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Impact of form factor variability on building energy assessment: A computational and empirical analysis for early-stage design

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Abstract

While energy efficiency is increasingly recognised as an integral factor in building design, form-related considerations in Nigeria remain underexplored. This study explores the influence of compactness on building energy demand and carbon emissions using computational simulations tailored for early-stage residential design. Ten distinct building forms consisting of six one-storey, three two-storey and one three-storey building were modelled in SketchUp to collect building entity data and systematically transformed for compactness assessment while maintaining the same volume and floor area. A weather file for location-based energy requirements was generated using Meteonorm, while dynamic thermal modelling, energy performance and carbon emissions were evaluated using EnergyPlus. Python programming was utilised for advanced statistical evaluation, pattern recognition and data visualisation. Findings revealed that single-storey buildings have higher surface-to-volume (SV) ratios and are more energy efficient than more compact, multi-storey counterparts. Principal Component Analysis (PCA) confirmed that building volume accounts for more than 97% of form factor variability, establishing it as the most dominant driver of compactness, while regression analysis reinforced its statistical significance (P-value = 0.038). However, cluster analysis demonstrated that energy efficiency is not solely a function of form factor but is informed by complex interplays between building morphology parameters and façade exposure. Unexpectedly, despite improvements in SV ratios of the transformed buildings, energy demand intensified by up to 30.27%, challenging conventional assumptions that compactness universally enhances energy efficiency. These findings highlight the limitations of compactness as a standalone metric for evaluating energy performance in tropical climates, stressing the need for integrating passive design strategies, such as solar-responsive façades and optimised building orientation, into form optimisation. This study redefines performance assessments for early-stage design by advocating for a more context-sensitive approach to building form in tropical climates.

Keywords: building compactness, building energy efficiency, early-stage design, form factor, tropical buildings

1. Introduction

Global temperatures have been on the increase due to anthropogenic activities since the industrial age, posing severe risks to both buildings and their occupants (Driga & Drigas, 2019). These challenges manifest as thermal discomfort and increased cooling demand, and in extreme scenarios, heightened mortality rates (Hong et al., 2023). Buildings experience degradation and façade overheating, resulting in diminished energy efficiency. Addressing these challenges requires urgent sustainability actions, a central focus of contemporary built environment research (Noah & Çağnan, 2021). One of the key determinants of a building's energy performance is its form, as its geometry directly influences thermal behaviour and heat gain (Algburi & Ferah, 2021). Rapid urbanisation, especially in hot climates, has intensified the demand for cooling, exacerbating the

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vulnerability of buildings to extreme temperatures, but modern developments often fail to harmonise with prevailing climatic conditions (Djeddou et al., 2024). Historically, local architectural styles were largely overshadowed by foreign influences, leading to the neglect of indigenous materials and climate-responsive designs (Adenaike & Opoko, 2024). In Nigeria, this issue is acute as architectural designs are frequently replicated without adequate adaptation for climatic differences. Aesthetic inclinations and societal influences often take precedence over environmental considerations, leading to inefficient buildings (Folorunso et al., 2017). Additionally, the persistent adoption of foreign architectural styles has contributed to a huge decline in indigenous, climate-responsive building techniques (Umar et al., 2019).

Efforts to enhance energy efficiency in the built environment have gained traction globally. For instance, countries like the UAE have promoted compact urban forms over sprawling developments to curb energy consumption (Galal Ahmed & Hossein Alipour, 2019). Nevertheless, building energy-efficiency remains a challenge, especially in developing countries, where economic expansion correlates with increased energy demand (Mohsenzadeh et al., 2021). Given that buildings contribute massively to global energy use, reducing their consumption is vital for achieving a carbon-neutral environment (Lian et al., 2023; Notodipuro & Mandala, 2022). Among the numerous factors that determine building energy performance, thermal properties, including form, material composition and microclimatic interactions, are particularly critical (Remon, 2019). Studies suggest that urban form and building geometric configurations play a significant role in determining energy demand (Mutani et al., 2020), by influencing heat stress, cooling loads and overall environmental sustainability (Alshboul & Alatrash, 2024; Freewan, 2022). Despite these known benefits, building form remains underexplored in sub-Saharan Africa's energy-efficiency discourse.

Furthermore, research have shown that building orientation exerts a considerable influence on energy demand in hot climates (Ahmed et al., 2021; Hatem & Karram, 2020), stressing the need for multi-factor assessment in building performance evaluation. The adoption of climate-responsive building design has been identified as one of the most effective strategies for reducing energy consumption (Ochedi & Taki, 2022). However, understanding the physics of buildings is critical for early-stage design performance evaluation (Kistelegdi et al., 2022), as even minor adjustments can affect energy efficiency, emissions and thermal comfort (Ahmadian et al., 2021; El-Agami et al., 2021; Lian et al., 2023; Liang et al., 2023). Optimising various building geometric configurations, including height and envelope characteristics—to achieve peak energy efficiency remains a complex task (Kheiri, 2018).

While substantial research has focused on building fabric materials and high-performance insulation to improve energy efficiency, fewer studies have isolated the explicit role of building form in shaping energy demand (Oh & Kim, 2019). Existing literature sometimes conflates form factor variations with changes in occupied floor area or total volumetric capacity, obscuring the actual thermodynamic leverage of building morphology. Although shape coefficients like surface-to-volume ratio and heat loss form factor are often employed to estimate building energy demand, they are insufficient on their own. Additional factors, including building orientation, window-to-wall ratio and solar radiation, must be considered for a more holistic assessment (Li et al., 2023; Yip et al., 2021). Moreover, the impact of building form on energy demand varies significantly across building types, reinforcing the need for context-specific evaluations (Song et al., 2020). Despite the growing body of knowledge on energy-efficient building design, research on form factor optimisation in tropical climates remains limited (Gupta & Deb, 2023; Kistelegdi et al., 2022; Li et al., 2024). This study addresses these gaps by providing a controlled, geometry-based investigation of form factor variability during early-stage residential building design in Nigeria. Its specific contributions are, first, the study isolates form factor effects by holding building volume, height and usable floor area strictly constant during morphological transformation—an approach rarely implemented in existing literature, where geometric changes are mostly confounded by scale-reliant variations. Second, the study presents simulated counter-evidence to the widely accepted "compactness-efficiency" assumption, where despite reductions in surface-to-volume ratio, compacted forms exhibited higher cooling energy demand due to increased façade exposure and solar heat gains, exposing a tropical performance paradox. The study highlights the need for integrating orientation, solar envelope design and climate considerations into form optimisation, offering architects and designers a more reliable basis for performance-driven massing decisions.

2. Literature Review

2.1. Vernacular to Modern Architecture: Energy Efficiency Implications

The demand for energy in buildings globally is expected to rise significantly due to urbanisation, making energy efficiency a critical issue Mahmoud (2022). Modernisation and advances in technology have shifted architectural focus away from preserving locally responsive buildings, leading to over-dependence on mechanical cooling (Umaru et al., 2022). Arbabzadeh et al. (2020) argue that early Modernist movements introduced geometrically abstract designs that created a disconnect between buildings and environmental adaptation, favouring aesthetic appeal over energy efficiency. Corroborating this paradigm shift, Lucchi (2023) notes that evolving architectural movements have systematically displaced the historic role of primary building form in meeting functional and climatic comfort requirements, creating an operational misalignment between contemporary modernism and energy efficiency. This trend led to the neglect of vernacular construction methods, which were inherently suited for their environments, diminishing both occupant comfort and energy efficiency (Agbete & Frank, 2020; Lodson et al., 2018; Nwalusi et al., 2022). Vernacular architecture has long demonstrated superior adaptability through the integration of energy-saving strategies tailored to specific environmental conditions (Noah & Çağnan, 2021). These buildings, characterised by compact forms and high thermal mass, have been shown to outperform modern buildings in energy-efficiency (Dada & Alibaba, 2023). In addition, the use of locally-sourced materials further reduces their environmental impacts by minimising carbon emissions (Djeddou et al., 2024). From an economic and environmental standpoint, improving building performance is pivotal, with energy efficiency as the primary objective (Aydın & Koçlar Oral, 2024; Belussi et al., 2019) . In this context, a performance-based design framework is essential for identifying architectural forms that align with sustainability objectives (Song & Sun, 2021), noting that regardless of the envelope materials used, the geometric properties of buildings are influential in energy performance outcome (Premrov et al., 2018). Existing building energy-efficiency assessment frameworks evaluate compactness alongside material properties, cultural practices or passive cooling strategies, making it difficult to isolate the contribution of building form alone. This creates a gap in understanding whether compactness itself drives energy efficiency or whether its benefits are reliant on broader envelope-related factors.

While several studies focus on improving energy efficiency through optimised and passive design strategies (Kistelegdi et al., 2022), a critical challenge remains. For instance, when designs fail to account for local climate impacts, they depend on active cooling systems, elevating energy consumption and emissions (Offor & Emenike, 2019). With the building envelope as the primary driver of heat transfer, the need for optimised geometric indicators such as floor area, perimeter and building height to achieve sustainable energy performance must be prioritised (D'Amico et al., 2021; Gamero-Salinas et al., 2020; Koźniewski et al., 2022; Ragab, 2022). In this regard, Sokar et al. (2023) emphasise that passive measures that are driven by envelope design and passive cooling integration serve as the most effective interventions to suppress energy loads before mechanical systems are integrated. An additional complexity in sustainable design is the challenge of estimating carbon footprints at the early design stage (Yadav & Kumar, 2022) because, unlike operational energy that can be measured, embodied carbon and lifecycle energy demand require predictive modelling. Nonetheless, building form optimisation and analysis emerges as a crucial tool for architects to evaluate and estimate energy consumption from the outset (Deng et al., 2020; Keskisalo & Matveinen, 2021).

2.2. Building Form Factor and Energy Efficiency

A building's form is the primary determinant of its energy performance, as it regulates heat flow and thermal efficiency. It encompasses salient parameters, such as height, width and depth (The Archspace, n.d.; Whole Building Design Guide, n.d.). As opined by Taştemir et al. (2024), optimising building design forms, particularly during preliminary architectural interventions, is a crucial task that can enhance design performance at a minimal cost. Several factors influence a building's form, including functional, aesthetic and cultural preferences (Archi-Monarch, n.d.). However, its most crucial role lies in predicting how efficiently its envelope encloses its volume; a quality quantified by form factor metrics such as surface-to-volume (SV) ratio (Araji, 2019; D'Amico & Pomponi, 2019), shape factor (Carpio & Carrasco, 2021; Zhao et al., 2023; Zhu et al., 2024), compactness ratio (Kahraman & Köymen, 2023; Koźniewski et al., 2022; Vasilenko, 2019) and heat loss form factor (HLFF) (Burrell, n.d.; Vidmar, 2019). The SV ratio is a widely used compactness indicator, mathematically expressed as the total envelope area per unit volume (Equation 1). A lower SV ratio is indicative of a more compact structure with reduced heat exchange through its envelope, enhancing energy efficiency.

