof Tile***	Medium Rough	0.010	0.9	1500	920
Screed Coating***	Smooth	0.005	0.5	1200	840
Wood (Lining)***	Medium Smooth	0.010	0.15	500	1340
Aerogel Blanket	Medium Smooth	0.020	0.0131 - 0.0136	100 - 150	1000

Table 5. 2: Mechanical & Thermal Properties of Construction Materials typically used in Brazil and Nigeria
Source: (Adepo, Imoukhuede, & James, 2018; Frota & Schiffer, 2001; Radhi, Assem, & Sharples, 2014)

Key: * Materials used in both Lagos and Belém
** Materials used in Lagos
*** Materials used in Belém

Material	**Thickness (m)**	**Thermal Transmittance; U-Factor $W/(m^2K)$**	**Solar Heat Gain Coefficient**
Glass Window	0.003	5.76	0.66

Table 5. 3: Properties of glazing system typically used in Nigeria and Brazil

The distribution of the construction materials and the insulation material on the surfaces of the models are shown in Tables 5. 4 – 5. 7 and Figures 5. 3 – 5. 5.

NB: The arrangement of all constructions is from outside to inside.

Construction	Materials				
External Wall 1	Acrylic texture	Plain plaster	Sandcrete block (230)	Plain plaster	Screed (Wall)
External Wall 2	Acrylic texture	Plain plaster	Sandcrete block (230)	Mortar	Ceramic (Wall)
Internal Wall 1	Screed (Wall)	Plain plaster	Sandcrete block (150)	Plain plaster	Screed (Wall)
Internal Wall 2	Screed (Wall)	Plain plaster	Sandcrete block (150)	Mortar	Ceramic (Wall)
Internal Wall 3	Ceramic (Wall)	Mortar	Sandcrete block (150)	Mortar	Ceramic (Wall)
Decking	Ceramic (Floor)	Mortar	Concrete Slab	Gypsum Lining	
Ground Floor; Floor	Concrete Slab	Mortar	Ceramic (Floor)		
Roof/Ceiling	Aluminum Roof Tile	Gypsum Lining			

Table 5. 4: Construction type and materials, Base variant (Lagos)
Source: Author

Construction	Materials				
External Wall 1	Acrylic texture	Plain plaster	Ceramic block	Plain plaster	Screed (Wall)
External Wall 2	Acrylic texture	Plain plaster	Ceramic block	Mortar	Ceramic (Wall)
Internal Wall 1	Screed (Wall)	Plain plaster	Ceramic block	Plain plaster	Screed (Wall)
Internal Wall 2	Screed (Wall)	Plain plaster	Ceramic block	Mortar	Ceramic (Wall)
Internal Wall 3	Ceramic (Wall)	Mortar	Ceramic block	Mortar	Ceramic (Wall)
Decking	Ceramic (Floor)	Mortar	Concrete Slab	Plain plaster	Screed (Wall)
Ground Floor; Floor	Concrete Slab	Mortar	Ceramic (Floor)		
Roof/Ceiling	Ceramic Roof Tile	Concrete slab	Wood (Lining)		

Table 5. 5: Construction type and materials, Base variant (Belém)
Source: Author

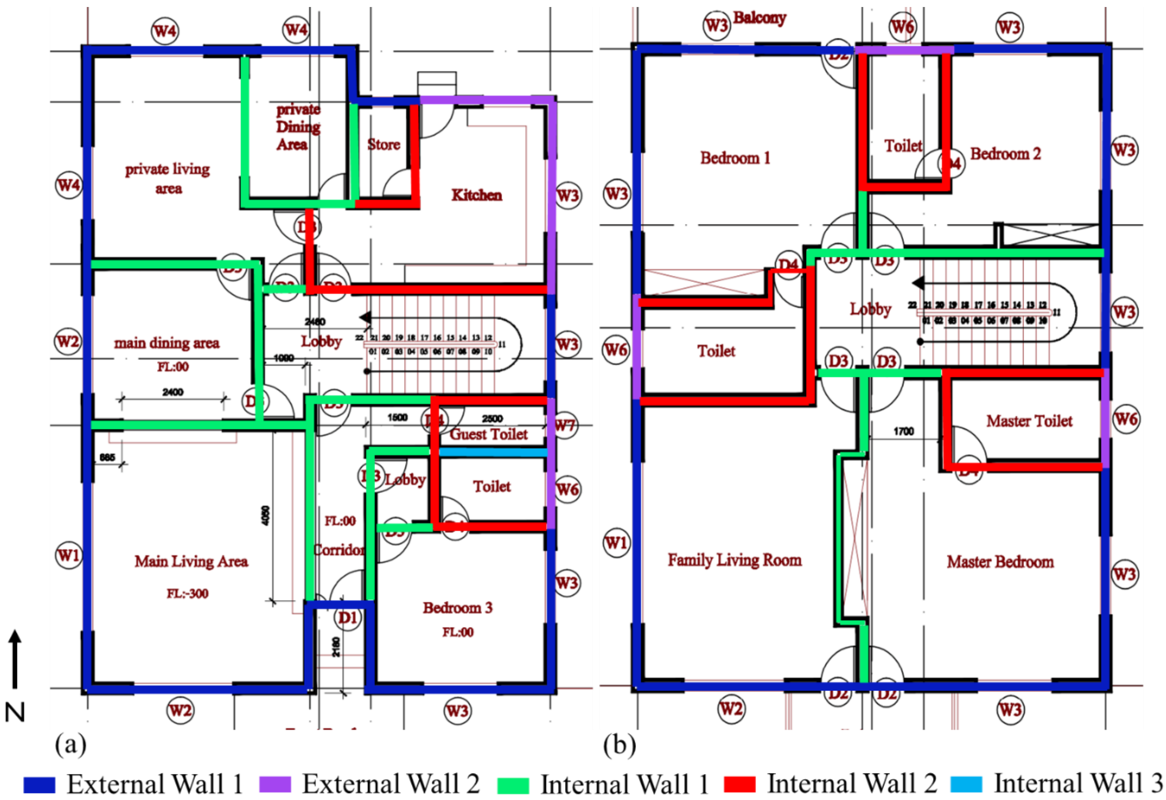

Figure 5. 3: Construction materials distribution: Base Variants (a) Ground Floor (b) First Floor
Source: Author

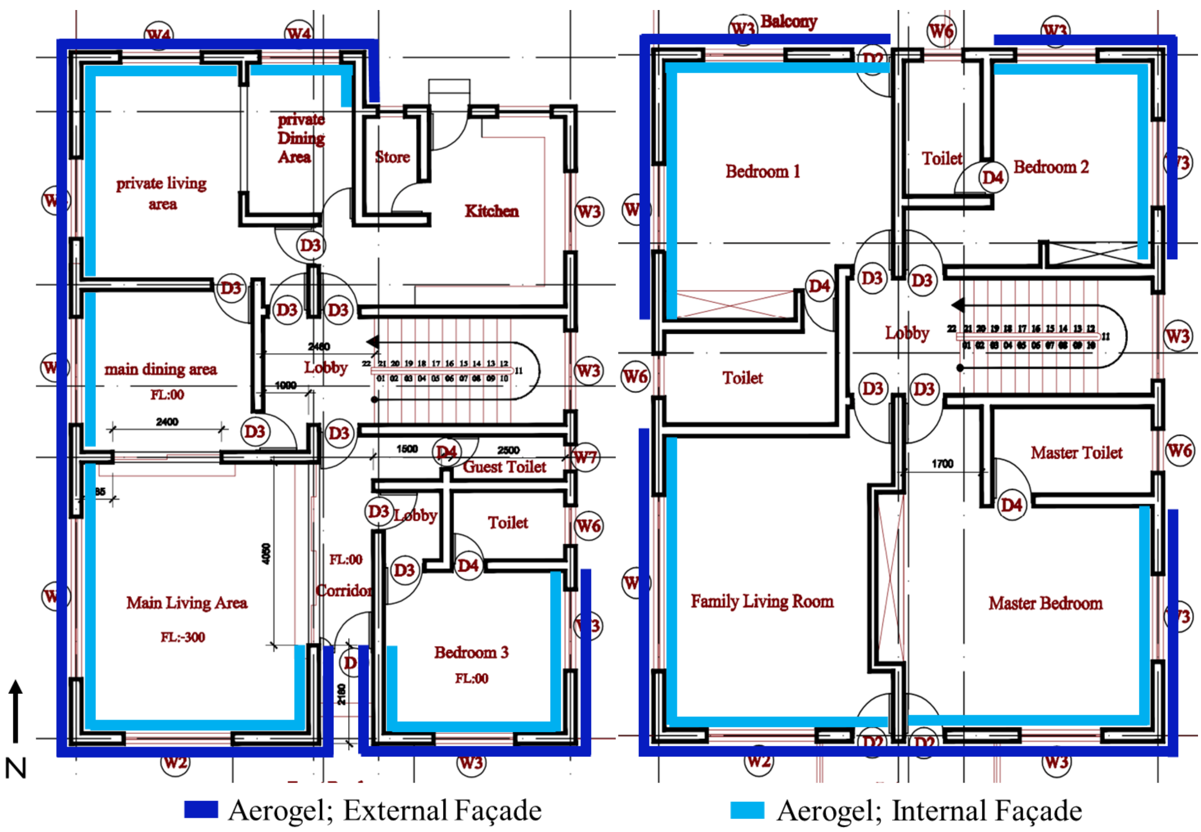

Figure 5. 4: Insulation material distribution: Variants 1 (External) & Variants 2 (Internal) Façades
Source: Author

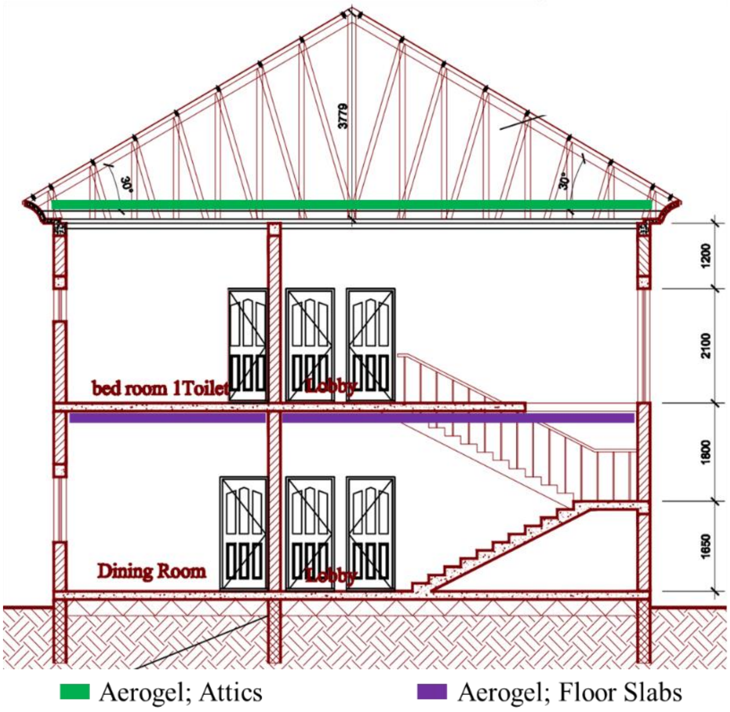

Figure 5. 5: Insulation material distribution: Variants 3 (Attics & Floor Slabs)
Source: Author

Construction	**Materials**						
Aerogel; External Façade	Acrylic texture	Screed (Wall)	Aerogel Blanket	Plain plaster	Sandcrete block	Plain plaster	Screed (Wall)
Aerogel; Internal Façade	Acrylic texture	Plain plaster	Sandcrete block	Plain plaster	Aerogel Blanket	Screed (Wall)	
Aerogel; Floor Slab	Ceramic (Floor)	Mortar	Concrete Slab	Aerogel Blanket	Gypsum Lining		
Aerogel; Attic	Aerogel Blanket	Gypsum Lining					

Table 5. 6: Insulation material distribution (Lagos)
Source: Author

Construction	**Materials**						
Aerogel; External Façade	Acrylic texture	Screed (Wall)	Aerogel Blanket	Plain plaster	Ceramic block	Plain plaster	Screed (Wall)
Aerogel; Internal Façade	Acrylic texture	Plain plaster	Ceramic block	Plain plaster	Aerogel Blanket	Screed (Wall)	
Aerogel; Floor Slab	Ceramic (Floor)	Mortar	Concrete Slab	Plain plaster	Aerogel Blanket	Screed (Wall)	
Aerogel; Attic	Aerogel Blanket	Concrete Slab	Wood (Lining)				

Table 5. 7: Insulation material distribution (Belém)
Source: Author

5.4 Thermal loads and Occupation Schedule

The main internal loads (metabolic rates, loads for illumination & equipment) were filled based on ASHRAE standard 55 rates, and local manufactures' rates. Values vary from 0 to 100%, where the value '0' means that there is no occupation or that the lights are on 'OFF' mode and that no equipment is connected, while the value '100' means that 100% of people (occupation) are present, or that the lights are on 'ON' mode and that equipment is in full usage. The inputs of schedules and occupation frequency were defined based on the most common occupation pattern found in the selected locations. Considering the size of the selected design, eight (8) residents were assumed in the buildings. Details of the internal load schedules for both Lagos and Belém are presented in Appendix A. Also, Tables 5. 8 & 5. 9 outlines the standards of the loads and metabolic rates considered for the simulations in both cities.

Internal Loads				
Space	**Equipment (W)**		**Illumination(W/m^2)**	
	Lagos	**Belém**	**Lagos**	**Belém**
Bedrooms	110	55	12	5
Living Rooms	110	55	15	6
Kitchen	220	220	15	6
Toilets	1500	5500	10	4
Store/Laundry	N/A	1000	10	4

Table 5. 8: Loads for Illumination & Equipment
Source: Author

Metabolic Rate (W/m^2) AD = 1.80 m^2/Person				
Activities	**Bedrooms**	**Living Rooms**	**Kitchen**	**Toilets**
Seated		104 (W/person)		
Resting	73 (W/person)			
Foot Activity			208 (W/person)	208 (W/person)

Table 5. 9: Metabolic rate for different activities
Source: (ASHRAE Standard 55-2017, 2017)

5.5 Thermal Zone Distribution

The designed models were divided into nine (9) thermal zones, consisting of connected spaces with similar functions and or materials. Thus, each thermal zone of the models consist of two (2) or more spaces joined together. Figure 5. 6 shows the distribution of the thermal zones considered for the simulations.

Figure 5. 6: Thermal zones distribution

Source: Author

5.6 Simulations

A whole building energy simulations were carried out on the designed models. Considering the outdoor climate is moderately high with little or no variation almost throughout the year in both selected locations (see Figure 5. 1), all simulations were run for a typical summer day. To evaluate the thermal behavior and the level of thermal comfort of the models, major parameters that influence the indoor space quality like air temperature, air relative humidity, and operative temperature were measured and the outcome was analyzed and compared to standard recommended values.

To effectively examine the influence of the proposed insulation material with regards to comfort improvement, all simulations were initially run with natural ventilation and no cooling system in the buildings. Then an ideal loads HVAC system was included to further evaluate the difference in the cooling load intensity (CLI) attained through the utilization of the insulation material. The simulations were run for the base variants, and then for variants 1, 2, and 3, and the results from the latter were compared to the former (percentage differences presented in parenthesis). EnergyPlus program was used to run the building energy simulations and the following output variables were considered (ASHRAE Standard 55-2017, 2017; ASHRAE Standard 62.1-2016, 2016; "Documentation | EnergyPlus," n.d.);

a) Zone Outdoor Air Drybulb Temperature, T_{od} (°C) was measured for a typical summer day. EnergyPlus uses each zone's centroid at a height above ground to measure its corresponding outside air temperature;
b) Zone Mean Air Temperature, T_m (°C) which is the average temperature of the indoor air temperature in each zone;
c) Zone Air Relative Humidity, RH (%), estimated through other output variables like; the 'Zone Air Temperature', the 'Zone Air Humidity Ratio', and the 'Outside Barometric Pressure'. Although a slight change in humidity has a limited impact on thermal comfort at moderate temperature and activity level, ASHRAE Standard 62. 1 recommends a maximum threshold of 65% RH for an ideal indoor space comfort. For this study, the range was set at 35-65% to represent a typical summer day comfort level and was compared to the actual measured values in each zone;
d) Zone Operative Temperature, T_o (°C) in a zone or space determines the human thermal comfort under normal weather conditions. This is dependent on the zone air temperature, the mean radiant temperature, and the air velocity. Indoor thermal comfort may be considered as a subjective component, thus, temperature recommendations may vary depending on various factors like location, climate condition, clothing level, activity level, etc.; however, ASHRAE 55 recommends a range between 67 – 82°F (19 – 27°C). A range of 22 – 26°C was set for a typical summer day comfort level and was compared to the actual recorded operative temperature in each zone.

6. RESULTS AND ANALYSIS

This section presents the analysis of the results obtained from the simulations of the base variants, and variants 1, 2, and 3 in both Lagos and Belém. The selected output variables were analyzed based on each floor and individual zones. However, zone 3, which serves as a circulation area in the designed models, was assumed to have no constant metabolic activities and other equipment usages, therefore, it was excluded from this analysis. Also, the insulation material was not included in zones 3 and 4, as thermal comfort is less likely required in the zones.

6.1 Zone Mean Air Temperatures, T_m (°C)

The recorded T_m for the base variant and variants 1, 2, and 3 in both Lagos and Belém are presented in Figures 6. 1 – 6. 4. From the charts, the outdoor air temperature (T_{od}) in Lagos was between 25 – 34°C, while in Belém, it was between 25 – 33°C.

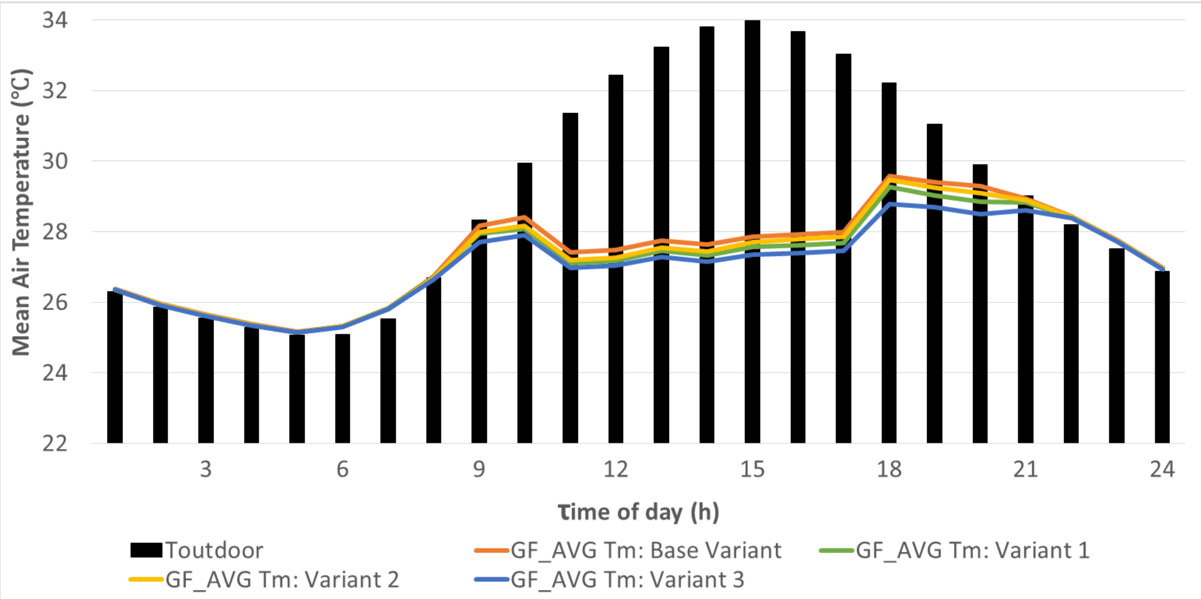

Figure 6. 1: Ground Floor (GF), Mean air temperature (Lagos)
Source: Author

For zones on the ground floor (GF), the corresponding mean air temperature (T_m) in both selected locations was nearly the same with the T_{od} notably during the night, from 22h up until 08h in the morning for the base variants and variants 1, 2, and 3. However, differences were recorded starting from 9h where the values decreased below the T_{od}. In Lagos, the base variant recorded a maximum value of 29.6°C and the minimum was 25.2°C. For variants 1, 2, and 3, the maximum values were 29.3°C (-1.0%), 29.5°C (-0.3%), and 28.8°C (-2.7%), respectively, while the minimum value was 25.1°C (-0.4%) all through variants 1, 2, and 3 (Figure 6. 1). In Belém, the base variant had a maximum value of 30.2°C and a minimum of 25.2°C. For variant 1, 2, and 3, the maximum values were 28.8°C (-4.6%), 29°C (-4.0%), and 29.8°C (-1.3%), respectively, while the minimum value was 25.1°C (-0.4%) all through variants 1, 2, and 3 (Figure 6. 2). A major difference in the T_m was observed in both locations between 17h – 19h and from 09h – 11h across all the variants, and this can be linked to the internal loads related to the zones within this period.

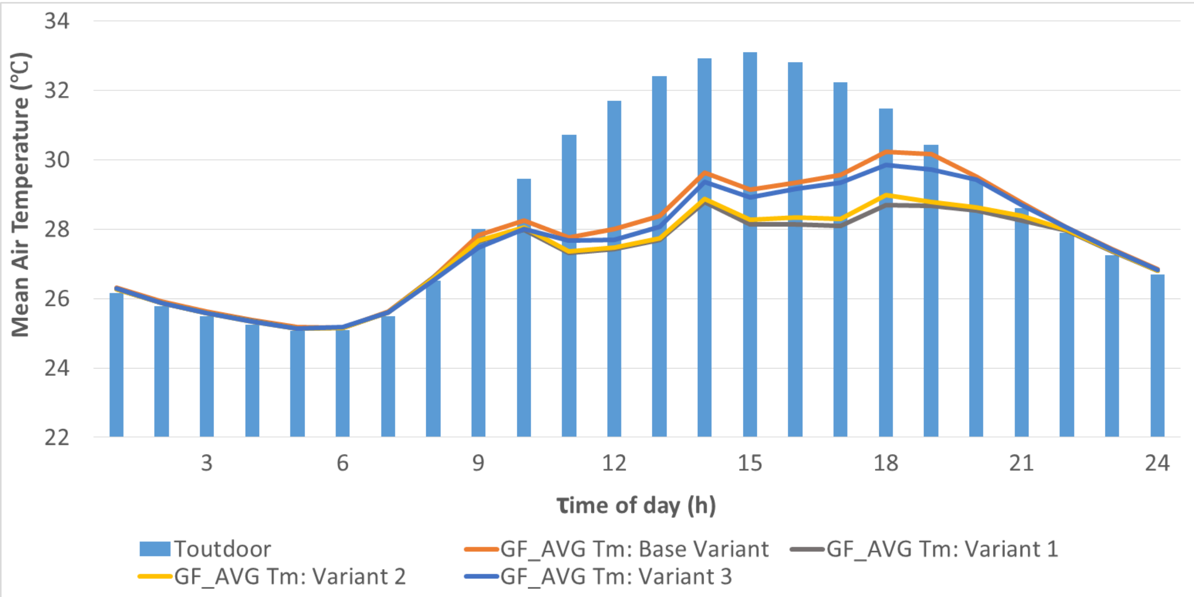

Figure 6. 2: Ground Floor (GF), Mean air temperature (Belém)
Source: Author

Looking further into the recorded T_m in individual zones on the GF (see Tables B. 1 & B. 2 and Figures B. 1 – B. 8 in Appendix B), for Lagos, the base variant recorded values as follows: Zone 1 recorded a maximum value of 28.6°C and the minimum was 25.2°C. For zone 2, the maximum value was 30.6°C with a minimum of 25.2°C. For zone 4, the maximum value was 30.2°C and the minimum was 25.1°C. While for zone 5, the maximum and minimum values were 30.5°C and 25.1°C, respectively. For variant 1, although the overall influence was not significant when compared to the base variant, minor differences were recorded in the zones where the insulation material was inserted. For zone 1, the maximum value remained the same while the minimum value decreased to 25.1°C (–0.4%). In zones 2 & 5, the maximum values decreased to 30.2°C (–1.3%) and 30.1°C (–1.3%), respectively, while the minimum values remained the same. Although zone 4 had no insulation, a slight decrease of 0.3% was recorded in the maximum value, ~30.1°C, while the minimum value remained the same. For variant 2, the difference in the recorded values with that of the base variant was barely noticeable in all the zones. For zone 1, the maximum value remained the same, while the minimum value decreased to 25.1°C (–0.4%). For zones 2 & 5, the maximum and minimum values remained the same. Also, the recorded values in zone 4 (with no insulation material) remained unaffected. For variant 3, the difference in the recorded values was evident in all the zones. For zone 1, the maximum and minimum values decreased to 28.5°C (–0.3%) and 25.1°C (–0.4%), respectively. For zones 2 & 5, the maximum values respectively decreased to 29.7°C (–2.9%) and 29.8°C (–2.3%), while the minimum values remained the same. In zone 4 (which had no insulation material), the maximum value decreased to 29.5°C (–2.3%) while the minimum value remained unchanged.

In Belém, the base variant recorded values as follows: Zone 1 recorded a maximum value of 29.7°C and the minimum was 25.1°C. For zone 2, the maximum value was 30.9°C with a minimum of 25.1°C. For zone 4, the maximum value was 32.7°C and the minimum was 25.2°C. While for zone 5, the maximum and minimum values were 30.4°C and 25.2°C, respectively. For Variant 1, substantial differences were recorded in the zones where the insulation material was inserted. In zone 1, 2, and 5, the maximum values decreased to 27.9°C (–6.1%), 29°C (–6.1%), and 29.1°C (–4.3%), respectively, while the minimum values remained the same. In zone 4 (which had no insulation material), the maximum value decreased to 32.6°C (–0.3%), while the minimum remained the same. For Variant 2, the zones where the insulation material was applied also recorded a significant difference. In zone 1, 2, and 5, the maximum values respectively decreased to 28°C (–5.7%), 29.5°C (–4.5%), and 29.2°C (–3.9%), while the minimum values remained the same. In zone 4, (which had no insulation material), the maximum value also decreased to 32.6°C (–0.3%), while the minimum value remained the same. For Variant 3, minor differences were recorded in the zones where the insulation material was inserted. In zone 1, 2, and 5, the maximum values decreased to 29.4°C (–1.0%), 30.6°C (–1.0%), and 29.9°C (–1.6%), respectively, while the minimum values remained the same. In zone 4, (with no insulation material), the maximum value also decreased to 32.6°C (–0.3%), while the minimum value remained the same.

For zones on the first floor (FF), the T_m in both selected locations was nearly the same with the T_{od} from 22h up until 08h in the morning for the base variants and variants 1, 2, and 3. Notable differences were recorded in the middle of the day where the values decreased below the T_{od}. In Lagos, the base variant recorded a maximum value of 33.7°C and the minimum was 25.3°C. For variants 1, the maximum and minimum values remained the same, for variant 2, the maximum value increased to 33.9°C (+0.6%) and the minimum decreased to 25.2°C (-0.4%), while for variant 3, the maximum value decreased to 31.6°C (-6.2%) and the minimum remained unaffected (Figure 6. 3). In Belém, the base variant had a maximum value of 32.7°C and the minimum was 25.3°C. For variants 1, 2, & 3, the maximum values decreased to 32.3°C (–1.2%), 32.5°C (–0.6%), and 32.3°C (–1.2%), respectively, while the minimum values remained unaffected (Figure 6. 4).

