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On the Emergence of Shipping Container Homes: Adaptation to Future Climate Projections

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ABSTRACT

Upcycling shipping containers for housing is increasingly recognised as a sustainable solution to housing challenges, particularly in developing economies like Nigeria. This study evaluates the thermal comfort and energy efficiency of shipping container homes under climate conditions projected for 2080. Using meteorological data for Abuja and Lagos under the Representative Concentration Pathway 8.5, a stand-alone shipping container home was simulated. The study incorporated fabric optimisation techniques, using polyurethane foam and polyisocyanurate board insulation, high-performance window glazing, and shading strategies. The findings reveal that without intervention, container homes would experience significant thermal discomfort, with annual discomfort hours exceeding 28°C in both cities. However, with insulation and shading, annual discomfort hours were reduced by up to 87%, and energy consumption decreased by 76%. These results highlight the critical role of insulation and shading in enhancing thermal comfort and reducing energy demand, making container homes a viable solution for sustainable housing in hot climates. The study underscores the need for policy support to promote the integration of advanced insulation and adaptive design strategies to ensure the resilience and sustainability of container homes in future climates.

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1. Introduction

From the reuse of stone, wood and marble, architecture has historically witnessed the transformation of various materials into buildings (Radwan, 2015). Timber frame construction has been prevalent in single-family home construction for a long time. However, the emergence of shipping containers as an alternative housing entity has captured the imagination of architects (Blanford & Bender, 2020). According to Risnandar and Primasetra (2021), a growing innovation in the construction industry is upcycling shipping containers for residential use. Using shipping containers for building homes is canvassed worldwide, even though it is unclear who pioneered it (De Asis, 2012). Although using shipping containers for homes is not new, it became a focus in Europe and America in the early 2000s, according to Hong (2017). Demand for new shipping containers in the maritime industry consistently rise due to changing regulations and economic trends. Consequently, old shipping containers become environmental waste if not recycled (Laksitoadi & Syarif, 2020). Despite governments' worldwide efforts to reduce waste generation, millions of used shipping containers end up as scrap (Oviya & Amraotkar, 2023). Containers are lightweight and have recyclable potential (Zha & Zuo, 2016). Some of the benefits of their use as residential dwellings are their flexibility (Alemdag & Aydin, 2015), low environmental impact, low cost, short construction period, circular economy, material sustainability (Berbesz & Szefer, 2018; Lee et al., 2017; Primasetra, 2019; Shen et al., 2019) and the promotion of the right to housing (Hong, 2017).

Upcycled shipping containers, a feature of urban architecture, are part of a movement that started with Archigram and the Metabolists in the 1960s (Schwarzer, 2013), but formalised for housing purpose in 1987, as asserted by Blanford and Bender (2020). Initially, shipping containers only fulfil the marine and logistic requirements provided by ISO; their use for residential purposes must be modified to fulfil the comfort requirements of inhabitants. The usefulness of shipping containers cuts across different spheres as they are not only recycled as simple family units but also as post-disaster housing (Cameron, 2019; Hong, 2017; Zafra et al., 2021; Zhang et al., 2014), small-scale enterprises (Obia, 2019) and as testing booths during the covid-19 pandemic (Lin et al., 2021). Studies show that not all countries accept the potential use of containers. For example, while Australia, the UK and the USA have all embraced their use for housing, in tune with the global trend to promote a circular economy and increase the use of recycled materials, Spain has declined to acknowledge their viability, raising concerns about potential uncertainties (Leton, 2023). More so, in Malaysia, their use as storage facilities is prioritised over housing units, according to Wong et al. (2018)

For countries with a significant population, the use of containers, when modified, is a good alternative for low-income earners (Thanekar et al., 2022) as the cost of apartment is on the increase with no sign of slowing down (Grebowski & Kałdunek, 2017). Applying shipping containers for residential use can help solve the housing poverty challenge in low-income countries (De Asis, 2012; Hong, 2017; Patil et al., 2021) and those with increasing population (Ling & Tan, 2018). Furthermore, Alemdag and Aydin (2015), Bernardo et al. (2022) and Tavsan and Bektas (2021) suggest that recycling shipping containers for housing developments constitutes a sustainable construction approach while Tamiru (2022) and Zafra et al. (2021) assert that their construction is strong enough to withstand strong wind and earthquake whilst fulfilling the structural and design requirements for use as a standard and comfortable living space. However, their use is only viable if they reduce environmental pollution (Robinson & Swindells, 2012), reduce energy consumption, construct costs, and increase project delivery (Mammadov, 2015). There are many shipping container studies and buildings around the world, but the area of energy efficiency, especially in a changing climate is lacking. Container homes, when designed as nearly zero-energy buildings, are significant towards the drive for a climate-neutral building stock (Koke et al., 2021).