The HLFF provides a more refined measure of building compactness by accounting for the portion of the building's actual heated floor area (Equation II). Unlike the SV ratio, which considers the volume of buildings, HLFF is based on the heated floor area (HFA), making it more applicable to energy performance assessments (Vidmar, 2019). Ideally, the HFA is calculated as 75% of the building's total floor area (TFA). Areas occupied by partitions, doors, stairs and unusable spaces are excluded from the TFA (Burrell, n.d.; Vidmar, 2019). Studies suggest that the HLFF usually ranges from 0.5 to 5, with values below 3 required to meet the Passivhaus standard.

$$Surface - to - Volume\ Ratio\ (SV) = \frac{Total\ Envelope\ Area\ (TEA)(m^2)}{Volume\ (V)(m^3)} \qquad \ldots Equation\ I$$

$$Heat\ Loss\ Form\ Factor\ (HLFF) = \frac{Total\ Envelope\ Area\ (TEA)(m^2)}{Heated\ Floor\ Area\ (HFA)(m^2)} \qquad \ldots Equation\ II$$

The compactness of a building plays a significant role in determining its thermal performance throughout its lifecycle (Alshboul & Alatrash, 2024; Li et al., 2024; Marincu et al., 2024; Zhu et al., 2024). Increasing surface areas reduces the compactness ratio, particularly for buildings with smaller floor areas (Kahraman & Köymen, 2023), but compactness alone does not always ensure buildings energy efficiency. While a higher SV ratio results in increased solar energy absorption and heat gains, it also elevates cooling demands, making form optimisation context-specific (Araji, 2019). The SV ratio consists of two components: a scale-dependent size factor and a scale-independent term shape factor (D'Amico & Pomponi, 2019). While the size factor relates to absolute building dimensions, the shape factor focuses on the building's proportionality, allowing for a standardised measure for comparing different building shapes independent of size. This distinction is essential for optimising energy performance, as buildings with similar volumes but different geometric properties can exhibit drastically different thermal characteristics.

The relationship between form factor and energy demand varies across different climates. For instance, in a hot climate of Egypt, buildings with an SV ratio below 0.38 are found to reduce cooling energy demand by over 30%, highlighting the efficiency of compact designs (Ragab, 2022). Moreover, a positive correlation exists between SV ratio and energy demand for cooling, such that a 0.01 increase in compactness ratio results in a 2.6% increase in energy consumption (Vasilenko, 2019). This aligns with findings from similar studies such as Puri (2021) and Ragab (2022), which emphasise that optimising the SV ratio yields substantial energy savings. Studies further identify optimal shape factors for selected climate zones: 0.29 for severe cold climates, 0.30 for cold regions, 0.23 for hot summer & cold winter climates, 0.31 for hot summers with warm winters and 0.33 for mild regions (Zhao et al., 2023). In Chile's cold oceanic climate, an optimal shape factor of ≤ 0.767 was identified as effective in reducing energy demand (Carpio & Carrasco, 2021).

Despite the widespread use of these metrics, most studies offer no control for building volume and floor areas when comparing forms' energy performance. As a consequence, compactness is often conflated with size, limiting the reliability of compactness-based comparisons across different building typologies. These form factor variabilities indicate that form optimisation must be tailored to specific contexts rather than universal application.

2.3. Building Form and Energy Performance

The energy performance of a building is influenced by its shape, size and orientation, all of which are critical factors in energy studies (Akbari & Nezhad, 2020). While square, rectangular, L-shaped and U-shaped buildings are the most commonly adopted forms, considering alternative geometries during the early design phase can immensely influence energy efficiency and mitigate the built environment's carbon emissions (Khalil, 2023; Li et al., 2024). However, studies show that the effectiveness of building form often depends on its function and climate conditions. Alshboul and Alatrash (2024) and Vasilenko (2019) argue that a compact building has the highest energy efficiency owing to its reduced exposure to external temperature interference. This aligns with findings from Marincu et al. (2024) and Mutani et al. (2020), who opine that compact buildings are generally less energy intensive due to a lower surface-to-volume ratio, consequently reducing heat loss and heat gain. In fact, Remon (2019) reports that compact buildings can reduce energy consumption by up to 81%; but the extent of savings depends on geographical and climate dissimilarities. These studies widely evaluate compactness without considering façade orientation, solar exposure or window distribution in tandem. They widely assume that reduced envelope area automatically translates to lower cooling demand, overlooking cases where compact forms may increase solar gains due to façade arrangement.

D'Amico and Pomponi (2019) further assert that the minimisation of exposed surface area is critical in energy-efficient design, highlighting that semi-cube forms, due to their geometric efficiency, enhance thermal performance. Similarly, Hadjhafsi et al. (2024) identify the square-shaped building as the most effective for residential energy conservation in the Saharan climate of Algeria. The benefits of compact shapes extend beyond residential dwellings. Mba et al. (2024), for context, note that square plans are particularly beneficial for educational buildings as they not only improve energy efficiency but also enhance natural ventilation. However, the notion that a singular building shape is universally optimal is misleading since the effectiveness of a given form is climate-dependent. Notably, in Iran's hot-dry climate, a rectangular form with an east-west orientation achieves the best performance compared to squares, hexagons, octagons and circular forms of identical floor area and height (Akbari & Nezhad, 2020). Conversely, El-Agami et al. (2021) report that in Egypt, circular buildings exhibited superior energy efficiency compared to square, rectangular and elliptical forms in distinctive locations. Mohsenzadeh et al. (2021) further validate this by concluding that circular buildings, compared to square, rectangular and triangular structures, are more efficient. Other building forms are found to be widely energy-inefficient; for instance, triangular buildings are widely associated with poor energy efficiency due to poor compactness. According to Hatem and Karram (2020), triangular buildings consume up to 20% more than circular forms and generally underperform when compared to other geometric configurations. On the contrary, research by Makhloufi and Louafi (2023) in Algeria challenges this notion, showing the superior performance of a triangular-based building over others in terms of energy efficiency. These findings imply that the thermal performance of buildings is varied and complex and does not rely on compactness or geometric properties alone.

For office buildings in the hot climate of Cairo, circular and oval forms showed superior energy performance over several other forms (Khalil et al., 2023). Similarly, Boronbaev (2023, 2024) highlight that spherical buildings offer high energy-saving potential due to their intrinsic nominal thermal bridges. Despite the theoretical advantages of circular buildings, their feasibility in practice is uncommon due to ergonomic and orientation challenges (Zankar et al., 2022). As Vasilenko (2019) admonishes, prioritising compactness alone over other factors may compromise building usability, since circular and spherical forms often present spatial inefficiencies in practical applications. Therefore, achieving a balance between geometric compactness, practical functionality and energy savings is crucial for building sustainability.

2.4. Building Height and Energy Use

Beyond geometric forms, building height and the number of storeys affect energy performance with mixed findings regarding their influences. Studies suggest that low-rise buildings exhibit the highest energy-saving potential, making them more ideal for energy-positive solutions (Ahmadian et al., 2021; Yadav & Kumar, 2022). Conversely, increasing a building's height, while maintaining the same floor area and envelope parameters, sometimes raises its compactness ratio and carbon emissions (Liang et al., 2023; Vasilenko, 2019). These inconsistencies arise because many studies do not maintain a constant floor area or volume during early-stage design interventions, when comparing buildings of different heights. Consequently, height-related findings are often confounded by changes in usable space or envelope area.

According to a study by Barssoum et al. (2020), adding storeys increased energy consumption by 60%, suggesting a strong correlation between building height and energy demand. This contradicts findings by Rahmani and Al-Sallal (2019), who observed a 46% reduction in energy demand when a school building in Abu Dhabi was transformed from single to two storeys, owing to self-shading and reduced solar exposure. Benkhelifa et al. (2019) support this finding by arguing that adding building storeys enhances energy efficiency by minimising heat loss per unit volume, reinforcing the notion that compactness under ideal conditions can be beneficial. Gamero-Salinas et al. (2020) assert that a high-rise building with a porous design achieves lower energy consumption compared to a compact, less porous one, further complicating the height-compactness-efficiency relationship.

From a geometric standpoint, larger buildings tend to have a lower surface-to-volume ratio, resulting in reduced heat loss per unit of volume (Vidmar, 2019). Several studies that evaluate building form and energy efficiency acknowledge that size, shape and compactness ratio interact in complex ways across different climatic conditions (Deng et al., 2020; Hatem & Karram, 2020; Pathirana et al., 2019), but a critical limitation in these studies is the failure to maintain a constant floor area and building volume when comparing buildings. A truly rigorous analysis of building forms must be evaluated with identical usable space to ensure that observed variations in energy performance differences stem only from its form, rather than differences in functional capacity or occupancy.

2.5. Thermal Bridges and Building Energy Performance

According to Parry and Strang (2021), thermal bridges are critical spots in a building envelope where heat flow deviates significantly from adjacent regions. These inefficiencies are particularly challenging in hot climates, where unwanted heat gains can elevate cooling energy demands. Alhawari and Mukhopadhyaya (2018) highlight that the presence of thermal bridges is an indicator of poorly performing buildings, exacerbating energy inefficiencies through unrestrained heat transfer. Similarly, Burrell (n.d.) describes the thermal envelope as the main interface through which heat is lost or gained, accentuating the significance of minimising thermal bridges to achieve energy efficiency.

Thermal bridges can be categorised into two main types: geometric and construction-based. Geometric thermal bridges occur at areas where there is an abrupt change in a building's shape, such as at eaves, junctions or external corners, making them integral in complex architectural forms. In contrast, construction thermal bridges occur when materials or components penetrate the building's insulation layer, as observed in cantilevers, exposed slabs and external porches.

Among these, exposed balcony slabs are challenging to curb, with reports indicating that they can account for up to 40% of thermal-bridging-related heat loss (Alhawari & Mukhopadhyaya, 2018; Pérez-Carramiñana et al., 2024). However, the impact of thermal bridges extends beyond energy consumption, influencing indoor comfort and material durability due to risks consideration. As mentioned by Guo et al. (2023), reducing the prevalence of thermal bridges not only improves energy efficiency in buildings, but also prevents interstitial condensation, which can degrade structural integrity over time. For early-stage design, where form factor optimisation plays a significant role in energy efficiency, the presence of thermal bridges on the building envelope can alter the expected energy performance of buildings. As a result, understanding and addressing thermal bridges is vital to ensure that form factor optimisation translates to real-world energy savings. Consequently, adopting simplified, thermally efficient design approaches can effectively minimise inefficiencies attributed to thermal bridges.

To ensure that the literature review directly informs the modelling strategy, and form transformation adopted in this research, Table 1 provides a structured synthesis of the key studies examined. By organising the literature according to research purpose, methodology, findings, limitations and relevance, the matrix clarifies the specific gaps—particularly in geometric isolation, compactness evaluation and early-stage predictive modelling—that shaped the methodological decisions presented in the next section.

Table 1 Critical Synthesis of Key Empirical and Theoretical Studies on Building Geometry and Energy Performance

Author(s) & Year	Research Purpose	Methodology	Key Findings	Limitations/Critical Gaps	Relevance to this Study
Adenaike and Opoko (2024)	To document local vernacular morphology in Nigeria.	Qualitative historical analysis.	Vernacular forms are compact and climate-responsive.	Descriptive; no simulation; no quantitative testing.	Provides cultural context but lacks computational validation — this study digitises Nigerian typologies.
Ahmadian et al. (2021)	To examine urban built form and density effects.	Urban-scale modelling of density and form.	Compact urban form reduces energy use.	Urban scale; not building-level geometry; no façade distribution analysis.	Shows compactness matters but lacks building-level geometric testing that the study addresses.
Akbari and Nezhad (2020)	To identify optimal aspect ratios and orientations in hot-dry climates.	Parametric modelling of rectangular forms with varying aspect ratios.	Moderate elongation improves solar performance.	Geometry and scale change simultaneously; confounding variables; no constant-volume control.	Demonstrates shape importance but lacks geometric isolation — the methodology of this study isolates proportionality.
Araji (2019)	To examine how SV ratio affects solar heat gain.	Simulation of various building geometries under solar exposure.	Higher SV increases solar heat gain.	Assumes a monotonic relationship; no constant-volume testing; no tropical climate validation.	Shows SV matters but does not evaluate compactness behaviour under tropical cooling conditions — this study fills this gap.
Benkhelifa et al. (2019)	To evaluate height effects on heating/cooling.	Simulation of Saharan buildings with varying heights.	Height reduces footprint and improves compactness.	Multi-storey forms treated as unglazed blocks; fenestration ignored.	Shows verticality matters but lacks WWR constraints that this study includes (fixed WWR).
D'Amico and Pomponi (2019)	To define a compactness measure separating size and shape effects.	Analytical decomposition of SV ratio and shape factor; no energy simulation.	Decouples scale-dependent size factors from scale-independent shape factors, establishing a geometric basis for compactness.	No thermal simulation; no tropical context; does not test how shape factor affects cooling loads.	Provides geometric foundation but lacks climatic and thermal validation — this study includes the missing performance evidence.
El-Agami et al. (2021)	To compare circular, square and rectangular massing forms.	Simulation of high-rise forms under Egyptian climate.	Circular forms outperform others.	Form changes alter envelope area, height and floor area; results are confounded.	Highlights geometric sensitivity but lacks controlled transformations that this study evaluates.
Hygh et al. (2012)	To use multivariate regression for early-stage energy prediction.	Regression modelling using geometric and mechanical variables.	Geometry can predict energy performance.	High parameter endogeneity: Requires extensive operational and mechanical boundary inputs rarely available during schematic massing.	Supports statistical modelling but limits transparency — the data analysis workflow in this study seeks to improve interpretability.
Mahmoud (2022)	To evaluate proportions and orientation in hot-arid climates.	Simulation of multiple building proportions.	Orientation strongly affects cooling demand.	Geometry, WWR and orientation vary together; no isolation of form factor.	Supports orientation relevance but lacks geometric isolation — this study decouples orientation from form.