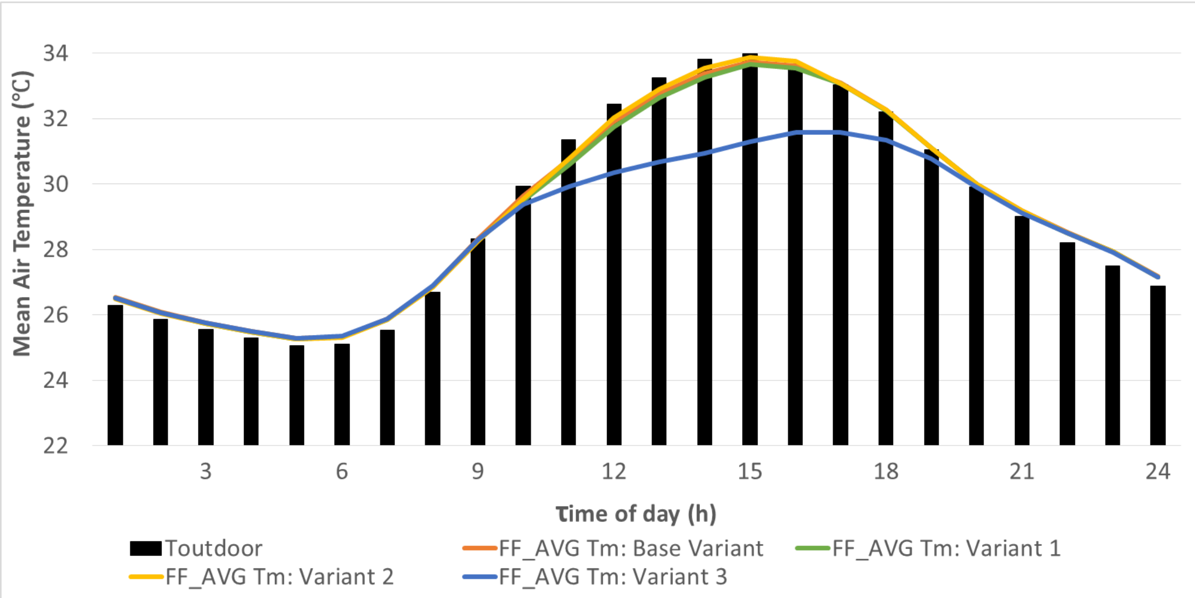

Figure 6. 3: First Floor (FF), Mean air temperature (Lagos)
Source: Author

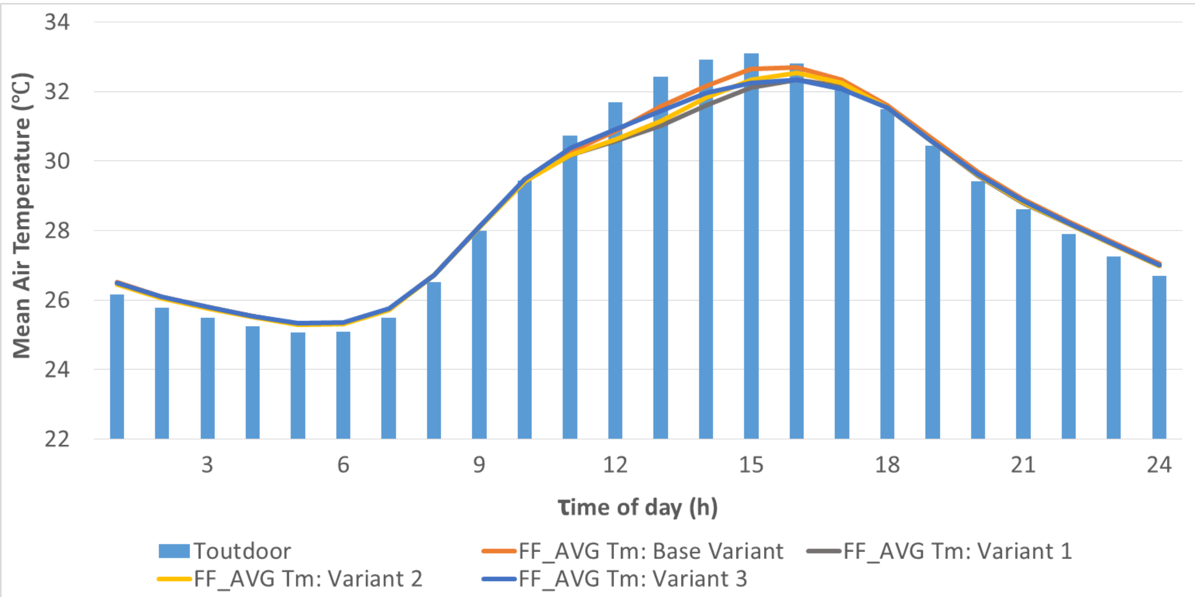

Figure 6. 4: First Floor (FF), Mean air temperature (Belém)
Source: Author

Observing the T_m recorded in individual zones on the FF (see Tables B. 1 & B. 2 and Figures B. 9 – B. 16 in Appendix B), in Lagos, the recorded values for the base variant were as follows: Zone 6 recorded a maximum value of 34°C, and the minimum was 25.3°C. For zone 7, the maximum value was 33.9°C with a minimum of 25.3°C. For zone 8, the maximum value was 33.4°C and the minimum was 25.2°C. While for zone 9, the maximum value was 33.7°C with a minimum of 25.2°C. For variant 1, the T_m was virtually the same as that of the base variant almost throughout the day with minor differences in some of the zones. For zone 6, the maximum value decreased to 33.9°C (–0.3%) while the minimum value remained the same. For zones 7, the maximum and minimum values remained the same. In zone 8, the maximum value decreased 33.2°C (–0.6%) while the minimum value remained unaffected. For zone 9, the maximum and minimum values remained the same. For variant 2, the insulation material virtually had a negative influence in most of the zones. In Zone 6, the maximum and minimum values remained the same. For zones 7, 8, and 9, the maximum values respectively increased to 34°C (+0.3%), 33.6°C (+0.6%), and 34°C (+0.9%), while the minimum values remained the same. For variant 3, a significant difference was recorded especially during the day (between 10 – 19h), however, a slight increase was also observed during the early hours of the day when the lowest T_m was recorded. In zone 6, the maximum value decreased to 31.5°C (–7.4%) while the minimum value increased to 25.4°C (+0.4%). Zones 7, 8, and 9 had similar results, the maximum values decreased to 33°C (–2.7%), 30.5°C (–8.7%), and 31.5°C (–6.5%), respectively, while the minimum values remained unchanged.

In Belém, the base variant recorded the following values: Zone 6 recorded a maximum value of 33.1°C and the minimum was 25.3°C. For zone 7, the maximum value was 33.1°C with a minimum of 25.2°C. For zone 8, the maximum value was 32.5°C and the minimum was 25.3°C. While for zone 9, the maximum value was 32.5°C with a minimum of 25.4°C. For Variant 1, minor differences were recorded in most of the zones. The maximum value decreased to 32.6°C (–1.5%) in zone 6, 33°C (–0.3%) in zone 7, 31.9°C (–1.8%) in zone 8, and 32.3°C (–0.6%) in zone 9, while the minimum values remained unchanged in all the zones. For variant 2, the recorded values were nearly the same as the base variant. In zone 6, the maximum value decreased to 32.8°C (–0.9%) while the minimum value remained the same. In zone 7, the maximum and minimum values remained unaffected. In zone 8, the maximum and minimum values both decreased to 32.1°C (–1.2%) and 25.2°C (–0.4%), respectively. While in zone 9, the maximum and minimum values remained the same. For variant 3, the difference was not significant in most of the zones. The maximum value decreased to 33°C (–0.3%) in both zones 6 & 7, while the minimum values increased to 25.4°C (+0.4%) in zone 6 and 25.3°C (+0.4%) in zone 7. In zone 8, the maximum and minimum values both decreased to 31.5°C (–3.1%) and 25.2°C (–0.4%), respectively. While in zone 9, the maximum value decreased to 32.3°C (–0.6%) and the minimum increased to 25.5°C (+0.4%).

Furthermore, in Lagos, variants 1 and 2 showed more influence for zones on the GF than the zones on the FF, while for variant 3, the effect was more evident on the zones of the FF than the zones on the GF. For Belém, the influence was more significant for zones on the GF than the zones on the FF across variants 1, 2, & 3. Also, in both selected locations, the T_m recorded on the FF zones was higher than that of the GF zones especially in the middle of the day and this can be linked to the effect of solar radiation on the FF zones within this period.

6.2 Zone Air Relative Humidity, RH (%)

Figures 6. 5 – 6. 8 presents the recorded RH for the base variant and variants 1, 2, and 3 in both Lagos and Belém. For the GF zones, it can be observed that in both selected locations, the recorded values were virtually the same in all the zones from 22h to around 09h in the base variants and variants 1, 2, and 3. Notable differences were recorded from 9 – 21h in all the variants, which corresponds to the change in the air temperature recorded within this period. Also, in Lagos, the values were slightly above the recommended maximum threshold of 65% RH during the early hours and in the middle of the day, while in Belém, the values were above the range throughout the day.

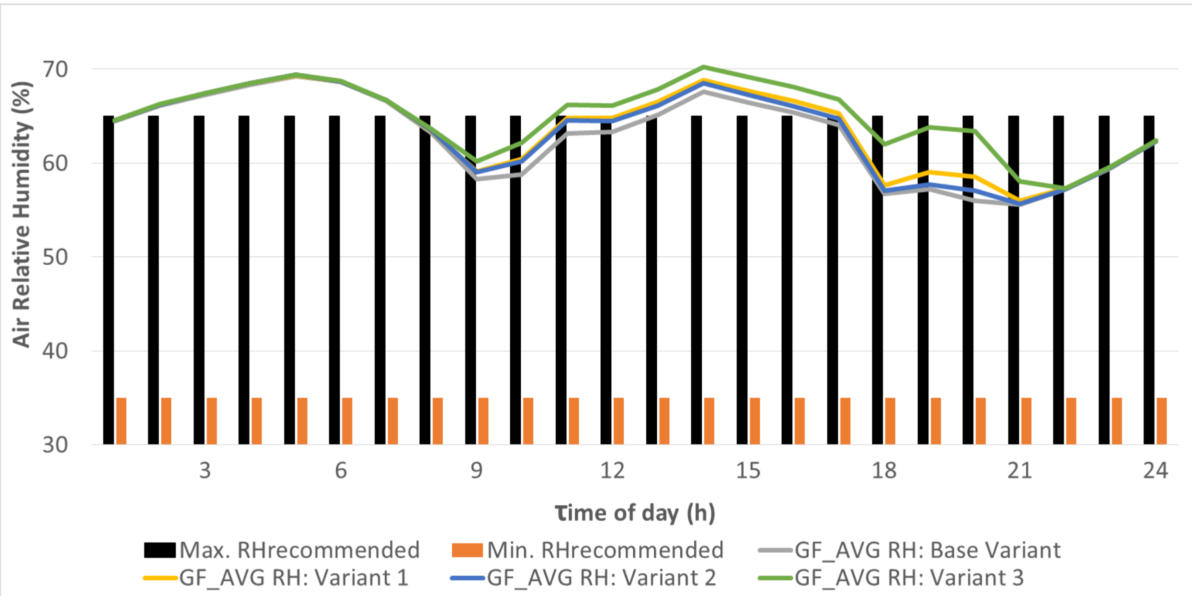

Figure 6. 5: Ground Floor (GF), Air relative humidity (Lagos)
Source: Author

In Lagos, the base variant recorded a maximum value of 69% while the minimum was 56%. For variants 1 & 2, the maximum and minimum values remained the same, while for variant 3, the maximum and minimum values both increased to 70% (+1.4%) and 57% (+1.8%), respectively(Figure 6. 5). In Belém, the base variant had a maximum value of 92%

while the minimum was 69%. Variants 1, 2, & 3 had the same increase in the maximum value, 93% (+1.1%), while the minimum values increased to 76% (+10%) for variants 1 & 2, and 71% (+2.9%) for variant 3 (Figure 6. 6).

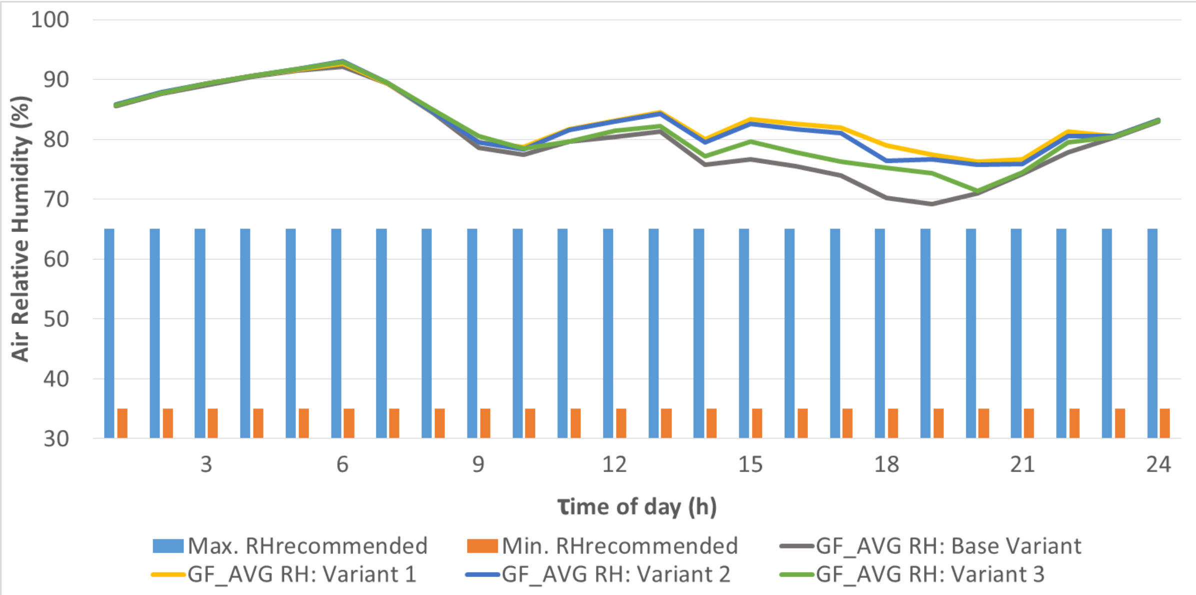

Figure 6. 6: Ground Floor (GF), Air relative humidity (Belém)
Source: Author

Comparing the RH recorded in individual zones of the GF (see Tables B. 1 & B. 2 and Figures B. 17 – B. 24 in Appendix B), In Lagos, the recorded values for the base variant were as follows: Zone 1 recorded a maximum value of 69% while the minimum was 57%. For zone 2, the maximum value was 69% with a minimum of 53%. For zone 4, the maximum value was 73% and the minimum was 55%. While for zone 5, the maximum value was 69% with a minimum of 54%. For variant 1, the recorded values were nearly the same as the results from the base variant. In zone 1, the maximum and minimum values remained the same. For zones 2, the maximum value remained the same but the minimum value increased to 54% (+1.9%). While for zone 5, the maximum and minimum values both increased to 70% (+1.4%) and 55% (+1.9%), respectively. There was no noticeable difference recorded in zone 4 (with no insulation material), the minimum and maximum values remained the same. For variant 2, the recorded values were again almost the same as the base variant in most of the zones. For zones 1 and 2, the maximum and minimum values were the same. In zone 5, the maximum value increased to 70% (+1.4%), while the minimum value remained the same. The recorded values in zone 4 (with no insulation material) remained unchanged. For variant 3, a significant difference was recorded in all the zones. For zone 1, the maximum value increased to 70% (+1.4%) while the minimum value remained the same. For zones 2, the maximum value remained the same while the minimum value increased to 57% (+7.5%). In Zone 5, the maximum and minimum values both increased to 71% (+2.9%) and 57% (+5.6%), respectively. For zone 4 (which had no insulation material), the maximum value also increased to 75% (+2.7%) while the minimum value remained the same.

In Belém, the base variant recorded the following values: Zone 1 recorded a maximum value of 93% while the minimum was 71%. For zone 2, the maximum value was 92% with a minimum of 67%. For zone 4, the maximum value was 92% and the minimum was 64%. While in zone 5, the maximum value was 92% with a minimum of 68%. For variant 1, a significant difference was recorded in most of the zones. For zone 1, the maximum and minimum values both increased to 94% (+1.1%) and 79% (+11.3%), respectively. For zone 2, the maximum and minimum values were 93% (+1.1%) and 74% (+10.4%), respectively. For zone 5, the maximum value remained the same, while the minimum value was 74% (+8.8%). The maximum value in zone 4 (which had no insulation) remained the same, while the minimum value slightly increased to 66% (+3.1%). For variant 2, differences were also recorded in all the zones. For zone 1, the maximum and minimum values increased to 95% (+2.2%) and 79% (+11.3%), respectively. For zone 2, the maximum and minimum values were 94% (+2.2%) and 72% (+7.5%), respectively. While for zone 5, the maximum value remained the same but the minimum value increased to 73% (+7.4%). For zone 4 (with no insulation on its walls), the minimum value increased to 66% (+3.1%), while the maximum value remained the same. For variant 3, minor changes were also recorded in all the zones. For zone 1, the maximum and minimum values both increased to 94% (+1.1%) and 73% (+2.8%). For zone 2, the maximum value was 94% (+2.2%) with a minimum of 69% (+3.0%). While in zone 5, the maximum value remained changed, while the minimum increased to 71% (+4.4%). For zone 4 (with no insulation material), the minimum value increased to 65% (+1.6%), while the maximum value decreased to 91% (–1.1%).

For the FF zones, the recorded RH was lower than the values recorded for the GF zones in both selected locations. The values were virtually the same in all the variants in Belém, while in Lagos, the values were also the same across all the variants from 20h to about 09h in the morning. However, a significant difference was recorded in the middle of the day especially for variant 3, basically due to the substantial decrease in the air temperature recorded within this period. Also, in Lagos, the recorded values were slightly above the recommended range during the early hours of the day (from 02 – 07h) in all the variants, however, they were seen to fall within the recommended range starting from 08h throughout the day. For Belém, the recorded values were above the recommended range nearly throughout the day, however, the values were within the recommended range between 01 – 07h.

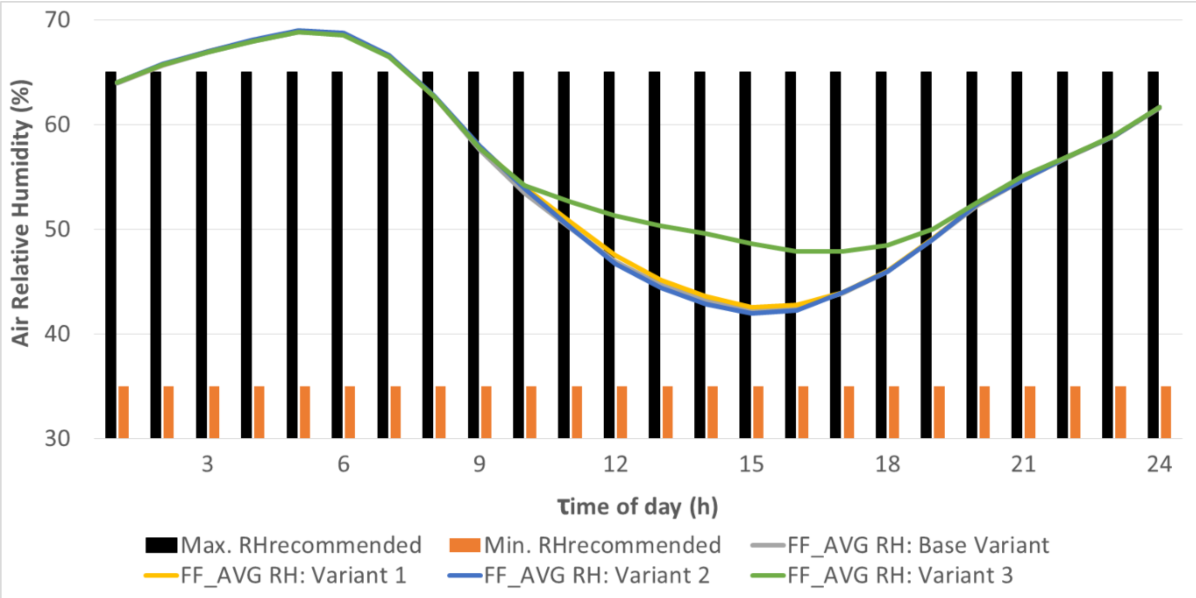

Figure 6. 7: First Floor (FF), Air relative humidity (Lagos)
Source: Author

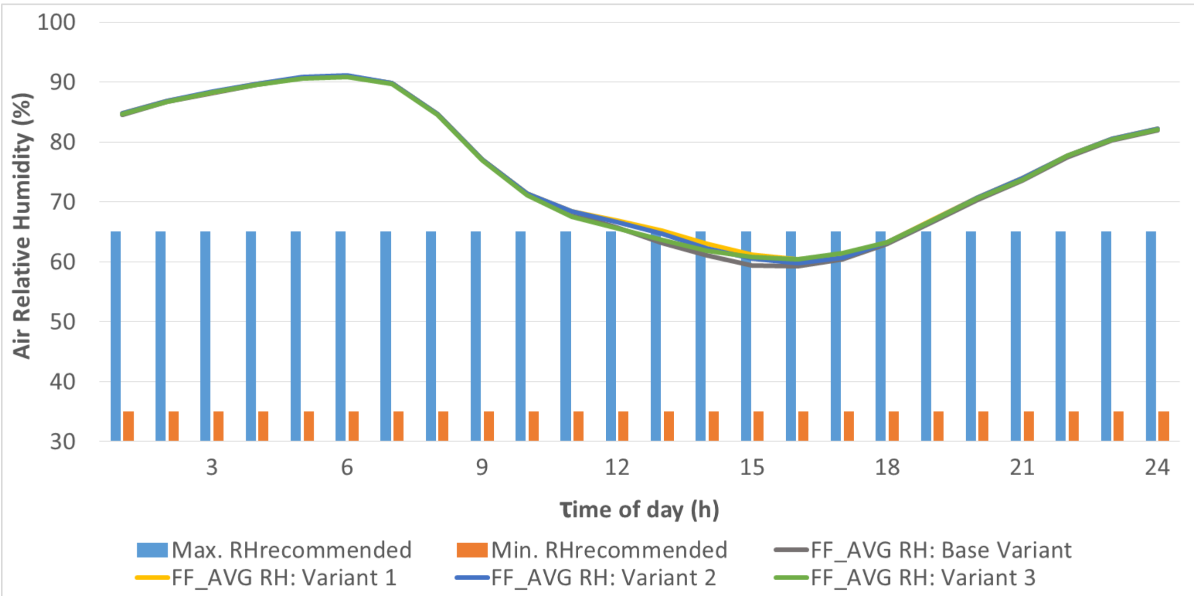

Figure 6. 8: First Floor (FF), Air relative humidity (Belém)
Source: Author

In Lagos the base variant recorded a maximum value was 69% and the minimum was 42%. For variant 1, the maximum value remained the same while the minimum increased to 43% (+2.4%), for variants 2, the maximum and minimum values remained unaffected, while for variant 3, the maximum values remained the same, whereas the minimum value increased to 48% (+14.3%) (Figure 6. 7). In Belém, the base variant had a maximum value of 91% and a minimum of 59%. For variants 1, 2, & 3, the maximum values remained unaffected, while the minimum value increased to 60 (+1.7%) all through the three variants (Figure 6. 8).

Concerning the RH values recorded in individual zones of the FF (see Tables B. 1 & B. 2 and Figures B. 25 – B. 32 in Appendix B), in Lagos, the base variant recorded the following values: Zones 6 and 7 both recorded a maximum value of 69% and a minimum of 42%. Zones 8 and 9 had the same maximum value of 69%, while the minimum value was 43% in zone 8 and 42% in zone 9. For variant 1, the recorded values were virtually the same as the base variant in most of the zones. In zone 6 and 7, the maximum and minimum values remained the same. For zone 8, the maximum value remained the same while the minimum increased to 44% (+2.3%). While in zone 9, the maximum and minimum values remained unaffected throughout the day. For variant 2, the values remained unchanged in all the zone throughout the day. For variant 3, a significant difference was recorded in all the zones. For zone 6, the maximum value decreased to 68% (–1.4%), while the minimum value increased to 48% (+14.3%). Zones 7, 8 and 9 had similar effect, the minimum values increased to 48% (+14.3%) in zone 7, 51% (+18.6%) in zone 8, and 48% (+14.3%) in zone 9, while the maximum values remained the same.

In Belém, the base variant recorded the following values: The maximum value was 91% all through Zones 6, 7, 8, & 9, while the minimum value was 58% in zones 6 & 7, and 60% in zones 8 & 9. For variant 1, minor differences were observed in most of the zones. For zones 6, the maximum value remained the same while the minimum increased to 60% (+3.4%). For zone 7, no difference was recorded in the recorded values. For zone 8, the minimum value increased to 62% (+3.3%) while the maximum remained unaffected. In zone 9, the maximum and minimum values both increased to 92% (+1.1%) and 61% (+1.7%), respectively. For variant 2, the differences were also not significant in most of the zones. In zone 6, the maximum value remained the same while the minimum increased to 59% (+1.7%). For zone 7, no difference was recorded in the recorded values. For zone 8, the minimum value increased to 61% (+1.7%) while the maximum remained unaffected. In zone 9, the maximum value increased to 92% (+1.1%) while the minimum value remained the same. For variant 3, the recorded values were nearly the same as the base variant in most of the zones. For zone 6, the maximum value decreased to 90% (–1.1%) while the minimum remained unaffected. In zone 7, the maximum and minimum values remained the same. In zones 8 & 9, the maximum values remained the same while the minimum values increased to 63% (+5.0%) in zone 8 and 61% (+1.7%) in zone 9.

Furthermore, the recorded values for the GF zones were higher than those of the FF in both selected locations. Also, minimum values were recorded when temperatures in the zones were at the highest point which implies that RH decreased with an increase in temperature and vice versa.

6.3 Zone Operative Temperatures, T_o (°C)

The outcome of the T_o for the base variant and variants 1, 2, and 3 in both Lagos and Belém are presented in Figures 6. 9 – 6. 12. For the GF zones, Lagos recorded a maximum value of 28.3°C and the minimum was 25.5°C for the base variant. Considering the recommended temperature range (22 – 26°C), the recorded values in all the zones were above the range almost throughout the day, however, values within the range were recorded between 02 – 08h. For variants 1, 2, and 3, the maximum values were 28°C (–1.1%), 28.2°C (–0.4%), and 27.6°C (–2.5%), respectively, while the minimum value was 25.2°C (–1.2%) for variants 1 & 2, and 25.1°C (–1.6%) for variant 3. Furthermore, although the recorded values were still above the recommended range in most part of the day, they were seen to fall within the range from 01 – 08h through variants 1, 2, and 3 (Figure 6. 9).

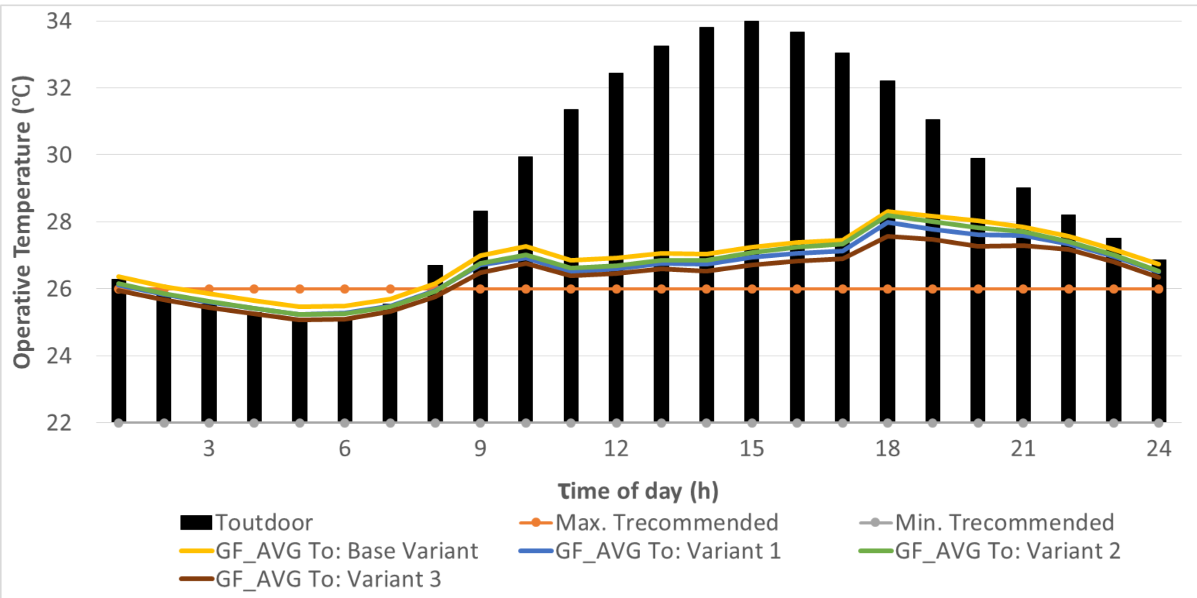

Figure 6. 9: Ground Floor (GF), Operative temperature (Lagos)
Source: Author

For the base variant in Belém, the maximum value was 29.3°C while the minimum was 25.3°C. The values were within the recommended range between 03 – 08h and above the range the rest of the hours of the day. For variants 1, 2, & 3, the maximum values were 27.8°C (–5.1%), 28°C (–4.4%), and 29°C (–1.0%), respectively, while the minimum value was 25.1°C

(–0.8%) for variants 1 & 2 and 25°C (–1.2%) for variant 3. The values were seen to fall within the recommended range from 01 – 08h through variants 1, 2, and 3 and above the range in the rest of the hours of the day (Figure 6. 10).