1.1 Study Objectives

This study looks to reduce the global warming impact of a single shipping container home in future climates using fabric insulation and optimisation techniques as the first phase to aid future research in mass housing with containers. The objectives include:

I. To evaluate the influence of Corten steel, which forms the envelope of shipping containers, on indoor temperature variance and energy consumption in container homes, with the goal of mitigating the impacts of global warming on residential comfort and sustainability in future climates.

II. To assess the combined effects of polyurethane and polyisocyanurate insulation on the energy efficiency of shipping container homes, highlighting their role in enhancing thermal comfort and providing sustainable climate adaptation solutions.

III. To explore various design strategies, including insulation and shading techniques, and their impact on indoor thermal comfort and energy requirements in shipping container homes, thereby establishing principles for efficient and sustainable mass housing using containers in the context of climate change.

2. Background Overview

The challenge of resource efficiency and environmental sustainability has become the consensus of architecture globally (Sun et al., 2017). The global construction industry is moving towards reuse, recycling and low-cost buildings with the adoption of shipping container houses gaining prominence (Hassan et al., 2022). Few people are familiar with container housing; some even find it inappropriate as a dwelling unit.(Tamiru, 2022). Container Architecture is “a type of architecture transformed from the steel intermodal containers” (Sun et al., 2017). In another term, El Messeidy (2018) refers to it as “Cargotecture” when used as a structural and architectural element that can accommodate human activity. Generally referred to as “Containers” for short, they are predominantly made from Corten steel with high resistance to corrosion and oxidation (Bowley & Mukhopadhyaya, 2017; Leton, 2023; Shen et al., 2019; Thanekar et al., 2022).

One of the disadvantages of using containers for housing is their limited size and difficulty in workability (Bowley & Mukhopadhyaya, 2017). As opined by Tamiru (2022), the lack of expertise to handle container reformation in developing countries remains a challenge. Furthermore, Blanford and Bender (2020) affirm that finding the right engineer for container modification is difficult. While opportunities for recycling, reuse and modification of containers are still being explored, there are opinions that their construction cost, flexibility and affordability remain valid only for small-scale projects.

In Nigeria, recycling containers for residential buildings is not a norm (Obia, 2019). The lack of awareness and acceptability has been found to limit their use, especially in warm and humid climates (Oviya & Amraotkar, 2023). Industry stakeholders are yet to embrace the potential of recycling these containers. This is one of the reasons some countries and regions have yet to take advantage of their availability to solve housing needs. A typical case is Lagos state, Nigeria, where the population growth does not commensurate with the available housing structure. The biggest concern for widespread acceptability in hot-humid climates is thermal comfort (Persada, 2020) because, in hot periods, these containers can be unbearably hot (Leton, 2023). In the context of providing shelter for IDPs in south-south Nigeria, some strategies to make containers comfortable for living include adding or extending the roof, insulating the interior surfaces and creating a double or extra wall system (Obia, 2020; Obia, 2019). With reference to Figure 1 below, it implies that the flat roof of the container will need insulation, and an extra roof with overhangs. At the same time, the side panels will need to be insulated internally or externally.

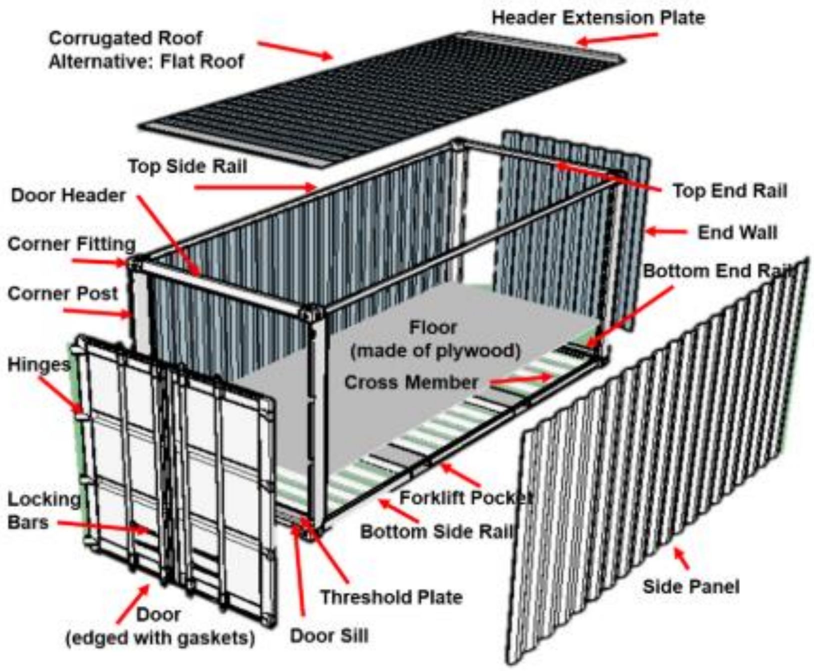

Figure 1 Schematic diagram of a standard shipping container Source: (Shen et al., 2019)

