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INTEGRATING MULTI-OBJECTIVE OPTIMISATION AND LIFE-CYCLE ASSESSMENT IN EARLY-STAGE BUILDING DESIGN

RESEARCH ARTICLE[1]

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ABSTRACT

The built environment is responsible for roughly 40% of global carbon emissions, compelling the need for targeted strategies that address impacts across the building life cycle. Early-stage building design still lacks integrated optimisation frameworks that quantify how material choices and envelope configurations influence life-cycle emissions and thermal comfort. This gap is critical in tropical climates, where the interaction between thermal mass, envelope performance, and operational loads is complex. Each stage of a building's life cycle generates different carbon profiles. Designers often rely on single-metric assessments, leading to design decisions that appear sustainable but perform poorly across the full life cycle. This study develops a combined multi-objective optimisation (MOO) and life-cycle assessment (LCA) method to evaluate and balance these competing objectives across alternative design scenarios. A DesignBuilder (V6) MOO algorithm was applied to an existing tropical case building constructed with sandcrete blocks. Two optimised substitutes were developed: one combining burnt brick external walls with a clay slate

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roof, and another with burnt brick external walls with a green roof. Preliminary simulations show that, although material substitution reduced embodied carbon, it increased operational carbon and worsened thermal discomfort. The optimisation processes generated 626 iterations and yielded 57 non-dominated solutions, with Pareto front analyses revealing a complex interplay between design variables and performance outcomes. Subsequent LCA of the buildings using OneClick LCA revealed that horizontal structural elements accounted for up to 89% of embodied carbon in the A1-A3 (materials) stages. While embodied carbon represented 19% of total life-cycle emissions in the case building, operational carbon dominated overall impacts, reaching 87% in the second optimised building. The study concludes that Pareto-based multi-objective optimisation presents a robust framework for navigating conflicting design goals. However, it must be integrated with life-cycle evaluation to identify design interventions that can deliver the greatest environmental and thermal performance gains.

ABSTRAK

Die bou-omgewing is verantwoordelik vir ongeveer 40% van globale koolstofvrystellings, daarom die behoefte aan geteikende strategieë wat die impakte oor die gebou se lewensiklus aanspreek. Vroeëstadium-gebouontwerp het steeds nie geïntegreerde optimeringsraamwerke wat kwantifiseer hoe materiaalkeuses en omhulselkonfigurasies lewensiklusvrystellings en termiese gemak beïnvloed nie. Hierdie gaping is krities in tropiese klimate, waar die interaksie tussen termiese massa, omhulselprestasie en operasionele laste kompleks is. Elke stadium van 'n gebou se lewensiklus genereer verskillende koolstofprofiele. Ontwerpers maak dikwels staat op enkelmetriese assesserings, wat lei tot ontwerpbesluite wat volhoubaar lyk, maar swak presteer oor die volle lewensiklus. Hierdie studie ontwikkel 'n gekombineerde multi-doelwit optimering (MOO) en lewensiklusassessering (LCA) metode om hierdie mededingende doelwitte oor alternatiewe ontwerpscenario's te evalueer en te balanseer. 'n DesignBuilder (V6) MOO-algoritme is toegepas op 'n bestaande tropiese gevalgebou wat met sandbetonblokke gebou is. Twee geoptimaliseerde plaasvervangers is ontwikkel: een wat gebrande baksteen-buitemure met 'n klei-leiklipdak kombineer, en 'n ander met gebrande baksteen-buitemure met 'n groen dak. Voorlopige simulasies toon dat, hoewel materiaalvervanging beliggaamde koolstof verminder het, dit operasionele koolstof verhoog het en termiese ongemak vererger het. Die optimeringsprosesse het 626 iterasies gegenereer en 57 nie-gedomineerde oplossings opgelewer, met Pareto-frontontledings wat 'n komplekse wisselwerking tussen ontwerpveranderlikes en prestasie-uitkomste onthul het. Daaropvolgende LCA van die geboue met behulp van OneClick LCA het aan die lig gebring dat horisontale strukturele elemente tot 89% van die beliggaamde koolstof in die A1-A3 (materiaal) stadiums verantwoordelik was. Terwyl beliggaamde koolstof 19% van die totale lewensiklusvrystellings in die gevallestudiegebou verteenwoordig het, het operasionele koolstof die algehele impak oorheers en 87% in die tweede geoptimaliseerde gebou bereik. Die studie kom tot die gevolgtrekking dat Pareto-gebaseerde multi-doelwit optimalisering 'n robuuste raamwerk bied vir die navigasie van botsende ontwerpdoelwitte. Dit moet egter met lewensiklus-evaluering geïntegreer word om ontwerpintervensies te identifiseer wat die grootste omgewings- en termiese prestasiewinste kan lewer.

1. INTRODUCTION

The construction industry accounts for roughly one-third of energy-related carbon emissions worldwide (IEA, 2019; Liang *et al.*, 2023; UNEP, 2023). These emissions are widely driven by operational energy use and the embodied carbon embedded in the materials and construction processes (Ibn-Mohammed *et al.*, 2013; IPCC, 2023). Efforts aimed at decarbonising the industry in line with climate action are advancing. However, despite the role of embodied carbon in greenhouse gas emissions, decarbonisation strategies are widely concentrated on reducing operational carbon in buildings (Hu, 2023; Khan *et al.*, 2022; Röck *et al.*, 2020). As global climate goals tighten to conform with the Paris Agreement, scholarly and industry-wide measures for achieving carbon neutrality across the construction industry are evolving (Al-Obaidy, Courard & Attia, 2022; Too *et al.*, 2022; ECF, 2020). For instance, optimisation techniques have emerged as an integral approach for evaluating complex design trade-offs for carbon reduction in buildings. According to Schwartz, Raslan and Mumovic (2016: 9) and Yu *et al.* (2015: 8), the multi-objective optimisation (MOO) technique, in particular, permits simultaneous integration of diverse competing design goals, including carbon emission, energy efficiency, indoor comfort, and cost. Its application has shown considerable potential for reducing a building's environmental impact (Bonamente *et al*., 2018; Gan *et al*., 2020; Yigit & Ozorhon, 2018).

Material selection at the early stage of a building plays a crucial role towards life-cycle carbon reduction and shapes the building's carbon profile during its operational and deconstruction phases. In tropical climates, where high ambient temperatures increase cooling demand, the choice of low-embodied carbon materials, along with the building's HVAC system, offers clear potential for improving energy efficiency and reducing emissions throughout its life cycle (Ahmed *et al.*, 2021: 8; Huang *et al.*, 2024: 20; Keyhani *et al.*, 2024: 11,12). However, studies exploring life-cycle carbon reduction through early-stage design interventions remain fragmented (Dossche, Boel & De Corte, 2017; Fenner *et al.*, 2018: 9). Currently, early-stage building design practice lacks integrated optimisation frameworks capable of simultaneously addressing thermal comfort and life-cycle carbon emissions. This study develops a MOO-LCA approach to reconcile these competing priorities by integrating life-cycle assessment with Pareto-based MOO techniques to evaluate carbon-comfort trade-offs in a tropical building in Nigeria. The aim is to determine how early-stage material choices can reduce life-cycle environmental impacts without increasing thermal discomfort. Through this integrated framework, the study advances a design decision-support approach for building performance modelling, where conflicting objectives often influence optimisation outcomes.

2. LITERATURE REVIEW

2.1 Embodied and operational carbon in buildings

In 2021, buildings in the European Union (EU) alone were responsible for nearly 40% of energy use and roughly 35% of greenhouse gas emissions (EC, 2020; EEA, 2023). Compared to the EU, buildings in Africa consume more energy (57%) and contribute significantly to global emissions (32%-75%), marking them as a crucial focus area for advancing environmental sustainability (Melaine, 2023; IEA, 2020). As noted by Akbarnezhad and Xiao (2017: 2), emissions from buildings are divided into embodied carbon (EC) and operational carbon (OC). EC is associated with the extraction, manufacture, transport, and assembly of construction materials, while OC relates to the energy used during a building's life. Influenced by its potential for reducing the carbon footprints of buildings, OC has received far more attention than EC. The focus of OC reduction is through heating, ventilation, and air conditioning (HVAC) systems, insulation, and other energy efficient practices (Pomponi & Moncaster, 2016: 17; Röck *et al*., 2020: 10). However, evidence suggests that this emphasis alone is no longer adequate to drive carbon neutrality in the built environment. As energy efficiency in buildings becomes more feasible, the share of embodied carbon in total life-cycle emissions continues to intensify, with some regions reporting that EC accounts for more than half of building-sector emissions (Zhu *et al*., 2020: 13).