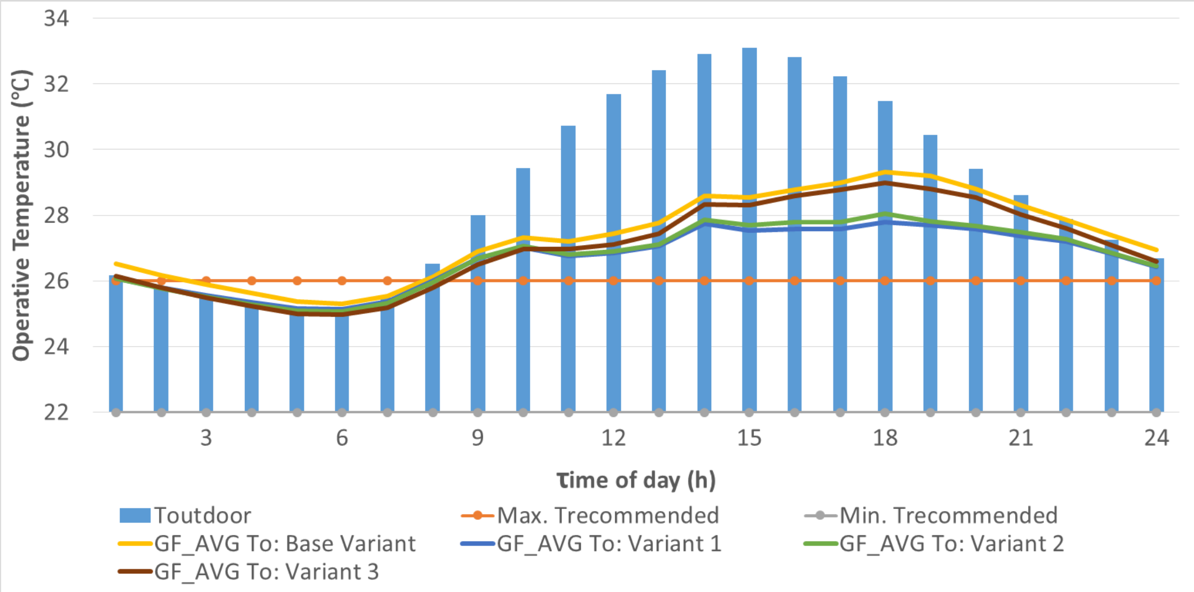

Figure 6. 10: Ground Floor (GF), Operative temperature (Belém)
Source: Author

Evaluating the T_o in individual zones of the GF (see Tables B. 1 & B. 2 and Figures B. 33 – B. 40 in Appendix B), in Lagos, the base variant recorded the following values: Zone 1 recorded a maximum value of 27.7°C while the minimum was 25.6°C. For zone 2, the maximum value was 29°C with a minimum of 25.4°C. For zone 4, the maximum value was 28.5°C and the minimum was 25.4°C. While for zone 5, the maximum value was 28.7°C with a minimum of 25.3°C. For variant 1, minor changes were recorded in the zones where the insulation material was inserted. In zone 1, the maximum and minimum values both decreased to 27.4°C (–1.1%) and 25.3°C (–1.2%). For zones 2, the maximum and minimum values were 28.6°C (–1.4%) and 25.1°C (–1.2%), respectively. While for zone 5, the maximum and minimum values were 28.4°C (–1.0%) and 25°C (–1.2%), respectively. There was no noticeable difference recorded in zone 4 (with no insulation material), the maximum value decreased to 28.4°C (–0.4%) while the minimum value remained the same. For variant 2, minor differences were also observed in the zones where the insulation material was inserted. In zone 1, the maximum and minimum values both decreased to 27.5°C (– 0.7%) and 25.3°C (– 1.2%), respectively. For zones 2 and 5, the minimum values respectively decreased to 25.1°C (–1.2%) and 25°C (–1.2%) but the maximum values remained unchanged. There was no effect recorded in zone 4 (with no insulation material), the maximum and minimum values remained the same throughout the day. For variant 3, a notable difference was also recorded in all the zones with the insulation material. For zone 1, the maximum and minimum values decreased to 27.2℃ (– 1.8%) and 25.1℃ (– 2.0%). For zones 2, the maximum and minimum values were 28.2℃ (– 2.8%) and 24.9℃ (–2.0%). While for Zone 5, the maximum value was 28.1℃ (–2.1%), with a minimum of 24.9℃ (–1.6%). Zone 4 (with no insulation material) recorded a maximum value of 27.9℃ (–2.1%) and a minimum of 25.2℃ (–0.8%).

In Belém, the base variant recorded the following values: Zone 1 recorded a maximum value of 29.4℃ while the minimum was 25.6℃. For zone 2, the maximum value was 29.9℃ with a minimum of 25.3℃. For zone 4, the maximum value was 30.2℃ and the minimum was 25.2℃. While in zone 5, the maximum value was 29.1℃ with a minimum of 25.1℃. For variant 1, there was a significant difference in the zones where the insulation material was applied. For zone 1, the maximum and minimum values both decreased to 27.6℃ (–6.1%) and 25.3℃ (–1.2%), respectively. For zone 2, the maximum value was 27.9℃ (–6.7%), while the minimum was 25℃ (–1.2%). In zone 5, the maximum value was 27.5℃ (–5.5%) and the minimum 24.9℃ (–0.8%). There was no significant difference recorded in zone 4 (with no insulation material), the maximum and minimum values were 30.1℃ (–0.3%) and 25.1℃ (– 0.4%), respectively. For variant 2, a significant difference was also observed in the zones where the insulation material was inserted. In zone 1, the maximum and minimum values both decreased to 27.7℃ (–5.8%) and 25.2℃ (–1.6%), respectively. For zone 2, the maximum value was 28.3℃ (–5.4%) while the minimum was 24.9℃ (–1.6%). In zone 5, the maximum and minimum values were 27.8℃ (–4.5%) 24.8℃ (–1.2%), respectively. In zone 4 (with no insulation material), the difference was barely noticeable, the maximum and minimum values were 30.1℃ (–0.3%) and 25.1℃ (–0.4%), respectively. For variant 3, there were minor differences in all the zones with the insulation material. In zone 1, the maximum and minimum values both decreased to 29.1℃ (–1.0%) and 25.1℃ (–2.0%), respectively. For zone 2, the maximum value was 29.6℃ (–1.0%) with a minimum of 24.7℃ (–2.4%). In zone 5, the maximum value was 28.8℃ (–1.0%) and the minimum was 24.7℃ (–1.6%). Similarly, there was no significant difference recorded in zone 4 (with no insulation material), the maximum and minimum values were 30.1℃ (–0.3%) and 25.1℃ (–0.4%), respectively.

For the FF zones, the recorded values were above the recommended range throughout the day in both selected locations. In Lagos, the base variant recorded a maximum value of 33.9℃, while the minimum was 26.6℃. For variant 1, the maximum and minimum values both decreased to 33.8℃ (-0.3%) and 26.5℃ (-0.4%), respectively. For variant 2, the maximum value increased to 34.2℃ (+0.9%) while the minimum value decreased to 26.4℃ (-

0.8%). For variant 3, the maximum value decreased to 31.6℃ (-6.8%) while the minimum value increased to 26.8℃ (+0.8%). Also, despite the decrease recorded, the values in all the three variants were still above the recommended range throughout the day (Figure 6. 11).

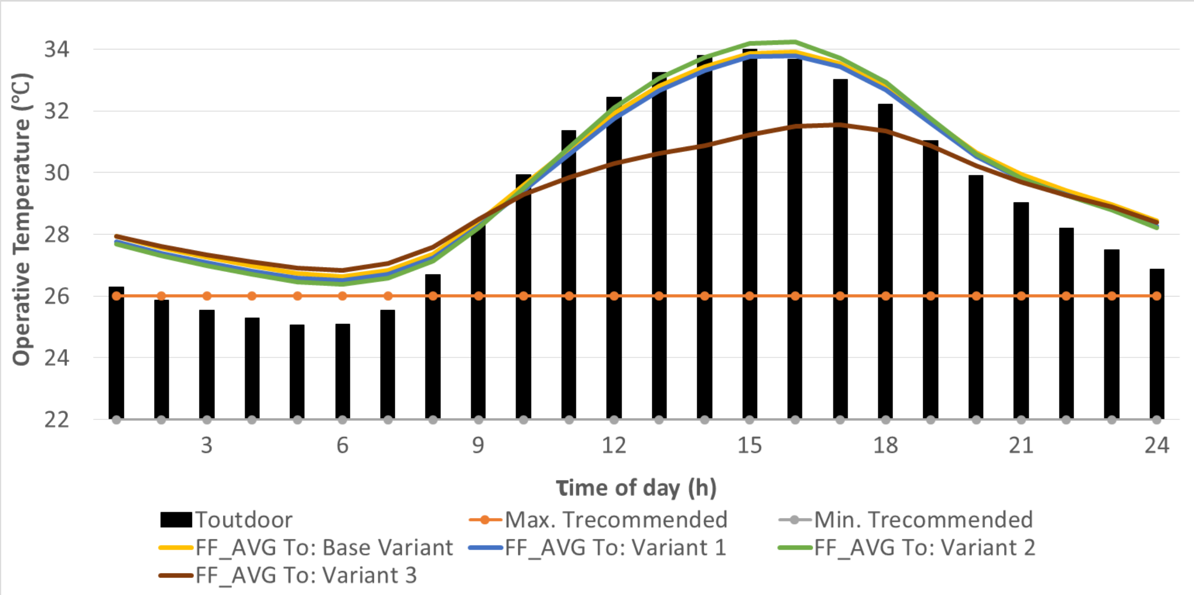

Figure 6. 11: First Floor (FF), Operative temperature (Lagos)
Source: Author

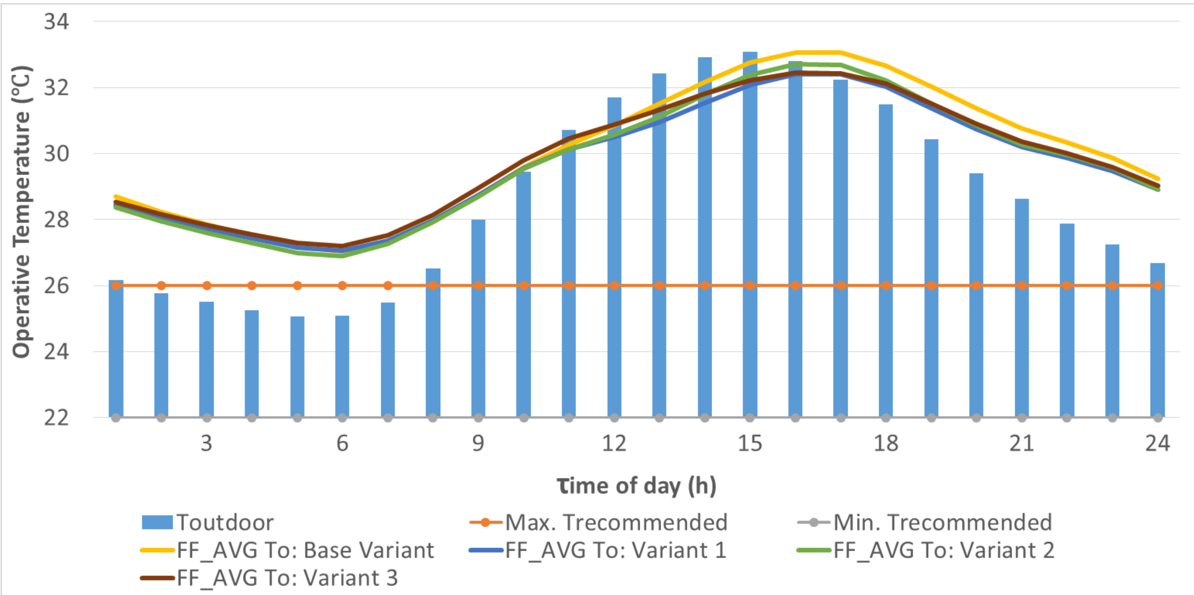

Figure 6. 12: First Floor (FF), Operative temperature (Belém)
Source: Author

In Belém, the base variant had a maximum value of 33.1℃ while the minimum was 27℃ (Figure 1). For variant 1, the maximum value decreased to 32.4℃ (–2.1%) while the minimum value increased to 27.1℃ (+0.4%). For variant 2, the maximum and minimum values both decreased to 32.7℃ (–1.2%) and 26.9℃ (–0.4%), respectively. For variant 3, the maximum value decreased to 32.4°C (–2.1%) while the minimum value increased to 27.2°C (+0.7%). Similarly, the values in all three variants were above the recommended range throughout the day (Figure 6. 12).

Based on the T_o recorded in individual zones of the FF (see Tables B. 1 & B. 2 and Figures B. 41 – B. 48 in Appendix B), the base variant in Lagos recorded the following values: Zone 6 recorded a maximum value of 34.1°C with a minimum of 26.7°C. For zone 7, the maximum value was 34.5°C while the minimum was 26.6°C. For zone 8, the maximum value was 33.3°C with a minimum of 26.6°C. While in zone 9, the maximum value was 33.8°C while the minimum was 26.7°C. For variant 1, minor differences were recorded in all the zones. For zone 6, the maximum and minimum values decreased to 34°C (–0.3%) and 26.5°C (–0.7%), respectively. For zones 7, the maximum value was 34.4°C (–0.3%) while the minimum was 26.4°C (–0.8%). In zone 8, the maximum and minimum values were 33.2°C (–0.3%) and 26.5°C (–0.4%), respectively. While in zone 9, the maximum value was 33.7°C (–0.3%) and the minimum was 26.5°C (–0.7%). For variant 2, the insulation material had a negative effect on the T_o in all the zones. In zone 6, the maximum value increased to 34.3°C (+0.6%), while the minimum value decreased to 26.4°C (–1.1%). For zones 7, the maximum value increased to 35°C (+1.4%) and the minimum value decreased to 26.3°C (–1.1%). While for zones 8 and 9, the maximum values increased to 33.7°C (+1.2%) and 34.1°C (+0.9%), respectively, then the minimum values decreased to 26.4°C (–0.8%) in zone 8 and 26.4°C (–1.1%) in zone 9. For variant 3, a significant difference was observed in all the zones, especially during the day. Zones 6 and 7 recorded maximum values of 31.5°C (–7.6%) and 33°C (–4.3%) while the minimum values increased to 26.9°C (+0.7%) and 27°C (+1.5%), respectively. In zone 8, the maximum value was 30.4°C (–8.7%) while the minimum value remained the same. While in zone 9, the maximum value decreased to 31.4°C (–7.1%) but the minimum value increased to 26.9°C (+0.7%).

In Belém, the base variant recorded the following values: Zone 6 recorded a maximum value of 33.3°C with a minimum of 27.1°C. For zone 7, the maximum value was 33.7°C while the minimum was 27°C. For zone 8, the maximum value was 32.5°C with a minimum of 26.8°C. While in zone 9, the maximum value was 32.9°C while the minimum was 27.3°C. For variant 1, noticeable differences were recorded in all the zones. For zones 6 & 7, the maximum values decreased to 32.6°C (–2.1%) and 33.1°C (–1.8%), respectively, while the minimum values remained the same. In zone 8, the maximum value decreased to 31.8°C (–2.2%) while the minimum increased to 26.9°C (+0.4%). In zone 9, the maximum and minimum values both decreased to was 32.3°C (–1.8%) and 27.2°C (–0.4%), respectively. For variant 2, there were minor differences observed in all the zones. In zone 6, the maximum and minimum values decreased to 32.8°C (–1.5%) and 26.9°C (–0.7%), respectively. For zone 7, the maximum value was 33.5°C (–0.6%) while the minimum was 26.8°C (–0.7%). In zone 8, the maximum value was 32.1°C (–1.2%) while the minimum remained the same. In zone 9, the maximum and minimum values were 32.7°C (–0.6%) and 27.1°C (–0.7%), respectively. For variant 3, the differences were not significant in all the zones. In zones 6 & 7, the maximum values respectively decreased to 32.9°C (–1.2%) and 33.4°C (–0.9%), while the minimum value increased to 27.3°C (+0.7%) in zone 6 and 27.3°C (+1.1%) in zone 7. In zone 8, the maximum value was 31.4°C (–3.4%) while the minimum value remained unaffected. In zone 9, the maximum value decreased to 32.3°C (–1.8%) while the minimum increased to 27.4°C (+0.7%).

Furthermore, in Lagos, variants 1 and 2 showed more influence for zones on the GF than the zones on the FF, while for variant 3, the effect was more evident on the zones of the FF than the zones on the GF. For Belém, the influence was more significant for zones on the GF than the zones on the FF across variants 1, 2, & 3. Despite the effect of the insulation material, the T_o in both Lagos and Belém was still above the recommended range in most part of the day, especially for the FF zones.

Based on the behavior of the insulation material in individual zones, in Lagos, it was observed that for the GF, zones 2 & 5 whose façades were facing north-east and south-east direction respectively, had the highest effect, while for the FF, zones 6 & 8 whose façades were facing north-west and south-west direction respectively, had the highest effect in terms of both the mean air & operative temperatures and the corresponding air relative humidity. In Belém, zones 1 & 2 whose façades were facing north-east and north-west direction respectively, had the highest influence on the GF, while for the FF, zones 6 & 8 whose façades were respectively facing north-west and south-west direction had the highest effect in terms of both the mean air & operative temperatures and the corresponding air relative humidity.

The variation in the behavior of the insulation material in individual zones implies that its performance depends mainly on the position and orientation of each zone in buildings alongside other internal loads associated with the zones. Also, comparing the outcome of the T_m, RH, and T_o in terms of thermal comfort improvement, it can be considered that the proposed insulation material demonstrated more significance in Lagos than in Belém. Based on the examined parameters, a summary of the approximate values and the corresponding percentage differences in both selected locations are summarized in Tables 6. 1 & 6. 2.

Output Variables		Base Variant		Variant 1		Variant 2		Variant 3	
		Max	Min	Max	Min	Max	Min	Max	Min
GF	T_m (°C)	29.6	25.2	29.3 (-1.0%)	25.1 (-0.4%)	29.5 (-0.3%)	25.1 (-0.4%)	28.8 (-2.7%)	25.1 (-0.4%)
	RH (%)	69	56	69 (0.0%)	56 (0.0%)	69 (0.0%)	56 (0.0%)	70 (+1.4%)	57 (+1.8%)
	T_o (°C)	28.3	25.5	28 (-1.1%)	25.2 (-1.2%)	28.2 (-0.4%)	25.2 (-1.2%)	27.6 (-2.5%)	25.1 (-1.6%)
FF	T_m (°C)	33.7	25.3	33.7 (0.0%)	25.3 (0.0%)	33.9 (+0.6%)	25.2 (-0.4%)	31.6 (-6.2%)	25.3 (0.0%)
	RH (%)	69	42	69 (0.0%)	43 (+2.4%)	69 (0.0%)	42 (0.0%)	69 (0.0%)	48 (+14.3%)
	T_o (°C)	33.9	26.6	33.8 (-0.3%)	26.5 (-0.4%)	34.2 (+0.9%)	26.4 (-0.8%)	31.6 (-6.8%)	26.8 (+0.8%)

Table 6. 1: Summary of recorded values on each floor (Lagos)
Source: Author

Output Variables		Base Variant		Variant 1		Variant 2		Variant 3	
		Max	Min	Max	Min	Max	Min	Max	Min
GF	T_m (°C)	30.2	25.2	28.8 (-4.6%)	25.1 (-0.4%)	29 (-4.0%)	25.1 (-0.4%)	29.8 (-1.3%)	25.1 (-0.4%)
	RH (%)	92	69	93 (+1.1%)	76 (+10.0%)	93 (+1.1%)	76 (+10.0%)	93 (+1.1%)	71 (+2.9%)
	T_o (°C)	29.3	25.3	27.8 (-5.1%)	25.1 (-0.8%)	28 (-4.4%)	25.1 (-0.8%)	29 (-1.0%)	25 (-1.2%)
FF	T_m (°C)	32.7	25.3	32.3 (-1.2%)	25.3 (0.0%)	32.5 (-0.6%)	25.3 (0.0%)	32.3 (-1.2%)	25.3 (0.0%)
	RH (%)	91	59	91 (0.0%)	60 (+1.7%)	91 (0.0%)	60 (+1.7%)	91 (0.0%)	60 (+1.7%)
	T_o (°C)	33.1	27	32.4 (-2.1%)	27.1 (+0.4%)	32.7 (-1.2%)	26.9 (-0.4%)	32.4 (-2.1%)	27.2 (+0.7%)

Table 6. 2: Summary of recorded values on each floor (Belém)
Source: Author

NB: In Tables 6.1 & 6.2, the values in parenthesis are the percentage differences recorded in relation to the base variants.

6.4 Simulation with HVAC System

A conditioning system was introduced into the models and new sets of simulations were run for all variants. The goal was to evaluate the reduction in the Cooling Load Intensity (CLI) achieved through the utilization of the insulation material in each of variants 1, 2, and 3 with reference to the base variant in both selected locations. Natural ventilation was disabled throughout the day in the conditioned zones. The system was programmed to maintain a maximum indoor temperature set point of 26°C in the buildings and the amount of energy needed to retain the setpoint was calculated in both selected locations (Figure 6. 13). Also, the cost in $/kW based on the tariff charges in the selected cities (@ US $0.076/kW in Lagos and US $0.12/kW in Belém) was registered to further determine the tariff savings gained in each of variants 1, 2, and 3, as related to the base variants (Figure 6. 14).

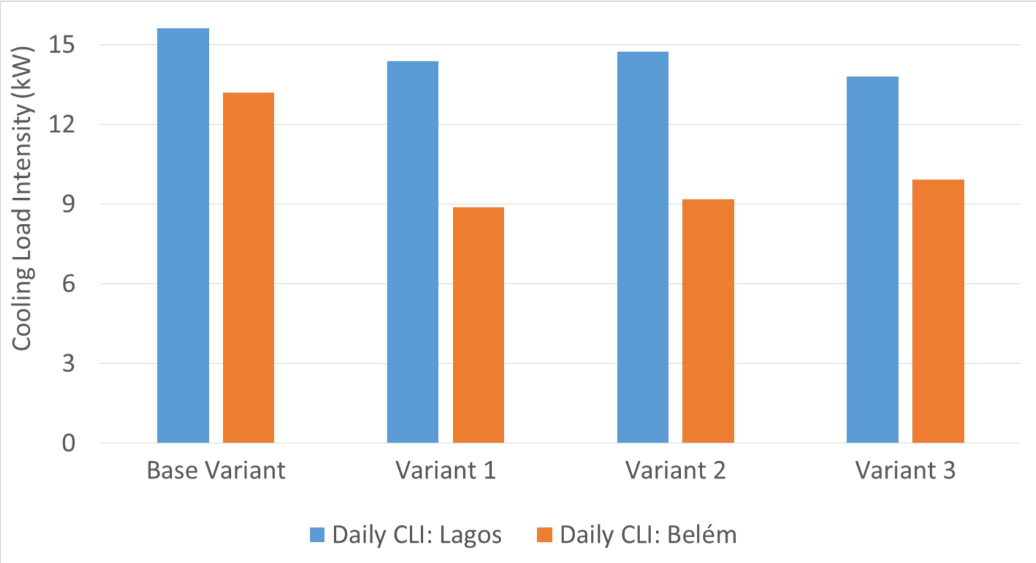

Figure 6. 13: Daily cooling load intensity (Daily CLI) (Lagos & Belém)
Source: Author

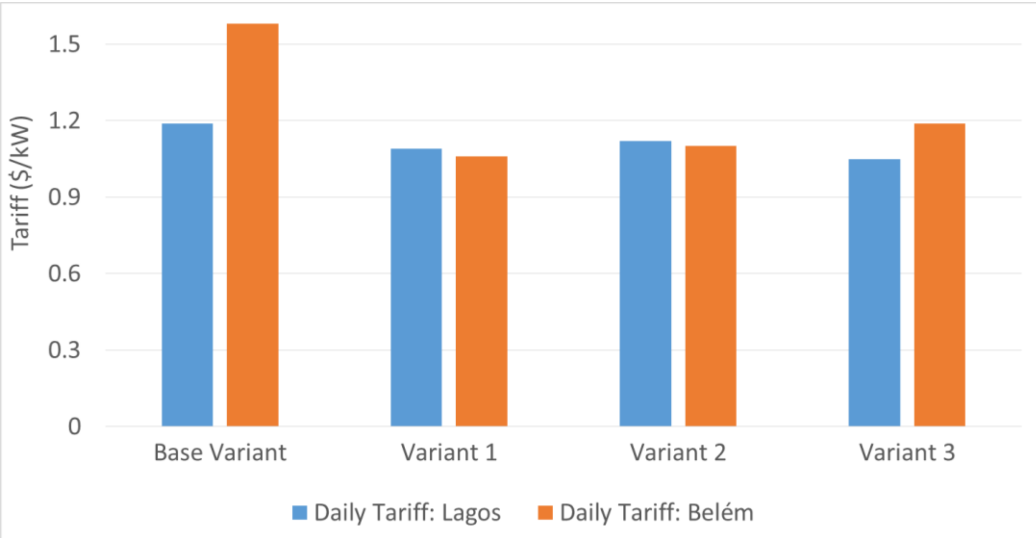

Figure 6. 14: Daily tariff (Lagos & Belém)
Source: Author

From Figure 6. 13 & 6. 14, it can be observed that in Lagos, variant 3, with CLI of 13.80 kW/day and a tariff of 1.05 US $/kW had the highest reduction, while in Belém, the highest reduction was recorded in variant 1 with CLI of 8.87 kW/day and a tariff of 1.06 US $/kW. Comparing the CLI and tariff savings of the two cities with reference to the base variants, it can be observed that the percentage differences were significantly higher in Belém than in Lagos. Thus, in terms of energy consumption reduction, it can be considered that aerogel demonstrated more significance in Belém than in Lagos.

Furthermore, since there is little or no variation in the weather throughout the year in both selected cities (see Figure 5. 1), the calculated CLI and tariff for the summer days were assumed to apply for the whole year and the corresponding annual figures were determined. A summary of the calculated CLI and Tariff for the summer days and the corresponding annual figures in both Lagos and Belém are highlighted in Table 6. 3.

Variants	Location	Daily		Annual		CLI savings (%)	Tariff savings (%)
		CLI (kW)	Tariff ($/kW)	CLI (kW)	Tariff ($/kW)		
Base Variant	Lagos	15.62	1.19	187.44	14.20	0.00	0.00
	Belém	13.20	1.58	158.40	19.01	0.00	0.00
Variant 1	Lagos	14.38	1.09	172.56	13.11	7.94	8.40
	Belém	8.87	1.06	106.44	12.77	32.80	32.90
Variant 2	Lagos	14.72	1.12	176.64	13.42	5.76	5.88
	Belém	9.17	1.10	110.04	13.20	30.50	30.40
Variant 3	Lagos	13.80	1.05	165.60	12.59	11.65	11.76
	Belém	9.93	1.19	119.16	14.30	24.80	24.70

Table 6. 3: Summary of calculated cooling load intensity & tariff (Lagos & Belém)
Source: Author

6.5 Limitations of the study and possible future research

a) The current study adopted a 2-story typical residential building to represent the selected regions and the approach view of the designed models were all directed to the north. However, further research may be necessary to effectively conclude the performance of the proposed insulation material in the selected locations. Smaller and larger building sizes rendered with aerogel material and with varying orientations need to be examined and compared.

b) Depending on occupants' behavior with energy utilization, the results obtained in this study may differ, thus, to ensure optimum performance of buildings, drills on climate change effect and energy savings benefits should be carried out regularly across building occupants.

c) In Lagos, although the obtained weather data considered for the simulations was modified to suit the climate of the selected location, a more accurate thermal comfort

& energy use prediction and representation may be obtained with the availability of the weather data of the selected location.

d) Lastly, the cost per square meter of the proposed insulation material was not included in this study. This could be evaluated to determine the initial cost and the expected payback period of investing in aerogel insulation in both selected locations with respect to its life cycle in buildings.