2.1 Insulation

The drawback of using a container for a home is its high thermal discomfort when installed without insulation (Leton, 2023; Primasetra, 2019), especially when trying to meet passive design standards. As asserted by Risnandar and Primasetra (2021), thermal considerations are the most critical when considering containers for residential use. Insulating the building fabric has been found to significantly regulate indoor temperature of buildings, leading to a cooler indoor environment (Alegbe, 2023). However, adding insulation to the interior of a container makes the space smaller and, when stacked together or joined for an elaborate room, raises thermal bridging fears (Bowley & Mukhopadhyaya, 2017). For container buildings to be habitable, insulation is an irreplaceable necessity (Elrayies, 2017; Leton, 2023) as it not only helps to increase thermal resistance but also reduces the stress on mechanical cooling systems (Jamaludin et al., 2021). As a consequence, where insulation is not provided, the high thermal conductivity of steel will increase the energy cost of the building (Mammadov, 2015)

A review on container buildings suggests numerous materials which can be used for insulating the walls. Their use, however, depends on factors such as climate, location, material availability, expertise and application surface (interior or exterior). Although insulating the outside diminishes the aesthetic appeal of the container, studies show that it is comparatively cheaper. Insulation can be made thick by using rock wool, cellulose, glass fibre or foam (Bowley & Mukhopadhyaya, 2017). The drawback of this method is that the insulation needs to be framed to protect against the weathering effect.

In addition, a study by Tong et al. (2022) in Beijing compares the performance of insulation materials like rock wool, extruded polystyrene (XPS), polyurethane and high-performance vacuum insulation panels (HVIP). Findings from the study show that the HVIP material can help conserve the space in the container due to its comparatively reduced thickness. Notwithstanding, not all insulating materials are thermally suitable for use in container buildings. For example, bamboo for insulating the interior is found to be incompatible with the equatorial climate, as investigated by Jamaludin et al. (2021) due to increased humidity levels. In the same way, Elrayies (2017) infers that while wool and cotton are eco-friendly insulation materials, they may lead to interstitial condensation.

3. Methodology

The study uses a 40-foot High-Cube container as a base model for planning and simulating a residential dwelling under future climate projections. The dwelling unit consists of a bed space (West-facing), a toilet, a kitchenette, and a living space (East-facing), as shown in Figure 2 below. The building is placed with the longer side along the West-East axis. Windows were placed on the North and South sides to minimise solar gains, avoiding the West and East sides entirely. Also, windows for the model are placed only on the North and South sides and away from the corner posts. Blanford and Bender (2020) emphasise the importance of maintaining structural integrity when modifying shipping containers. These initial considerations are essential because the orientation, structure, window properties and location of a shipping container affect users' thermal comfort (Thanekar et al., 2022). While the modular design of shipping containers allows for flexibility in the placement of windows and orientation (Karadag & Keskin, 2021), Zafra et al. (2021) suggest placing openings for windows and doors far from the corner posts to reduce the strain of the container. Table 1 shows the sizes of containers according to ISO standards.

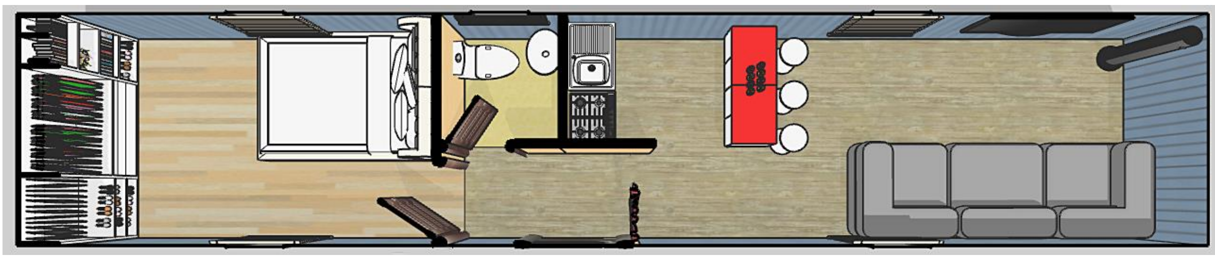

Figure 2 Plan view of the container model

Table 1 Iso Container Sizes. Source: (Laksitoadi & Syarif, 2020)