When left unaddressed, embodied carbon can negatively impact both the economic and environmental value of buildings. Javaid *et al.* (2022: 9, 15) assert that EC reduction presents untapped opportunities for cost savings, mainly when combined with efficient construction methods. Yet, balancing operational and embodied carbon often introduces complex design trade-offs, where operational carbon savings may not be justified by an embodied carbon offset in certain design strategies (Wild, 2022). In regions such as Spain, whole-life carbon assessments of buildings have revealed that, while embodied carbon in a residential apartment accounts for roughly one-third of total emissions, using recycled materials and insulating exterior walls led to reduced life-cycle emissions (Izaola, Akizu-Gardoki & Oregi, 2023: 8).

2.2 Building materials and embodied carbon

Globally, the shift towards low-carbon construction has intensified the incorporation of low-embodied carbon materials into building design (Palomar-Torres *et al*., 2025: 14). The main contributors to embodied carbon in buildings are the production of carbon-intensive materials such as concrete, cement, steel, bricks, and insulation. According to life-cycle impact studies, the material stage alone accounts for up to 90% of the embodied carbon in buildings (Li *et al*., 2017). In addition, structural systems such as concrete and steel are found to be the highest emitters, accounting for approximately 36% and 24% of total emissions, respectively (George & Jacob, 2018: 3). From a circularity perspective, the use of low-carbon, reclaimed or recycled material has shown to reduce a building's embodied carbon (Arenas & Shafique, 2024: 1; Carpio & Carrasco, 2021: 11). For instance, substituting concrete with low-carbon alternatives such as fly ash, GGBS-based concrete, and timber composites can significantly cut back embodied carbon (Craft *et al*., 2024). In a study by Gan *et al.* (2017: 11), replacing steel with recycled scrap or electric arc furnace steel led to embodied carbon reduction of up to 60%. A study by Paiva *et al.* (2022) in Brazil shows that bio-based earth mortars mixed with bamboo particles reduced carbon emissions when compared to conventional cement-based mortars.

In pilot projects across sub-Saharan Africa, natural materials such as rammed earth and lime-plastered walls have been useful in construction to reduce environmental impact. Table 1 presents a selection of locally sourced materials and their application in the Nigerian context. These materials are recommended for design strategies that combine carbon-saving goals and climate resilience in tropical contexts (Wiik, Fufa & Andresen, 2018). For multi-floor buildings, the use of prefabricated lightweight timber-based and upcycled materials was found to significantly reduce embodied carbon without compromising thermal performance (Mulya *et al*., 2024). Other strategies adopted in the industry to decarbonise buildings include prioritising adaptive reuse of existing buildings over new construction (Kumari *et al*., 2020), sourcing materials locally with consideration to the carbon intensity of manufacturing processes (Cheng *et al*., 2013), and developing national regulatory frameworks and material databases (Gillespie & McIlwaine, 2021: 8). Nonetheless, it is crucial to note that material selection cannot always be driven by carbon concerns alone, as some low-impact materials may possess high ‘embodied water’ footprints, thus introducing trade-offs that complicate sustainable decision-making (Dixit & Pradeep Kumar, 2022).

Table 1: Low-embodied carbon materials and their application in Nigeria

Material	*Application*	*Description/Benefit*	*Source*
Adobe	Walls	Sun-dried bricks from a mixture of clay-rich soil, water and fibrous material such as straw. Low-carbon, thermal mass, biodegradable, breathable, and high climate resilience	Mora-Ruiz *et al.*, 2025; Mendonça & Vieira, 2022; Polidori *et al.*, 2025
Bamboo and bamboo shingles	Walls, columns, ceilings, shading screens, floors, trusses, roofs, cladding	Fast-growing grass with woody stems. Rapidly renewable, high strength-to-weight ratio, carbon sequestration, lightweight, flexible, weather resistant, biodegradable, locally available	Jacob Lembi *et al.*, 2021; Unegbu *et al.*, 2025; Kumar Boiti *et al.*, 2022; Rincón, Montoya & Archila, 2023
Cellulose insulation	Wall and roof Insulation	Recycled paper or plant fibre treated for fire and pest resistance. Biodegradable, good thermal and acoustic insulation	Pal, Goyal & Sehgal, 2021; Di Luigi *et al.*, 2023
Clay tiles	Roofing, floors	Kiln-fired natural clay shaped into tiles. Lower carbon footprint than concrete or metal roofing, durable with long lifespan, locally available, thermally stable, recyclable, and inert	Le, Whyte & Biswas, 2019; Ayati *et al.*, 2022
Compressed earth bricks (CEBs)	Walls, load-bearing structures	Machine-compressed soil blocks (stabilised or unstabilised). Locally produced, 30%-43% lower embodied CO_2 than sandcrete, cost-effective, high thermal mass	Abubakar *et al.*, 2018; Ojerinde *et al.*, 2018; Obaje, Ciroma & Obaje, 2022; Mora-Ruiz *et al.*, 2025; Preethi & Reddy, 2024; Asman *et al.*, 2020
Cork	Wall and floor Insulation, cladding, acoustic panels	Harvested bark of cork oak, processed into lightweight, resilient material. Renewable and biodegradable, excellent thermal and acoustic insulation, carbon-negative production	Alegbe & Hammed, 2024; Moura *et al.*, 2025
Natural fibres (*e.g.*, rice hulls, cotton husks)	Wall and roof insulation, composite panels	Agricultural by-products processed for thermal/acoustic insulation. Renewable and biodegradable, good thermal insulation	Yakub *et al.*, 2024; Arrigoni *et al.*, 2017

Material	*Application*	*Description/Benefit*	*Source*
Natural plasters (*e.g.*, lime)	Wall and ceiling finishes (internal or external)	Plaster made from lime, sand, and sometimes fibres. Biodegradable, breathable, and moisture-regulating, requires less production energy, recyclable, and non-toxic	Kayan, Jitilon & Azaman, 2021; Malathy *et al.*, 2023; Rodriguez-Navarro *et al.*, 2023; Laveglia *et al.*, 2024
Rammed earth	Walls, floors	Compacted layers of moist subsoil. Durable, fire-resistant high thermal mass, low processing energy	Adeniyi & Mohamed, 2019; Mora-Ruiz *et al.*, 2025; Nouri, Safehian & Mir Mohammad Hosseini, 2023; Venkatarama Reddy, Leuzinger & Sreeram, 2014
Reclaimed timber	Wall cladding, floors, beams, doors	Previously used wood repurposed for new construction. Reduces deforestation, diverts waste from landfills, carbon storage	Greene *et al.*, 2023; Minunno *et al.*, 2021; Felmer *et al.*, 2022; Souaid *et al.*, 2024
Recycled steel and plastic bricks	Walls, partitions, paving	Bricks made from processed post-consumer steel or plastic waste. Reduces virgin material use, durable and weather resistant, recyclable, diverts waste from landfills	Adeniyi & Mohamed, 2019; Olotuah, Olotuah & Olotuah, 2018; Unegbu *et al.*, 2025; Edike, Ameh & Dada, 2020
Rice husk ash (RHA)	Cement substitute in concrete, plaster, floor screed	By-product from burning rice husks, rich in amorphous silica. Reduces cement use and carbon emissions, recycles agricultural waste, enhances durability and resistance to chemical attack	Olotuah *et al.*, 2018; Olumodeji, Ayodele & Oluborode, 2023; Ojerinde *et al.*, 2018; Henry & Lynam, 2020
Straw bale	Wall insulation, structural walls	Compressed blocks of straw from cereal crops, used with timber frames. Excellent thermal insulation, renewable and biodegradable, uses agricultural waste	Koh & Kraniotis, 2021; Yakub *et al.*, 2024; Palladino *et al.*, 2021; Li *et al.*, 2024; Tlaiji *et al.*, 2022
Timber	Structural framing, wall cladding, flooring, roofing, doors, windows	Processed wood from trees used in various building components. Renewable and recyclable, locally available, low embodied energy compared to steel and concrete, carbon sequestration, biodegradable (if untreated)	Alegbe, 2022; Kręt-Grześkowiak *et al.*, 2024; Tupenaite *et al.*, 2023