Taştemir et al. (2024)	To develop a geometry-based decomposition method for early-stage energy prediction.	Parametric modelling of residential building geometries using decomposition-based predictive algorithms.	Demonstrates that geometric variables can be decomposed to predict energy behaviour in early design stages.	Uses parametric forms; no constant-volume control; no tropical context; does not test compactness paradox.	Strengthens the methodological foundation workflow by validating geometry-driven early-stage prediction.
Yip et al. (2021)	To develop an early-stage net-zero design methodology.	Sensitivity analysis of form and envelope parameters.	Form influences energy demand.	Non-linear interactions not fully explained; no tropical context.	Shows form matters but lacks tropical compactness testing — this study fills this gap.

3. Methodology

This study uses an integrated empirical and simulation-based approach to evaluate the impact of building form variability on energy efficiency at the early design stage. The methodology is structured into four key phases as shown in Figure 1 below.

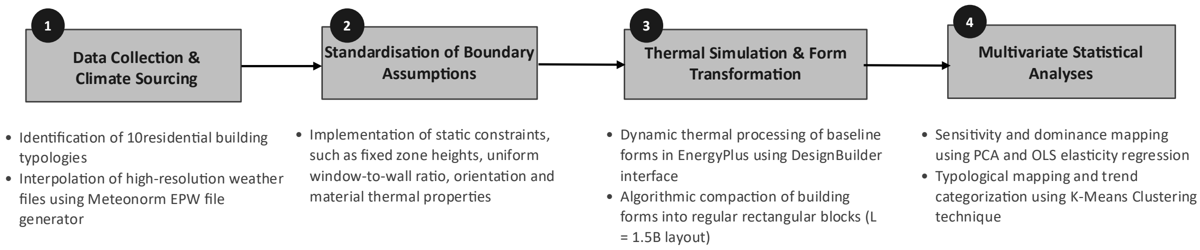


Figure 1 Methodological flowchart

3.1. Data Collection

Ten residential building drawings were collected from the archives of three architectural firms in Edo State, Nigeria, representing projects designed between 2015 and 2025. The study collected a mix of residential buildings with single to three storeys. No on-site measurements were conducted; instead, digitised architectural drawings were analysed to extract building parameters such as volume, envelope and floor areas. Additionally, contemporary climate data for the study location were generated using Meteonorm, widely used for its capability to interpolate high-resolution historical and future climate datasets (Viganò et al., 2024). This dataset serves as a key input in DesignBuilder simulations, ensuring that the models reflect actual climatic conditions. To ensure internal consistency, all extracted geometric parameters were cross-checked against the original CAD drawings and validated using SketchUp entity data before simulation. By doing so, envelope areas and volumetric values used in subsequent analyses were accurate and comparable across all building forms.

3.2. Standardisation of Assumptions

To isolate the effect of form factor on energy efficiency, the following assumptions were applied across all models:

I. **Fixed Building Height:** Each of the models within a group is assigned a constant height. For instance, single-storey and two-storey buildings are allotted a height of 3 meters and 6 meters, respectively. This is to ensure that changes in energy performance arise from changes in form rather than height differences.

II. **Absence of Internal Partitions:** No internal partitions from the building drawing were assigned, aligning with recommendations that early-stage design studies should focus on overall building form (Orçun & Onur, 2022).

III. **Window-to-Wall Ratio (WWR):** A uniform 30% WWR was applied to the building facades in DesignBuilder to align with design recommendations by El-Agami et al. (2021) and Pathirana et al. (2019).

IV. **Consistent Location and Orientation:** The buildings were simulated at the same geographical coordinates and reoriented west-east to minimise discrepancies due to site-specific variations.

V. **Uniform Material Properties:** Insulation, glazing and construction material properties were kept uniform across the models to ensure variations in performance are solely from geometric differences. These properties are key determinants of energy demands, particularly in tropical climates (Gupta & Gregg, 2018; Zhao et al., 2023).

VI. **Roof Height Exclusion:** The roof profile was excluded from form factor calculations to maintain a standardised volumetric form and reduce geometric thermal bridges during assessment.

VII. **Minimum Width Constraint:** A minimum width constraint (≥ 6 meters) was maintained in the transformed buildings to ensure architectural planning feasibility while adopting an elongated plan form (L = 1.5B) and to minimise east-west solar gains, a strategy proven to reduce cooling loads and enhance energy efficiency in hot climates (Fereidani et al., 2021).

VIII. **Geometric Simplification and Thermal Bridge Considerations:** Complex architectural forms, such as those with recesses, projections, articulated corners or irregular massing, introduce geometric thermal bridges that create discontinuities in heat flow. These changes distort energy anomalies unrelated to geometric proportionality. Because the objective of this study is to isolate the influence of form-factor, façade distribution, and solar exposure under constant conditions, geometric transformations were restricted to simple rectangular massing. This approach ensures that observed differences in cooling demand arise from geometric changes rather than construction-based thermal anomalies.

Other simulation constraints, including their parameters and operational specifications, are presented in Table 2 below.

Table 2 Fixed Simulation Control Parameters in DesignBuilder

Category	Parameter	Operational Value / Specification	Reference Standard Basis
Microclimate	Weather Profile Source File	Edo State, Nigeria (Meteonorm Data)	Tropical Savanna (Aw)—(Beck et al., 2023)
Opaque Envelope	External Wall U-Value	1.109 W/m²K	225 mm sandcrete blocks with 35 mm external and internal plaster layers—Local construction specifications
	Roof System	1.893 W/m²K	Flat roof, box form for preliminary analysis; Aluminium roofing sheets with wooden frames
Glazing Assembly	Fenestration Glass Specification	Single clear 3 mm sheet glass—1.960 W/m²K	Regional baseline
	Total Solar Heat Gain Coefficient (SHGC)	0.691	EnergyPlus regional glazing standard
Internal Loads	Occupancy Density	0.02 (people/m²)	Fixed residential operational profiles
	Lighting Power Density	5.0 W/m²	DesignBuilder default value
HVAC Scheduling	Cooling system CoP	2.5 with grid electricity supply	Local supply
	Infiltration Rate	3.0 ac/h	Mixed-mode DesignBuilder ventilation setup

3.3. Simulation and Form Transformation

Using DesignBuilder, digital models of the forms were developed, incorporating the standardised assumptions and Meteonorm-generated climate data. The simulation process involved two key stages:

I. **Baseline Energy Performance Assessment:** Each of the models was simulated to extract performance metrics such as energy consumption and cooling loads.

II. **Form Transformation:** The original building configurations were modified to assess how form transformation impacts performance metrics. The transformed buildings followed a more elongated form that minimised solar exposure, reducing direct solar gains, while maintaining the same volume, height and floor areas as the original buildings in an L = 1.5B configuration. The transformation is particularly justified in tropical climates where solar exposure contributes immensely to cooling loads (Gupta & Deb, 2023).

The decision to adopt an L = 1.5B proportional constraint in the geometric transformation is grounded in established architectural design principles, climate-sensitive building design, and habitable space functional requirements. Studies show that moderate elongation reduces solar gains compared to highly stretched forms and that rectangular forms with controlled elongation outperform excessively stretched building shapes in hot climates. Moreover, early-stage architectural interventions consider ergonomics during space planning. Other constraints may collapse the width of the buildings below feasible planning limits, where WWR distribution would become unrealistic. Hence, the adopted transformation constraint ensures that the minimum breadth of the transformed buildings can meet basic architectural design requirements for occupied spaces.

3.4. Data Analysis Procedures

A multi-tiered analytical approach was applied to derive insights from the collected data. The analysis was conducted using descriptive statistics, Principal Component Analysis (PCA), and Ordinary Least Squares (OLS) regression and K-Means clustering in Python's Jupyter Notebook, utilising libraries such as Pandas, NumPy, Seaborn and Matplotlib. Although the dataset consists of ten building cases, PCA and clustering were applied not to infer population generalisations but to identify dominant geometric trends and classify form-based performance patterns. This aligns with early-stage architectural workflows where datasets are inherently limited.

3.4.1. Descriptive and Statistical Analysis

Descriptive statistics were used to characterise form factor variability between the original and transformed buildings. Metrics such as mean, standard deviation and ranges were derived to assess energy demand variance and compactness. Multivariate linear regression modelling operates as an effective screening tool during preliminary stages, demonstrating that high explanatory power can be achieved when inputs such as orientation and building shape parameters are evaluated (Hygh et al., 2012). This study builds directly upon this statistical screening philosophy, integrating ordinary least squares (OLS) sensitivity and principal component analysis (PCA) dimensionality mapping to extract geometric rules tailored for the study climate.

3.4.2. Principal Component Analysis (PCA) and Regression Analysis

Principal Component Analysis (PCA) was employed to identify the most influential variables affecting form factor and energy demand by reducing dimensionality and retaining key patterns in the dataset. Regression analysis, on the other hand, was conducted to quantify the statistical relationship between building volume, envelope area and surface-to-volume ratio. SV ratio was included as a dependent variable despite being derived from envelope area and volume because the regression was used to evaluate the strength of multicollinearity and to quantify the relative influence of each geometric parameter. This ensured that observed trends are statistically significant rather than occurring by random chance.

3.4.3. Comparative and Cluster Analyses

To substantiate results, boxplots were used to elucidate variations in heat loss form factor and surface-to-volume ratio across the building configurations. Additionally, a comparative analysis of the original and transformed building forms was performed to quantify energy savings, indoor comfort improvements and embodied carbon differences. Lastly, cluster analysis was used to group buildings based on their form factor characteristics, verifying that similar building typologies exhibited comparable performance metrics. By integrating multiple analytical approaches, findings from the study ensure robustness, reliability and statistical confidence, reinforcing the significance of form factor consideration in building performance.

3.5. Embodied Carbon Estimation and Operative Temperature Derivation

Preliminary carbon accounting was compiled using the carbon calculation screening matrix embedded within DesignBuilder (DesignBuilder, V7.0). Material carbon intensities are drawn from the University of Bath Inventory of Carbon and Energy (ICE) database (Circular Ecology, 2025), a globally recognised and validated lifecycle inventory reference for embodied carbon of materials. The lifecycle system boundary adopted the EN 15978 modules (British Standards Institution, 2012) and covers only the material (A1-A3) and operational emission (B6) lifecycle stages. The carbon tallies accumulate footprints arising exclusively from the raw materials extraction and processing, while operational emissions were derived from annual consumption.