		20' High-Cube Container	40' High-Cube Container	45' High Cube Container	20' Container	40' Container
Exterior Dimensions	Length	6058 mm	12192 mm	13176 mm	6058 mm	12192 mm
	Width	2438 mm	2438 mm	2438 mm	2438 mm	2438 mm
	Height	2896 mm	2896 mm	2896 mm	2591 mm	2591 mm
Interior Dimensions	Length	5898 mm	12032 mm	13556 mm	5898 mm	12032 mm
	Width	2344 mm	2344 mm	2344 mm	2344 mm	2344 mm
	Height	2695 mm	2695 mm	2695 mm	2385 mm	2385 mm
Floor Area		13.82 m²	28.20 m²	31.78 m²	13.82 m²	28.20 m²

3.1 Location and Meteorological Data

The Federal Capital Territory of Nigeria, Abuja and the commercial city of Lagos are adopted for the study experiments based on the emerging trend of using shipping containers for residential and commercial use in these locations. The hypothetical container building in Abuja is located at coordinates 9.0765°N, 7.3986°E and an elevation of 457 meters above sea level. In contrast, the container building in Lagos is situated at coordinates 6.6018°N, 3.3515°E with an elevation of 13 meters above sea level. The existing terrain, vegetation and structures were not considered during the simulation. In addition, hourly climate data for the locations were generated using Meteonorm v8.2.0. Specifically, EnergyPlus files for RCP 8.5 in 2080 were collected from the weather file generator. Annual dry bulb temperature, relative humidity, wind speed and direction and global radiation and illumination data were used for simulation in the energy assessment tool.

3.2 Simulation, Calibration and Evaluation of Model

3.2.1 Simulation Software and Parameter Calibration

In this study, DesignBuilder version 6.1.0.006, which incorporates EnergyPlus 8.9, was employed as the primary simulation software for creating and analysing detailed building models. DesignBuilder's integrated platform facilitated the intuitive creation of comprehensive models, including building geometry, material properties, internal loads, HVAC systems, and environmental conditions. By utilising the integrated EnergyPlus engine, in-depth simulations of energy flows, specifically focusing on cooling, lighting, and ventilation was conducted. These simulations allowed for iterative adjustments to optimise building performance, thereby ensuring accurate predictions of energy consumptions and thermal comfort.

The calibration of parameters in DesignBuilder involved various settings categorised under different sections, including Activity, Construction, Openings, Lighting, and HVAC. For the Activity settings, the "TM59_2-Bedlivingkitchen" template was used. The occupancy density was set at 0.0722 persons per square meter, which corresponds to two persons per occupied floor area of the case building. A metabolic rate of 1.0 met, typical for an adult male, was used, and no holiday schedule was assigned to enable a full-year assessment. The cooling set point was adjusted to 25°C, with a cooling setback of 28°C. The minimum fresh air supply was set at 10 litres per person. A lighting target illuminance of 100 watts was used, and electricity from the grid was the sole fuel source for the building model.

In the Construction settings, the "Uninsulated, Lightweight" template was applied, using Corten steel for walls, floors, and ceilings in the initial simulation. For the Openings, a 30% window-to-wall ratio was maintained, with windows 1.5 meters high and a sill height of 0.8 meters. The windows were installed with aluminium frames without thermal breaks, having a frame width of 0.04 meters.

Regarding the Lighting settings, the general lighting was calibrated to 5.0 watts per square meter per 100 lux, using suspended luminaires. Exterior lighting was scheduled to turn off during the daytime.

Lastly, the HVAC settings incorporated a mixed-mode ventilation template to reflect typical conditions where both mechanical and natural ventilation methods are used. Cooling was powered by electricity from the grid, and no heating was implemented in the model. The cooling system's seasonal coefficient of performance (CoP) was 1.8, and natural ventilation was defined by zone, with a rate of 5 air changes per hour (ac/h).

This detailed approach to simulation and parameter calibration in DesignBuilder provided a robust foundation for assessing and enhancing building energy performance, ensuring the accuracy and reliability of the findings.

3.2.2 Evaluation Process for Thermal Comfort and Energy Performance Testing

The evaluation process for testing the thermal comfort and energy performance of the container followed a four-stage approach as described below:

I. Stage 1: Base Model Simulation

To establish a benchmark for comparison with future climate scenarios and evaluation of adaptation strategies, the case model underwent modelling using contemporary weather data specific to the locations. The parameters of the case model are detailed in Table 2 below, featuring a floor area of 27.7m² and a volume of 74.7m³. In the initial stage of simulation, the model used a 6mm clear single-glazed window fitted with aluminium frames and internal blinds with medium reflectivity slats suitable for the study area. Additionally, a 0.6m roof overhang was incorporated around all sides of the container to provide shading.