2.3 Building form and its role in carbon emissions

Building form and other features such as size, orientation, and window properties play a fundamental role in determining the operational energy efficiency of buildings (Chobanov, 2016; Feng *et al.*, 2024). These parameters occasionally exert conflicting influences on the overall performance of buildings. For instance, studies indicate that the window-to-wall ratio significantly impacts carbon emissions, by regulating heat gain in buildings (Hamida *et al.*, 2022: 19; Troup *et al.*, 2019; Wang *et al.*, 2023), while operational energy, needed to maintain indoor comfort, accounts for the most significant share of life-cycle carbon emissions (Iddon & Firth, 2013: 16; Liang *et al*., 2023). These challenges occur due to multiple and sometimes conflicting design goals, which can be resolved through optimisation techniques. Optimising buildings from competing objectives to achieve competing design requirements involves understanding the relationships between building elements and their distinct roles in emission reduction. Schwartz *et al.* (2016: 9) and Seyedzadeh *et al.* (2018: 2) recommend that early-stage building energy evaluation pertaining to form, material choice, and orientation should be prioritised, as each has the potential to influence emissions independently. The practice of evaluating the carbon influence of a building's physical components, widely regarded as the 'fabric-first approach', has proven to be a valuable strategy for reducing embodied carbon emissions (DesigningBuildings, 2021). An integrated approach by Nazari *et al.* (2024: 12) further emphasises that both form and fabric of a building must be considered collectively to properly evaluate emission trade-offs.

2.4 Multi-objective optimisation in building performance evaluation

Since 2010, optimisation techniques have been influential in addressing building energy performance challenges, by conveying critical insights into measures for reducing the environmental impact of both new and retrofit buildings (Costa-Carrapiço, Raslan & González, 2020; Dede *et al*., 2019). Among these methods, the MOO framework stands out as a unique and compelling method because of its capability to evaluate multiple design goals within an optimisation setup (Yu *et al*., 2015). As noted by Chen, Janssen and Schlueter (2018: 7, 8), the application of MOO techniques is particularly effective in achieving defined optimisation targets in energy-efficient and low-carbon building design. In a study by Tavakolan *et al.* (2022), the effectiveness of MOO using simulation-based algorithms was demonstrated in finding optimal design configurations that minimise both energy use intensity and carbon emissions. Likewise, Yigit and Ozorhon (2018: 2) used genetic algorithms within an optimisation framework to identify effective design solutions in building performance evaluation. However, emerging research recognises that MOO techniques can be very complex and often rely on the inherent relationship between design parameters in the simulation environment. Despite advancements in computational methods for building optimisation, many designers struggle to identify an approach that balances building systems and design objectives (Alghamdi *et al*., 2022: 24; Halhoul Merabet *et al*., 2021: 32; Lu *et al*., 2024: 16). This gap stems from limited understanding, computational limits, and insufficient training in optimisation modelling. To achieve the most effective parametric optimisation outcomes, Evins (2013: 10-13) suggests that the process must be iterative rather than linear, for accurate and reliable performance outcomes.

2.5 Pareto front optimisation in multi-objective decision making

The application of Pareto-based optimisation methods has gained significant traction in building performance evaluation to address the complexity in MOO and decision-making. Pareto-based MOO is one of the most feasible approaches that enables designers to navigate numerous design objectives with greater clarity and accuracy (Bre, Roman & Fachinotti, 2020; Chen, Tsay & Ni, 2022). As mentioned by Kesireddy and Medrano (2024), the Pareto front represents a set of optimal design solutions where a design objective cannot be improved without compromising another. By implication, every point on the Pareto front is an outcome derived through the compromise of one design objective for another. Moreover, optimal solutions are uniquely represented on the Pareto graph to inform designers of design outcomes; an approach integral in architectural and engineering design processes, where decisions are not governed by a single criterion.

Bre *et al.* (2020: 6-8) used a metamodel-based optimisation framework, combined with artificial neural networks and NSGA-II algorithm to assess energy performance trade-offs to enable designers visualise Pareto optimal solutions that balance heating and cooling demands. Complemented by a Backpropagation Neural Network, Chen *et al.* (2022: 388) advanced the framework, by integrating carbon emissions, indoor discomfort hours, and cost to support the identification of design solutions and reducing emissions by over 50% without compromising comfort. Okumura *et al.* (2023: 8) demonstrate the use of supervised algorithms in resource-constrained environments to refine Pareto fronts for building facility control, emphasising that, with limited data sets, the optimisation process can yield meaningful outcomes. In the context of renovation strategies, Decorte *et al.* (2020) also used Pareto analysis to compare life-cycle cost, life-cycle assessment, and monetised environmental parameters, revealing a misalignment between financial and environmental goals that are key aspects in growing climate-change pressures. A notable advancement in Pareto-based optimisation is the direct integration of decision-making frameworks into the optimisation process, as illustrated by Kesireddy and Medrano (2024), where non-dominated solutions are ranked according to user-defined objectives.

The reviewed literature highlights the need for an approach that integrates low energy materials, optimised building parameters, and whole-life carbon assessment, in a multi-objective framework to reduce emissions in buildings. Global standards such as PAS2050 and ISO/TS 14067 have pushed the debate on life-cycle carbon assessment forward but the lack of a unified approach to applying these standards across a building's life cycle is limited (Fenner *et al*., 2018). Navigating the interplay of building materials, form, occupancy, and energy use to evaluate performance-based designs is both time- and resource-intensive. With the urgent imperative to reduce emissions in the global built environment, mainly in expanding regions such as Nigeria, integrating life-cycle carbon analysis with MOO at the design stage is essential for informed decision-making towards decarbonisation, aligning with the UN's Sustainable Development Goal 13 (Climate Action). As emphasised by Al-Obaidy *et al.* (2022), the built environment must undergo a profound transformation to meet the ambitious 2050 carbon-neutrality targets.

3. MATERIALS AND METHODS

3.1 Research design

This study adopts a quantitative, simulation-based approach to optimise building design parameters and demonstrate how early-stage material choices interact with building systems to influence both embodied carbon and thermal comfort decisions in tropical buildings in Nigeria. It combines numerical simulations with multi-objective optimisation techniques, aligning with previous research such as Machairas, Tsangrassoulis and Axarli (2014) and Croitoru *et al.* (2016), demonstrating its effectiveness. Nigeria's National Building Energy Efficiency Code (BEEC), developed by the Federal Ministry of Power, Works and Housing, establishes minimum energy efficiency requirements for new buildings and recommends the use of internationally recognised simulation tools endorsed by the American Society of Housing, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the Institute of Electrical and Electronics Engineers (IECC) for energy modelling (New Climate Institute, 2017). In the absence of a country-specific life-cycle carbon assessment framework, this study adopts internationally recognised simulation and LCA methodologies as the basis for early-stage energy modelling and embodied carbon assessment, consistent with prevailing practice among Nigerian building designers who rely on global standards for life-cycle building optimisation. A virtual model was developed using an existing building's as-built material properties, occupancy schedules, and environmental boundary conditions to facilitate a baseline simulation. Using the EnergyPlus engine integrated within DesignBuilder (DB), an initial simulation of the case building was conducted to analyse its thermal comfort and carbon performance. Through Pareto front visualisations in DB, two optimised models of the case building, First Optimisation and Second Optimisation, were created with the goal of enhancing performance through fabric substitution. The models were exported from the DB interface to OneClick LCA tool, where a full life-cycle carbon assessment was conducted to evaluate the impacts of the design alternatives. While DB provides insights into design-performance trade-offs, the OneClick LCA platform offers a granular assessment of embodied and operational carbon distribution across the buildings' lifecycles (Marios, 2024) to guide early-stage design decisions that minimise life-cycle carbon while improving thermal comfort in Nigerian buildings.