Thermal indoor environment parameters for the buildings were captured continuously using deterministic physics-based calculation nodes executed within EnergyPlus. EnergyPlus establishes the hourly zone Operative Temperature (T_o) by evaluating internal radiative and convective fields under standardised airflow conditions using the formula:

$$T_o = 0.5 \times T_{air} + 0.5 \times MRT \qquad \ldots Equation\ III$$

Where :

T_{air} = calculated indoor mean air temperature (^{0}C) at the central thermal zone node

MRT= calculated mean radiant temperature (^{0}C) integrating the surface temperature vectors of all enclosing envelopes

4. Results

Table 3 summarises the geometric parameters and performance of ten distinct building forms. The first six cases represent single-storey buildings that exhibit more expansive ground floor cover but with smaller volumes, while Cases 7 – 10 represent multi-storey buildings with larger envelope areas and volumes. Table 4, on the other hand, represents the corresponding features and performance of the transformed buildings. Noticeably, a clear trend exists where the surface-to-volume (SV) ratio and the heat loss form factor (HLFF) consistently decrease as building volume and the number of floors increase. Specifically, the transformation process reduced the heat loss form factor by up to 7.6%, aligning with studies such as Hajtmanek et al. (2023) and Camporeale and Mercader-Moyano (2019) that infer that optimised buildings are characterised by better heat loss form factors, leading to improved energy efficiency.

However, despite these geometric modifications, the energy demand of the transformed buildings increased by up to 30.27% (Case 8), supporting studies that suggest that compactness alone, without energy-efficient measures, does not lead to energy efficiency (Galal Ahmed & Hossein Alipour, 2019; Marincu et al., 2024). These findings challenge the conventional notion that improving building compactness leads to reduced energy demand, particularly in tropical climates where orientation and façade exposure massively influence cooling demand.

Table 3 Case Buildings Parameters

Case Buildings																
Case Number	Building Form	Number of Floors	Total Wall Area (m²)	Roof Area (m²)	Total Envelope Area (m²)	Total Floor Areas (m²)	Heated Floor Area (m²)	Building Volume (m³)	Building Height (m)	Surface-to-Volume Ratio	Heat Loss Form Factor	Energy Consumption (kWh/m²)	Cooling Energy (kWh/m²)	Operative Temperature (°c)	Embodied Carbon (kgCO2)
Case 1		1	218.710	239.050	457.760	239.050	179.288	717.150	3	0.638	2.553	315.49	109.9	27.4	79542.6
Case 2		1	139.200	114.590	253.790	114.590	85.943	343.770	3	0.738	2.953	323.73	118.14	27.61	40004.6
Case 3		1	190.800	197.960	388.760	197.960	148.470	593.880	3	0.655	2.618	318.38	112.8	27.49	66367
Case 4		1	200.490	207.900	408.390	207.900	155.925	623.700	3	0.655	2.619	315.79	110.21	27.41	69800.7
Case 5		1	273.600	326.590	600.190	326.590	244.943	979.770	3	0.613	2.450	311.56	105.98	27.28	107414.7
Case 6		1	192.590	189.640	382.230	189.640	142.230	568.920	3	0.672	2.687	318.1	112.51	27.45	64098.8
Case 7		2	472.500	265.090	737.590	530.180	397.635	1,590.54	6	0.464	1.855	332.78	127.19	28.86	105092.6
Case 8		2	374.400	167.730	542.130	335.460	251.595	1,006.38	6	0.539	2.155	340.65	135.06	28.96	70794.7
Case 9		2	432.000	212.240	644.240	424.480	318.360	1,273.44	6	0.506	2.024	335.46	129.88	28.85	87699.4
Case 10		3	572.400	170.350	742.750	511.050	383.288	1,533.15	9	0.484	1.938	360.55	154.97	29.71	84816.9

Table 4 Transformed Buildings Parameters

Transformed Buildings															
Case Number	Building Form	Number of Floors	Total Wall Area (m²)	Roof Area (m²)	Total Envelope Area (m²)	Total Floor Areas (m²)	Heated Floor Area (m²)	Building Volume (m³)	Building Height (m)	Surface-to-Volume Ratio	Heat Loss Form Factor	Energy Consumptio n (kWh/m²)	Cooling Energy (kWh/m²)	Operative Temperature (°c)	Embodied Carbon (kgCO2)
Case 1		1	189.36	239.05	428.41	239.05	179.29	717.15	3	0.597	2.390	407.85	128.85	27.85	77858.1
Case 2		1	131.10	114.59	245.69	114.59	85.94	343.77	3	0.715	2.859	420.54	141.81	28.12	39527.6
Case 3		1	172.32	197.96	370.28	197.96	148.47	593.88	3	0.623	2.494	409.7	130.97	27.9	65370
Case 4		1	176.60	207.90	384.50	207.90	155.93	623.70	3	0.616	2.466	408.95	130.21	27.88	68416.4
Case 5		1	221.34	326.59	547.93	326.59	244.94	979.77	3	0.559	2.237	402.48	123.74	27.73	104471.3
Case 6		1	168.66	189.64	358.30	189.64	142.23	568.92	3	0.630	2.519	410.45	131.72	27.92	62815.1
Case 7		2	398.82	265.09	663.91	530.18	397.64	1,590.54	6	0.417	1.670	431.63	152.9	29.51	100910.6
Case 8		2	317.22	167.73	484.95	335.46	251.60	1,006.38	6	0.482	1.928	443.76	165.03	29.68	67333.8
Case 9		2	356.86	212.24	569.10	424.48	318.36	1,273.44	6	0.447	1.788	436.59	157.85	29.58	82807.2
Case 10		3	479.54	170.35	649.89	511.05	383.29	1,533.15	9	0.424	1.696	468.49	189.76	30.56	79632.9

5. Discussion

5.1. Building Form Transformation and Compactness

Descriptive statistics of the datasets in Tables 3 and 4 were first examined to provide a basic understanding of key parameters influencing building form variability. The analyses focused on building envelope characteristics, energy performance, operative temperature variance, building initial cost and preliminary embodied carbon assessment. The analyses reveal substantial changes in the building attributes following the transformation of the original forms. Single-storey buildings (Cases 1-6), with a building height of 3 meters, generally have higher surface-to-volume ratios and heat loss form factors. This is due to the heat loss tendencies of the exposed surface areas compared to the buildings' volumes. A larger external surface area compared to enclosed volume exposes more pathways for heat to escape or enter (Li et al., 2024).

Conversely, multi-storey buildings (Cases 7-10), with height above 3 meters, show lower SV ratios because increasing the building height and enclosed volume typically leads to a smaller ratio of envelope area per unit of heated floor area. In this study, the Global Form Factor was considered for the multi-storey simulation, where internal separating floors are not factored, but considered as a single thermal envelope. One of the improvements is the reduction in the mean SV ratio of the buildings, which decreased from 0.596 to 0.551. This reduction suggests that all the transformed buildings become more compact, simply by assuming a rectangular shape. A similar trend is observed where a comparison of Heat Loss Form Factor (HLFF) and SV ratios highlights the overall shift towards lower values in the transformed buildings (Figure 2). The reduction in the mean HLFF, which declined by 7.6%, aligns with expectations, as compact buildings tend to exhibit lower heat loss due to reduced envelope area and geometric thermal bridges. Building shape or footprint matters, as among single-storey or multi-storey cases, a more spread-out or irregular shape tends to have a higher form factor than a regular or consolidated footprint.

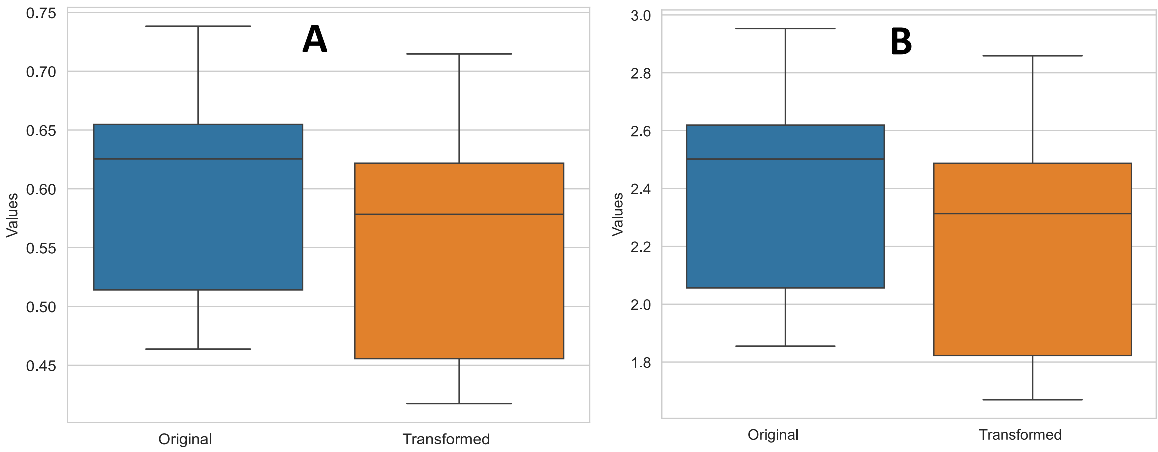


Figure 2 Boxplot comparing HLFF (A) and SV ratio (B) of buildings

The Total Envelope Area, one of the contributing factors to a building's compactness, also experienced approximately a 9% reduction, decreasing from an average of 515.78 m² in the original buildings to 470.30 m² in the transformed buildings (Figure 3). The transformed buildings maintained the same building floor area, floor numbers and building volume as the original counterpart. A large building, if designed with a compact geometry, can have a lower SV ratio and heat loss form factor. For example, Case 7, with the largest volume and envelope area, exhibits the smallest SV ratio in both configurations, suggesting a strong relationship between building compactness and exposed surface area and volume. Generally, transforming the buildings to a more compact form while maintaining the usable floor area and volume yielded lower SV ratios.

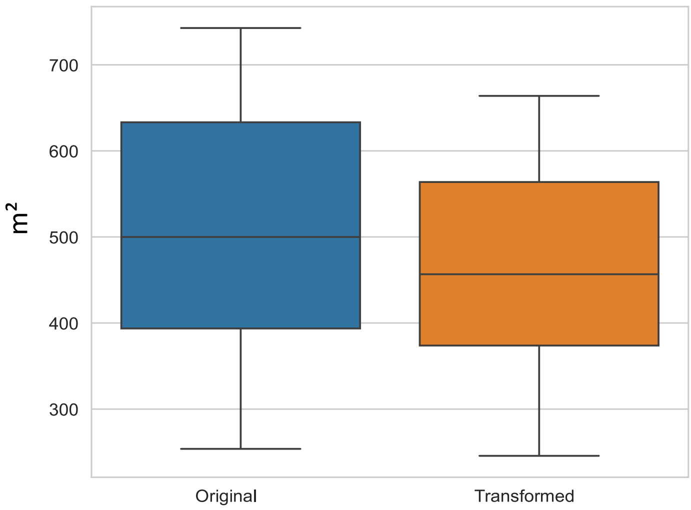


Figure 3 Total envelope area comparison

5.2. Energy Performance Implication of Compact Building Forms

Emerging studies show that increasing the compactness of buildings improves their thermal performance but, in this regard, the mean cooling energy demand of the transformed buildings with lower SV ratios exhibited an unexpected increase of approximately 19.4% (Figure 4). One possible explanation is that changes in façade exposure, which did not account for energy-efficient measures, might have offset the expected energy savings.