II. Stage 2: Model Simulation under Future Climate Scenarios

In Stage 2, the base model in its original fabric envelope was simulated using imported EnergyPlus (epw) weather files projected for the year 2080 for both locations. This simulation aims to assess how the container's thermal comfort and energy performance might be affected by anticipated future climate conditions. The base model parameters remain unchanged from Stage 1, ensuring consistency in the building envelope and internal configurations. However, the key variation lies in the weather data input, which reflects the climatic conditions projected for the future.

III. Stage 3: Insulation and Optimisation

The base model in this stage had the steel walls and ceiling fitted with polyurethane foam and polyisocyanurate board insulation. As suggested by Elrayies (2017), polyurethane insulation is effective and compatible with a hot-humid climate. The insulated wall has a combined thickness of 73mm with a U-value of 0.284 w/m²k, reducing the total occupied floor area by approximately 7% to 25.73m².

Table 2 Case Building Parameter

	Fabric	Conductivity (w/m-k)	Specific Heat (J/Kg-k)	Density (Kg/m³)	U-Value (w/m²k)
Wall, Ceiling and Floor	3mm ISO 10456 Steel	17	460	7900	5.876
Floor Finishes	25mm Plywood	0.15	1420	700	2.969
Partition	75mm Wood/Gypsum Board	0.25	1000	900	1.887

IV. Stage 4: Design Strategies Implementation

In the Final stage, some key design strategies (see Figure 3) suggested by Architecture2030 (2021) for the study locations were implemented. They include extended overhangs (see Figure 3-A) to shade exposed walls, high-performance window glazing (see Figure 3-B) and shading for windows (see Figure 3-C). Roof overhangs were designed to span an added 1.2m. Windows were fitted with external 0.5m louvres, side fins, and overhangs, while the original glazing was replaced with double-coloured glazing with a 0.146 total solar transmission value (SHGC). The simulations were carried out under HVAC conditions with no heating. The results of the simulation are a function of the Predicted Mean Vote (PMV) model, ASHRAE's recommendation for the zone in which most people feel comfortable.

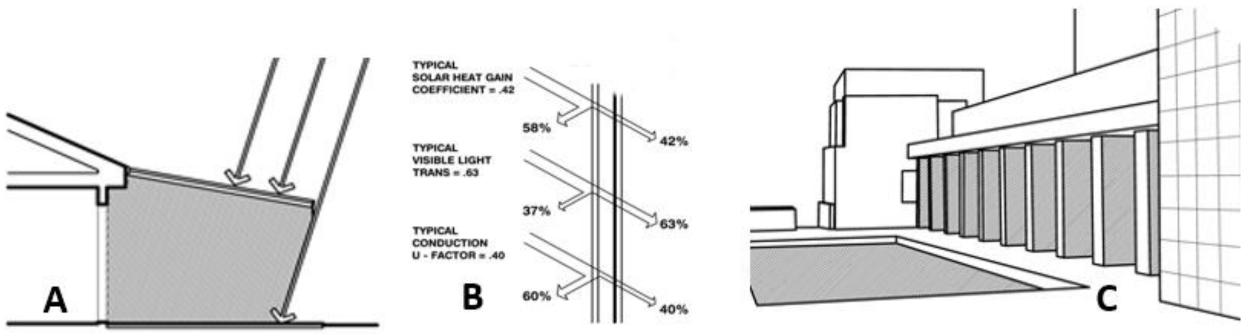

Figure 3 Key Design Strategies used in the experiments. Source: (Architecture2030, 2021)

4. Results and Discussion

Studies such as Nyong and Niang-Diop (2006) and Alegbe and Mtaver (2023) have highlighted the increasing prevalence of extreme weather conditions, which could result in higher temperatures in the study area. Therefore, the evaluation of the container home placed particular emphasis on its adaptation to potential future climate scenarios.

4.1 Results

A comparison has been established between Stage 1 and Stage 2. The result is presented in Table 3 below.