3.2 Virtual models and specifications

3.2.1 Case building (base model)

This study used an existing one-floor residential apartment building as the base model for embodied carbon assessment and optimisation. The building is located in Edo State, within Nigeria's South-South geopolitical zone, and consists of a three-bedroom block (Figure 1). It is constructed mainly with 225 mm thick hollow sandcrete block walls and finished externally with cement-sand plaster (Figure 2). A representative digital twin of the building was developed using the original architectural features, including internal layout, floor area, fenestration details, and wall thickness. These were drafted in AutoCAD and subsequently imported into DesignBuilder (DB). DB is a dynamic simulation tool powered by the EnergyPlus engine and supports file sharing and importation to facilitate building energy modelling (DesignBuilder, 2024a). Its graphical interface allows for accurate zoning and parameter definition, supporting performance simulation under varying design conditions.

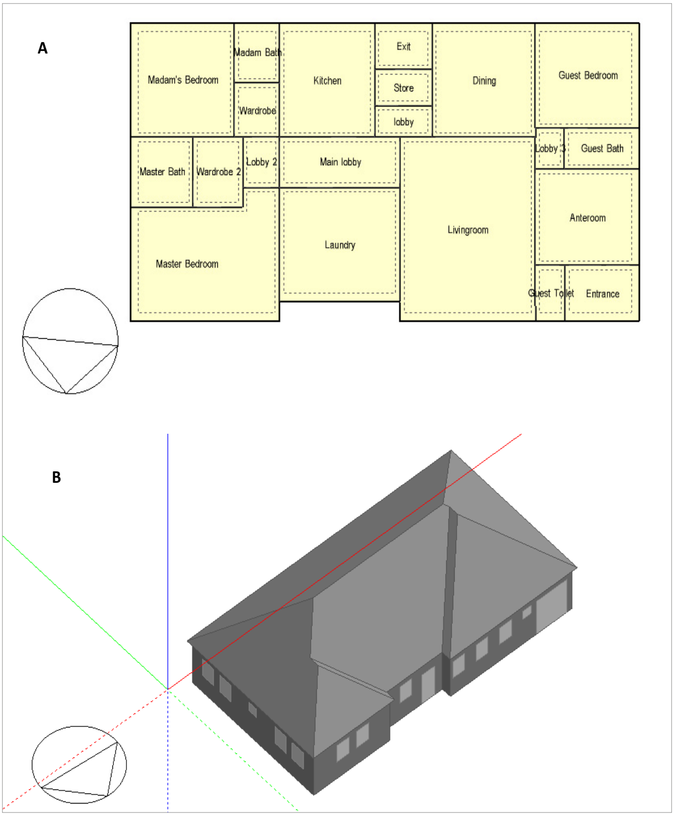

Figure 1: DesignBuilder floor plan (A) and 3D model (B) of the case building

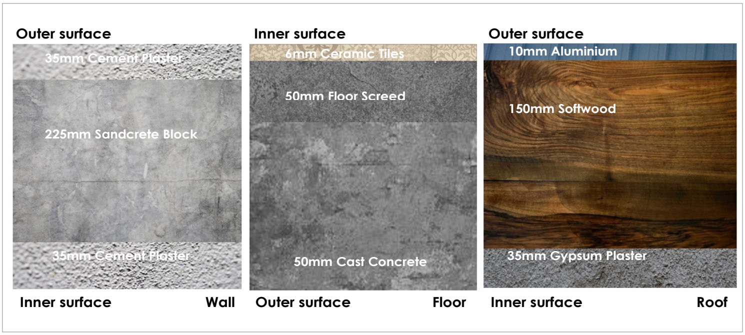

Figure 2: Base model: Wall, floor, and roof composition

The virtual model was configured using the building's as-built properties to facilitate a baseline simulation. Details including wall and roof construction, orientation, HVAC type, lighting loads, and internal gains were systematically defined, as represented in Table 2, while window-to-wall ratio by façade orientation is presented in Table 3.

Table 2: Baseline parameters of case building

Category	*Parameter*	*Specification / Description*
General info	Location	Benin City, Edo State, Nigeria
	Building type	3-bedroom residential apartment
	Occupied floor area	140.5 m²
	Occupied volume	421.4 m³
	Storeys	1
Wall	Wall type	Uninsulated 225 mm hollow sandcrete block (external) and 150 mm hollow sandcrete block (partition)
	Finish	35 mm cement-sand plaster (both sides)
	U-value	1.891 W/m²K
	Embodied carbon	40.15 $kgCO_2e/m^2$
Roof (unoccupied)	Roof type	Pitched corrugated aluminium on timber roof trusses,
	U-value	2.836 W/m²K
	Embodied carbon	275.07 $kgCO_2e/m^2$
Floor	Floor type	150 mm mass concrete floor, finished with 6 mm ceramic tiles
	U-value	2.103 W/m²K
	Embodied carbon	59.47 $kgCO_2e/m^2$
Openings	Window type	Aluminium frame with clear single glazing
	Window-to-wall ratio (WWR)	30% (overall) See Table 3 for façade-to-façade details
	Glazing U-value	6.121 W/m²K
	Solar heat gain coefficient (SHGC)	0.81
	Frame U-value	5.881 W/m²K
Building orientation	Principal façade	South
	Orientation sensitivity	Full variation for simulation scenarios
Internal conditions	Occupancy profile	4 persons, active 24/7
	Occupancy density	0.0284
	Equipment load	5 W/m²
	Lighting load	5 W/m² — within the BEEC permitted maximum of 6 W/m² for residential use
	Infiltration rate	1.0 ACH (air changes per hour)
Mechanical systems	Cooling system	Cooling system COP = 2.5 (Electricity from grid)
	Heating system	None

Table 3: Window-to-wall ratio by façade orientation

Façade orientation	*Total wall area (m^2)*	*Total window area (m^2)*	*WWR (%)*
North facing	50.14	7.34	14.64
South facing	51.24	7.20	14.05
West facing	28.34	2.53	8.93
East facing	31.58	4.68	14.82

The overall 30% WWR stated in Table 2 represents the default value applied during the baseline simulation, with an adjustment range of 10%-80% in search of optimal solutions. The façade-by-façade values in Table 3 reflect the as-built configuration of the case building. For parametric modelling, these baseline characteristics served as the foundation for redefining design variables, *i.e.*, parameters whose values were deliberately varied during the optimisation process to investigate carbon emissions. They include changes in both external and internal wall, variation in roof insulation thickness, modifications to the window-to-wall ratio, and the adjustment of building orientation. This flexibility within the simulation platform supported the identification of configurations that reduced both embodied and operational carbon while maintaining occupant thermal comfort.

3.2.2 Case building optimisation (optimised models)

Two optimised models of the case building (first optimisation) and (second optimisation) were developed with the goal of enhancing performance through fabric improvements. An appraisal of the latest Inventory of Carbon and Energy (ICE) database (Circular Ecology, 2025) guided the selection of low-embodied carbon materials to replace those of the case building. In the first optimised model, the exterior fabric was redesigned, using a layered composition of 100 mm aerated brick, 50 mm cellulose insulation cavity, and a 30 mm cork board interior finish (Figure 3). This new wall configuration has a total thickness of 280 mm, and a U-value of 0.353 W/m²K. Internal partitions were replaced with 100 mm softwood frames finished on both sides with 35 mm cork board, resulting in an entirely wood-based partition system with a U-value of 0.372 W/m²K. In addition, the roof structure in the first optimised model was modified to include four distinct layers including a 15 mm slate outer layer, a 35 mm fibre board insulation layer, timber trusses, and a 35 mm gypsum plaster finish. The resulting U-value of the optimised roof assembly was 0.389 W/m²k. For the floor, timber planks were layered with a vapour sealant, a 35 mm cellulose insulation layer, and a 15 mm cork board finish, achieving a combined U-value of 0.419 W/m²k. The case building windows were substituted with triple-glazed, low-emissivity glass with wooden frames to limit solar gains through windows.