7. CONCLUSIONS

This study examined the performance of aerogels in terms of thermal comfort improvement and energy consumption reduction against the conventional materials utilized in constructing residential buildings in Lagos, Nigeria, and Belém-Pará, Brazil. This was carried out through modeling and computational building energy simulations, considering the climates in each selected location.

Based on the study, it was recorded that the building sector alone is responsible for almost 40% of the world's total energy consumption with an anticipation of a continuous increase. This signifies that there is a need to explore various strategies that could reduce the energy demand of buildings alongside the consideration of alternative sources to boost energy supply if demands are to be fully met. To tackle this, the adoption of energy efficiency culture through insulation materials is seen to be the optimal solution. One of the most outstanding materials for insulation is aerogel since it has the lowest thermal conductivity when compared to other insulation materials. It also has a wide range of possible applications in building as it can be produced in various forms. The performance of aerogel in this study was examined through a typical residential building design comparable to both selected locations. The designs were first modeled with common conventional materials utilized in each selected location as base variants. Then they were later modified by including aerogel blanket on various surfaces of the models. Major parameters that influence indoor environmental quality were measured through building energy simulations and the results obtained in both cities were compared to standard recommended values. Also, their corresponding energy consumption and tariff charges are reported.

The outcome of the simulations showed that in Lagos, the proposed insulation material had the highest influence when inserted in the attic and floor slabs of the designed model (variant 3), while in Belém, the insulation material had the highest significance when inserted on the external façades of the designed model (variant 1). The following conclusions were drawn based on the examined output variables:

a) Concerning the mean air temperature, with reference to the base variants, a reduction of about 2.7% for zones on the ground floor and up to 6.2% for zones on the first floor was attained in Lagos. For Belém, the reduction was approximately 1.2% for zones on the first floor and up to 4.6% for zones on the ground floor. Also, in both selected locations, the T_m recorded on the FF zones was higher than that of the GF zones especially in the middle of the day and this can be linked to the effect of solar radiation on the FF zones within this period.

b) For the air relative humidity, the recorded values were within the recommended range nearly throughout the day in Lagos, while in Belém, the values were above the recommended range virtually throughout the day. Also, the application of the insulation material slightly increased the recorded values. However, the increase may have little or no difference to the thermal comfort within the buildings since a slight increase in relative humidity has a limited impact on thermal sensation. In addition, maximum RH values were recorded when the temperatures in the zones were at the minimum level. This signifies that relative humidity decreases with an increase in temperature and vice versa.

c) For the corresponding operative temperature, as related to the base variants, a decrease of about 2.5% for zones on the ground floor and up to 6.8% for zones on the first floor was achieved in Lagos. For Belém, the reduction was between 2.1% for zones on the first floor and up to 5.1% for zones on the ground floor. However, despite the decrease in the recorded values due to the effect of the insulation material, the operative temperature was still above the recommended range nearly throughout the day in both selected locations especially for zones on the first floor.

Comparing the overall outcome of the simulations in terms of thermal comfort improvement, it can be concluded that aerogel had more significance in Lagos than in Belém. Further on, with the introduction of the HVAC system into the designed models, variant 3 and variant 1 still had the highest reduction of energy consumption in Lagos and Belém, respectively. With respect to the base variants, the cooling load intensity and tariff decreased to more than 11% in Lagos, while in Belém, the decrease was almost 33%. Comparing the overall results of the simulations in terms of energy consumption reduction, it can be concluded that aerogel had more influence in Belém than in Lagos since the percentage savings were significantly higher in Belém.

Furthermore, the variations observed in the behavior of the insulation material to individual zones of the models imply that aerogel's performance depends mainly on the position and orientation of each zone in buildings alongside other internal loads associated with the zones. In addition, the variations may be linked directly to the local construction materials utilized in each location i.e. for thermal comfort improvement, aerogel may be more suitable and compatible with the conventional materials utilized in Lagos than in Belém, while in terms of energy consumption reduction, aerogel may be more fitting in Belém than in Lagos.

Finally, aerogel demonstrated significant potential with respect to both thermal comfort improvement and energy consumption reduction on the designed models. Therefore, this study suggests that its application should highly be considered in both selected locations, for that will reduce energy demand for cooling and in turn improve thermal comfort to building occupants. Also, owing to its exceptional low thermal conductivity feature and the recent advancement in its synthesis process, its demand is expected to increase in the coming years. Several studies are being carried out particularly for building thermal insulations alongside other industrial applications while hoping to identify strategies that could reduce its cost to a comparable rate to its counterparts. The findings in this study provide a stepping-stone for the design and construction of efficient & sustainable residential buildings for tropical climates in Nigeria and Brazil.

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APPENDIX A

Schedules for the main internal loads

The schedules considered for each space in the buildings are summarized below. The value ‘0’ means that there is no occupation or that the lights are on 'OFF' mode and that no equipment is connected, while the value '100' means that 100% of people (occupation) are present, or that the lights are on 'ON' mode and that equipment is in full usage. Since culture and family structure differs, schedules were filled based on the most common occupation pattern found in each selected location, although, some spaces have a similar schedule.

Spaces with a similar schedule pattern are listed below:

a) Entrance Corridor: This is the entrance of the building with no people activities or electrical equipment usage. Lights are on between 05 – 10h and between 17 – 23h on both weekdays and weekends;
b) Access Lobby: This space serves as a connector to other spaces of the building, therefore there is no constant occupation. Lights are on between 05 – 10h and between 17 – 23h on both weekdays and weekends and no electrical equipment usage;
c) Main Living Area: This space accommodates four (4) people. The occupation frequency for the weekdays is 25% between 07 – 09h, 12 – 13h, 17 – 19h, and from 22 – 23h, then it is 50% between 20 – 22h. For the weekends, it’s 25% from 09 – 10h, 20 – 20h, and 22 – 23h, then 50% from 10 – 11h, 14 – 15h, 18 – 19h, and 21 – 22h. It’s 75% between 12 – 13h and 100% from 11 – 12h and 15 – 18h. For the illumination, the lights are on from 07 – 10h and 17 – 23h for both weekdays and weekends. Electrical equipment is on from 07 – 09h, 12 – 13h, 17 – 19h, and 20 – 23h for the weekdays, while for the weekends, it is on from 09 – 13h, 14 – 19h, and 20 – 23h;
d) Main Dining Area: This space is designed to accommodate four (4) people. The occupation frequency for the weekdays is 25% between 07 – 09h, and from 13 – 14h, then it is 50% between 19 – 20h. For the weekends, it’s 25% form 07 – 08h, 09 – 10h, 12 – 13h, 14 – 15h, 18 – 19h, and 20 – 21h, then 50% from 08 – 09h, and 100% from 13 – 14h, and from 19 – 20h. For the illumination, the lights are on from 07 – 10h and 17 – 23h for both weekdays and weekends. Electrical equipment is on throughout the day for both weekdays and weekends;

e) Kitchen: This space is designed to accommodate four (4) people. The occupation frequency for the weekdays is 25% between 06 – 07h, 08 – 10h, 12 – 13h, 18 – 19h, and from 20 – 21h, then it is 50% between 07 – 08h and 19 – 20h. For the weekends, it's 25% from 07 – 08h, 09 – 10h, 18 – 19h, and 20 – 21h, then 50% between 08 – 09h and from 19 – 20h. It's 75% between 12 – 13h. For the illumination, the lights are on from 06 – 10h and 17 – 23h for both weekdays and weekends. Electrical equipment is on throughout the day for both weekdays and weekends;
f) Private Living: This space accommodates four (4) people. The occupation frequency for the weekdays is 25% between 08 – 09h, 14 – 15h, 17 – 19h, and from 22 – 23h, then it is 50% between 07 – 08h and from 21 – 22h. For the weekends, it's 25% from 22 – 23h, then 50% from 07 – 08h, 09 – 12h, 13 – 14h, and 17 – 18h. It's 75% between 14 – 15h and 100% from 15 – 17h. For the illumination, the lights are on from 07 – 10h and 17 – 23h for both weekdays and weekends. Electrical equipment is on from 07 – 09h, 14 – 15h, 17 – 19h, and 20 – 23h for the weekdays, while for the weekends, it is on from 07 – 12h, 13 – 18h, and 20 – 23h;
g) Private Dining: This space is designed to accommodate four (4) people. The occupation frequency for the weekdays is 50% between 07 – 08h and from 11 – 13h, then it is 75% between 08 – 09h and from 20 – 21h and 100% from 19 – 20h. For the weekends, it's 50% from 07 – 08h, 11 – 12h, 13 – 14h, and 18 – 19h, then 75% from 12 – 13h, and between 20 – 21h, and it is 100% from 08 – 09h, and 19 – 20h. For the illumination, the lights are on from 07 – 10h and 17 – 23h for both weekdays and weekends. Electrical equipment is on throughout the day for both weekdays and weekends;
h) Family Living Area: This space accommodates four (4) people. The occupation frequency for the weekdays is 25% between 08 – 09h and from 20 – 21h, then it is 50% from 21 – 22h. For the weekends, it is 25% from 20 – 21h and between 22 – 23h, then 50% from 09 – 11h, and 100% from 21 – 22h. For the illumination, the lights are on from 07 – 10h and 17 – 23h for both weekdays and weekends. Electrical equipment is on from 08 – 09h and 20 – 22h for the weekdays, while for the weekends, it is on from 09 – 11h and 20 – 23h;
i) Guest Toilet: This space accommodates one (1) person. The occupancy and light usage is 100% between 12 – 13h for weekdays and 13 – 14h & 17 – 18h for the weekends, with no electrical equipment usage;
j) Bedroom2: This bedroom is designed to accommodate two (2) people, the frequency of occupation during the weekdays is 100% between 01 – 05h and from 23 – 01h then

50% from 05 – 06h and 21 – 23h, for the weekends, it's 100% between 01 – 07h and from 23 to 01h then 50% from 08 – 09h and 22h – 23h. For the illumination, it's on (100%) between 05 – 06h and 22 – 00h for the weekdays, and between 05 – 07h, 08 – 09h and around 22 – 00h for the weekends. Electrical equipment is used between 05 – 06h and 21 – 23h on weekdays while on the weekends they are used from 05 – 07h, 08 – 09h and between 22 – 23h;

k) Bedroom2 Toilet: This space accommodates one (1) person. The occupancy and light schedule is 100% between 06 – 08h & 21 – 23h for weekdays and 07 – 09h, 12 – 13h & 21 – 23h for the weekends. Electrical equipment usage is 100% between 06 – 08h & 21 – 23h for weekdays and 07 – 09h & 21 – 23h for the weekends.

While spaces with different schedule pattern are:

a) Master Bedroom: This bedroom is designed to accommodate two (2) people in both cities. For Lagos, the frequency of occupation during the weekdays is 100% between 01 – 02h and from 00 – 01h then 50% from 02 – 06h, 21 – 22h and 23 – 00h, for the weekends, it's 100% between 01 – 05h, then 50% from 05 – 07, 22 – 23h and from 00h – 01h. For the illumination, it's on (100%) between 05 – 06h and 21 – 00h for the weekdays, and between 05 – 07h and around 22 – 00h for the weekends. Electrical equipment is used between 05 – 06h and 21 – 00h on weekdays while on the weekends they are used from 05 – 07h and between 22 – 00h. For Belém, the frequency of occupation during the weekdays is 100% between 01 – 06h and from 23 – 01h then 50% from 06 – 07h, and between 21 – 23h, for the weekends, it's 100% between 01 – 07h and from 23 – 01h, then 50% from 07 – 09, and between 22 – 23h. For the illumination, it's on (100%) between 05 – 07h and 21 – 00h for the weekdays, and between 06 – 09h and around 22 – 00h for the weekends. Electrical equipment is used between 05 – 07h and 21 – 00h on weekdays while on the weekends they are used from 06 – 09h and between 22 – 00h;

b) Master Bedroom Toilet: This space accommodates one (1) person in both cities. For Lagos, the occupancy and light schedule is 100% between 06 – 07h & 22 – 23h for weekdays and 07 – 08h, 14 – 15h & 23 – 00h for the weekends. Electrical equipment usage is 100% between 06 – 07h & 22 – 23h for weekdays and 07 – 08h & 22 – 23h for the weekends. For Belém, the occupancy and light schedule is 100% between 06 – 08h & 21 – 23h for weekdays and 07 – 09h, 14 – 15h & 22 – 00h for the weekends.

Electrical equipment usage is 100% between 06 – 08h & 21 – 23h for weekdays and 07 – 09h & 22 – 00h for the weekends;

c) Bedroom 3: For Lagos, This bedroom is designed to accommodate two (2) people, the frequency of occupation during the weekdays is 100% between 01 – 05h and from 23 – 01h then 50% from 05 – 07h and 22 – 23h, for the weekends, it's 100% between 01 – 07h and from 00 to 01h then 50% from 07 – 08 and 23h – 00h. For the illumination, it's on (100%) between 05 – 07h and 22 – 00h for the weekdays, and between 05 – 08h and around 23 – 00h for the weekends. Electrical equipment is used between 05 – 07h and 22 – 23h on weekdays while on the weekends they are used from 05 – 08h and between 23 – 00h. While for Belém, The bedroom is designed to accommodate one (1) person, the frequency of occupation during the weekdays is 100% between 01 – 05h, 06 – 07h and from 22 – 01h, for the weekends, it's 100% between 01 – 08h and from 23 to 01h. For the illumination, it's on (100%) between 06 – 07h and 22 – 00h for the weekdays, and between 06 – 08h and around 23 – 00h for the weekends. Electrical equipment is used between 06 – 07h and 22 – 00h on weekdays while on the weekends they are used from 06 – 08h and between 23 – 00h;

d) Bedroom 3 Toilet: This space accommodates one (1) person in both cities. For Lagos, The occupancy, light, and electrical equipment usage is 100% between 05 – 07h & 21 – 23h for weekdays and 07 – 09h & 22 – 00h for the weekends, while for Belém, it is 100% between 05 – 06h & 21 – 22h for weekdays and 08 – 09h & 22 – 23h for the weekends;

e) Store/laundry: This space accommodates one (1) person. The occupancy and light usage is 100% between 08 – 09h and from 17 – 18h for weekdays and 09 – 10h & 17 – 18h for the weekends, with no electrical equipment usage for Lagos. For Belém, the space serves as a store and a laundry. The occupancy, and light, and electrical equipment usage is 100% between 10 – 11h, and from 17 – 18h for weekdays and 13 – 14h & 17 – 18h for the weekends;

f) Bedroom1: For Lagos, This bedroom is designed to accommodate one (1) person, the frequency of occupation during the weekdays is 100% between 02 – 05h and from 22 – 23h, for the weekends, it's 100% between 05 – 06h and from 00 to 01h. For the illumination, it's on (100%) between 04 – 05h and 22 – 23h for the weekdays, and between 05 – 06h and around 00 – 01h for the weekends. Electrical equipment is used between 04 – 05h and 22 – 23h on weekdays while on the weekends they are used between 05 – 06h. For Belém, the bedroom is designed to accommodate two (2) people, the frequency of occupation during the weekdays is 100% between 01 – 05h and from 23 – 01h then 50% from 05 – 07h, and between 22 – 23h, for the weekends, it's 100% between 01 – 07h and from 22 – 01h, then 50% from 07 – 09, and between 21 – 22h. For the illumination, it's on (100%) between 05 – 07h and 21 – 23h for the weekdays, and between 05 – 09h and around 21 – 23h for the weekends. Electrical equipment is used between 05 – 07h and 22 – 23h on weekdays while on the weekends they are used from 05 – 09h and between 21 – 23h;

g) Bedroom1 Toilet: This space accommodates one (1) person in both cities. For Lagos, The occupancy and light schedule is 100% between 05 – 06h & 23 – 00h for weekdays and 06 – 07h, 13 – 14h & 23 – 00h for the weekends. Electrical equipment usage is 100% between 05 – 06h & 23 – 00h for weekdays and 06 – 07h & 23 – 00h for the weekends. For Belém, The occupancy and light schedule is 100% between 05 – 07h & 21 – 23h for weekdays and 07 – 09h, 12 – 14h, 21 – 22h, and 23 – 00h for the weekends. Electrical equipment usage is 100% between 05 – 07h & 21 – 23h for weekdays and from 07 – 09h, 21 – 22h & between 23 – 00h for the weekends.

APPENDIX B

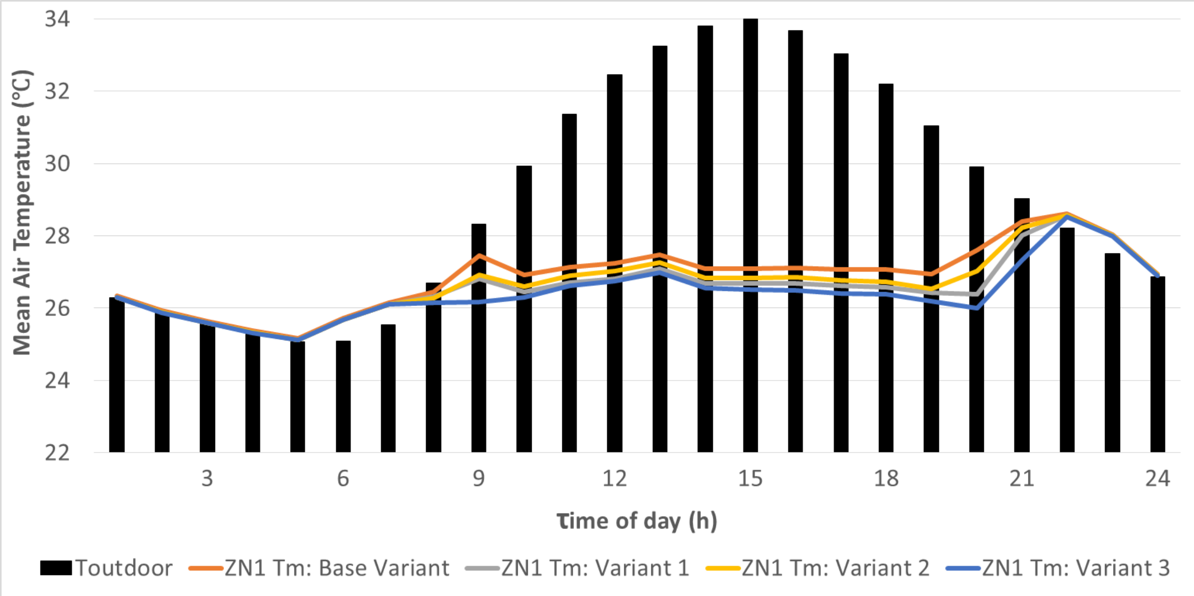

Figure B. 1: Zone 1, Mean air temperature (Lagos)
Source: Author

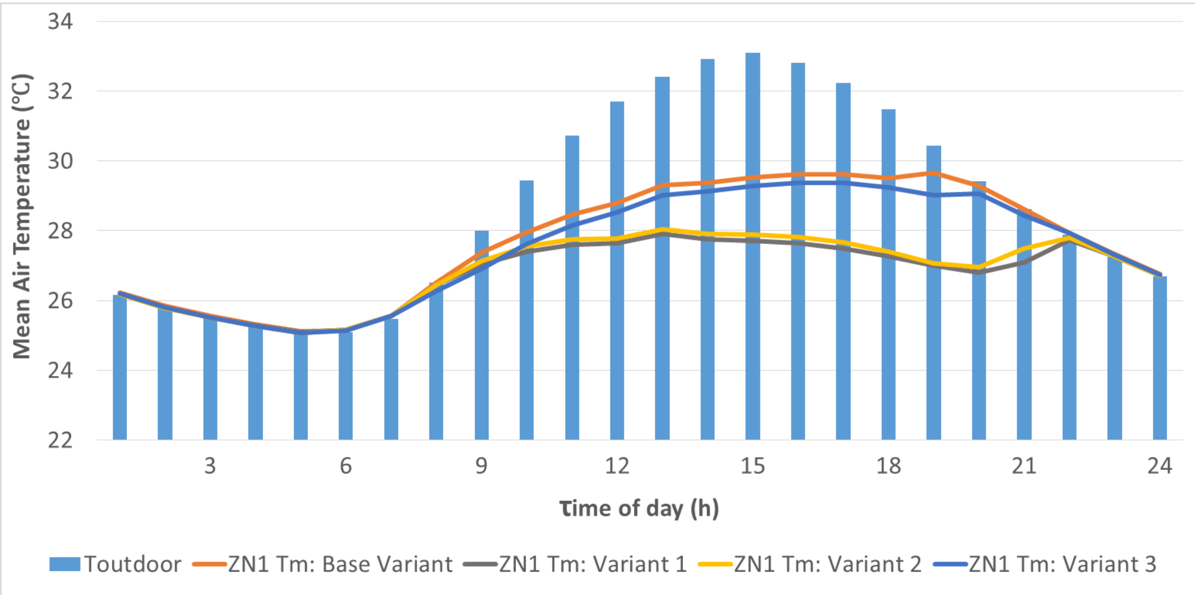

Figure B. 2: Zone 1, Mean air temperature (Belém)
Source: Author

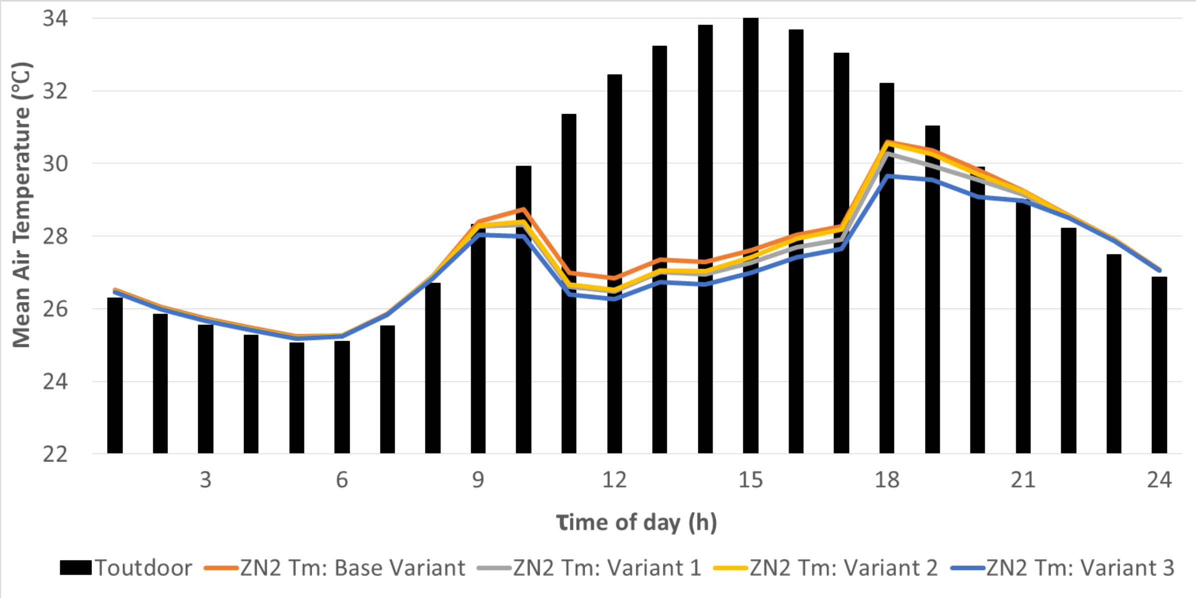

Figure B. 3: Zone 2, Mean air temperature (Lagos)

Source: Author

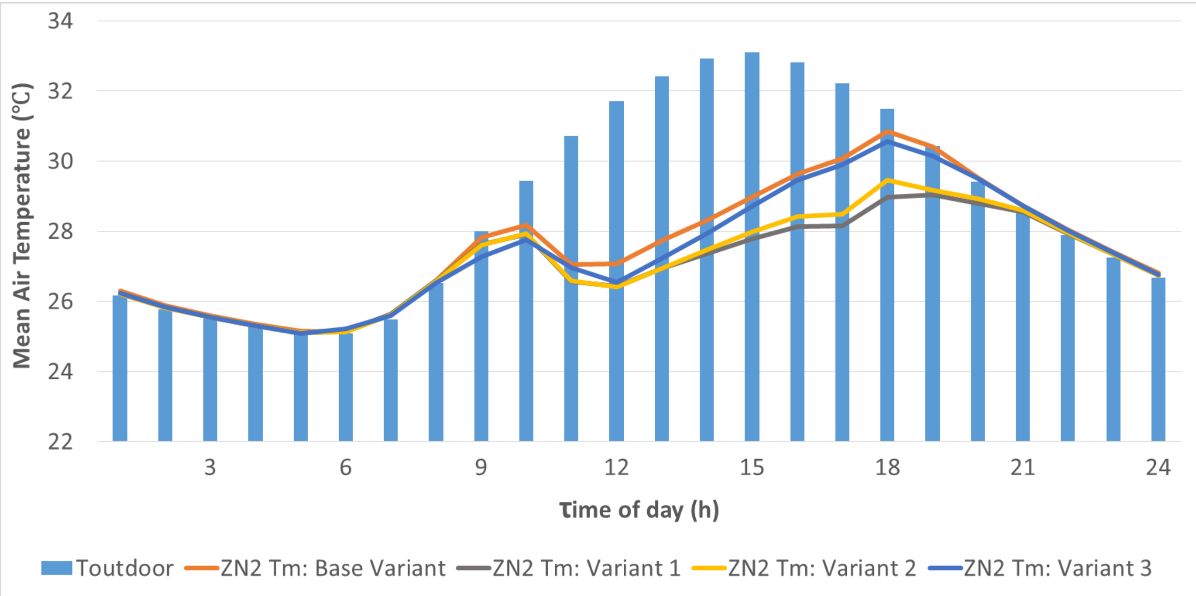

Figure B. 4: Zone 2, Mean air temperature (Belém)