Table 3 Base Model Performance Evaluation- Current and Future Climate Scenarios

	Contemporary		**2080**	
Parameters Evaluated	**Abuja**	**Lagos**	**Abuja**	**Lagos**
Bedroom hours above 28⁰C	1,483.50	1,282.00	3,158.00	3,093.50
Livingroom hours above 28⁰C	1,543.50	1,166.50	3,372.00	3,297.00
Mean annual operative temperature (⁰C)	25.17	25.28	27.37	27.52
Energy per total building area (kwh/m²)	223.56	245.07	319.92	361.30
cooling energy (kwh/m²)	198.76	219.94	295.12	336.15
lighting electricity (kwh/m²)	24.80	25.13	24.80	25.14

Evaluating the base model's performance across current and future climates provides significant insights into its thermal comfort and energy efficiency. In both Abuja and Lagos, the hours exceeding 28°C in bedrooms and livingrooms are significantly impacted by future climate scenarios, with a projected increase of up to 59% by 2080. This escalation suggests a potential rise in discomfort due to higher temperatures, underscoring the urgency for adaptive strategies to mitigate heat gains within the container. Additionally, the mean annual operative temperatures exhibit a marked increase of 8% from contemporary to future projections in both cities. By 2080, Abuja and Lagos are expected to experience an average rise of approximately 2°C in operative temperatures, highlighting the mounting heat challenges facing the base model. This temperature increase not only affects occupant comfort but also drives up cooling energy demands, with corresponding upticks of about 32% and 34% in cooling energy consumption per square meter for the Abuja and Lagos models respectively.

Furthermore, the energy consumption metrics illustrate the strain of heightened temperatures on building operations. Across both cities and scenarios, there is a demonstrated increase of over 30% in overall energy use per square meter, primarily due to elevated cooling demands. This trend underscores the critical necessity for adaptive strategies aimed at enhancing energy efficiency and reducing reliance on mechanical cooling systems, particularly in light of rising temperatures and their associated economic and environmental costs.

To elaborate on these findings, the succeeding sections provide a comprehensive analysis of comfort, energy performance, and embodied carbon across Stages 2, 3, and 4. These sections delve into how each stage influences the container models' thermal comfort for occupants, energy efficiency in operational use, and the embodied carbon footprint associated with their construction and materials. The comparative data presented in Tables 4-6 offer insights into the evolution of these key performance metrics throughout the stages of evaluation.

4.1.1 Comfort

Research conducted in tropical regions shows that people generally find 28^{0}C to be a comfortable temperature (Jegede & Taki, 2021; MOP, 2016). Despite the simulations being based on climate projections for 2080 (accounting for a leap year), the discomfort hours outlined in Table 4 for both the bedroom and livingroom were computed for the typical annual duration of 8760 hours. Furthermore, this study provides insights into the mean building temperature throughout the year, specifically during the hottest month, March, for the three simulation stages in both locations.

Table 4 Comfort and Operative Temperatures

	ABUJA			LAGOS		
	Stage 2	**Stage 3**	**Stage 4**	**Stage 2**	**Stage 3**	**Stage 4**
Bedroom Hours above 28^{0}C	3158	668	21	3093.5	740	6
Livingroom Hours above 28^{0}C	3372	442	24.5	3297	449	10.5
Mean Annual Operative Temperature (^{0}C)	27.37	24.66	24.03	27.52	24.93	24.28
Mean Operative Temperature for March (^{0}C)	29.48	25.57	25.11	28.88	25.88	25.21

4.1.2 Energy

The total energy consumption for the buildings at different stages has been compiled and is presented in Table 5 below. These results encompass the total building energy usage under HVAC conditions, including both cooling and lighting energy, which collectively contribute to the overall energy consumption of the buildings.

Table 5 Energy Consumption during the Different Stages of the Models

	ABUJA			LAGOS		
	Stage 2	**Stage 3**	**Stage 4**	**Stage 2**	**Stage 3**	**Stage 4**
Energy per Total building area (kwh/m^2)	319.92	104.65	80.61	361.3	118.22	88.35
Cooling Energy (kwh/m^2)	295.12	78.7	54.65	336.15	91.91	62.04
Lighting Electricity (kwh/m^2)	24.8	25.95	25.96	25.14	26.31	26.31

4.1.3 Embodied Carbon

The embodied carbon of the container building at various stages is presented in Table 6 below. The calculation assumes identical material usage across different locations, with no specific adjustments for emissions prior to the building's use stage. Consequently, the emission values remain consistent between locations but show a significant increase as additional materials are introduced in subsequent stages.

Table 6 Carbon Emissions of the Models

	ABUJA & LAGOS		
	Stage 2	**Stage 3**	**Stage 4**
Embodied Carbon ($kgCo_2$)	19307.4	19486.5	19770.6

4.2 Discussion

The detailed results illustrate that shipping container homes in Abuja and Lagos respond differently to insulation and shading interventions due to their distinct climatic conditions. Abuja, with its inland position and higher elevation, experiences lower humidity and more significant temperature fluctuations, benefiting greatly from insulation and shading, which reduce daytime heat and promote cooler nights. In contrast, Lagos, characterised by high humidity and consistent temperatures due to its coastal location, faces a constant heat load, making these interventions less effective overall but still beneficial. The findings underscore the need for climate-specific adaptations to optimise comfort and energy efficiency in different regions.