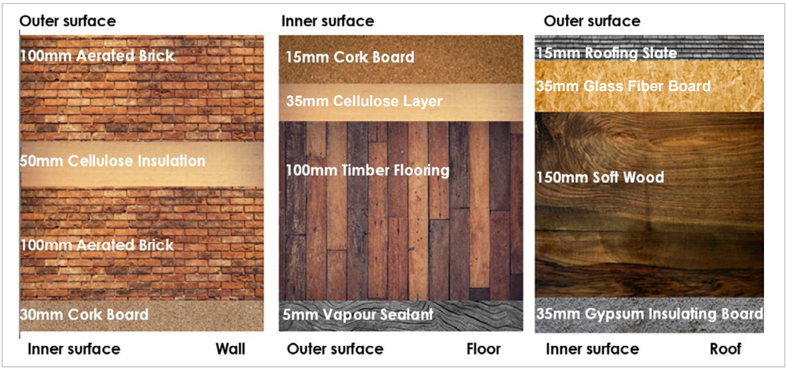

Figure 3: First optimised model: Wall, floor, and roof composition

The second optimised model was developed from the first optimised alternative, by incorporating a green roof system and window shading features. The optimised roof includes a 200 mm plant outer layer, a 50 mm gravel-based soil layer, a 50 mm cork board insulation layer, a butadiene rubber damp-proof membrane, and a 100 mm aerated concrete slab (Figure 4). This configuration yields a slightly lower U-value of 0.336 W/m²K compared to the slate-based pitched roof in the first optimised model. The parameters of the vegetation layer are summarised in Table 4. Key thermal properties of the green roof construction include a thermal conductivity of 0.225 W/mK, specific heat capacity of 1200 J/kgK, density of 1100 Kg/m³, thermal absorptance of 0.95, and solar absorptance of 0.8. In addition, the windows in the second optimised model were equipped with high reflectivity interior blinds, positioned 15 mm from the inner glazing to further reduce solar heat gain.

The overarching aim of the optimised models was to investigate the extent to which fabric material substitution can influence carbon emissions and indoor comfort.

Figure 4: Second optimised model: Wall, floor, and roof composition

Table 4: Green roof construction parameters

Parameter	*Value*	*Units*	*Notes*
Height of plants	0.20	m	Moderate height sedum/native grass layer
Leaf area index (LAI)	3.5	—	Dense vegetation suited for high evapotranspiration
Leaf reflectivity (albedo)	0.20	—	Reflects moderate solar energy, typical for tropical vegetation
Leaf emissivity	0.95	—	High emissivity for effective heat release
Minimum stomatal resistance	100	s/m	Allows high transpiration
Maximum volumetric moisture content	0.50	—	Lightweight green roof media with good retention
Minimum residual volumetric moisture content	0.08	—	Accounts for minimum water holding capacity
Initial volumetric moisture content	0.25	—	Rational value for tropical start-up simulation

3.3 Building simulations and life-cycle assessment

3.3.1 Multi-objective optimisation simulations

An initial simulation of the case building was conducted to analyse its thermal comfort and embodied carbon performance. This step ensured all geometric, material, and operational inputs such as occupancy schedules, climate data, construction layers, and HVAC settings were accurately defined and capable of producing the expected simulation outputs. The preliminary simulation was used not only to validate the accuracy and realism of the base model's inputs, but also to establish a reliable performance baseline. This baseline, therefore, served as a reference for the optimised scenarios. The outputs from this simulation helped identify the most influential parameters for MOO. The simulation employed a standard EnergyPlus Weather (EPW) file generated using the Meteonorm weather file generator, representing typical meteorological conditions for the building's location. The building, situated in a very hot humid climate zone (ASHRAE Climate Zone 1A), is characterised by consistently elevated temperatures and humidity throughout the year (Stackhouse & Westberg, 2015). The life-cycle assessment followed the EN 15978 system boundary framework (British Standards Institution, 2011), capturing potential impacts for a 60-year period for the full A-to-C stages: materials production (A-A3), construction processes (A4-A5), use-stage embodied processes (B1-B5), operational energy (B6), and end-of-life impacts (C1-C4), as depicted in Figure 5.

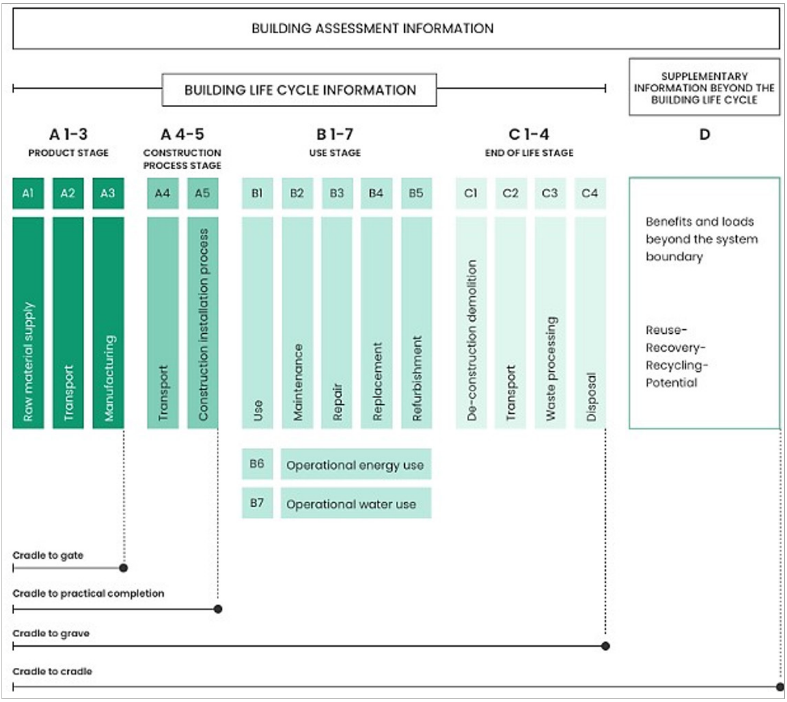

Figure 5: System life cycle boundary diagram illustrating the life-cycle stages included in the assessment.

Source: OneClick LCA, n.d.

A parametric optimisation set-up was configured and managed in DB to facilitate multi-objective decision-making. This process offers a unique opportunity to configure up to ten design variables such as building height, window-to-wall ratio, and glazing type, which can be evaluated in combination with a maximum of two intuitive design objectives such as "minimise carbon emissions" and "minimise energy consumption". This decision approach helps identify design options that best meet performance expectations in the simulation environment (DesignBuilder, 2024b). In DB, two design objectives were stipulated: "minimise LCA carbon" and "minimise thermal discomfort" (Table 5). Thermal discomfort was evaluated based on ASHRAE 55 adaptive comfort model with 90% acceptability (ASHRAE, 2020). The design variables considered were thermal mass, insulation, mechanical ventilation, site orientation, natural ventilation rate, and window-to-wall percentage. The MOO employed the Java Evolutionary Algorithm (JEA), which implements the Non-dominated Sorting Genetic Algorithm II (NSGA-II) with real-valued encoding. This algorithm is fully GUI-based, requires no scripting, has a fast setup time, includes built-in-Pareto front visualisation, and integrates seamlessly with the DesignBuilder simulation Core.

Table 5: Multi-objective optimisation parameters

Parameter	*Value/ Description*
Optimisation algorithm	NSGA-II (Non-Dominated Sorting Genetic Algorithm II), real-valued encoding
Objective functions	Minimise lifecycle CO_2 (kg). Minimise discomfort hours (ASHRAE 55 Adaptive 90%)
Decision variables	Window-to-wall ratio, thermal mass, insulation, mechanical ventilation rate, natural ventilation rate, site orientation
Lower bounds	WWR: 10%; thermal mass: 0; insulation: 0; mechanical ventilation: 0 ac/h; natural ventilation rate: 0 ac/h; orientation: 0°
Upper bounds	WWR: 80%; thermal mass: 2; insulation: 3; mechanical ventilation: 10 ac/h; natural ventilation rate: 12 ac/h; orientation: 355°
Step size	WWR: 2%; thermal mass: 1; insulation: 1; mechanical ventilation: 0.2 ac/h; natural ventilation rate: 0.1–1.0 ac/h; orientation: 5°
Initial population	Randomly generated within bounds
Population size	50 per generation
Number of generations	10 generations per model
Crossover rate	0.9
Mutation rate	0.02-0.05
Stopping criterion	Maximum generations reached
Number of objectives	Two (life-cycle CO_2 + discomfort hours)

3.3.2 Life-cycle carbon assessment – OneClick LCA

One of the limitations of the embodied carbon assessment in DesignBuilder is its inability to account for carbon emissions across all life-cycle stages of the building. Life-cycle assessment (LCA) tools such as OneClick LCA allow for a comprehensive analysis, capturing emissions from raw material extraction through disposal, that is, stages A1 to C4 (Marios, 2024). The models were exported from DB to OneClick LCA tool, where a full life-cycle embodied carbon assessment was conducted, divulging aspects of the building structure, and life-cycle stages that escalate environmental impacts. The embodied energy and emissions data used in the assessment relied on the integrated Environmental Product Declaration (EPD) database within the LCA tool. This database provides standardised material impact factors aligned with EN 15804 and ISO 14040 (British Standards Institution, 2021, 2020), ensuring consistency and compatibility across all material categories evaluated in the study.