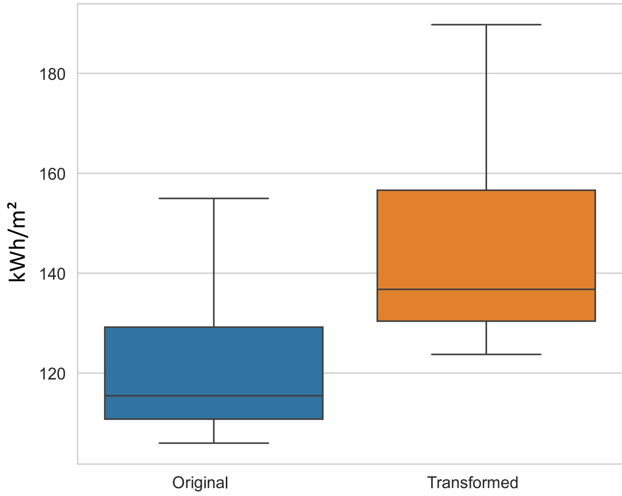


Figure 4 Cooling energy comparison-original vs. transformed buildings

It was observed that the transformed building's reduced energy efficiency is due to increased solar exposure, mainly via the south-facing façades. Since the modelling set-up assigned a fixed 30% window-to-wall ratio, the transformed buildings, with their longer façades, resulted in significantly more exposed areas to direct solar radiation. This prolonged exposure of the buildings could have led to high indoor heat gain, consequently increasing cooling load. In contrast, the case buildings with irregular forms and geometric thermal bridges, varied orientations and complex geometries may have inadvertently provided self-shading on large surfaces. This finding provides insights into form optimisation for early-stage design, noting that without shading or strategic adjustments to window placements, excessive heat buildup could occur, leading to increased energy demand (Kabanshi et al., 2023; Ran et al., 2022).

The relationship between form factor and energy demand in the early design phase is further depicted in Figure 5 using Seaborn's scatter plots. The plots reveal a moderate to strong correlation between SV ratio and energy demand, with 6 out of the 10 data points placed within the regression threshold and clustered next to the regression line. The downward-sloping regression lines indicate that for the building collection, those with high SV ratios tend to have reduced energy demand. However, Case 10 (three floors) and Case 2 (one floor) are outside the confidence interval (above the regression line), suggesting the model may have underestimated energy demand for these buildings. While the latter has the highest SV ratio with a moderate energy demand, the former has a small SV ratio but with an elevated energy demand, possibly owing to the energy loadings of the multiple floors of the building. Conversely, Case 5 (one floor) falls below the regression threshold due to its complex geometry and large floor area but emerged as the most energy-efficient building, implying that specific forms, due to their geometric configurations, may exhibit better thermal performance. Although a comparatively lower SV ratio is typically associated with improved energy performance (Rahmani & Al-Sallal, 2019), the transformed buildings' increased energy demand suggests that for operational buildings, energy-efficiency strategies need to be featured.

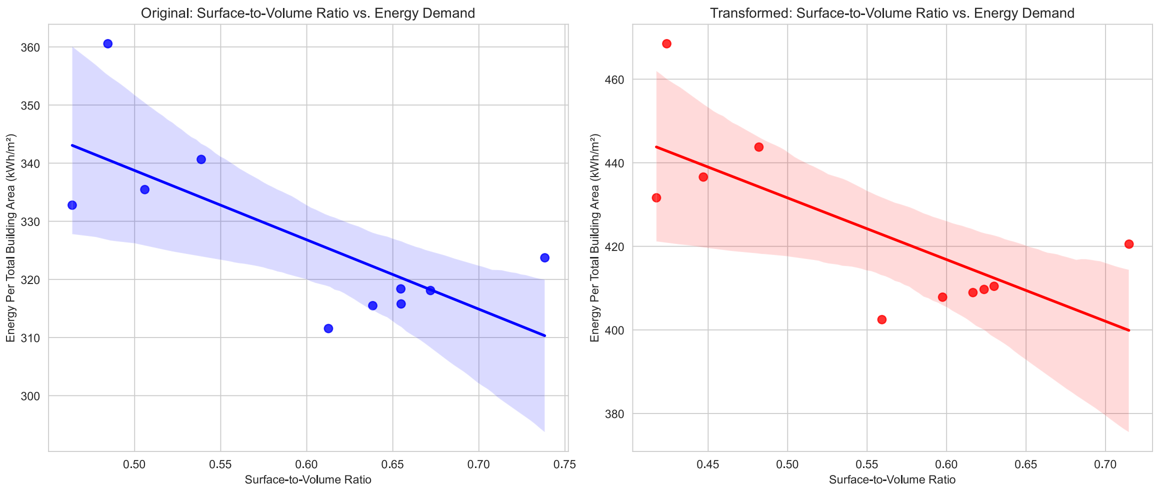


Figure 5 Scatter plot showing the relationship between buildings' SV ratios and energy demand

5.3. Impact of Form Factor on Thermal Comfort and Embodied Carbon

As reflected in the mean annual operative temperatures' columns (Tables 3 and 4), thermal comfort exhibited a slight increase of 2%. This increase is mainly attributed to excessive heat gains due to exposed window openings and walls. However, the narrow standard deviation of ±1.04 °C across the dataset suggests that these temperature variations are relatively small, which can be improved using passive design strategies. Notwithstanding, even minor temperature increases can translate into higher cooling loads, further explaining the observed energy demand increase highlighted in Section 5.2. Conversely, the overall mean embodied carbon emissions of the buildings reduced by 3.4% from 77,563 kgCO_2e to 74,914 kgCO_2e, which can be attributed to the changes in envelope area between the original and building forms. This variance in embodied carbon across building forms is depicted in Figure 6 below.

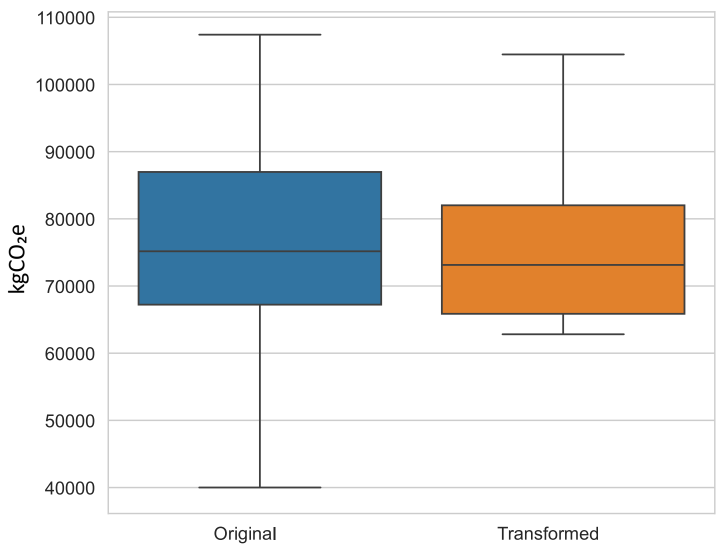


Figure 6 Embodied carbon comparison of building forms

While compactness may reduce envelope material use, other factors such as size and building use influence embodied carbon levels (He et al., 2024; Kern et al., 2021). As depicted in Figure 7, improving building compactness does not reduce embodied carbon, since the least compact buildings account for the smallest embodied carbon, while more compact buildings tend to have high embodied carbon. Specifically, Case 5 (one floor) and Case 7 (two floors), far above the best-fit regression line and with the largest floor areas, account for the most embodied carbon, yet with varied SV ratios. Also, Case 2 (one floor) and Case 8 (two floors), with the smallest floor areas and below the confidence interval, also have diverse SV ratios and embodied carbon. Most of the buildings with high SV ratios have low to moderate embodied carbon, while the majority with low SV ratios have high embodied carbon. Predicting embodied carbon using early design form optimisation is a complex task requiring other building elements for accurate estimates and reliability.

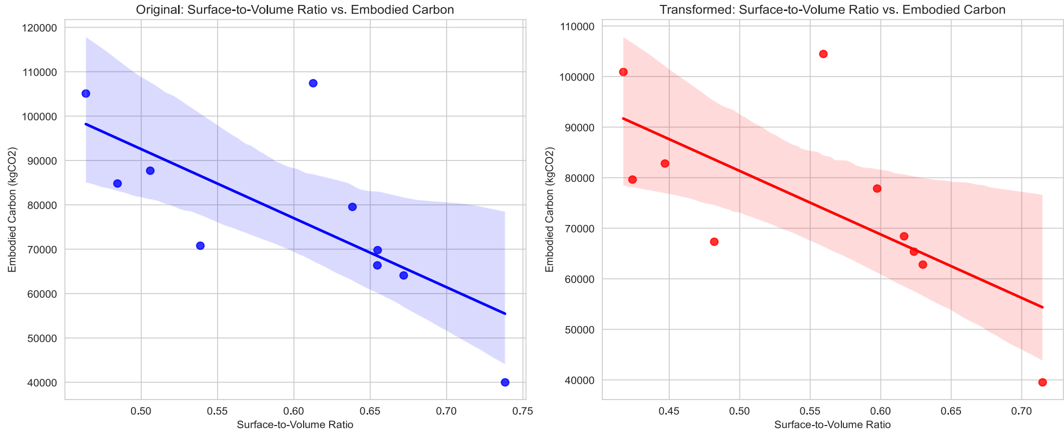


Figure 7 Scatter plot showing the relationship between buildings' SV ratio and embodied carbon

5.4. Factors Influencing Form Factor Variability

5.4.1. Principal Component Analysis (PCA) of Energy Performance Metrics

A Principal Component Analysis (PCA) biplot (Figure 8) is a visual representation of the interconnection between Volume, Total Envelope Area, Surface-to-Volume (SV) Ratio and Energy per Total Building Area. The PCA analysis was conducted using data from the original building forms as presented in Table 3. It shows how these variables interact along the first two principal components (PC1 and PC2), which together explains much of the variability in the dataset. Understanding these patterns is essential for optimising building forms for energy efficiency and sustainability.

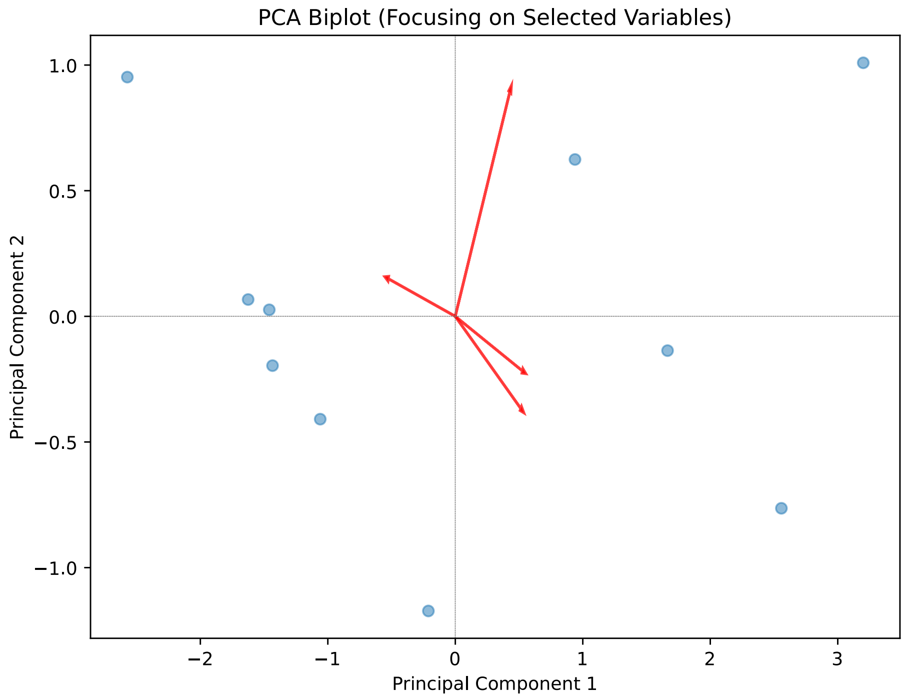


Figure 8 Biplot of principal component loadings

The principal component (PC) loadings clarify this interconnectedness by measuring the contributions of these variables to PC1 and PC2. In PC1, Volume (0.53) and Total Envelope Area (0.51) have strong positive loadings (see vectors in Figure 8), implying that this component is primarily driven by building size. The SV ratio, on the other hand, has a negative loading of -0.52, reinforcing its inverse relationship with Volume and Envelope Area. As corroborated by D'Amico and Pomponi (2019), the negative influence of SV ratio suggests that buildings with lower SV ratios are typically associated with larger volumes. Energy per Total Area also contributes to PC1 with a moderate loading of 0.43, implying that while size-related factors do influence energy use, they are not the sole determinants.