Source: Author

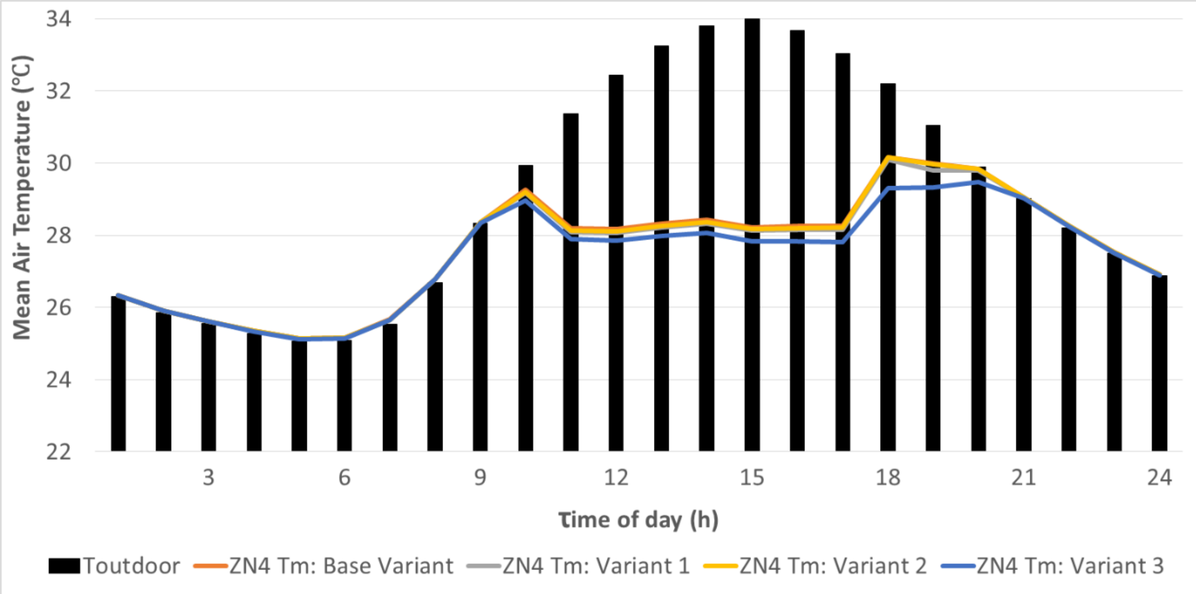

Figure B. 5: Zone 4, Mean air temperature (Lagos)
Source: Author

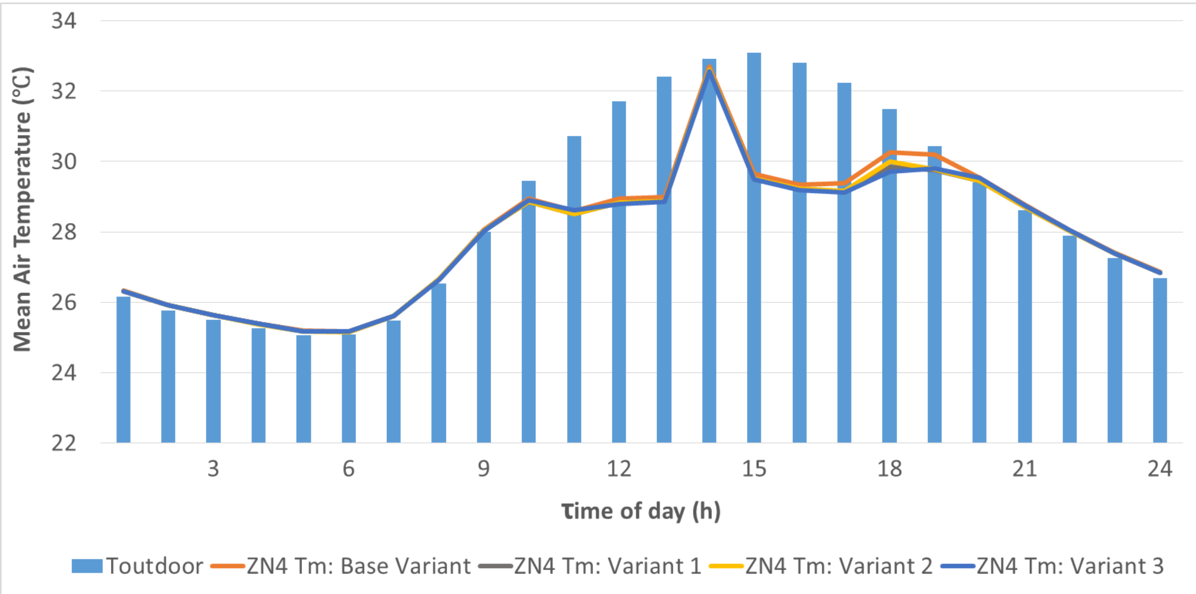

Figure B. 6: Zone 4, Mean air temperature (Belém)
Source: Author

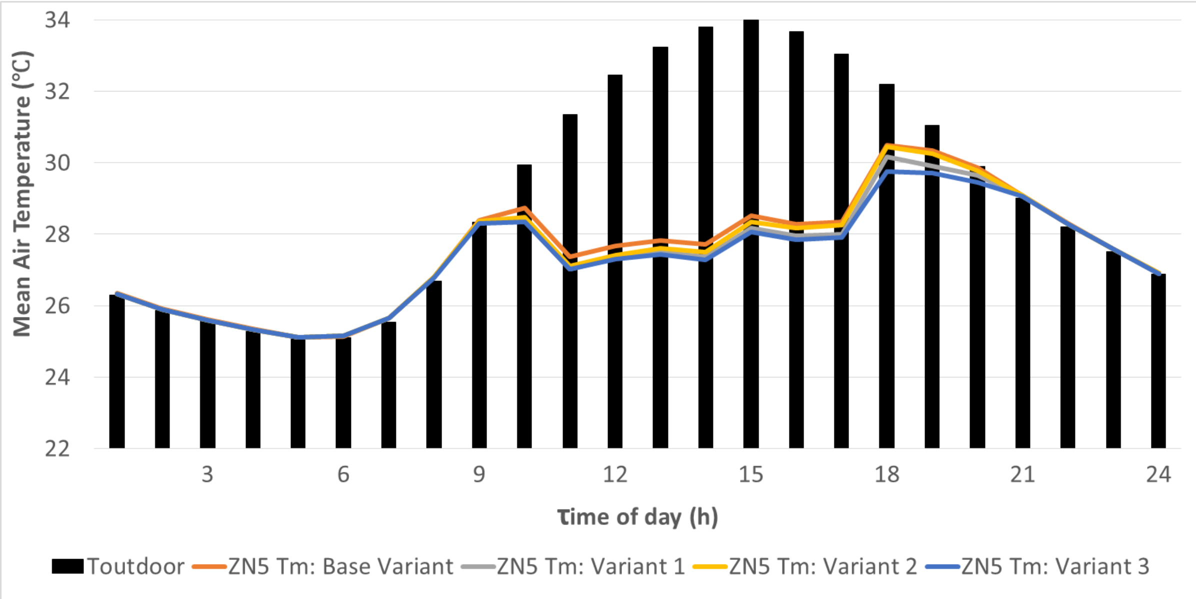

Figure B. 7: Zone 5, Mean air temperature (Lagos)
Source: Author

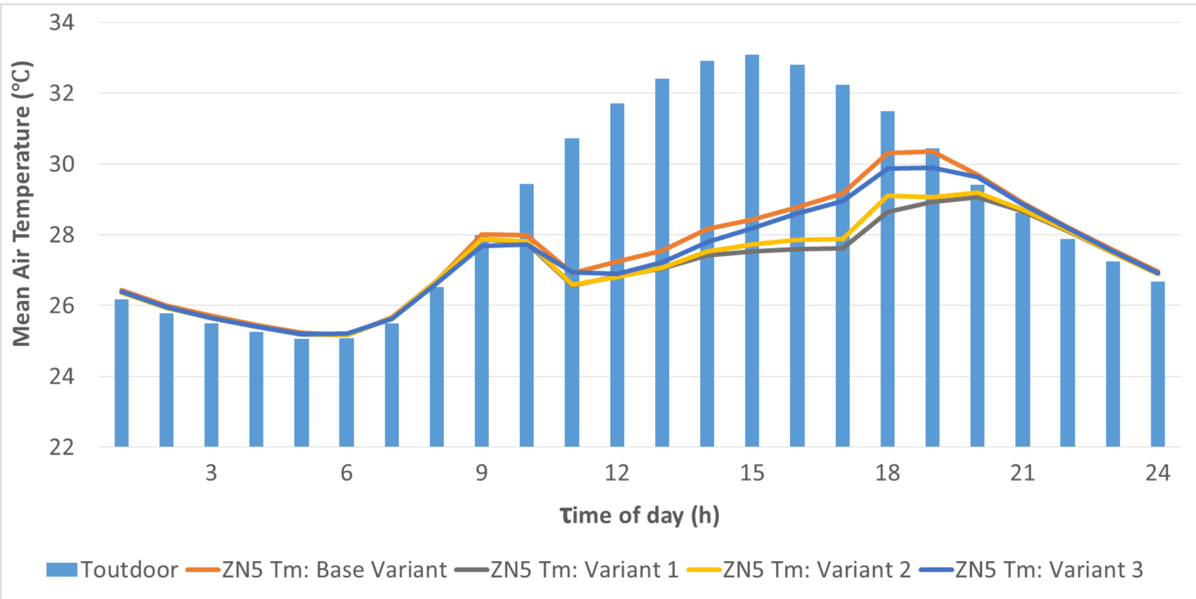

Figure B. 8: Zone 5, Mean air temperature (Belém)
Source: Author

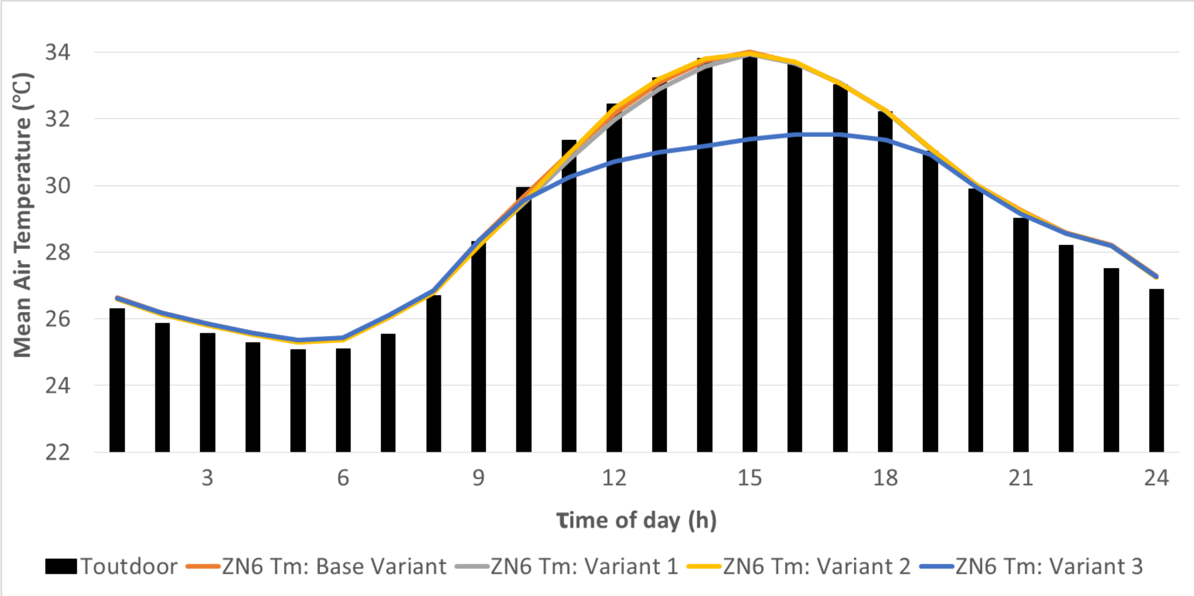

Figure B. 9: Zone 6, Mean air temperature (Lagos)
Source: Author

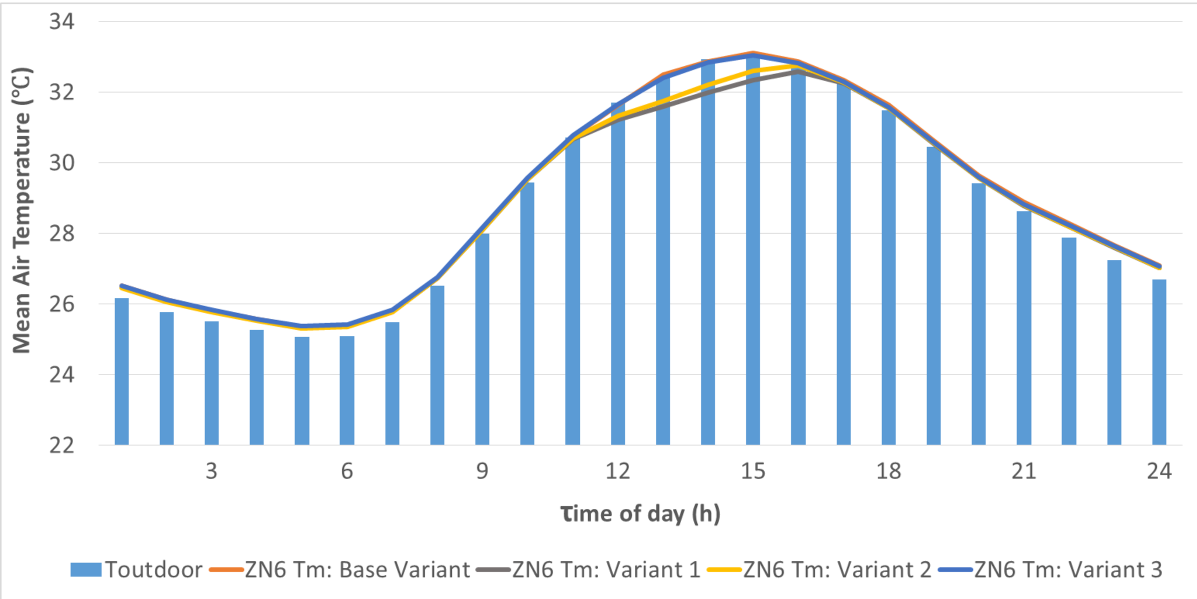

Figure B. 10: Zone 6, Mean air temperature (Belém)
Source: Author

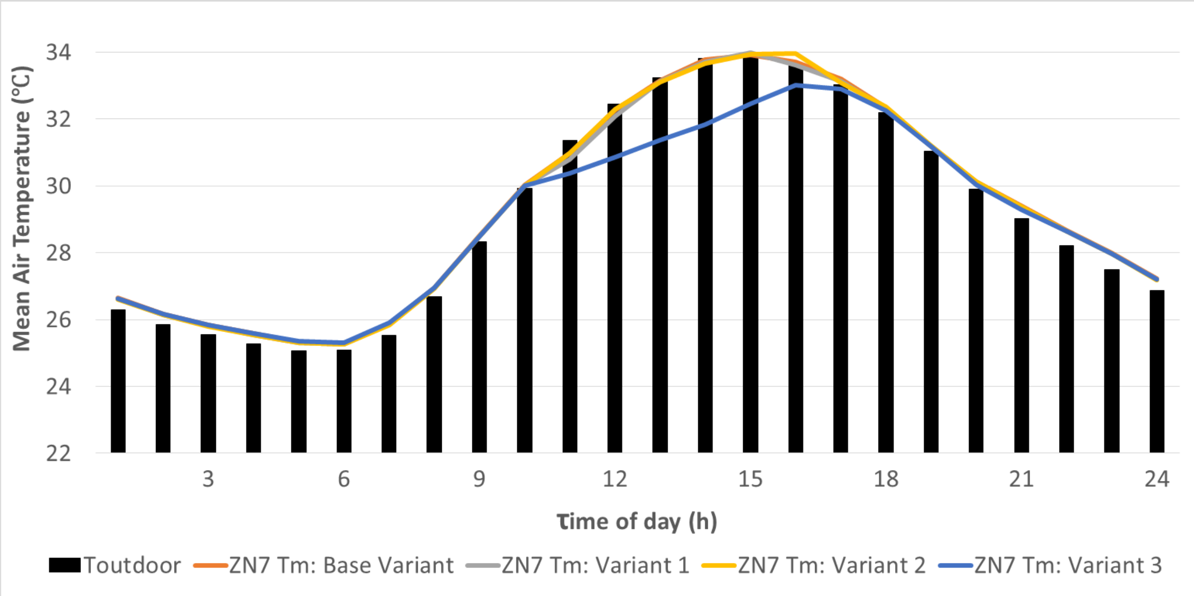

Figure B. 11: Zone 7, Mean air temperature (Lagos)

Source: Author

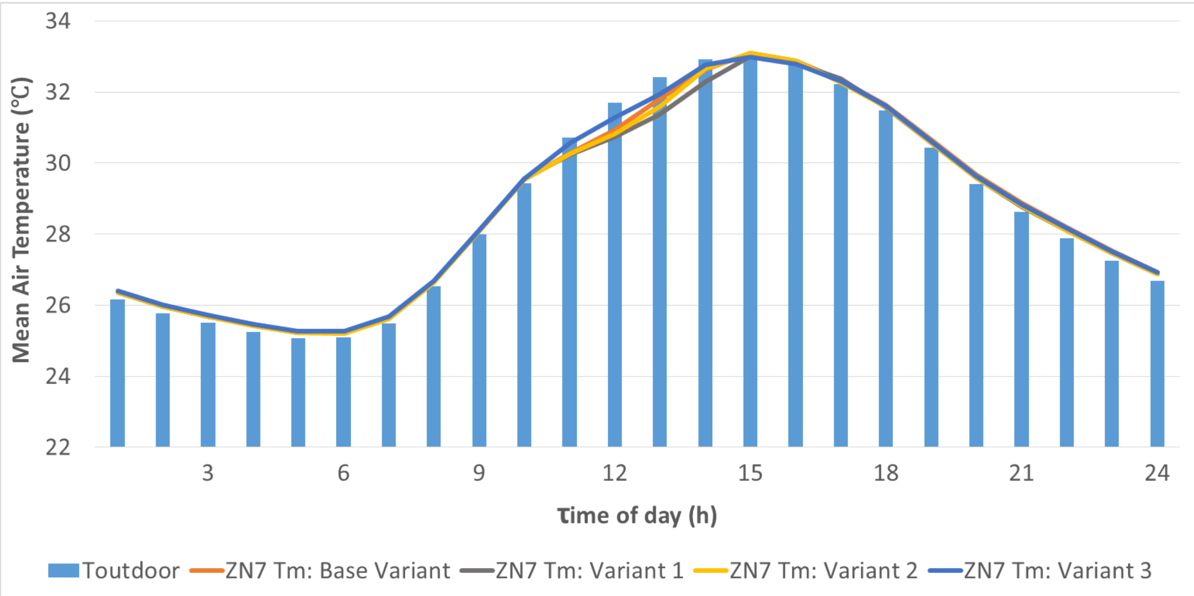

Figure B. 12: Zone 7, Mean air temperature (Belém)

Source: Author

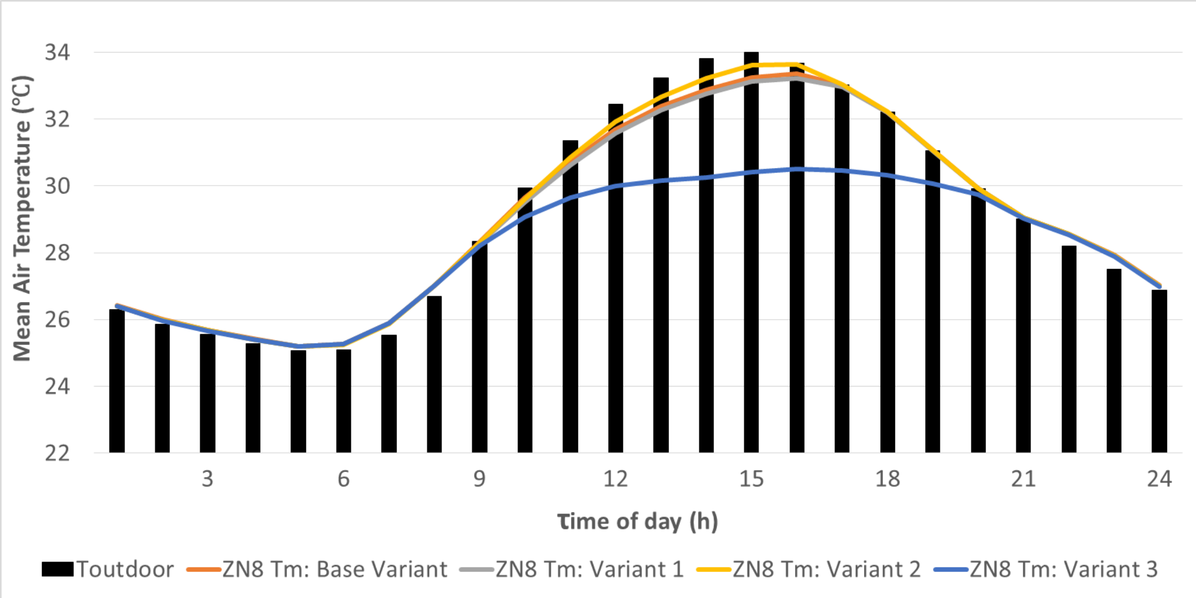

Figure B. 13: Zone 8, Mean air temperature (Lagos)

Source: Author

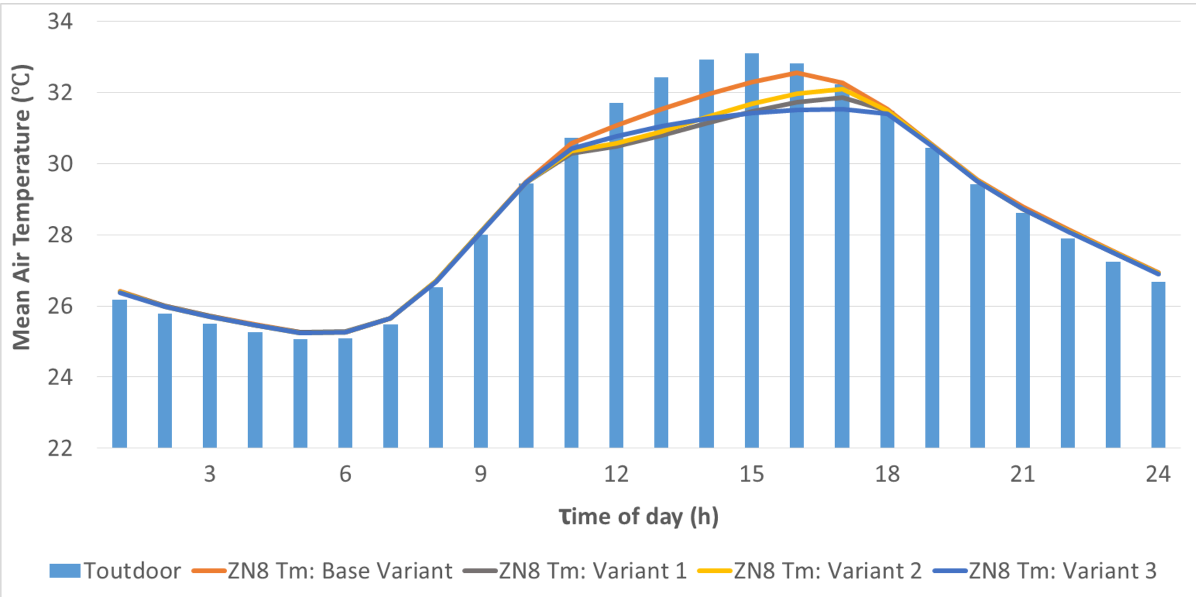

Figure B. 14: Zone 8, Mean air temperature (Belém)

Source: Author

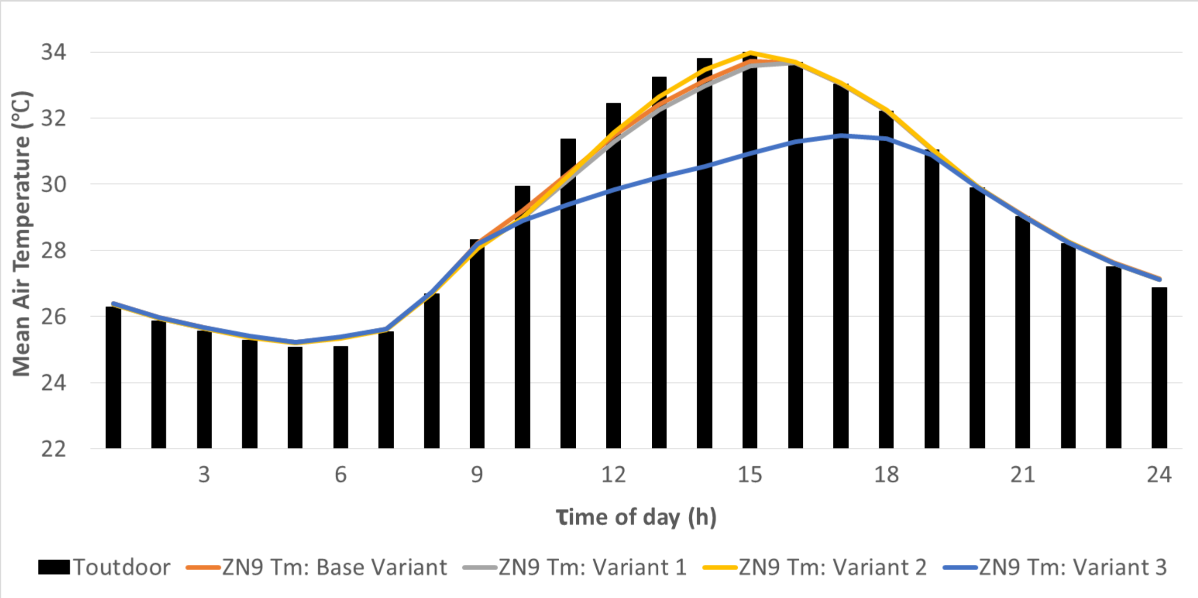

Figure B. 15: Zone 9, Mean air temperature (Lagos)

Source: Author

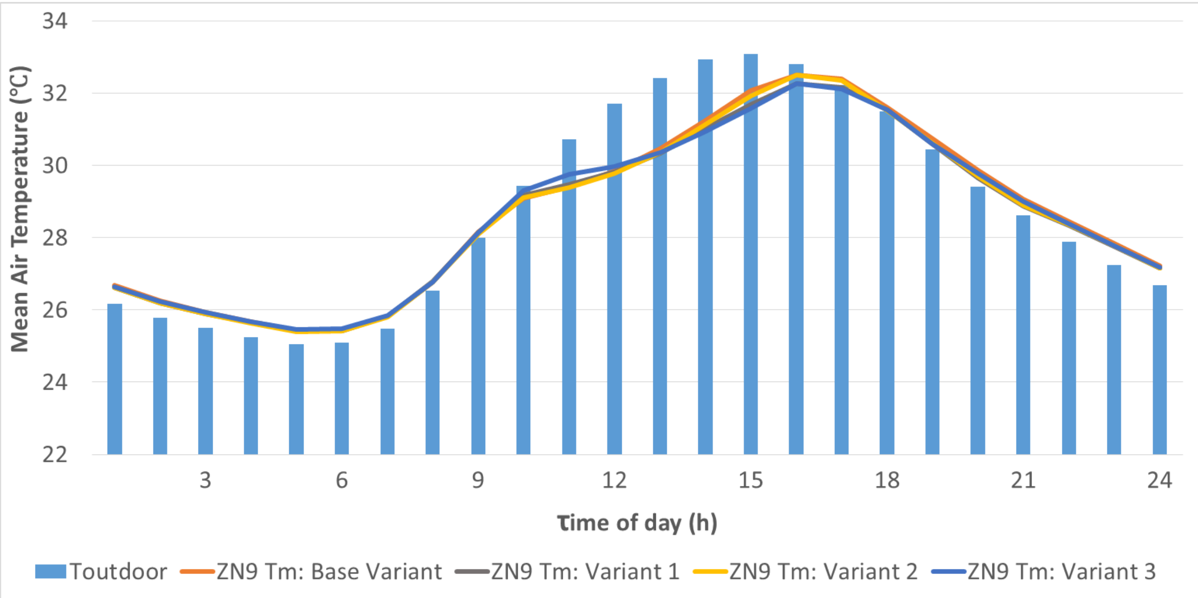

Figure B. 16: Zone 9, Mean air temperature (Belém)

Source: Author

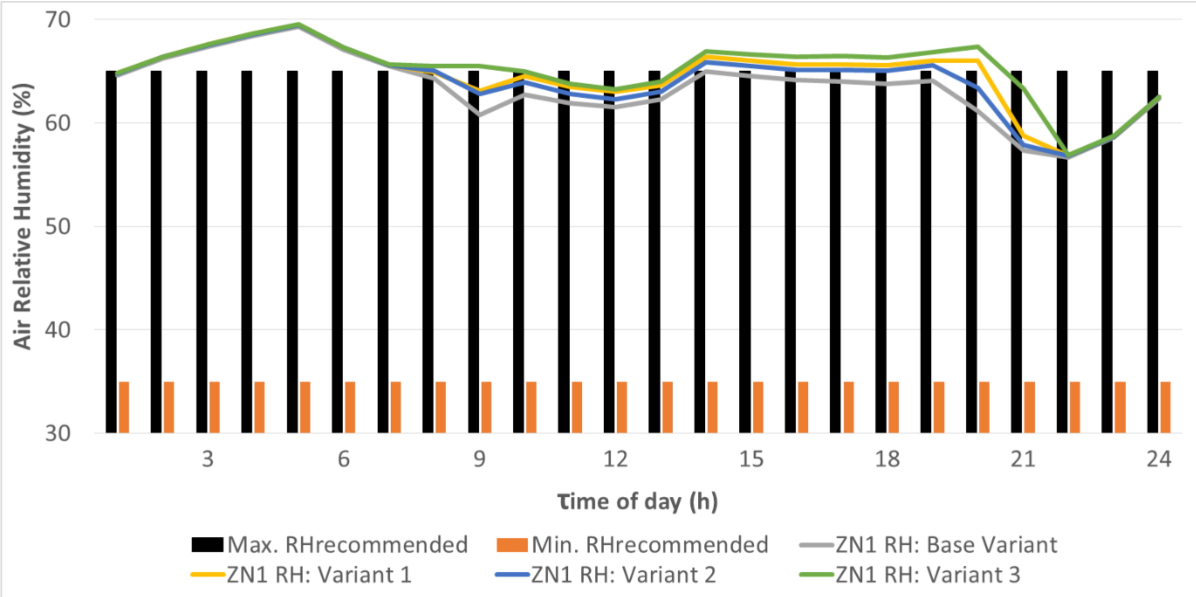

Figure B. 17: Zone 1, Air relative humidity (Lagos)