4. RESULTS AND DISCUSSION

4.1 Embodied carbon and energy use

The results of the simulation of the case building indicate a total embodied carbon of 107,496.90 $KgCO_2e$ (Table 6). Sensitivity analysis revealed that roughly 54% of the embodied carbon was attributed to the aluminium roofing material, suggesting a key area for substitution with low embodied carbon alternatives. Among the construction entities, the roof, walls, and floors account for 64%, 13%, and 10% of the total embodied carbon, respectively. Further investigation shows that wood-based products such as plywood exhibited the lowest embodied carbon values. Metals such as aluminium have long been identified as major contributors to embodied carbon emissions, due to their energy-intensive production processes (Saevarsdottir, Kvande & Welch, 2020; Farjana, Huda & Mahmud, 2019), thus, minimising their use can significantly lower the overall carbon footprint of buildings (Raabe *et al*., 2022; Teeuwen *et al*., 2024). These findings align with established building energy studies such as Cheng, Zhou and Zhou (2023) and Arceo, Saxe and MacLean (2023), which identify the material production stage as the main contributor to embodied carbon in buildings. Furthermore, structural elements, including roof systems and floor slabs, are widely reported to account for the majority of a building’s upfront embodied carbon (Eleftheriadis, Duffour & Mumovic, 2018).

Table 6: Simulation results

		Case building	*First optimised*	*Second optimised*
Embodied carbon ($KgCO_2e$)		107,496.90	40,207.20	39,274.00
Embodied carbon- primary roof material ($KgCO_2e$)		57,518.10 (Aluminium)	173.20 (Slate)	1,327.30 (Green roof top layer)
Construction elements ($KgCO_2e$)	Roof	68,984.40	9,049.60	6584.40
	Wall (external)	14,039.80	6,354.20	6,354.20
	Floor	11,124.10	6,199.10	6,199.10
Energy per conditioned area (Kwh/m^2)		350.75	471.50	467.38
Cooling load (Kwh/m^2)		145.10	266.19	261.72
Discomfort hours (%)	Bedroom 1 (south-west)	40.45	82.76	81.43
	Bedroom 2 (north-west)	40.18	80.91	79.82
	Bedroom 3 (north-east)	34.83	81.26	80.45

When compared to the case building, the first optimised alternative demonstrates a significantly lower embodied carbon footprint, with a total embodied carbon of 40,207.20 $KgCO_2e$, approximately 63% lower than the case building. This reduction was essentially achieved by replacing the aluminium roofing sheets with slate tiles. The second optimised model, which features a green roof and external window shading, achieved a further reduction, roughly 64% and 2% lower than the case building and first optimised model, respectively. These reductions are consistent with a broader body of evidence, demonstrating that targeted material interventions can deliver substantial embodied carbon savings (Khan *et al.*, 2025; D'Amico, Pomponi & Hart, 2021). The green roof outcome is further supported by previous studies that used green roof construction to reduce the building's environmental impacts, and delivering measurable reductions in net embodied carbon through biogenic carbon sequestration in vegetative layers (Mousavi *et al.*, 2023; Pragati *et al.*, 2023; Nasr *et al.*, 2024).

Operational energy results were evaluated, using site energy outputs from DB, with site-based emission factors applied to convert annual energy consumption into operational carbon. Source energy and upstream generation losses were not included in this study. The energy consumption of the buildings varied across each material optimisation. For instance, the total energy use per conditioned area increased by 34%, from 350.75 Kwh/m^2 in the case building to 471.5 Kwh/m^2 in the first optimised model. A marginal decrease, compared to the first optimised, was noted in the second optimised design, which recorded 467.38 Kwh/m^2. These changes are influenced by the inherent thermal properties of the substituted materials. Precisely, materials such as concrete tend to reduce internal heat gains, due to their thermal mass properties (Kuczyński & Staszczuk, 2020; Salehpour *et al.*, 2023; Hu, Liu & Niu, 2020), while lightweight alternatives, preferred in terms of embodied carbon emissions, often result in reduced thermal inertia, leading to higher operational energy demands (Roque *et al.*, 2020; Rabenseifer *et al.*, 2025). This trade-off between low-carbon material selection and increased operational cooling demand is well documented in building energy research. A study by Peng, Deng and Hong (2019) demonstrates that materials with lower thermal mass are associated with increased indoor thermal discomfort and higher operational energy requirements in residential buildings. While thermal mass plays a crucial role in enhancing indoor comfort, the simulation results suggest that neither of the optimised buildings improves indoor comfort, particularly in the bedrooms. This suggests the need for additional adaptive and material interventions beyond those already applied, as the materials used in the optimised models increased the cooling load of the buildings. Relative to the case building, cooling load increased by 46% in the first optimised model and 45% in the second alternative. The slight reduction in the cooling demand of the second model is attributed to the green roof integration. This location-based result is consistent with previous findings on the cooling potential of vegetated roofs in hot and humid climates (García *et al.*, 2022; Robbiati *et al.*, 2022).

4.2 Pareto-based multi-objective optimisation

The building models were further evaluated using a MOO technique in DB to identify optimal design solutions that balances the goals of reducing life-cycle carbon and discomfort hours. These solutions represent varying compromises between competing design objectives, where the improvement of one objective may supersede the importance or need for the other. The design variables considered include window-to-wall percentage, cooling set-point temperatures, set-back temperatures, site orientation, as well as natural and mechanical ventilation rates. The case building simulation involved 217 iterations, resulting in 43 non-dominated solutions along the Pareto front. The first optimised building passed through 202 iterations, resulting in four optimal solutions, while the second optimised design required 207 continuous iterations to arrive at 10 optimal design solutions, as depicted in Figure 6. These variations in the frequency of optimal solutions across models reflect the complexity introduced by changes in material composition. The Pareto-based simulation of the case building reveals LCA emissions ranging from 1,053,361.40 $KgCO_2e$ to 1,137,109.45 $KgCO_2e$, with corresponding discomfort hours spanning from 8266 to 8461 hours annually (Table 7). A notable inverse relationship was observed among the Pareto solutions, where the design alternative with the lowest carbon emissions coincided with the highest discomfort hours, while the alternative with the highest carbon emissions produced the lowest discomfort hours. This observation underscores the intrinsic nature of Pareto-based optimisation, where achieving gains in one performance metric inevitably compromises another. In such instances, the designer is tasked with evaluating the relative importance of each outcome and selecting a solution that aligns best with the building's performance goals as deeply rooted in current optimisation literature (Bejarano, Espitia & Montenegro, 2022; Kesireddy & Medrano, 2024; Petchrompo *et al*., 2022).

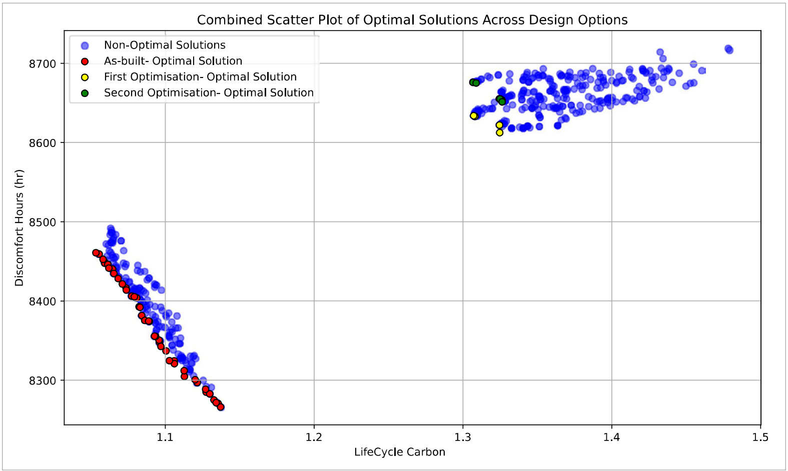

Figure 6: Pareto front solutions for evaluated buildings

Table 7: Pareto-based life-cycle carbon emission and discomfort hours

Building	*Life-cycle carbon emission range (KgCO$_2$e)*	*Discomfort hours range (8760/yr)*
Case building	1,053,361.40-1,137,109.45	8,266-8,461
First optimised building	1,307,160.69-1,324,662.58	8,612-8,644
Second optimised building	1,306,649.47-1,326,282.35	8,651-8,676