In contrast, PC2 is overwhelmingly influenced by Energy per Total Area, with the highest loading of 0.89. This confirms that energy performance varies independently of size-related parameters and is largely responsible for the differentiation captured along this axis. The vector position of Energy loading, perpendicular to other variables, implies little or no direct influence by other variables. Furthermore, the negative loading of Total Envelope Area (-0.37) on PC2 suggests that buildings with large envelope areas are weakly associated with low energy use. A clear example is a comparison between Case 8 and 9. Despite Case 8 having a lower total surface area (542.130 m^2) and a lower SV ratio (0.539), its energy use is higher at 340.65 kwh/m^2. In contrast, Case 9, with a larger total surface area (644.240 m^2) and a slightly lower SV ratio (0.506), records a lower energy consumption of 335.46 kwh/m^2. The strength of energy use on PC2 indicates that other factors likely dominate energy performance, making it crucial to look beyond building form when evaluating energy efficiency.

5.4.2. Regression Analysis of Form Factor Variance

A regression analysis was further conducted on the dataset to determine the degree to which building volume and envelope area influence the surface-to-volume (SV) ratio of buildings. The objective is to ascertain the primary determinant driving variations in the SV ratio, which is crucial for understanding compactness. The regression models for the building configurations exhibit high explanatory power, with R-squared values above 94%, indicating that building volume and total envelope area together explain nearly all variations in the SV ratio. However, despite the inclusion of both independent variables, the results show that building volume plays a far more significant role in determining the SV ratios than the envelope area. For the original form, the model has an R-squared value of 0.955, meaning that 95.5% of the variability in the form factor is explained by the predictors, while the transformed buildings model has an R-squared value of 0.947. The high adjusted R-squared values (0.942 for the original and 0.932 for the transformed buildings) reinforce the reliability of these models. The statistical significance of the models is further supported by F-statistics of 73.71 (p = 1.98e-05) for the case buildings and 62.45 (p = 3.44e-05) for the transformed buildings, confirming that at least one of the independent variables plays a crucial role.

5.4.2.1. Impact of Building Volume on Surface-to-Volume Ratio

Across both building configurations, the regression analysis shows that building volume is the dominant factor driving SV ratio variations. For instance, in the original forms, the regression coefficient for building volume is -0.0003, with a p-value of 0.038, making it statistically significant. Likewise, in the transformed buildings, the coefficient remains negative (-0.0002) but with a p-value of 0.051 (slightly above the significance threshold). There is a strong tendency for voluminous buildings to have small SV ratios, leading to more compact forms. In Figure 9 below, Cases 7, 8, 9 (two floors) and 10 (three floors) have the largest volumes and lower SV ratios, while Case 2 (one floor), with the least volume, possesses the highest SV ratio. The reason for this is straightforward: SV ratio is expressed as the ratio of the total envelope area by building volume (Equation I). For buildings with larger volumes than their envelope area, the SV ratio would be small, while buildings with more surface area than their volumes will have large SV ratios. Since volume remains fixed for each of the buildings, the only way to achieve a lower SV ratio is by reducing the total envelope area. This is the reason all the transformed buildings achieved lower SV ratios compared to their original forms.

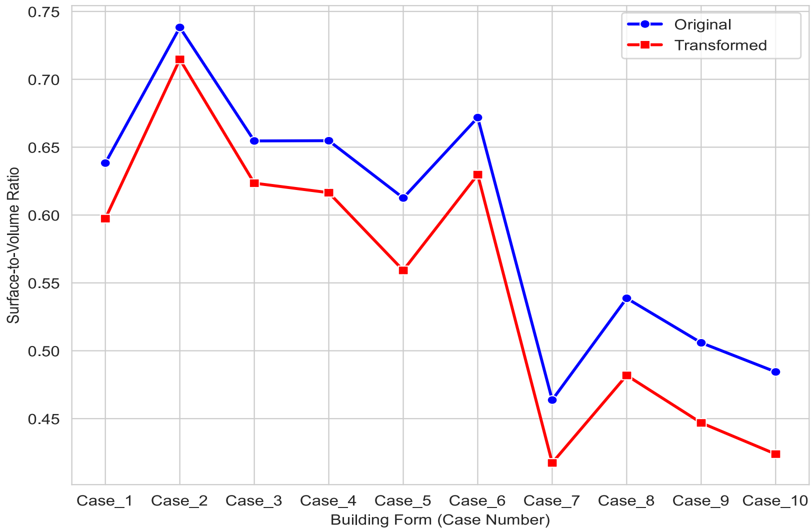


Figure 9 Comparison of surface-to-volume ratios for different building forms

5.4.2.2. Impact of Envelope Area on Surface-to-Volume Ratio

Despite its presence in the regression model, the building's total envelope area does not significantly influence the SV ratio. In the original form, the coefficient for total envelope area is 0.0001, but its p-value of 0.662 shows that its effect is not statistically significant. Likewise, in the transformed buildings, the coefficient is even smaller (4.047e-05), and the p-value is extremely high (0.905), confirming no meaningful impact. This result suggests that merely adjusting a building's envelope area does not independently dictate its SV ratio unless it is accompanied by changes in its volume. The reduction in envelope area during transformation directly lowered the SV ratio, but the analysis from the previous section reveals that this relationship is primarily driven by volume rather than the envelope area.

A Pearson correlation heatmap (Figure 10) shows the connection between SV ratio and key building parameters and performance metrics. Broadly, a correlation coefficient value ranges from -1 to 1, with values of 1 or close to 1 suggesting a perfect or strong positive relationship, while values of -1 or close to -1 indicate a perfect or strong negative correlation. A positive correlation suggests that as one variable increases, the other also increases linearly, while a negative correlation indicates that as one variable increases, the other decreases proportionately. A correlation value of 0 indicates that there is no linear relationship between the variables. In this regard, a strong negative correlation exists between envelope area and surface-to-volume ratio in both building forms, -0.96 for the original form and -0.95 for the transformed building. This implies that as the building envelope area increases, the SV ratio tends to decrease proportionately. However, as discussed earlier, this relationship is mainly influenced by building volume, the principal determinant of SV, with a correlation coefficient of -0.98 and -0.97 in the original and transformed buildings, respectively.

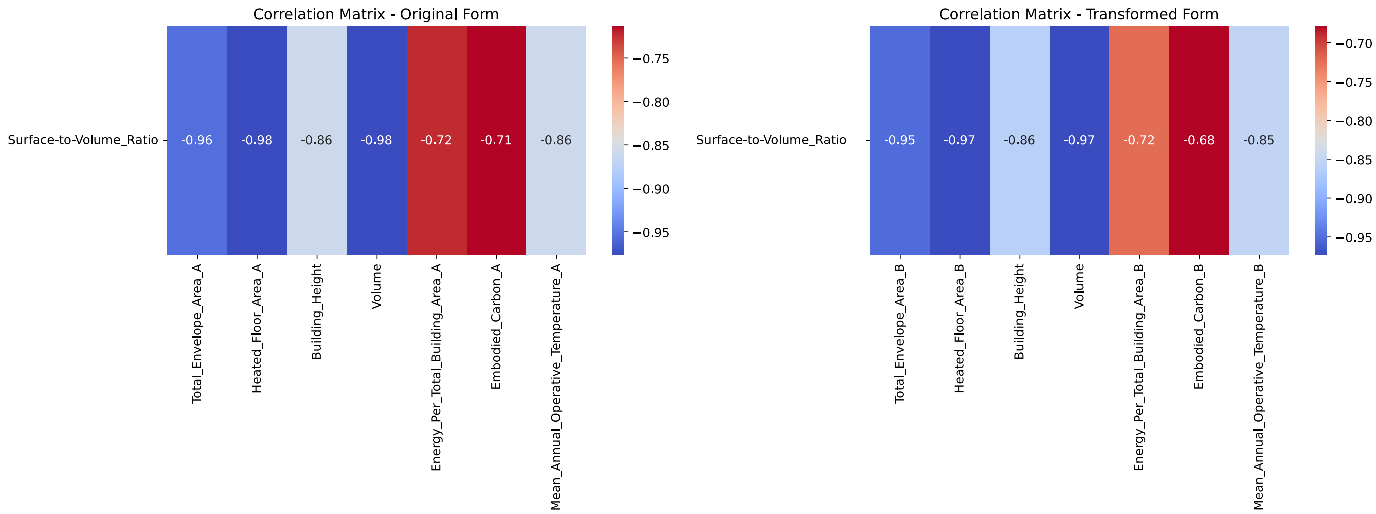
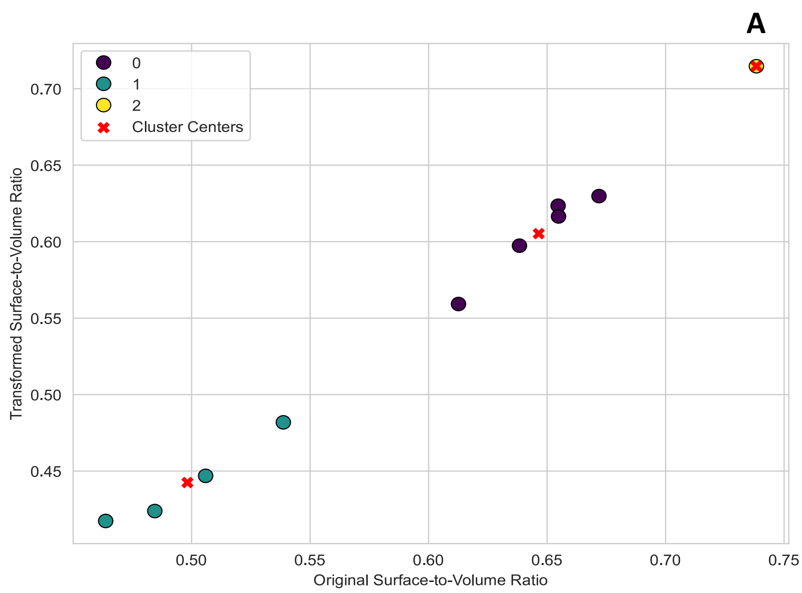


Figure 10 Pearson correlation matrix of building forms

5.5. Building Form Clusters and Overall Implications

K-Means clustering algorithm was used to cluster the buildings based on surface-to-volume ratio and their energy efficiency (Figure 11), uncovering patterns that would have otherwise remained obscured. The analyses highlight three distinct clusters, each representing different relationships between form and energy efficiency. From Figure 11A, the first cluster (0) encompasses building Cases 1, 3, 4, 5 and 6 (one floor). These buildings, with moderate SV ratios, all share a single-storey configuration in both configurations, indicating their volumetric efficiency remained relatively stable despite morphological adjustments. On the other hand, the second cluster (1) comprises building Cases 7-10, all two-storey buildings except for Case 10 (three storeys). This cluster contains buildings with the largest volumes, yet the lowest SV ratios, corroborating the significance of large-volume buildings in reducing SV ratio, as highlighted in section 5.4.2.1. Since buildings in cluster 0 are single-storey, and cluster 1 are multi-storeys, building levels positively correlate with compactness, indicating the likelihood for taller buildings to be more compact (Vasilenko, 2019). Nonetheless, a single-storey building (Case 2) appears as an outlier in cluster 2, mainly due to its comparatively lower volume (343.77 m^3) and significantly high SV ratios: 0.74 and 0.72 for the original and transformed buildings, respectively. The isolated position of this case suggests that not all single-storey buildings behave similarly when transformed, as some may still experience significant SV ratio reductions depending on their initial complexity.