Source: Author

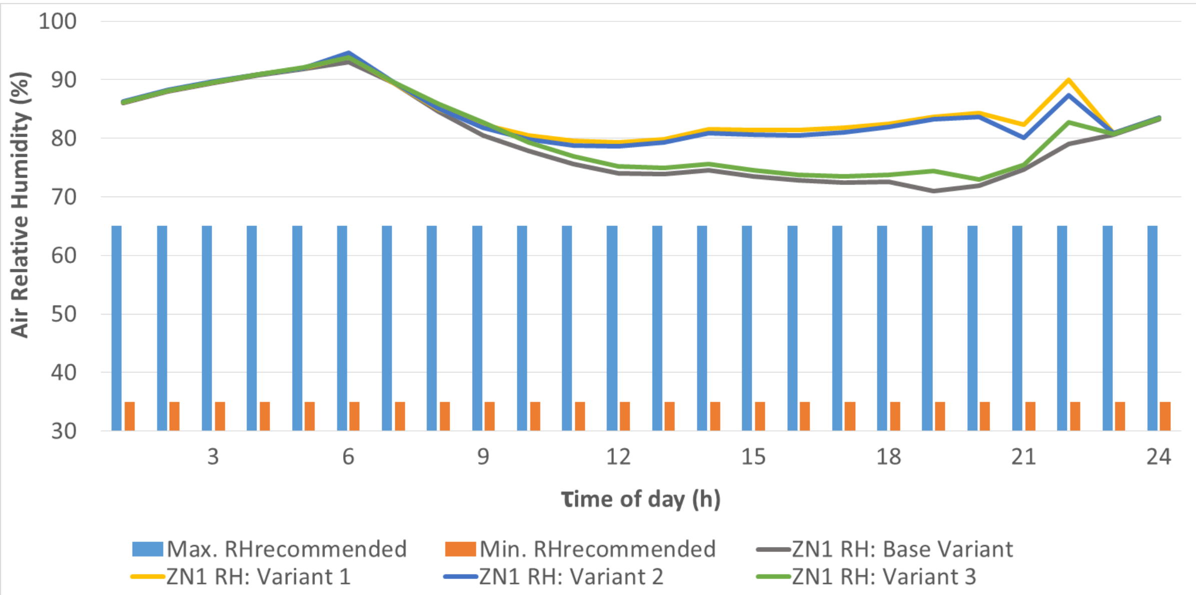

Figure B. 18: Zone 1, Air relative humidity (Belém)

Source: Author

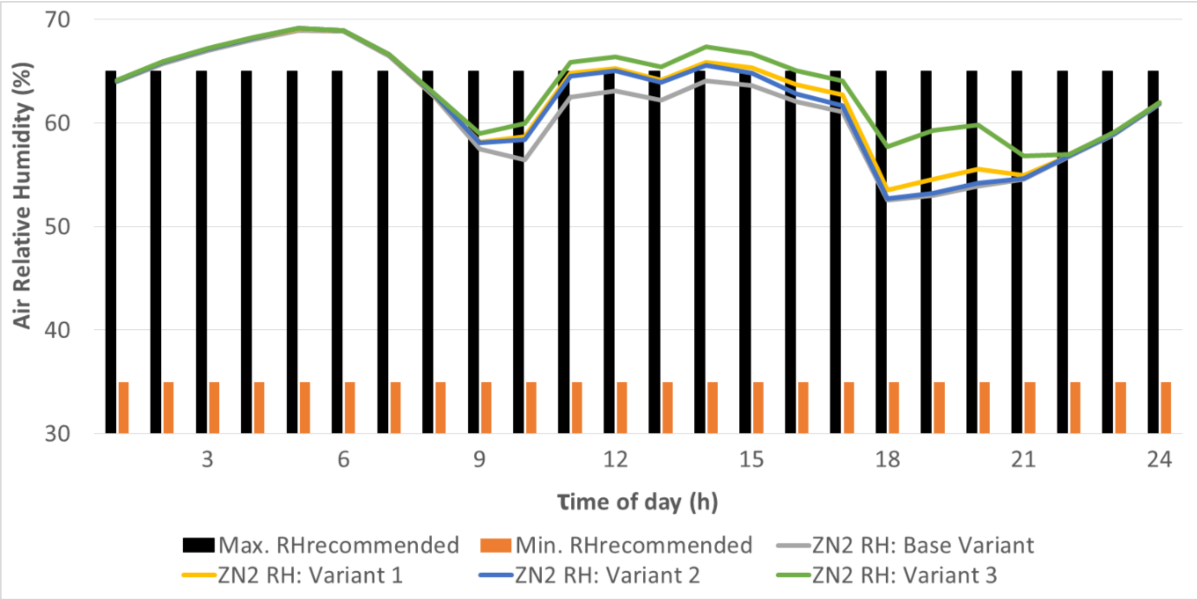

Figure B. 19: Zone 2, Air relative humidity (Lagos)

Source: Author

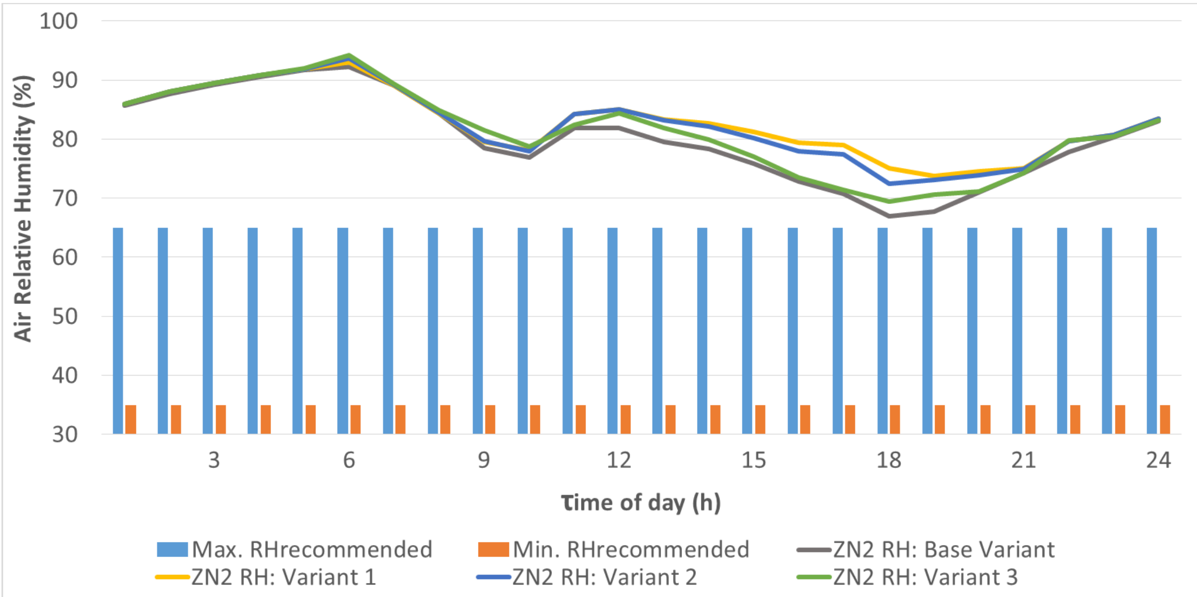

Figure B. 20: Zone 2, Air relative humidity (Belém)

Source: Author

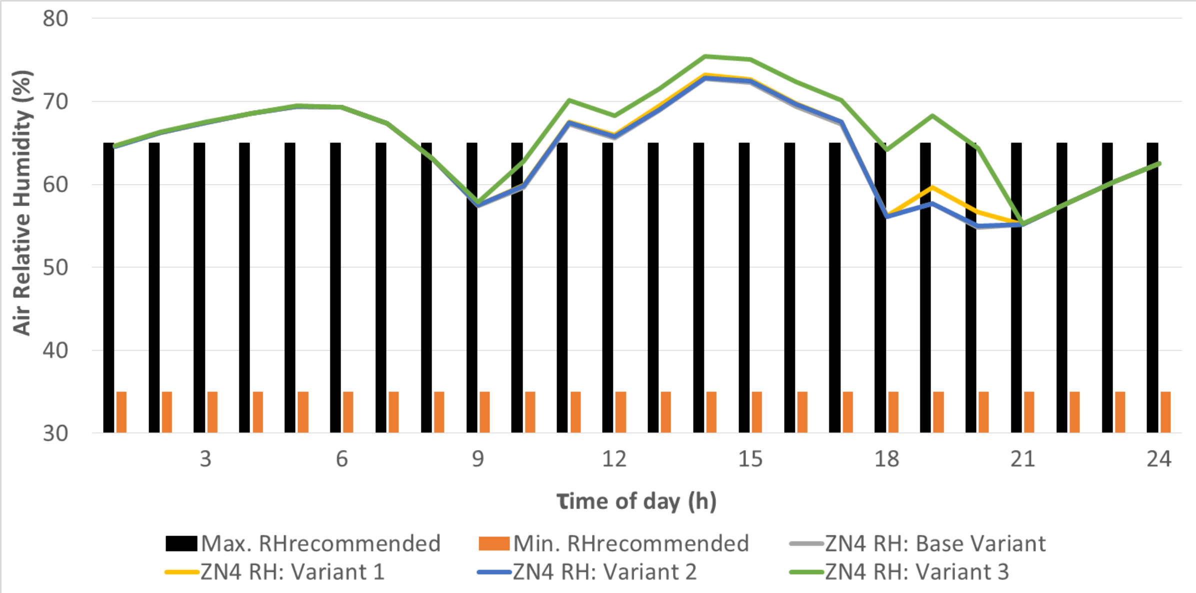

Figure B. 21: Zone 4, Air relative humidity (Lagos)
Source: Author

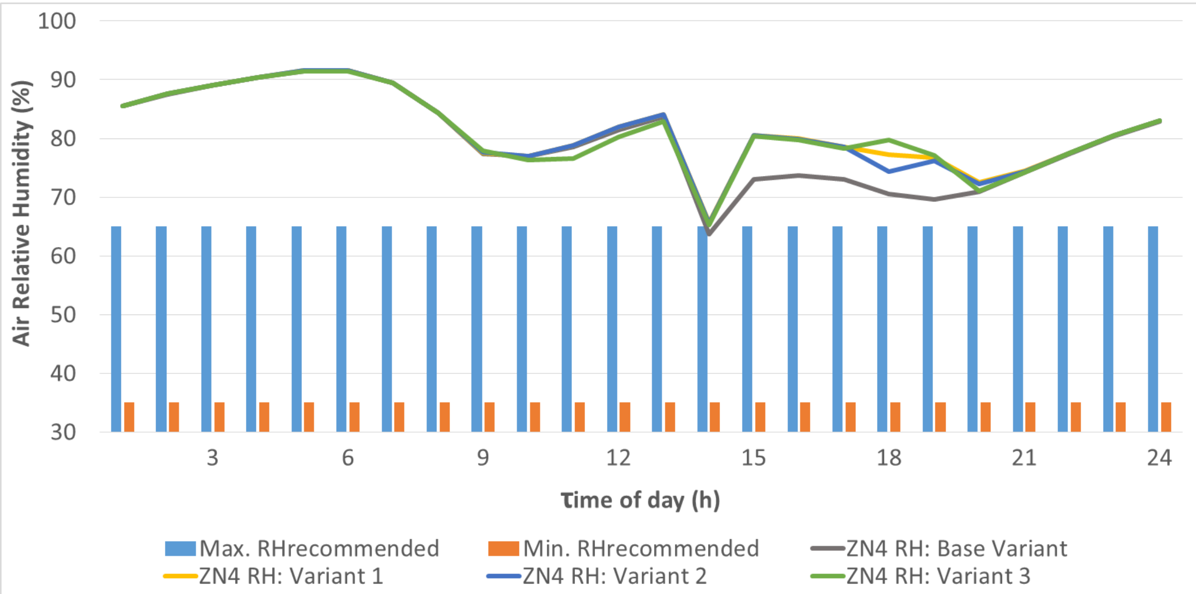

Figure B. 22: Zone 4, Air relative humidity (Belém)
Source: Author

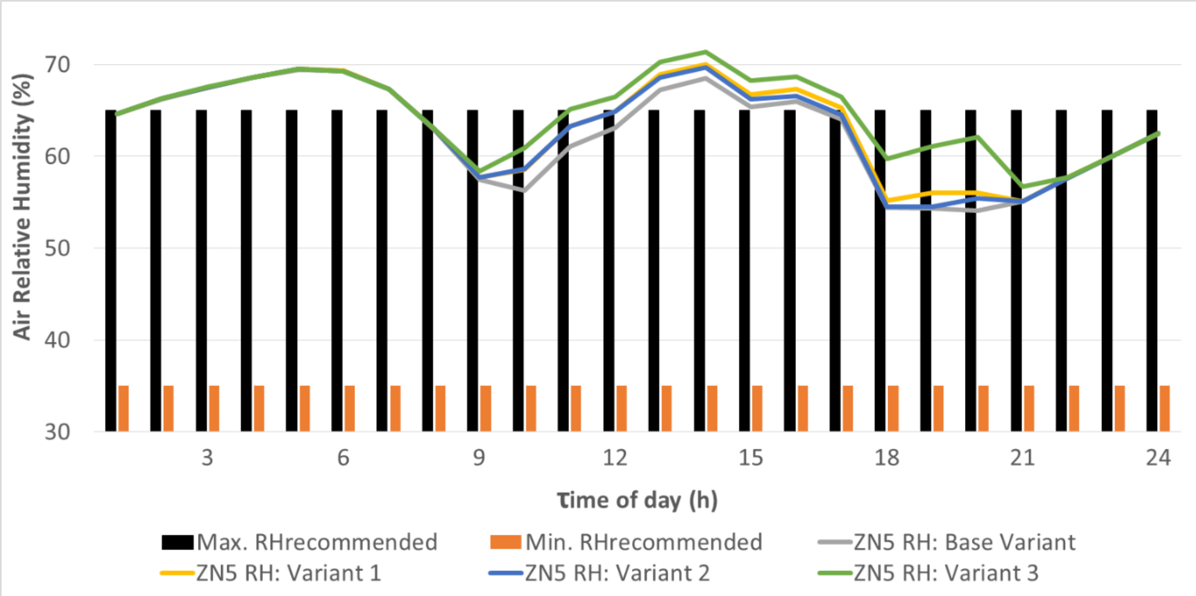

Figure B. 23: Zone 5, Air relative humidity (Lagos)
Source: Author

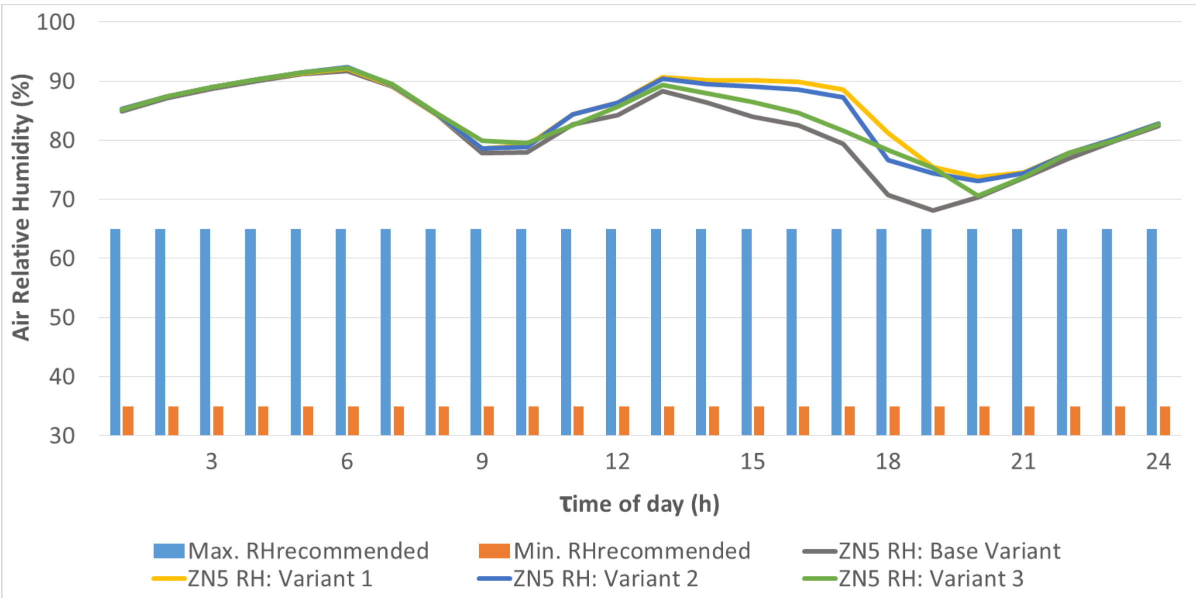

Figure B. 24: Zone 5, Air relative humidity (Belém)
Source: Author

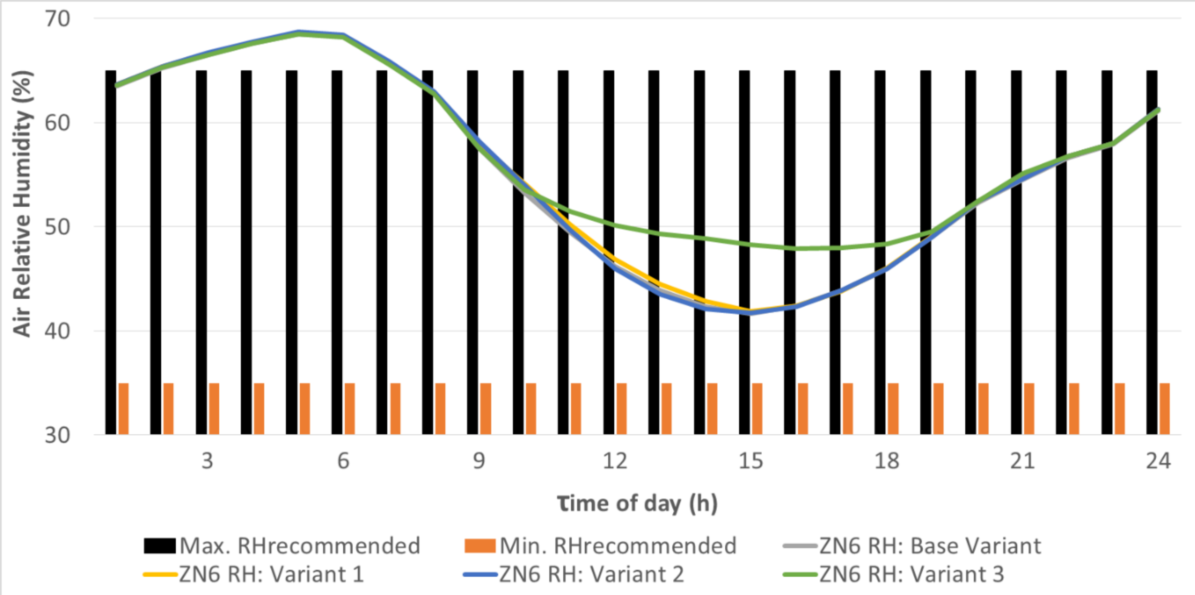

Figure B. 25: Zone 6, Air relative humidity (Lagos)
Source: Author

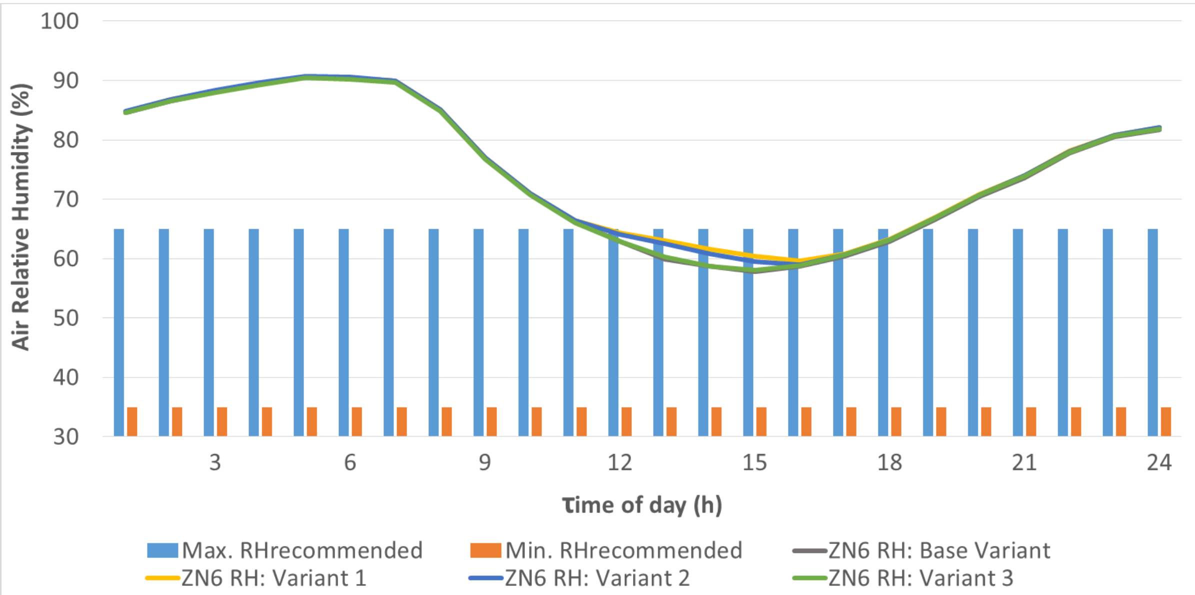

Figure B. 26: Zone 6, Air relative humidity (Belém)
Source: Author

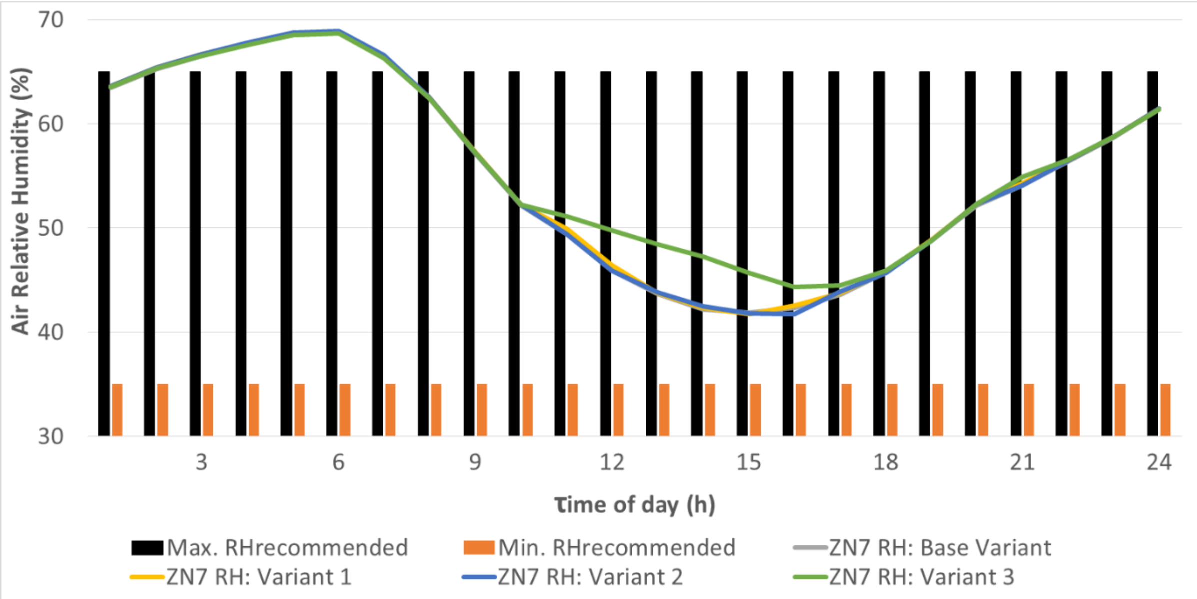

Figure B. 27: Zone 7, Air relative humidity (Lagos)

Source: Author

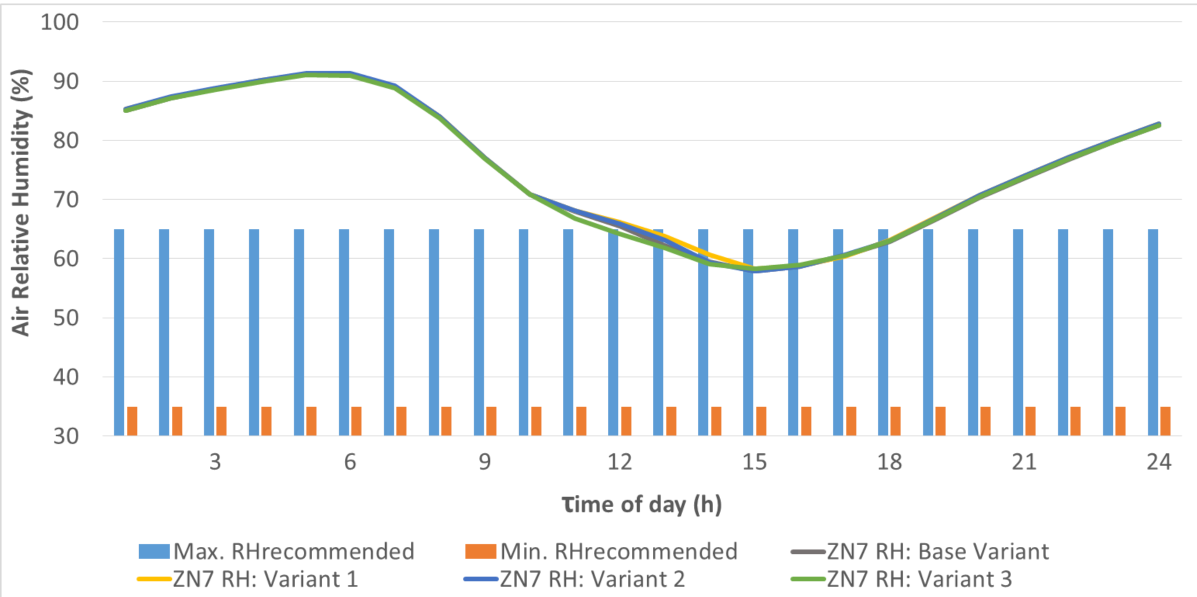

Figure B. 28: Zone 7, Air relative humidity (Belém)