As outlined in Table 7, both life-cycle carbon emissions and discomfort hours increased in the optimised buildings. Note that embodied carbon assessment for the optimised alternatives was shown in section 4.1 to reduce, compared to the case building. Conversely, operational energy increased in the optimised model compared to the case building. The core of DesignBuilder simulation focuses on operational energy use (DesignBuilder, n.d.), while pareto-based evaluations account for both embodied and operational emissions across the building's life cycle. The contrast between the first optimised model and the case building reflects a wider trend in performance-based design, where what qualifies as an ideal solution changes as parameters are refined through iterative processes. This evolution aligns with literature such as Brown and Mueller (2018: 6-11), Natanian, Aleksandrowicz and Auer (2019: 5-8) and Sayın and Çelebi (2020: 6-11), advocating for evolutionary, performance-driven design processes to shape the trajectory of optimisation. The challenge of balancing embodied carbon savings against operational carbon and comfort penalties is not unique to this study. A review of residential building LCA studies in humid subtropical and tropical climates found that life-cycle GHG emissions are widely dominated by operational energy, highlighting that material improvements alone are insufficient to achieve whole-life carbon neutrality (Satola *et al.*, 2021). The second optimised design, characterised by a green roof construction, yielded optimal solutions favouring north-facing orientations, higher natural ventilation rates, and comparatively high window-to-wall ratios. Despite having similar designs with the first optimised model, it shows a slightly higher range of life-cycle carbon emissions and discomfort hours, slightly deviating from the comparatively favourable outcome. This result exposes the significance of a multi-objective and life-cycle perspective for building simulation to uncover the challenges to which low-carbon buildings in the tropics can be exposed, and the need for early-stage design optimisation. Green roof systems are acknowledged as technically elaborate and potentially cost-prohibitive in residential buildings, especially in developing economies (Fachinello Krebs & Johansson, 2021). Their inclusion in this study served to explore the full performance envelope alternatives and to test whether the environmental performance gains they offer can justify their complexity. A comparative assessment across all three models suggests that optimal solutions cluster around higher natural ventilation rates and north-to-northwest facing orientations, indicating that passive design strategies could counterbalance the operational and comfort penalties introduced by material substitutions. These findings, while not universally prescriptive due to the complexity of MOO, highlight recurring patterns that can serve as strategic points for design interventions. Again, no single design solution can be universally declared optimal, but these varied patterns point to valuable directions for future explorations into energy-conscious and carbon-efficient building design.

4.3 OneClick life-cycle impact analysis of design alternatives

Reducing life-cycle carbon emissions in buildings requires a comprehensive understanding of the contributions made by different life-cycle stages. A fragmented approach that excludes this integrated perspective risks producing superficial or misdirected carbon-reduction strategies. As highlighted from preliminary simulations, the optimised models have lower embodied carbon through material substitutions, but their overall life-cycle carbon emissions increased (see Figure 6 and Table 7), which is indicative of emissions mainly from operational energy. An integrated LCA (Figure 7) traces emissions across all stages of the buildings from material extraction to end-of-life, providing a more integrated perspective of life-cycle emissions, enabling informed decisions in building optimisation.

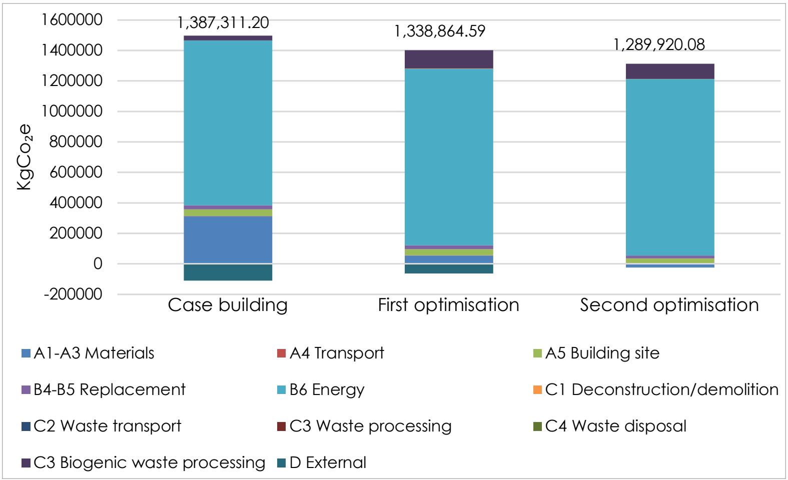

Figure 7: Life-cycle impact of buildings

4.3.1 Material-related carbon emissions

The case building, as expected, recorded the highest embodied carbon emissions, due to its use of carbon-intensive materials. Specifically, its A1-A3 emissions were approximately 82% and 93% higher than those of the first and second optimised models, respectively. This stresses the vital role of material selection in reducing embodied carbon, consistent with past studies, including Chen *et al.* (2023), Hawkins *et al.* (2020) and Lützkendorf and Balouktsi (2022). A particularly noteworthy result emerged from the second optimised model, which showed a negative A1-A3 carbon value of -23,733.23 $KgCO_2e$ (Figure 8). This outcome is attributed to its green roof feature, whose layered vegetative components such as organic growing media and plant biomass provide measurable biogenic carbon sequestration. While this sequestration benefit can significantly reduce net embodied carbon, it is crucial to recognise that such biogenic storage is not permanent, as carbon may gradually be released through decomposition or maintenance processes over the building's operational life (Van Den Oever *et al*., 2024: 21, 36; Vilčeková *et al*., 2024: 9).

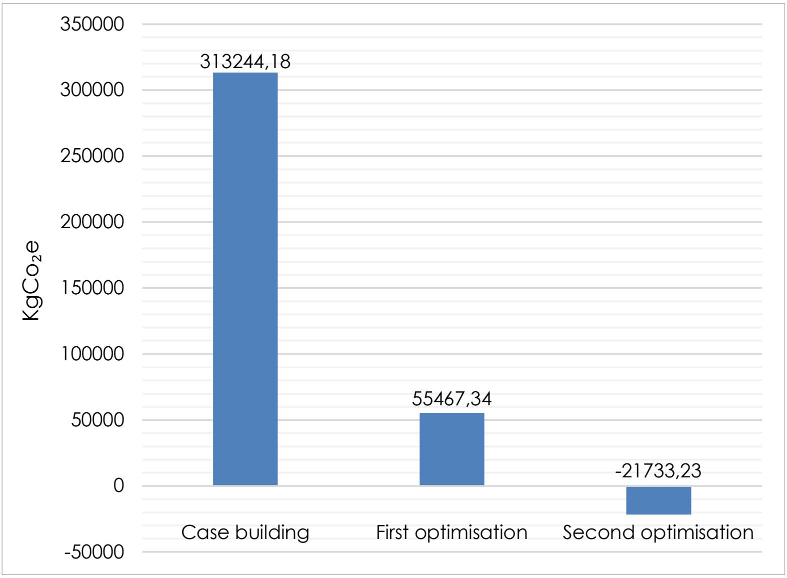

Figure 8: A1-A3 (materials stage) carbon emissions

In contrast, the first optimised building, which features a slate roof, showed higher A1-A3 emissions. Slate, although durable, has a high embodied carbon, due to its energy-intensive quarrying and processing phases. It is critical to emphasise that the material emissions captured at the A1-A3 stage emissions account for walls, façades, internal partitions, floors, beams, doors, and windows. A further disaggregation of the embodied carbon by structural classification shows a consistent pattern in emission hotspots across the three designs, with substantial variance in emission contributions (Figure 9). In the case building, for instance, roughly 89% of the embodied carbon is ascribed to horizontal structures, including beams, floor slabs, and roof systems. Vertical structures and façades accounted for 7%, while 3% was attributed to other structural and non-structural components. This heavily lopsided distribution emphasises the carbon intensity of conventional floor and roof construction, mostly dependent on reinforced concrete, which has been regularly acknowledged as a major contributor to global embodied carbon emissions (Limphitakphong, 2020; Hart, D'Amico & Pomponi, 2021). This targeted life-cycle evaluation presents an indispensable strategic insight for reducing embodied carbon, by addressing the most carbon-intensive components within the building envelope, which are not elucidated in the prior simulations. In fact, several studies confirm that early interventions through a fabric-first approach, by substituting high-embodied materials with low-carbon alternatives, can yield substantial reductions in total carbon emissions (Eyre *et al*., 2023). In the case of the buildings assessed in this study, optimising or replacing the concrete floor composition could unlock additional carbon savings without compromising structural performance requirements or architectural intent.