4.2.1 Thermal Comfort and Adaptation Strategies

The results obtained from the Predicted Mean Vote (PMV) model highlight the substantial challenge of achieving thermal comfort in container homes by the year 2080 under projected climate conditions for Abuja and Lagos. In Abuja, maintaining thermal comfort will require cooling and dehumidification for 71% of the 8,760 annual hours, with window shading essential for 31% of the time. The requirements in Lagos are even more stringent, with cooling and dehumidification needed for 98% of the annual hours and shading for 28.8% of the period. This high cooling demand reflects the extreme heat and humidity projected for Lagos, exacerbating the challenge of maintaining indoor comfort.

The introduction of polyurethane foam and polyisocyanurate board insulation significantly reduced annual discomfort hours by 79% in West-facing and up to 87% in East-facing spaces in both cities. The referenced comfort temperature of 28°C are based on a study by Jegede and Taki (2021) for this climate. When added strategies such as shading and optimised window glazing were implemented, discomfort hours were reduced to 6 annually in Lagos and 21 in Abuja, indicating that with proper insulation, container homes can be nearly comfortable year-round, effectively addressing the projected rise in ambient temperatures. Furthermore, the average operative temperature during the hottest month of March was reduced by up to 4°C in both cities (Table 4), showcasing the effectiveness of insulation in moderating indoor temperatures. This finding aligns with research carried out by Ishan et al. (2019) and Oviya and Amraotkar (2023) that emphasise the critical role of insulation in enhancing thermal comfort in buildings.

4.2.2 Energy Efficiency and Reduction Measures

The uninsulated container home exhibited high energy consumption due to significant heat transfer through the steel walls of the container. The high thermal conductivity of steel resulted in elevated cooling demands to maintain indoor comfort, particularly during the hottest periods of the year (Table 5). Adding polyurethane foam and polyisocyanurate board insulation reduced energy consumption by up to 67% in both cities. Corroborated by studies done by Alvarez-Feijoo et al. (2020), Robinson and Swindells (2012), and Tong et al. (2022), this significant reduction highlights the importance of high-performance insulation in minimising energy requirements for cooling in hot climates.

The integration of advanced shading devices and high-performance window glazing in Stage 4 further reduced energy consumption by up to 76%, with more pronounced savings observed in Lagos due to its higher cooling load requirements. The optimised container model in Lagos demonstrated a greater need for energy efficiency measures compared to Abuja (Figure 4), reflecting the more severe thermal conditions in Lagos. This highlights the necessity of location-specific strategies to optimise energy performance in container homes. In cold climates, energy savings can be higher than the results presented in these locations. A study by Sun et al. (2017) in the cold regions of China accounts for up to 90% in energy savings when the performance of regular containers was compared to optimised alternatives. Although widely accepted as a green building entity, the low thermal properties of container buildings compared to conventional buildings greatly hinder their energy-saving potential, especially in future climates (Suo et al., 2023).

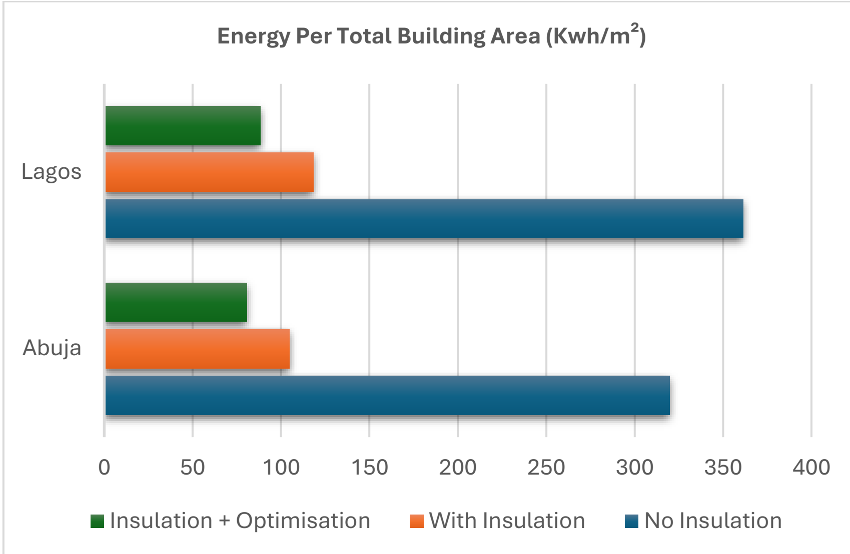

Figure 4 Energy consumption in the container models

4.2.3 Broader Implications for Sustainable Housing

The findings highlight the potential of shipping container homes as a sustainable solution for housing in regions facing significant climate challenges. The effective reduction in discomfort hours and energy consumption through adaptive measures demonstrates the viability of container homes as part of climate-resilient housing strategies. This aligns with the global push towards sustainable building practices and the reduction of carbon footprints in the residential sector.