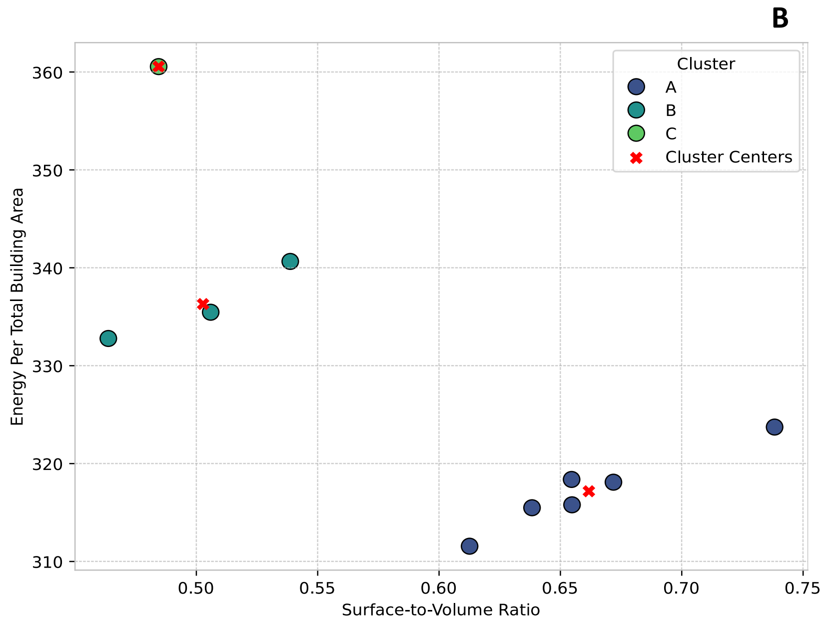


Figure 11 Buildings cluster based on SV ratios (A), and buildings energy efficiency (B)

The cluster result, as illustrated in Figure 11B, reveals intriguing insights into the relationship between surface-to-volume (SV) ratio and building energy performance. The building forms are classified into Clusters A, B and C, highlighting unexpected patterns that challenge conventional assumptions about form factor and energy efficiency. Cluster A consists of building Cases 1 to 6 (single storey), with high SV ratios. Ideally, a high SV ratio is expected to lead to greater heat loss and higher energy demand, but these buildings in the cluster exhibit the best energy performance, with values ranging between 310 kWh/m² and 325 kWh/m². This counterintuitive finding suggests that factors beyond compactness, such as internal heat gain tendencies, may be compensating for their inherently inefficient form. Some of these buildings have complex geometries (see Table 3) that offer self-shading of the envelope, possibly reducing heat gains.

Furthermore, Cluster B includes Cases 7, 8 and 9 (two storeys) with moderate SV ratio, with Case 7 having the lowest ratio (0.464). This cluster is more compact compared to Cluster A; however, their small SV ratio did not automatically translate to better energy efficiency, as they exhibit higher energy demand. The implication of this finding is that while compactness reduces heat loss, other factors such as increased thermal loads and heated floor areas may contribute to their poor energy efficiency. Cluster C, on the other hand, is a three-storey building with an incredibly low SV ratio (0.484), but its energy demand is the highest, owing to its treated floor areas and volumetric properties, which demand increased cooling requirements, overriding the benefits of its compact form. Findings from these analyses insinuate that compactness alone does not guarantee energy efficiency in buildings, as those with exceptionally low SV ratios can still have high energy demands compared to other forms with higher SV ratios. This study emphasises the importance of early design decisions which must transcend simple form optimisation. Building energy performance is influenced by a complex interplay of form, internal loads and passive design strategies that may not be accounted for in the early phases of building design; hence, making energy demand trajectory vis-à-vis form factor optimisation unpredictable (Li et al., 2014; Yao et al., 2021; Zhuravchak et al., 2022).

6. Conclusion and Recommendations

6.1. Conclusion

This study examined the impact of form factor variance on early-stage design performance in Nigeria using computational and empirical analyses. Findings from the study challenge conventional assumptions that compact buildings are energy efficient. Out of ten buildings evaluated in their original and transformed cases, single-storey buildings with higher surface-to-volume (SV) ratios exhibited better energy efficiency compared to the most compact building (three storeys). Principal component analysis (PCA) further revealed that building volume and envelope area explained more than 97% of observed form factor differences, while regression analysis confirmed building volume as the key player in form factor variability ($p = 0.038$). With a p-value of 0.662, it was concluded that building envelope area had no statistical significance on form factor changes. By implication, building form optimisation should prioritise volume over envelope area reduction.

Cluster analysis, however, highlighted that building energy efficiency is informed by the interplay between SV ratio, volume and building façade exposure to solar radiation. Case 2, a single-storey building, emerged as an outlier among the buildings with a disproportionately high heat loss form factor (2.95) and SV ratio (0.74), owing to its lesser floor area and volume. Despite SV ratio reductions of 3.19% to 12.50% following form transformation (L = 1.5B), energy demand unexpectedly increased by 28.68% to 30.27%, suggesting that compactness alone does not ensure energy efficiency. These findings emphasise the importance of shading and passive cooling considerations in form optimisation for representative estimates of operational energy and embodied carbon during early design development.

6.2. Recommendations

Based on the study findings, the following recommendations have been outlined to inform building designers, policymakers and researchers on building form optimisation for energy efficiency in tropical climates.

1. Optimisation of Compactness and Façade Exposure

Compact buildings should be designed with solar exposure mitigation in mind, especially for multi-storey buildings. Passive strategies such as dynamic shading, glazing optimisation and low-albedo material use should be incorporated for enhanced energy efficiency.

2. Prioritisation of Volumetric Efficiency

Since building volume is the primary driver of form factor, energy-efficient designs should focus on optimising volume without compromising functional architectural requirements and passive cooling strategies.

3. Development of Hybrid Form Factor Indices

Future research should consider integrated metrics that combine form factor, façade exposure, material performance and cooling strategies to provide more reliable energy efficiency predictions for early-stage design.

4. Empirical Validation Through Longitudinal Studies

While this study provides valuable insights, longitudinal studies incorporating real-world occupancy patterns are needed to validate the effectiveness of form optimisation in the long-term in tropical climates.

5. Exploration of Morphological Adaptations in High-Rise Buildings

Given the high energy demand of the three-storey building, despite its low SV ratio, future studies should explore alternative high-rise morphologies such as stepped massing, double-skin façades and natural ventilation corridors to mitigate heat stress in compact multi-storey tropical buildings.

CRediT Authorship Contribution Statement

Mark Alegbe: Conceptualisation, Writing – original draft, review & editing, Writing – Methodology, Investigation, Simulation, Results interpretation. Hammed Nasiru: Writing – formatting, editing & literature review. John Lekwauwa Kalu: Data curation, Investigation, Visualisation. Laurence Chukwuemeka: Data curation, Visualisation. Nnamdi Diribe: Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

Ethics Committee Approval

Approval from an ethics committee was not required for this research.

References

Adenaike, F. A., & Opoko, A. P. (2024). Thresholds of architectural morphology of Yoruba buildings in Southwest Nigeria till the millenia. *European Journal of Theoretical and Applied Sciences*, *2*(2), 180–193. https://doi.org/10.59324/ejtas.2024.2(2).17

Agbete, M. A., & Frank, O. L. (2020). Modern vernacular architecture: An ecological approach towards energy efficiency; toreduce climate change impact in Nigeria. *IOSR Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT)*, *14*(3), 20–34.

Ahmadian, E., Sodagar, B., Bingham, C., Elnokaly, A., & Mills, G. (2021). Effect of urban built form and density on building energy performance in temperate climates. *Energy and Buildings*, *236*, 110762. https://doi.org/10.1016/J.ENBUILD.2021.110762

Ahmed, N., Abdel-Hamid, M., Abd El-Razik, M. M., & El-Dash, K. M. (2021). Impact of sustainable design in the construction sector on climate change. *Ain Shams Engineering Journal*, *12*(2), 1375–1383. https://doi.org/10.1016/j.asej.2020.11.002

Akbari, H., & Nezhad, F. S. H. (2020). Optimum form, aspect ratio and orientation of building based on solar energy receiving in hot-dry climate: Case studies of Isfahan, Semnan, Kashan and Kerman cities, Iran. *Journal of Solar Energy Research (JSER)*, *5*(1), 341_350. https://doi.org/10.22059/JSER.2020.299320.1145

Algburi, O., & Ferah, B. (2021). *Simulation comparative study to highlight the relation between building form and energy consumption*. International Conference on Advanced Engineering, Technology and Applications.

Alhawari, A., & Mukhopadhyaya, P. (2018). Thermal bridges in building envelopes – An overview of impacts and solutions. *International Review of Applied Sciences and Engineering IRASE*, *9*(1), 31–40. https://doi.org/10.1556/1848.2018.9.1.5

Alshboul, A., & Alatrash, D. (2024). Natural design procedures for enhancing energy efficiency in buildings [Article]. *International Journal of Design and Nature and Ecodynamics*, *19*(5), 1527–1539. https://doi.org/10.18280/ijdne.190507

Araji, M. T. (2019). *Surface-to-volume ratio: How building geometry impacts solar energy production and heat gain through envelopes* IOP Conference Series: Earth and Environmental Science, Graz. *323*(1), pp. 012034. https://doi.org/10.1088/1755-1315/323/1/012034

Arbabzadeh, M., Etessam, I., & Shemirani, M. (2020). Passive thermoregulation in vernacular and biomimetic architecture in hot and arid climate. *International Journal of Architecture, Engineering and Urban Planning*, *30*(2), 198–211. https://doi.org/10.22068/ijaup.30.2.198

Archi-Monarch. (n.d.). *Form in architecture*. Archi-Monarch. Retrieved March 6, 2025 from https://archi-monarch.com/form-in-architecture/

Aydın, M. A., & Koçlar Oral, G. (2024). Evaluation of building energy performance based on settlement scale design parameters using BIM tools. *Gazi University Journal of Science*, *37*(2), 501–518. https://doi.org/10.35378/gujs.1277880

Barssoum, M., Knudsen, H., Macdonald, I., & Vuong, E. (2020). *A parametric study on the impact of geometric building shapes on energy consumption*. Proceedings of the eSIM:11th Conference of IBPSA, Canada.

Beck, H. E., McVicar, T. R., Vergopolan, N., Berg, A., Lutsko, N. J., Dufour, A., Zeng, Z., Jiang, X., van Dijk, A. I. J. M., & Miralles, D. G. (2023). High-resolution (1 km) Köppen-Geiger maps for 1901–2099 based on constrained CMIP6 projections. *Scientific Data*, *10*(1), 724. https://doi.org/10.1038/s41597-023-02549-6

Belussi, L., Barozzi, B., Bellazzi, A., Danza, L., Devitofrancesco, A., Fanciulli, C., Ghellere, M., Guazzi, G., Meroni, I., Salamone, F., Scamoni, F., & Scrosati, C. (2019). A review of performance of zero energy buildings and energy efficiency solutions. *Journal of Building Engineering*, *25*, 100772. https://doi.org/https://doi.org/10.1016/j.jobe.2019.100772

Benkhelifa, A., Bekkouche, S., Allaoui, T., Cherier, M., Hamdani, M., Mihoub, R., & Djeffal, R. (2019). Application of the building height concept to energy-efficient heating and cooling for Saharan buildings. *Modelling, Measurement and Control 80*(2-4), 71–78. https://doi.org/10.18280/mmc_c.802-405

Boronbaev, E. (2023). *Energy saving architecture concept: Buildings with low energy consumption and emissions in Kyrgyzstan*. E3S Web of Conferences, *405*, pp. 04039. https://doi.org/10.1051/e3sconf/202340504039

Boronbaev, E. (2024). *Energy saving architecture: Multidisciplinary improvement of buildings shape, energy-efficiency, microclimate, seismic-resistance and prevention influences of thermal bridges and mold growth*. Proceedings of the International Conference on Geosynthetics and Environmental Engineering, Singapore. *374*, pp. 251–259. https://doi.org/10.1007/978-981-99-4229-9_22

British Standards Institution. (2012). *BS EN 15978:2011: Sustainability of construction works. Assessment of environmental performance of buildings*. Calculation method. In: British Standards Institute.