Source: Author

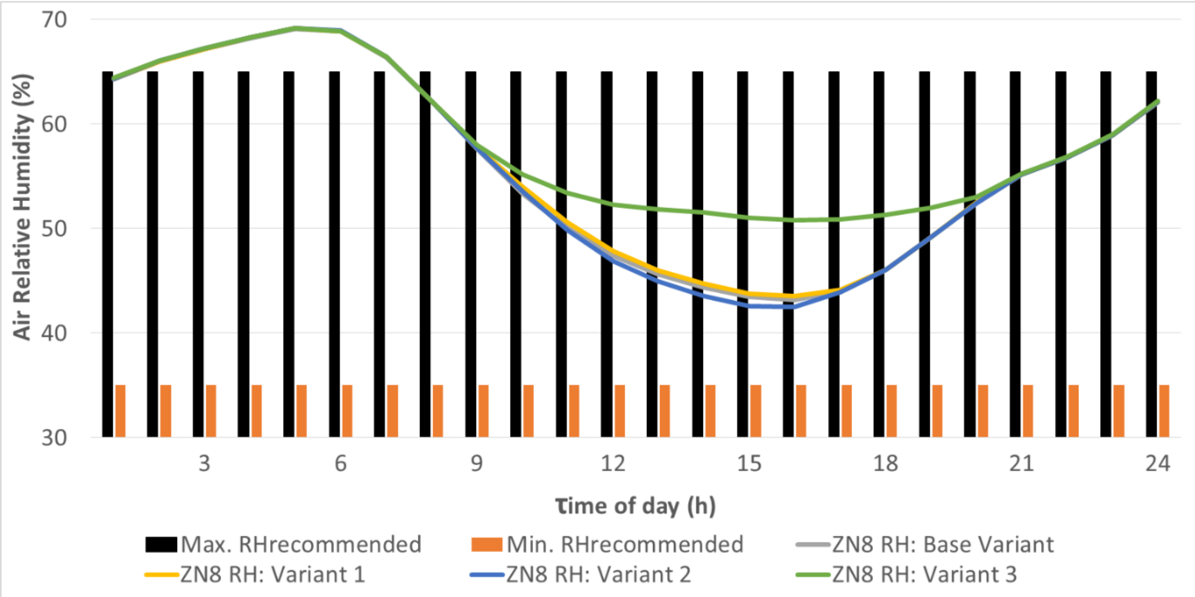

Figure B. 29: Zone 8, Air relative humidity (Lagos)

Source: Author

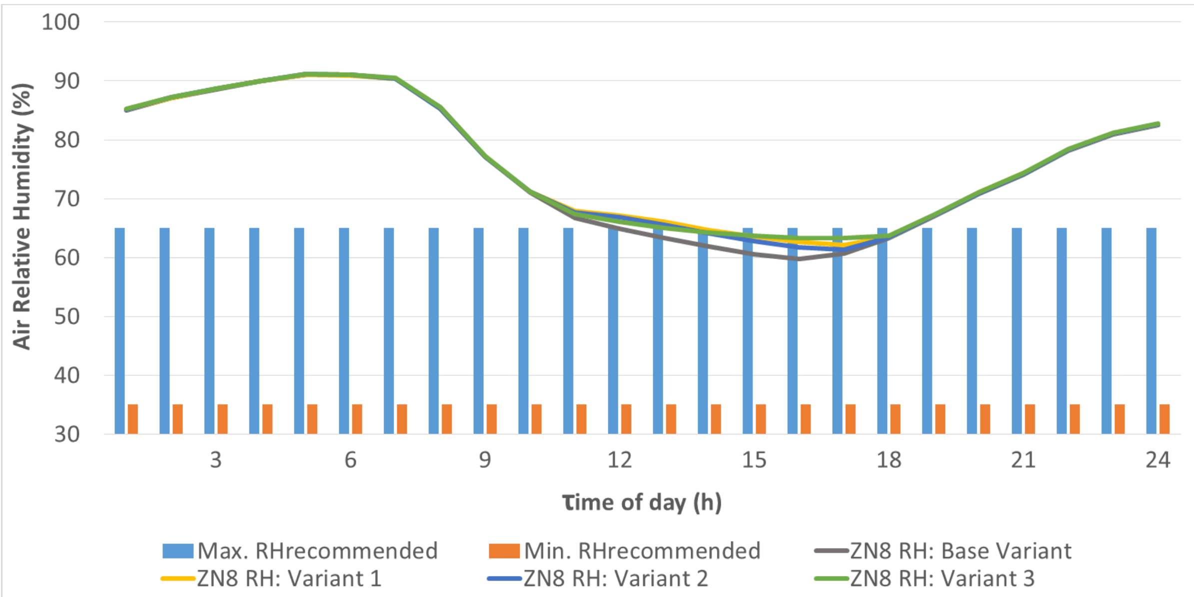

Figure B. 30: Zone 8, Air relative humidity (Belém)

Source: Author

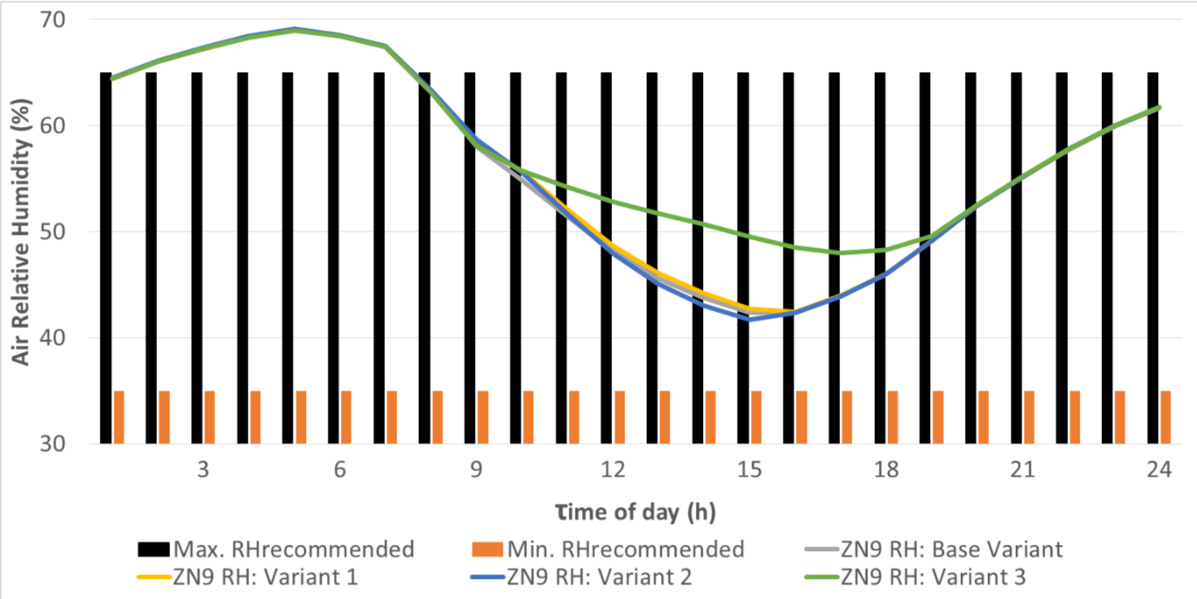

Figure B. 31: Zone 9, Air relative humidity (Lagos)
Source: Author

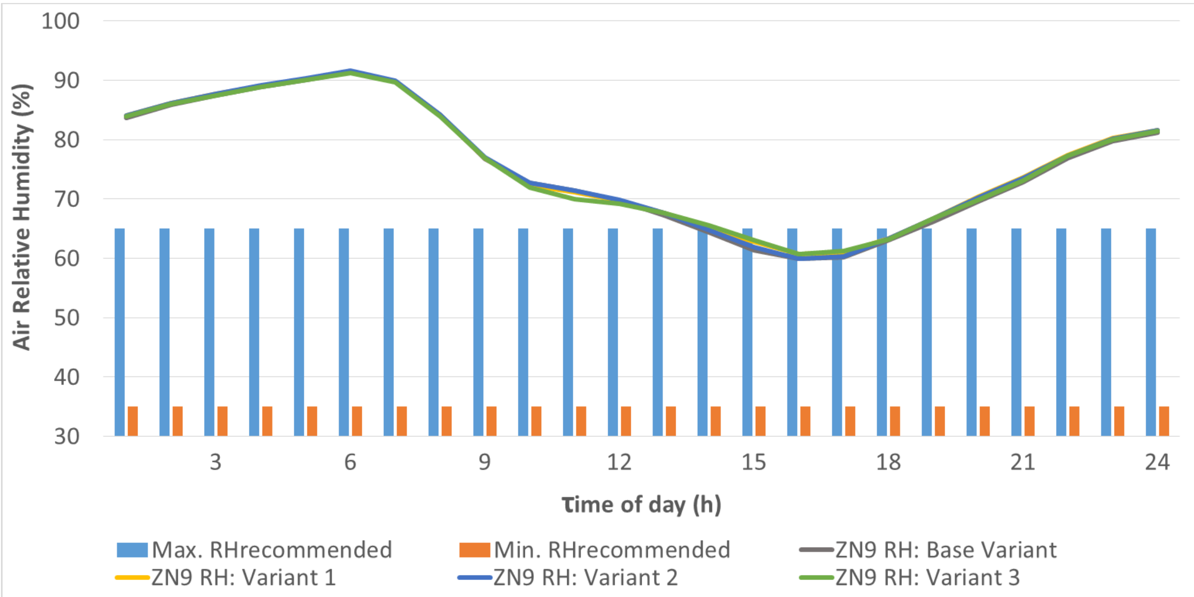

Figure B. 32: Zone 9, Air relative humidity (Belém)
Source: Author

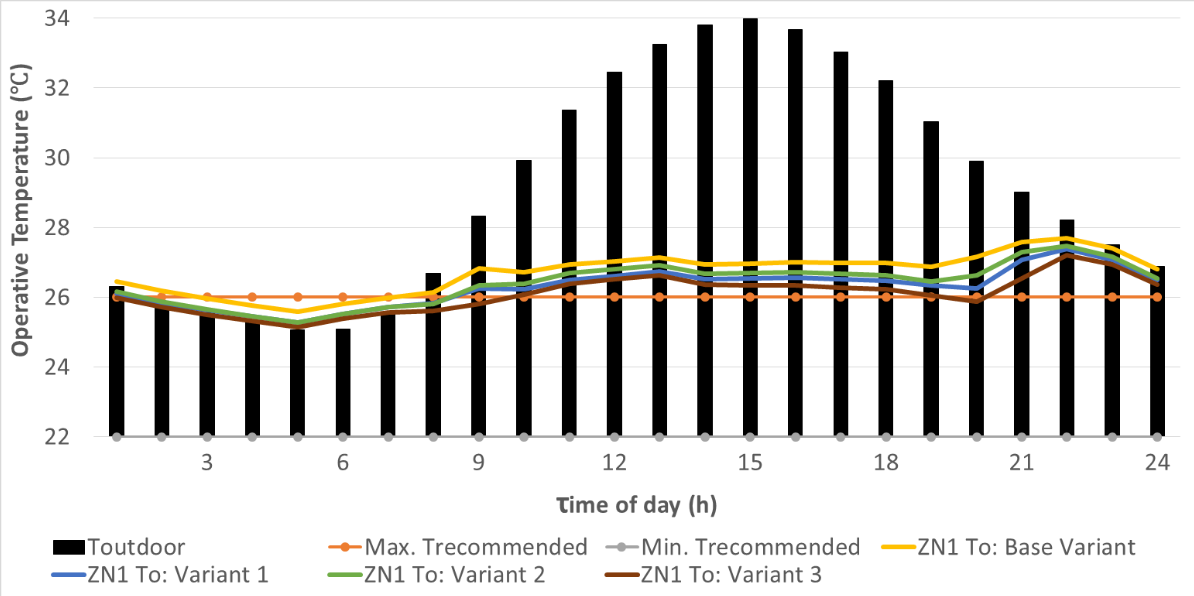

Figure B. 33: Zone 1, Operative temperature (Lagos)

Source: Author

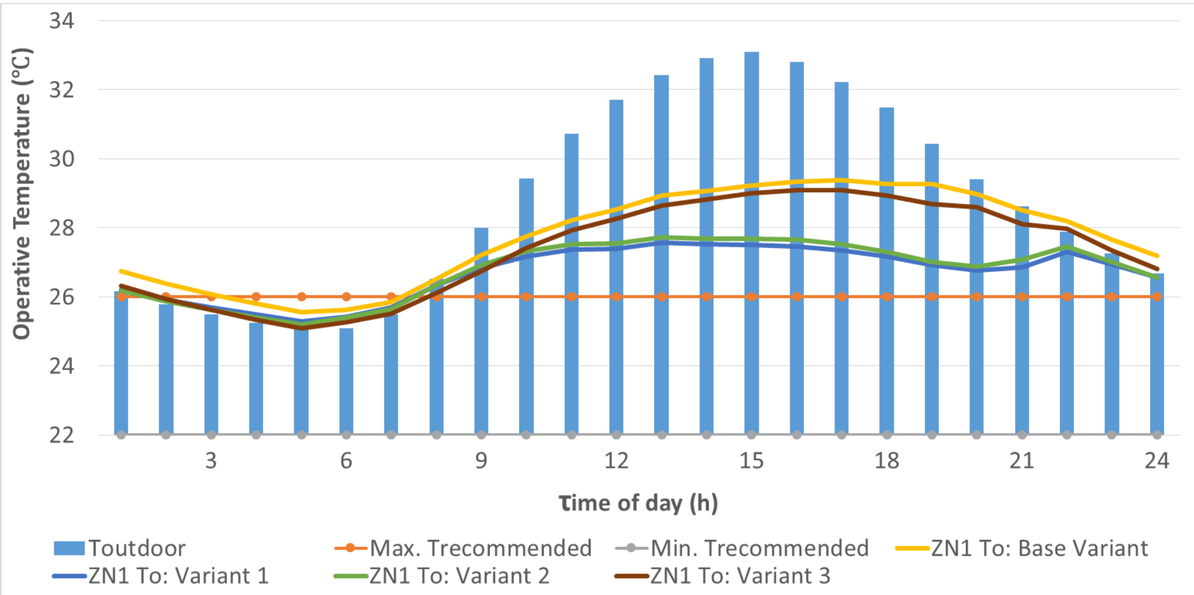

Figure B. 34: Zone 1, Operative temperature (Belém)

Source: Author

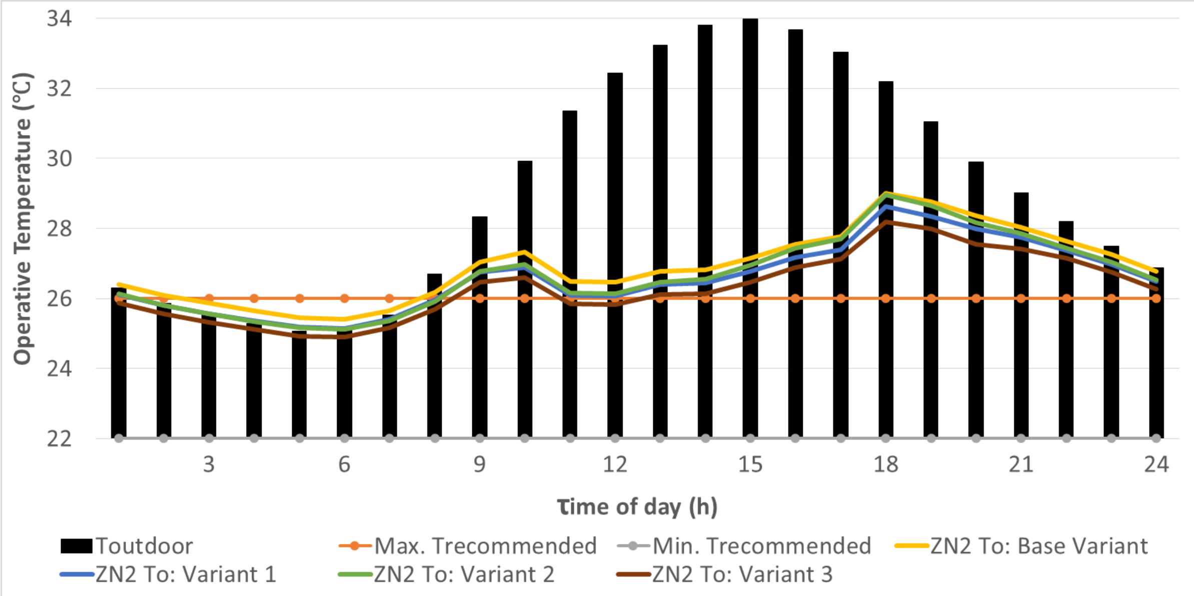

Figure B. 35: Zone 2, Operative temperature (Lagos)
Source: Author

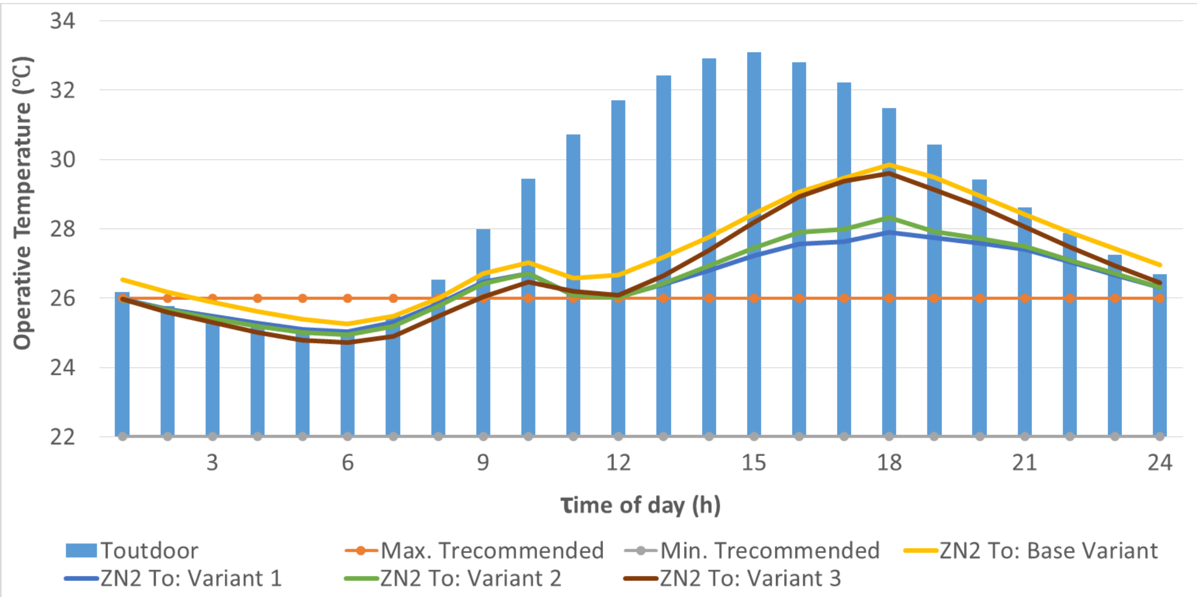

Figure B. 36: Zone 2, Operative temperature (Belém)
Source: Author

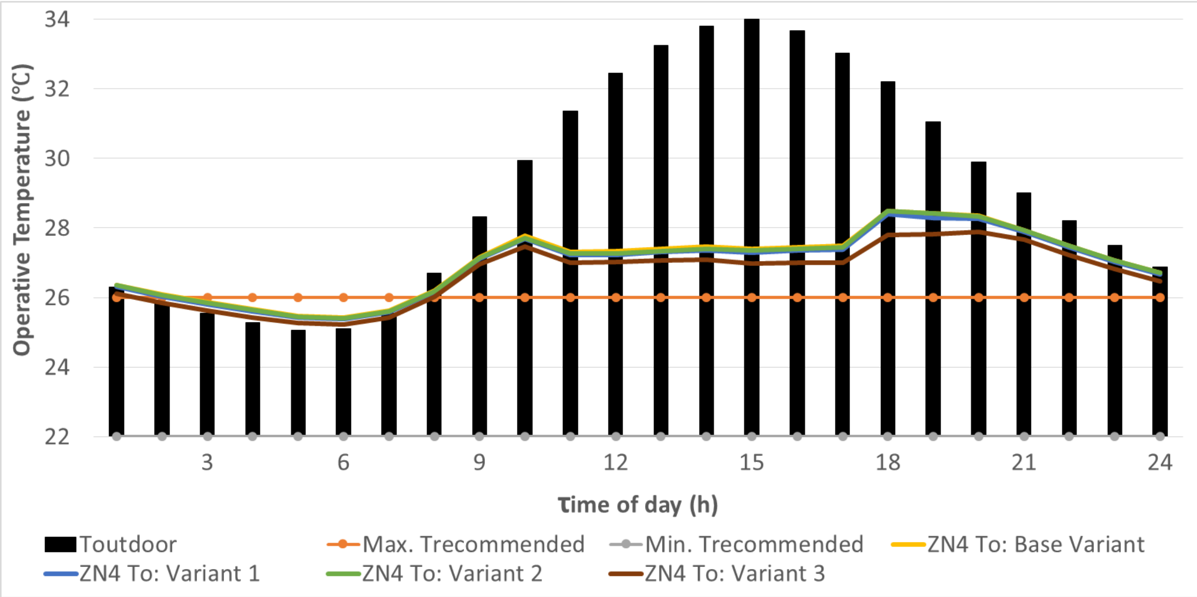

Figure B. 37: Zone 4, Operative temperature (Lagos)
Source: Author

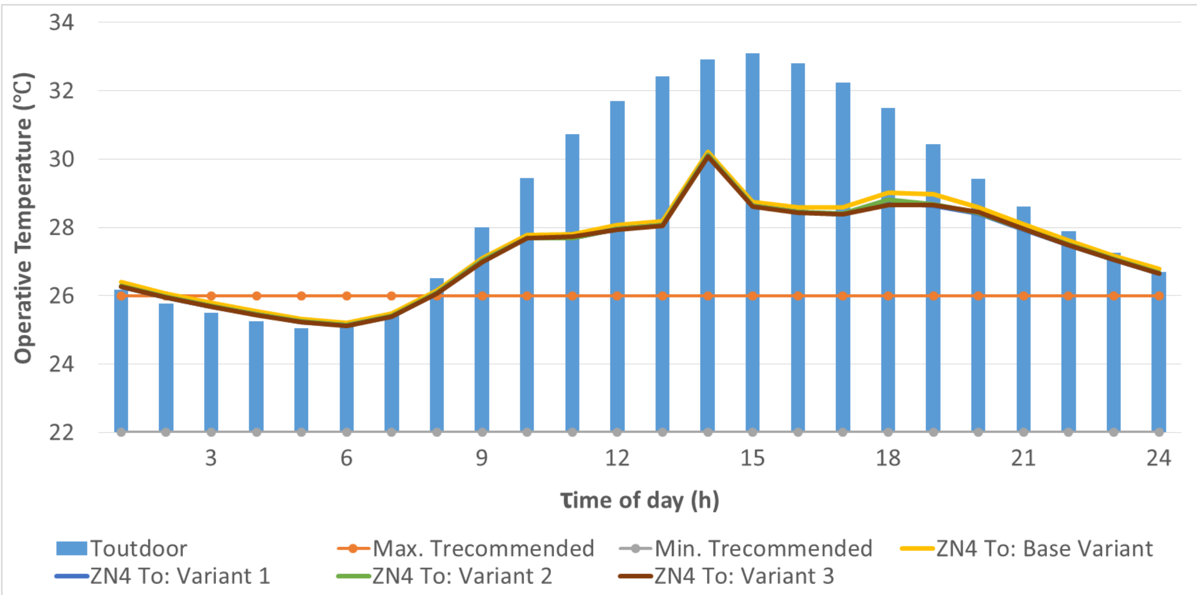

Figure B. 38: Zone 4, Operative temperature (Belém)
Source: Author

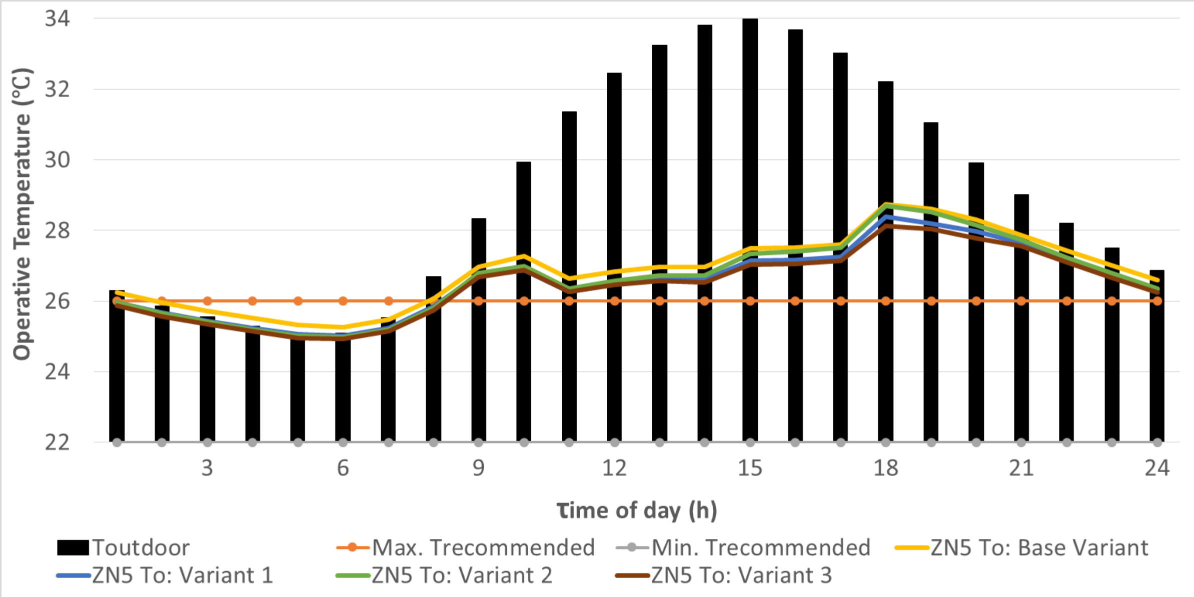

Figure B. 39: Zone 5, Operative temperature (Lagos)

Source: Author

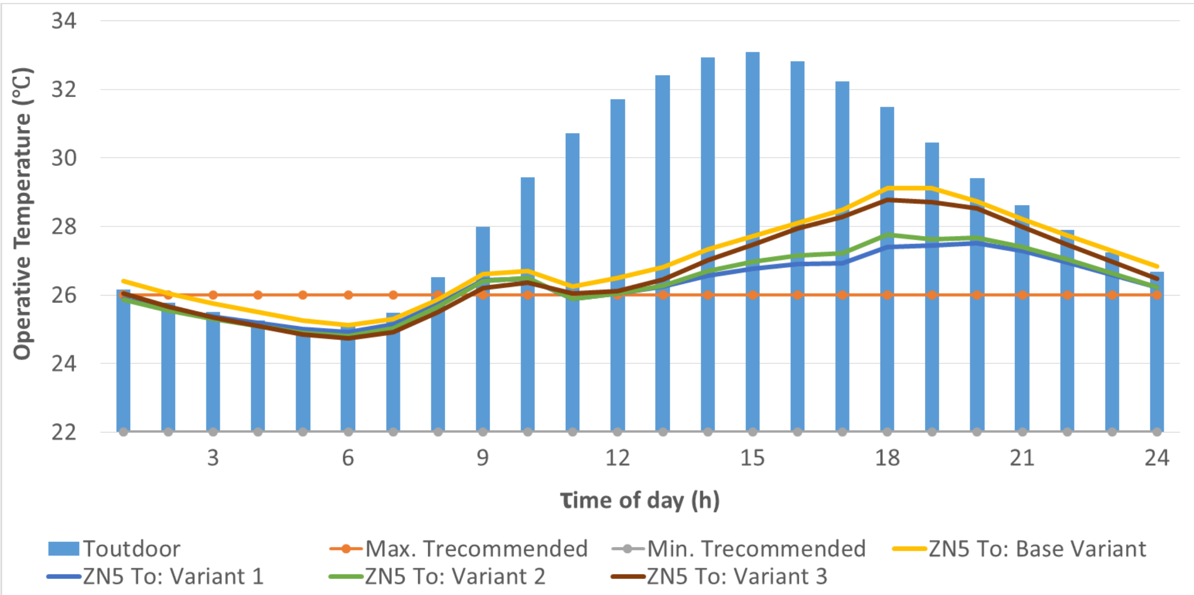

Figure B. 40: Zone 5, Operative temperature (Belém)