The use of repurposed shipping containers offers a cost-effective alternative to traditional construction methods, significantly reducing overall construction costs and material waste. This approach supports the principles of a circular economy, promoting the reuse and recycling of materials to minimize environmental impact (Madkour, 2017). While the addition of insulation and other materials slightly increased the embodied carbon of the container buildings, the long-term benefits of reduced operational energy consumption outweigh this initial increase. The optimised container model showed a marginal increase in embodied carbon by about 2.34% compared to the uninsulated model with 19307kgCO_2 of embodied carbon (Table 6), a small trade-off for the substantial energy savings achieved.

4.2.4 Limitations and Future Research

The study's focus on Abuja and Lagos limits the generalisability of the findings to other regions with different climatic conditions. Future research should expand to include a broader range of locations to provide a more comprehensive understanding of the performance of container homes in diverse climates.

Also, the simulation models did not consider the impact of surrounding environmental features such as vegetation, and adjacent structures, which could influence the thermal performance and energy consumption of the container homes. Incorporating these factors in future studies could provide more accurate predictions of building performance. Future research should focus on long-term assessments of the impacts of various climate scenarios on the thermal comfort and energy efficiency of container homes. This includes studying the effects of changes in precipitation patterns, extreme weather events, and seasonal variations on the performance of container homes. Further investigation into new and emerging insulation materials and technologies is necessary to identify more efficient and sustainable solutions for enhancing the thermal performance of container homes. This could include exploring the use of high-performance vacuum insulation panels, phase change materials, and other innovative insulation solutions.

5. Conclusion and Recommendations

5.1 Conclusion

This study shows that shipping container homes can substantially reduce discomfort hours and energy consumption through adaptive measures. These findings emphasise their viability as a sustainable housing solution amid climate change. Effective integration of advanced insulation and shading strategies is pivotal for enhancing their thermal performance and energy efficiency. The use of recycled materials, particularly repurposed shipping containers, plays a critical role in mitigating global warming impacts and reducing environmental waste. While concerns persist about their adaptability to future climates and meeting carbon emission goals, this study's comprehensive assessment of thermal comfort strategies in tropical climates reveals promising results. Enhancements in window glazing, wall insulation, and shading significantly decreased discomfort hours and lowered energy demands. The key findings of the study are summarised as follows:

I. The study found a significant decrease in annual discomfort hours (temperatures exceeding 28°C) in the interior spaces of the buildings. This reduction went from approximately 38% to as low as 0.1%.
II. During the hottest month, the mean operative temperature within the buildings dropped by about 4°C, enhancing indoor comfort.
III. The study observed a remarkable decrease in overall energy consumption, with reductions reaching up to 76%. Cooling energy constituted approximately 70% of total energy use.
IV. Despite the higher overall energy consumption in Lagos compared to Abuja, significant energy savings were noted, demonstrating the effectiveness of the energy-saving measures.
V. Implementing energy reduction and comfort strategies resulted in a slight increase of 2.3% in the embodied carbon energy of the buildings.

These outcomes highlight effective strategies for bolstering the sustainability and resilience of container homes, contributing to global efforts to minimize carbon footprints. However, uncertainties remain about the long-term viability of repurposed shipping containers post-service life. Therefore, future research should include a comprehensive lifecycle assessment to inform ongoing advancements in container home sustainability.

5.2 Recommendations

I. To foster the adoption of shipping containers for housing, policymakers should establish frameworks that incentivise advanced insulation and shading strategies in container home designs. This could include subsidies for retrofitting existing structures, tax incentives promoting sustainable building practices, and regulations encouraging the use of recycled materials in construction.

II. Architects and builders should prioritise high-performance insulation and strategic shading to optimise thermal comfort and energy efficiency in container homes. Particularly, careful consideration of window placement to minimize solar heat gains and the implementation of shading devices are crucial. Caution is advised regarding elevating container homes on platforms in this climate, as this may increase cooling loads depending on specific climate conditions.

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