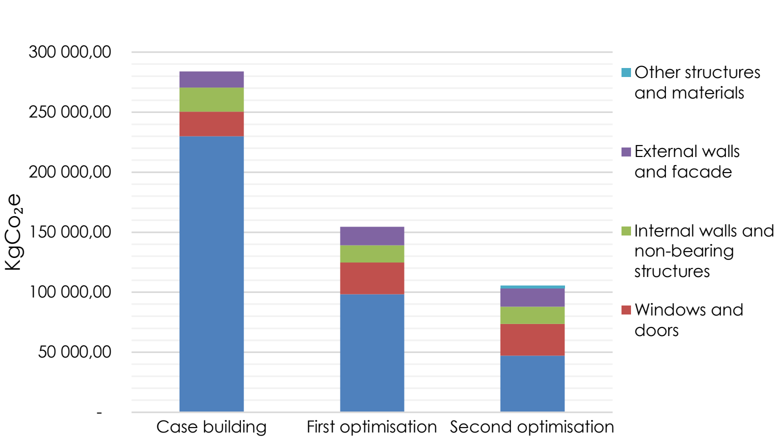

Figure 9: Carbon emission classification by building elements

4.3.2 Operational carbon emissions

As widely established in existing literature, operational carbon emissions often represent the most sizeable portion of a building's whole life carbon (WLC) footprint. Numerous studies have shown that operational energy can account for over 50% and, in many cases, over 70% of total life-cycle emissions (Liang *et al*., 2023: 16; Venkatraj *et al*., 2020; Dilsiz *et al*., 2019: 6), especially in buildings located in hot regions. The dominance of operational carbon emissions in the tropics is most pronounced in energy-intensive residential buildings (Fachinello Krebs & Johansson, 2021). The findings from this study align with such assertions, reaffirming the dominant influence of operational carbon on WLC emissions. As described earlier in Section 4.3 (Figure 7), operational energy (B6) massively influences life-cycle carbon outcomes. In the case building, material-stage embodied carbon accounts for 19% of total emissions, while operational carbon accounts for a significant 67%. This embodied carbon share is consistent with reported emissions of up to 52% for conventional residential buildings by Dilsiz *et al.* (2019). The disparity between embodied and operational carbons widens in the optimised models with operational carbon of 79% and 87%, in the first and second optimised models, respectively. For operational energy alone, the case building, first optimised, and second optimised models account for 78%, 87% and 90% of total emissions (Figure 10).

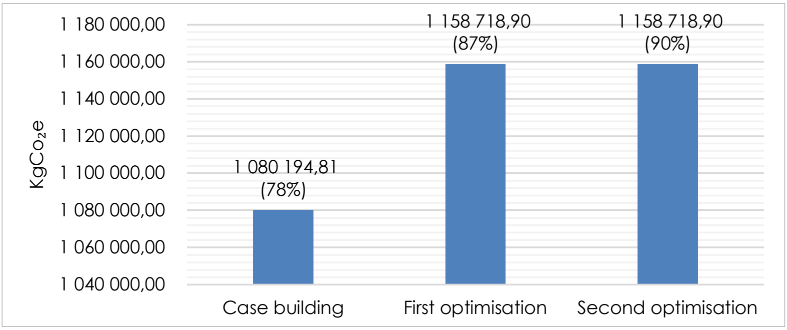

Figure 10: B6 (energy) phase percentage of total operational carbon emissions

While the pareto front optimisation and visualisation is instrumental in identifying optimal design solutions, it does not offer a detailed evaluation of life-cycle impacts, as shown using OneClick life-cycle assessment tool. Pareto-based optimisation prioritised life-cycle performance based on design objectives such as reducing discomfort hours and energy consumption, yet its interpretation of life-cycle carbon was skewed, due to its focus on operational energy. This led to an apparent but misleading portrayal where the optimised designs appeared to produce higher life-cycle carbon than the case model. However, when assessed holistically through OneClick LCA's full-spectrum life-cycle analysis (Figure 7), the picture clearly changes. In fact, both optimised models outperformed the case building in total WLC terms. The case building recorded a life-cycle carbon emission of 1,387,311.20 $KgCO_2e$. By contrast, the first optimised model demonstrated a 3.5% reduction (1,338,864.59 $KgCO_2e$), while the second achieved a 7% reduction (1,289,920.08 $KgCO_2e$). These results validate findings from related studies that early-stage building optimisation and material enhancement, even when they increase life-cycle operational energy, can result in significant long-term carbon savings (Ayoobi & Inceoğlu, 2024; Elbeltagi, Wefki & Khallaf, 2023).

5. CONCLUSIONS AND RECOMMENDATIONS

The outcome of this study reiterates the need for an integrated approach to operational and embodied carbon reductions in building performance evaluation. Prioritising energy performance or thermal comfort requirements, without accounting for life-cycle impacts, risks achieving only biased optimisation and missing opportunities for genuine life-cycle carbon reduction. Relying on an aspect of life-cycle carbon is insufficient to achieve carbon neutrality in the construction industry. High embodied materials such as concrete and steel are some of the largest contributors to embodied carbon. Pareto-based MOO was applied to buildings with different materials to identify best-performing design solutions that balance the objectives of reducing carbon emissions and energy consumption. The case building, sited in Edo State, Nigeria, was simulated with its baseline configuration of sandcrete block walls and aluminium roofing. Two optimised alternatives with aerated bricks and timber-based materials were explored to assess life-cycle carbon emission and comfort, as a method for early-stage design decision-making. Results from preliminary simulation showed that the original building has an embodied carbon of 107,496.90 $KgCO_2e$ emissions, with 54.8% of this attributed to the aluminium roof. Material substitution reduced embodied carbon by 63% in the first optimised model, while the second model with a green roof system achieved a 64% reduction relative to the case building. However, these substitutions increased cooling demand by approximately 46%, due to the weak thermal resistance of the low carbon materials. The Pareto front analysis revealed that, while material substitutions lowered embodied carbon, they resulted in higher life-cycle carbon emissions, highlighting the need for adaptive strategies and life-cycle impact evaluation. OneClick life-cycle assessment tools were used for comprehensive life-cycle evaluation. Results showed that the first optimised model reduced life-cycle carbon by 3.5%, and the second by 7%, demonstrating the potential for whole-life carbon improvements when both embodied and operational impacts are considered together.

The study concludes that, for early-design decision-making, a multifaceted approach that combines low-embodied materials, adaptive building strategies, and life-cycle impact analysis is vital to reduce the long-term environmental impact of buildings. Although operational energy remains the dominant contributor to life-cycle carbon emissions, attention must be paid to embodied carbon reduction in buildings, if genuine progress towards carbon neutrality is to be attained. Relying solely on an aspect of building performance optimisation such as operational energy, embodied carbon, passive design or indoor environmental quality risks overlooking the benefits of whole life-cycle impacts.

A key limitation of this study is that the optimisation models focused primarily on material substitution rather than its combination with a range of passive design strategies, even though passive measures are widely recognised for their influence on indoor comfort and operational performance. The discomfort hours recorded in the optimised buildings are an acknowledged consequence of the study's deliberate methodological scope, designed as a phase of ongoing optimisation investigations, focusing specifically on fabric and material performance in a building's life cycle.

Subsequent phases of the wider research will extend the optimisation to include passive design strategies, which are expected to reduce discomfort hours substantially. Consequently, future studies and industry practice should integrate adaptive comfort strategies within a full life-cycle assessment framework. Embedding life-cycle carbon evaluation at the early design stages is essential to support balanced, low-carbon design choices that address both immediate comfort needs and long-term environmental sustainability goals.

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