Source: Author

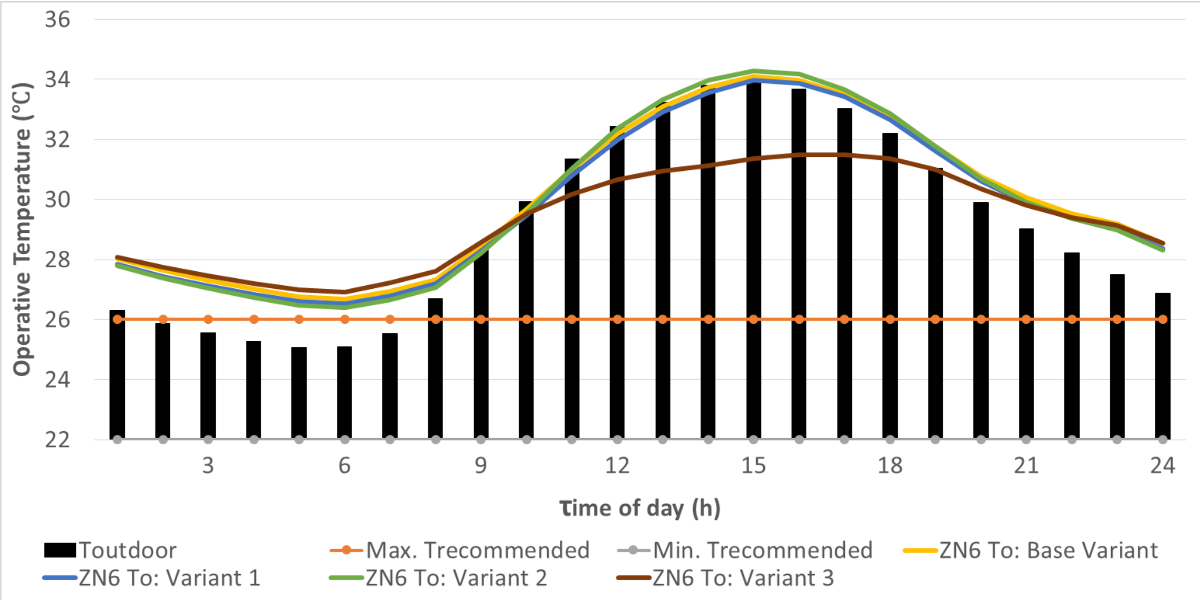

Figure B. 41: Zone 6, Operative temperature (Lagos)
Source: Author

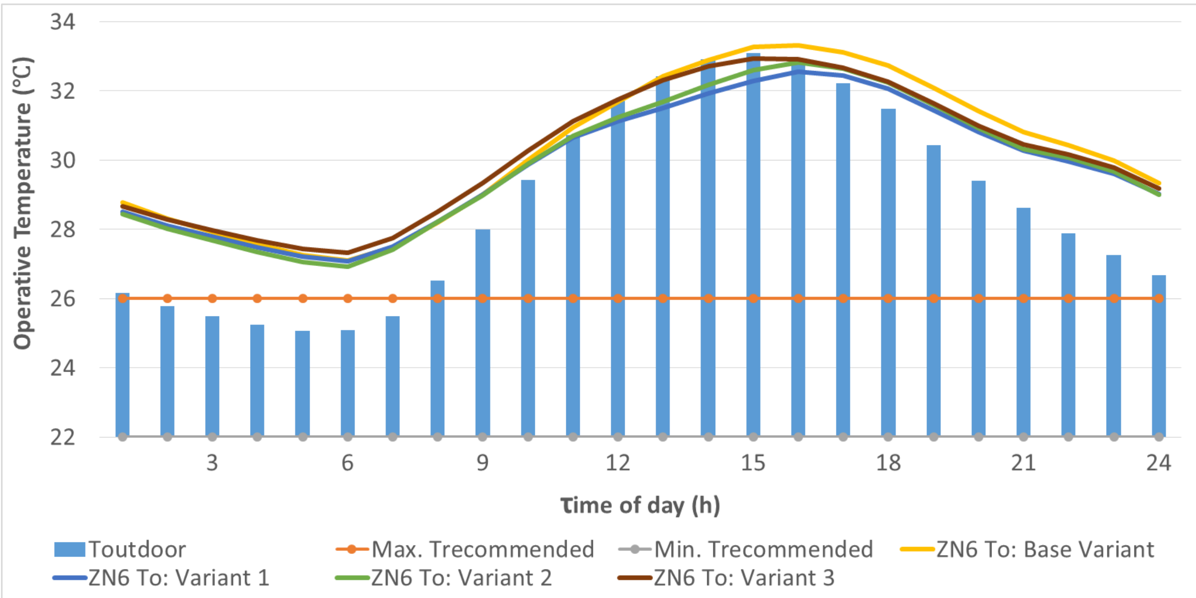

Figure B. 42: Zone 6, Operative temperature (Belém)
Source: Author

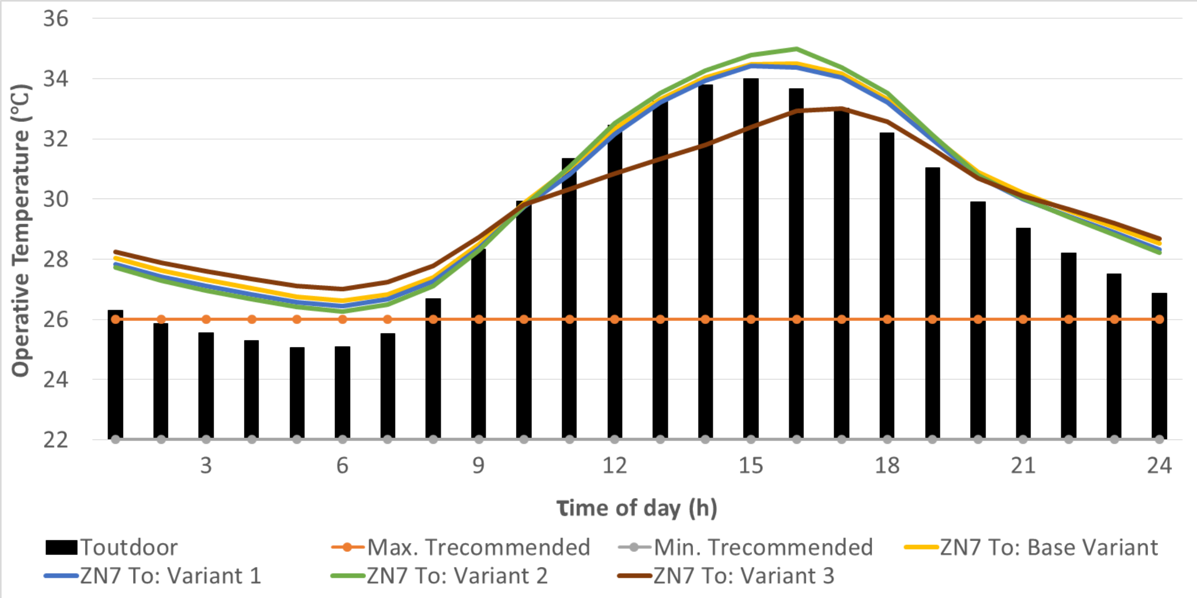

Figure B. 43: Zone 7, Operative temperature (Lagos)
Source: Author

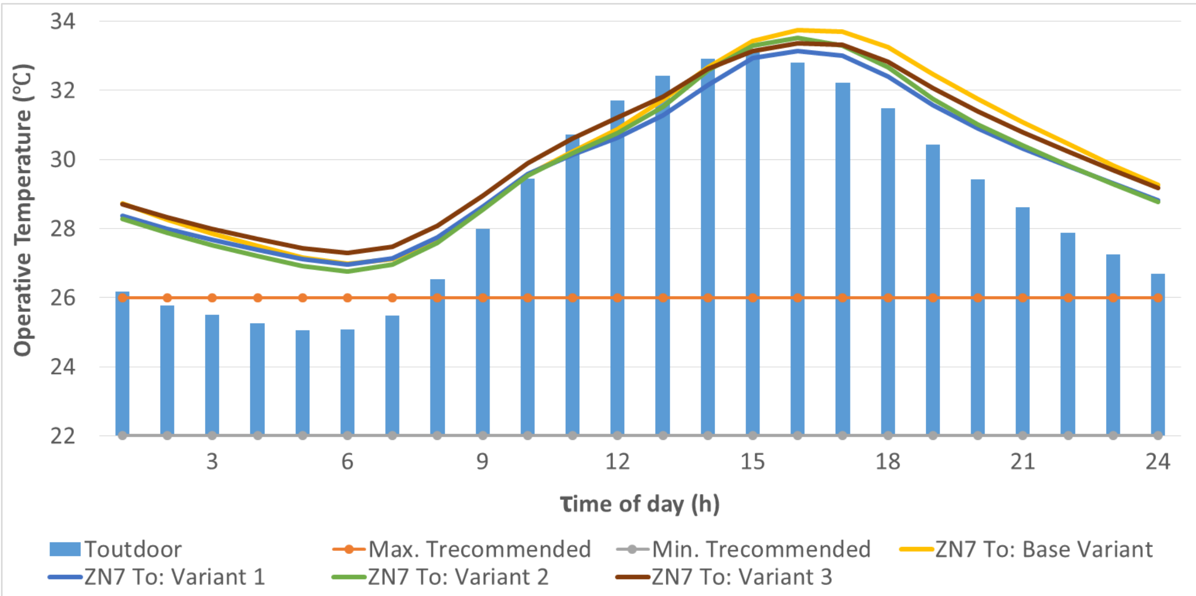

Figure B. 44: Zone 7, Operative temperature (Belém)
Source: Author

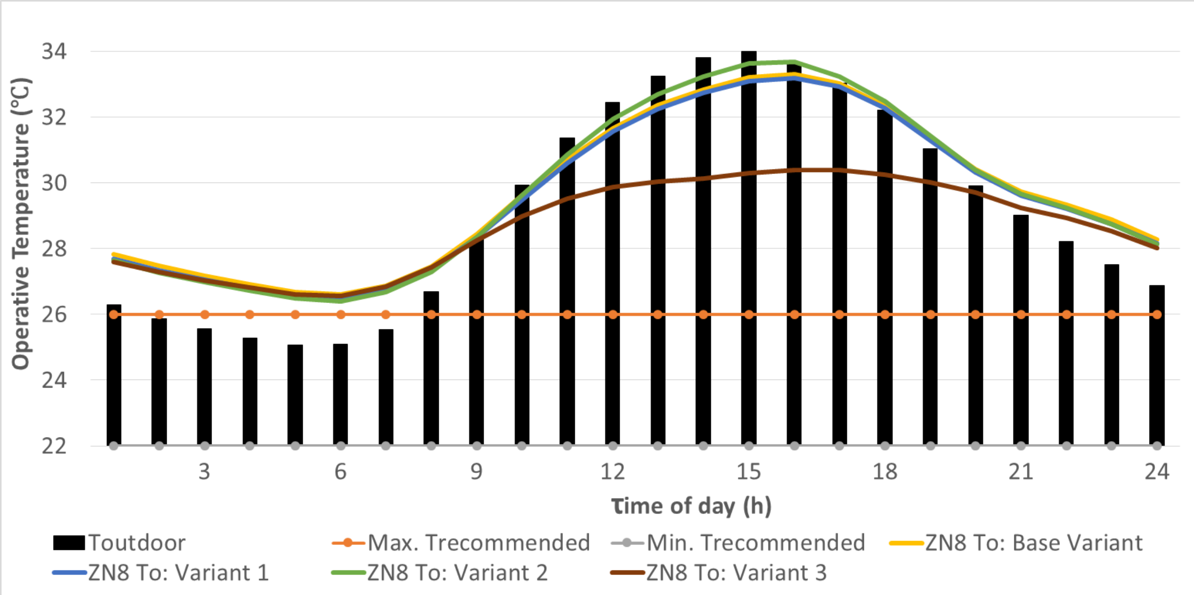

Figure B. 45: Zone 8, Operative temperature (Lagos)

Source: Author

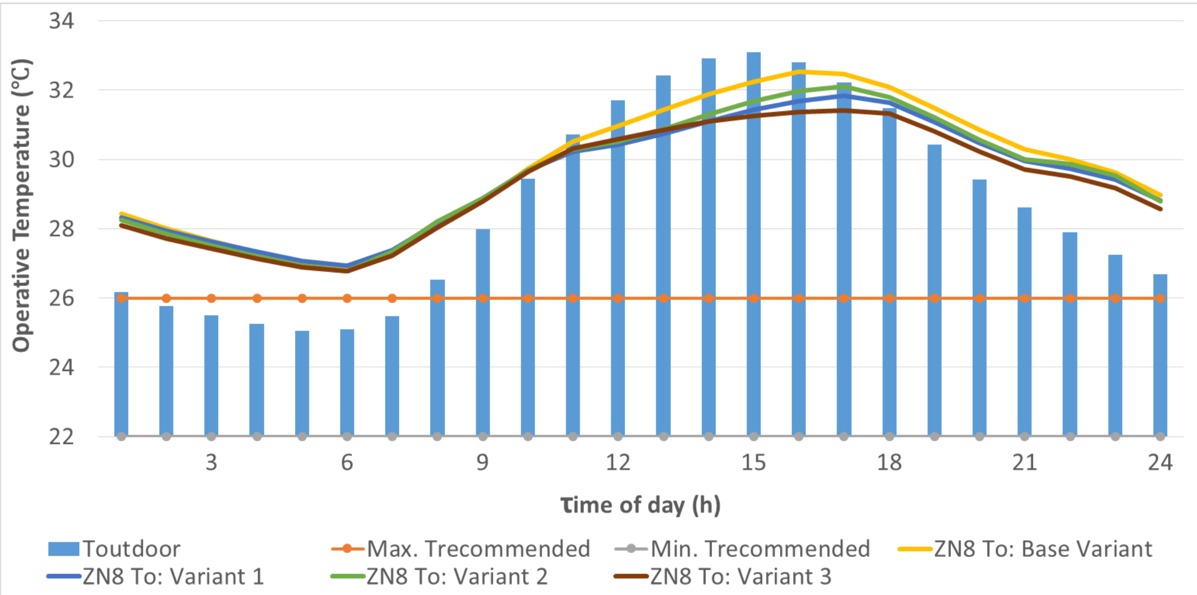

Figure B. 46: Zone 8, Operative temperature (Belém)

Source: Author

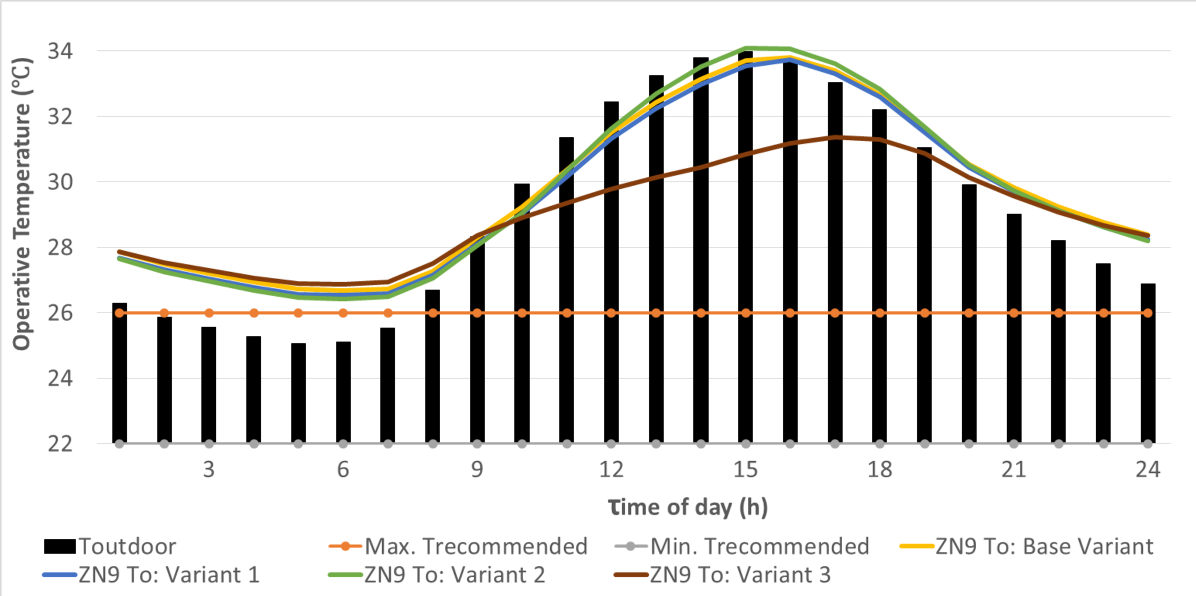

Figure B. 47: Zone 9, Operative temperature (Lagos)

Source: Author

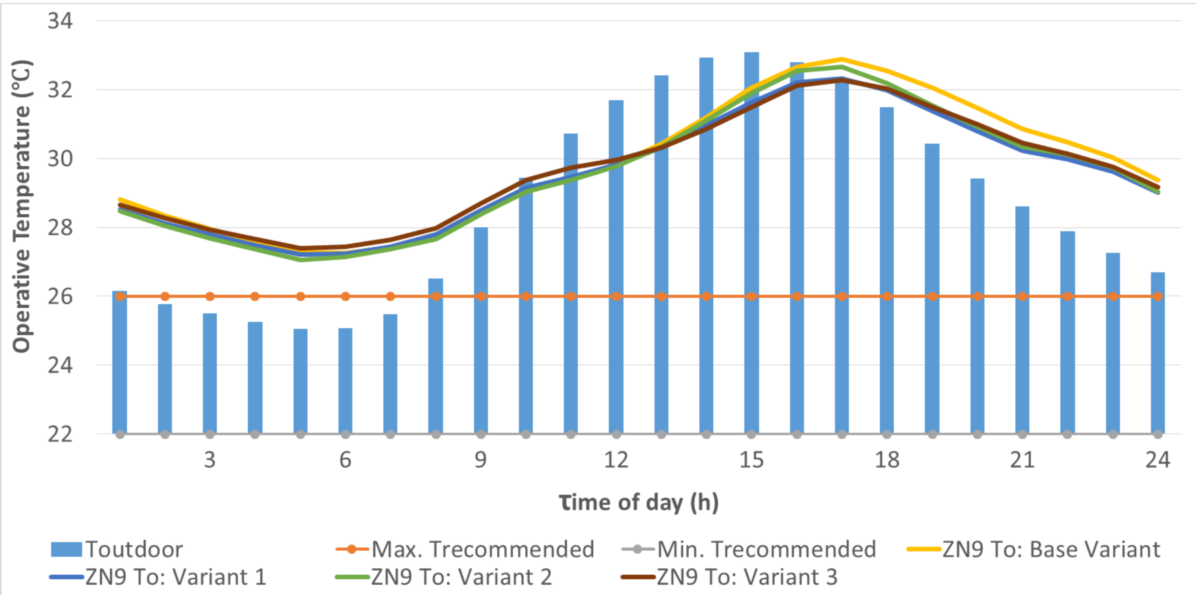

Figure B. 48: Zone 9, Operative temperature (Belém)

Source: Author

Output Variables		Base Variant Max	Base Variant Min	Variant 1 Max	Variant 1 Min	Variant 2 Max	Variant 2 Min	Variant 3 Max	Variant 3 Min
ZN1	T_m (°C)	28.6	25.2	28.6 (0.0%)	25.1 (-0.4%)	28.6 (0.0%)	25.1 (-0.4%)	28.5 (-0.3%)	25.1 (-0.4%)
	RH (%)	69	57	69 (0.0%)	57 (0.0%)	69 (0.0%)	57 (0.0%)	70 (+1.4%)	57 (0.0%)
	T_o (°C)	27.7	25.6	27.4 (-1.1%)	25.3 (-1.2%)	27.5 (-0.7%)	25.3 (-1.2%)	27.2 (-1.8%)	25.1 (-2.0%)
ZN2	T_m (°C)	30.6	25.2	30.2 (-1.3%)	25.2 (0.0%)	30.6 (0.0%)	25.2 (0.0%)	29.7 (-2.9%)	25.2 (0.0%)
	RH (%)	69	53	69 (0.0%)	54 (+1.9%)	69 (0.0%)	53 (0.0%)	69 (0.0%)	57 (+7.5%)
	T_o (°C)	29	25.4	28.6 (-1.4%)	25.1 (-1.2%)	29 (0.0%)	25.1 (-1.2%)	28.2 (-2.8%)	24.9 (-2.0%)
ZN4	T_m (°C)	30.2	25.1	30.1 (-0.3%)	25.1 (0.0%)	30.2 (0.0%)	25.1 (0.0%)	29.5 (-2.3%)	25.1 (0.0%)
	RH (%)	73	55	73 (0.0%)	55 (0.0%)	73 (0.0%)	55 (0.0%)	75 (+2.7%)	55 (0.0%)
	T_o (°C)	28.5	25.4	28.4 (-0.4%)	25.4 (0.0%)	28.5 (0.0%)	25.4 (0.0%)	27.9 (-2.1%)	25.2 (-0.8%)
ZN5	T_m (°C)	30.5	25.1	30.2 (-1.3%)	25.1 (0.0%)	30.5 (0.0%)	25.1 (0.0%)	29.8 (-2.3%)	25.1 (0.0%)
	RH (%)	69	54	70 (+1.4%)	55 (+1.9%)	70 (+1.4%)	54 (0.0%)	71 (+2.9%)	57 (+5.6%)
	T_o (°C)	28.7	25.3	28.4 (-1.0%)	25 (-1.2%)	28.7 (0.0%)	25 (-1.2%)	28.1 (-2.1%)	24.9 (-1.6%)
ZN6	T_m (°C)	34	25.3	33.9 (-0.3%)	25.3 (0.0%)	34 (0.0%)	25.3 (0.0%)	31.5 (-7.4%)	25.4 (+0.4%)
	RH (%)	69	42	69 (0.0%)	42 (0.0%)	69 (0.0%)	42 (0.0%)	68 (-1.4%)	48 (+14.3%)
	T_o (°C)	34.1	26.7	34 (-0.3%)	26.5 (-0.7%)	34.3 (+0.6%)	26.4 (-1.1%)	31.5 (-7.6%)	26.9 (+0.7%)
ZN7	T_m (°C)	33.9	25.3	33.9 (0.0%)	25.3 (0.0%)	34 (+0.3%)	25.3 (0.0%)	33 (-2.7%)	25.3 (0.0%)
	RH (%)	69	42	69 (0.0%)	42 (0.0%)	69 (0.0%)	42 (0.0%)	69 (0.0%)	44 (+4.8%)
	T_o (°C)	34.5	26.6	34.4 (-0.3%)	26.4 (-0.8%)	35 (+1.4%)	26.3 (-1.1%)	33 (-4.3%)	27 (+1.5%)
ZN8	T_m (°C)	33.4	25.2	33.2 (-0.6%)	25.2 (0.0%)	33.6 (+0.6%)	25.2 (0.0%)	30.5 (-8.7%)	25.2 (0.0%)
	RH (%)	69	43	69 (0.0%)	44 (+2.3%)	69 (0.0%)	43 (0.0%)	69 (0.0%)	51 (+18.6%)
	T_o (°C)	33.3	26.6	33.2 (-0.3%)	26.5 (-0.4%)	33.7 (+1.2%)	26.4 (-0.8%)	30.4 (-8.7%)	26.6 (0.0%)
ZN9	T_m (°C)	33.7	25.2	33.7 (0.0%)	25.2 (0.0%)	34 (+0.9%)	25.2 (0.0%)	31.5 (-6.5%)	25.2 (0.0%)
	RH (%)	69	42	69 (0.0%)	42 (0.0%)	69 (0.0%)	42 (0.0%)	69 (0.0%)	48 (+14.3%)
	T_o (°C)	33.8	26.7	33.7 (-0.3%)	26.5 (-0.7%)	34.1 (+0.9%)	26.4 (-1.1%)	31.4 (-7.1%)	26.9 (+0.7%)

Table B. 1: Summary of recorded values in individual zones (Lagos)

Source: Author

Output Variables		Base Variant		Variant 1		Variant 2		Variant 3	
		Max	Min	Max	Min	Max	Min	Max	Min
ZN1	T_m (°C)	29.7	25.1	27.9 (-6.1%)	25.1 (0.0%)	28 (-5.7%)	25.1 (0.0%)	29.4 (-1.0%)	25.1 (0.0%)
	RH (%)	93	71	94 (+1.1%)	79 (+11.3%)	95 (+2.2%)	79 (+11.3%)	94 (+1.1%)	73 (+2.8%)
	T_o (°C)	29.4	25.6	27.6 (-6.1%)	25.3 (-1.2%)	27.7 (-5.8%)	25.2 (-1.6%)	29.1 (-1.0%)	25.1 (-2.0%)
ZN2	T_m (°C)	30.9	25.1	29 (-6.1%)	25.1 (0.0%)	29.5 (-4.5%)	25.1 (0.0%)	30.6 (-1.0%)	25.1 (0.0%)
	RH (%)	92	67	93 (+1.1%)	74 (+10.4%)	94 (+2.2%)	72 (+7.5%)	94 (+2.2%)	69 (+3.0%)
	T_o (°C)	29.9	25.3	27.9 (-6.7%)	25 (-1.2%)	28.3 (-5.4%)	24.9 (-1.6%)	29.6 (-1.0%)	24.7 (-2.4%)
ZN4	T_m (°C)	32.7	25.2	32.6 (-0.3%)	25.2 (0.0%)	32.6 (-0.3%)	25.2 (0.0%)	32.6 (-0.3%)	25.2 (0.0%)
	RH (%)	92	64	92 (0.0%)	66 (+3.1%)	92 (0.0%)	66 (+3.1%)	91 (-1.1%)	65 (+1.6%)
	T_o (°C)	30.2	25.2	30.1 (-0.3%)	25.1 (-0.4%)	30.1 (-0.3%)	25.1 (-0.4%)	30.1 (-0.3%)	25.1 (-0.4%)
ZN5	T_m (°C)	30.4	25.2	29.1 (-4.3%)	25.2 (0.0%)	29.2 (-3.9%)	25.2 (0.0%)	29.9 (-1.6%)	25.2 (0.0%)
	RH (%)	92	68	92 (0.0%)	74 (+8.8%)	92 (0.0%)	73 (+7.4%)	92 (0.0%)	71 (+4.4%)
	T_o (°C)	29.1	25.1	27.5 (-5.5%)	24.9 (-0.8%)	27.8 (-4.5%)	24.8 (-1.2%)	28.8 (-1.0%)	24.7 (-1.6%)
ZN6	T_m (°C)	33.1	25.3	32.6 (-1.5%)	25.3 (0.0%)	32.8 (-0.9%)	25.3 (0.0%)	33 (-0.3%)	25.4 (+0.4%)
	RH (%)	91	58	91 (0.0%)	60 (+3.4%)	91 (0.0%)	59 (+1.7%)	90 (-1.1%)	58 (0.0%)
	T_o (°C)	33.3	27.1	32.6 (-2.1%)	27.1 (0.0%)	32.8 (-1.5%)	26.9 (-0.7%)	32.9 (-1.2%)	27.3 (+0.7%)
ZN7	T_m (°C)	33.1	25.2	33 (-0.3%)	25.2 (0.0%)	33.1 (0.0%)	25.2 (0.0%)	33 (-0.3%)	25.3 (+0.4%)
	RH (%)	91	58	91 (0.0%)	58 (0.0%)	91 (0.0%)	58 (0.0%)	91 (0.0%)	58 (0.0%)
	T_o (°C)	33.7	27	33.1 (-1.8%)	27 (0.0%)	33.5 (-0.6%)	26.8 (-0.7%)	33.4 (-0.9%)	27.3 (+1.1%)
ZN8	T_m (°C)	32.5	25.3	31.9 (-1.8%)	25.3 (0.0%)	32.1 (-1.2%)	25.2 (-0.4%)	31.5 (-3.1%)	25.2 (-0.4%)
	RH (%)	91	60	91 (0.0%)	62 (+3.3%)	91 (0.0%)	61 (+1.7%)	91 (0.0%)	63 (+5.0%)
	T_o (°C)	32.5	26.8	31.8 (-2.2%)	26.9 (+0.4%)	32.1 (-1.2%)	26.8 (0.0%)	31.4 (-3.4%)	26.8 (0.0%)
ZN9	T_m (°C)	32.5	25.4	32.3 (-0.6%)	25.4 (0.0%)	32.5 (0.0%)	25.4 (0.0%)	32.3 (-0.6%)	25.5 (+0.4%)
	RH (%)	91	60	92 (+1.1%)	61 (+1.7%)	92 (+1.1%)	60 (0.0%)	91 (0.0%)	61 (+1.7%)
	T_o (°C)	32.9	27.3	32.3 (-1.8%)	27.2 (-0.4%)	32.7 (-0.6%)	27.1 (-0.7%)	32.3 (-1.8%)	27.4 (+0.4%)

Table B. 2: Summary of recorded values in individual zones (Belém)

Source: Author

NB: The values in parenthesis are the percentage differences recorded with respect to the base variants.