Burrell, E. (n.d.). *Heat loss form factor*. Greenspec. Retrieved 8th March 2025 from https://www.greenspec.co.uk/building-design/heat-loss-form-factor/

Camporeale, P., & Mercader-Moyano, P. (2019). Towards nearly zero energy buildings: Shape optimization of typical housing typologies in Ibero-American temperate climate cities from a holistic perspective. *Solar Energy*, *193*, 738–765. https://doi.org/10.1016/j.solener.2019.09.091

Carpio, M., & Carrasco, D. (2021). Impact of shape factor on energy demand, CO2 emissions and energy cost of residential buildings in cold oceanic climates: Case study of South Chile. *SUSTAINABILITY*, *13*(17), 9491. https://doi.org/10.3390/su13179491

Circular Ecology. (2025). *Inventory of carbon & energy (ICE) database v4.1*. circularecology.com/news/ice-database-v4-1-released

D'Amico, B., & Pomponi, F. (2019). A compactness measure of sustainable building forms. *Royal Society Open Science*, *6*(6), 181265. https://doi.org/10.1098/rsos.181265

D'Amico, B., Pomponi, F., & Hart, J. (2021). Global potential for material substitution in building construction: The case of cross laminated timber. *Journal of Cleaner Production*, *279*, 123487. https://doi.org/10.1016/j.jclepro.2020.123487

Dada, A. D., & Alibaba, H. Z. (2023). *Comparison analysis between the components of vernacular and modern architectures for sustainable housing in Niger State* IOP Conference Series: Earth and Environmental Science, *1210*(1), pp. 012011. https://doi.org/10.1088/1755-1315/1210/1/012011

Deng, X., Wang, M., Sun, D., & Fan, Z. (2020). *Effect of building form on energy consumption of academic library buildings in different climate zones in China*. IOP Conference Series: Earth and Environmental Science, *531*, pp. 012060. https://doi.org/10.1088/1755-1315/531/1/012060

DesignBuilder. (V7.0). *LCA And Embodied carbon*. Retrieved 11 August 2026 from https://designbuilder.co.uk/helpv7.0/Content/Carbon.htm

Djeddou, B., Daich, S., & Femmam, A. (2024). The impact of urban form on the energy efficiency of residential buildings in a hot climate. Case study: Ouargla city. *Journal of Building Physics*, *48*(5), 1–29. https://doi.org/10.1177/17442591241289579

Driga, A. M., & Drigas, A. S. (2019). Climate change 101: How everyday activities contribute to the ever-growing issue. *International Journal of Recent Contributions from Engineering, Science & IT (iJES)*, *7*(1), 22–31. https://doi.org/10.3991/ijes.v7i1.10031

El-Agami, M., Hanafy, G., & Osman, M. (2021). Investigating the effect of high-rise buildings' mass geometry on energy efficiency within the climatic variation of Egypt. *SUSTAINABILITY*, *13*(19), 10529. https://doi.org/10.3390/su131910529

Fereidani, N. A., Rodrigues, E., & Gaspar, A. R. (2021). A review of the energy implications of passive building design and active measures under climate change in the Middle East. *Journal of Cleaner Production*, *305*, 127152.

Folorunso, C., Akingbohungbe, D., & Ogunruku, M. (2017). Choice prediction factors in building exterior finishes' selection in Lagos, Nigeria: Clients' perspective. *International Journal of Research in Engineering and Social Sciences*, *7*(1), 14–20.

Freewan, A. (2022). Energy-efficient solutions depending on building forms design with tilted South and North Facades. *Buildings*, *12*, 753. https://doi.org/10.3390/buildings12060753

Galal Ahmed, K., & Hossein Alipour, S. M. (2019). *Investigating the effect of urban compactness on energy efficiency in recent urban communities in UAE*. IOP Conference Series: Materials Science and Engineering, *603*(2), pp. 022092. https://doi.org/10.1088/1757-899X/603/2/022092

Gamero-Salinas, J., Kishnani, N., Monge-Barrio, A., Gandhi, B., Bilgi, M., & Sánchez-Ostiz, A. (2020). *The influence of building form on energy use, thermal comfort and social interaction A post-occupancy comparison of two high-rise residential buildings in Singapore* 35th PLEA Conference. Planning Post Carbon Cities., *1*, pp. 61. https://doi.org/10.17979/spudc.9788497497947

Guo, M., Wu, Y., & Miao, X. (2023). Thermal bridges monitoring and energy optimization of rural residences in China's cold regions. *SUSTAINABILITY*, *15*(14), 11015. https://doi.org/10.3390/su151411015

Gupta, R., & Gregg, M. (2018). Assessing energy use and overheating risk in net zero energy dwellings in UK. *Energy and Buildings*, *158*, 897–905. https://doi.org/10.1016/j.enbuild.2017.10.061

Gupta, V., & Deb, C. (2023). Envelope design for low-energy buildings in the tropics: A review. *Renewable and Sustainable Energy Reviews*, *186*, 113650. https://doi.org/10.1016/j.rser.2023.113650

Hadjhafsi, L., Benaissa, F. T., Redjem, A., & Derradji, K. (2024). Residential building forms and energy efficiency in the Saharan climate: the case of Adrar, Algeria. *Geomatics, Landmanagement and Landscape*, *2*, 85–98. https://doi.org/10.15576/GLL/2024.2.06

Hajtmanek, R., Morgenstein, P., Hubinský, T., Legény, J., & Špaček, R. (2023). Determination of solar-surface-area-to-volume ratio: Early design stage solar performance assessment of buildings. *Buildings*, *13*(20), 296. https://doi.org/10.3390/buildings13020296

Hatem, H. M., & Karram, M. A. (2020). *Integrating layout geometry with architectural requirements to achieve energy-efficient office buildings in Egypt*. ASHRAE Topical Conference Proceedings, pp. 610–617.

He, H., Zhao, Z., Yan, H., Zhang, G., Jing, R., Zhou, M., Wu, X., Lin, T., & Ye, H. (2024). Urban functional area building carbon emission reduction driven by three-dimensional compact urban forms' optimization. *Ecological Indicators*, *167*, 112614. https://doi.org/10.1016/j.ecolind.2024.112614

Hong, T., Malik, J., Krelling, A., O'Brien, W., Sun, K., Lamberts, R., & Wei, M. (2023). Ten questions concerning thermal resilience of buildings and occupants for climate adaptation. *Building and Environment*, *244*, 110806. https://doi.org/10.1016/j.buildenv.2023.110806

Hygh, J. S., DeCarolis, J. F., Hill, D. B., & Ranji Ranjithan, S. (2012). Multivariate regression as an energy assessment tool in early building design. *Building and Environment*, *57*, 165–175. https://doi.org/10.1016/j.buildenv.2012.04.021

Kabanshi, A., Choonya, G., Ameen, A., Liu, W., & Mulenga, E. (2023). Windows of opportunities: Orientation, sizing and PV-shading of the glazed area to reduce cooling energy demand in Sub-Sahara Africa. *Energies*, *16*(9), 3834. https://doi.org/10.3390/en16093834

Kahraman, Ö., & Köymen, E. (2023). The influence of building form compactness on energy efficiency in accommodation structures: The case of Türkiye. *Sakarya University Journal of Science*, *27*(5), 1055–1078. https://doi.org/10.16984/saufenbilder.1253136

Kern, A. P., Postay, R., Schneck, E. R., Mancio, M., González, M. A. S., & Guerra, G. (2021). Cost and environmental impacts reduction through building compactness. *Engineering, Construction and Architectural Management*, *28*(4), 1176–1195. https://doi.org/10.1108/ECAM-03-2020-0147

Keskisalo, M., & Matveinen, M. (2021). *Form factor for efficient low carbon construction* InnoRenew CoE International Conference (Book of Abstracts), Online. pp. 12.

Khalil, A. (2023). *Design optimization of building form and fenestration for daylighting and thermal energy in three variations of the hot climate of Egypt*. Building Simulation Conference Proceedings, Shanghai, China. pp. 2274–2282. https://doi.org/10.26868/25222708.2023.1649

Khalil, A., Lila, A., & Ashraf, N. (2023). Optimization and prediction of different building forms for thermal energy performance in the hot climate of cairo using genetic algorithm and machine learning. *Computation*, *11*(100), 192. https://doi.org/10.3390/computation11100192

Kheiri, F. (2018). A review on optimization methods applied in energy-efficient building geometry and envelope design. *Renewable and Sustainable Energy Reviews*, *92*, 897_920. https://doi.org/10.1016/j.rser.2018.04.080

Kistelegdi, I., Horváth, K. R., Storcz, T., & Ercsey, Z. (2022). Building geometry as a variable in energy, comfort, and environmental design optimization—A review from the perspective of architects. *Buildings*, *12*(100), 69. https://doi.org/10.3390/buildings12010069

Koźniewski, E., Sadowska, B., & Banaszak, K. (2022). Geometric aspects of assessing the anticipated energy demand of a designed single-family house. *Energies*, *15*(9), 3308. https://doi.org/10.3390/en15093308

Li, C., Hong, T., & Yan, D. (2014). An insight into actual energy use and its drivers in high-performance buildings. *Applied Energy*, *131*, 394–410. https://doi.org/10.1016/j.apenergy.2014.06.032

Li, J., Liang, C., & Zhou, W. (2024). A review of building physical shapes on heating and cooling energy consumption. *Energies*, *17*(22), 5766. https://doi.org/10.3390/en17225766

Li, J., Yue, T., & Zhang, Y. (2023). Experimental and simulation study on the modified shape coefficient of building integrated thermal considerations for heating buildings in solar-enriched areas. *Solar Energy*, *264*, 112060. https://doi.org/10.1016/j.solener.2023.112060

Lian, H., Zhang, J., Li, G., & Ren, R. (2023). The relationship between residential block forms and building carbon emissions to achieve carbon neutrality goals: A case study of Wuhan, China. *Sustainability (Switzerland)*, *15*(22), 15751. https://doi.org/10.3390/su152215751

Liang, Y., Yuan, X., Pan, Y., & Kosonen, R. (2023). *Passive design and shape optimization for carbon emissions reduction for residential-and-commercial buildings in cold climate zone* Healthy Buildings Europe 2023: Beyond Disciplinary Boundaries, Germany. *2*, pp. 947–953.

Lodson, J., Ogbeba, J. E., & Elinwa, U. K. (2018). A lesson from vernacular architecture in Nigeria. *Journal of Contemporary Urban Affairs*, *2*(1), 84–95. https://doi.org/10.25034/ijcua.2018.3664

Lucchi, E. (2023). Energy and climatic performances of modern architecture: A complete overview of building physics implications. *Engineering Proceedings*, *53*(1), 19. https://doi.org/10.3390/IOCBD2023-15203

Mahmoud, A. R. (2022). The influence of buildings proportions and orientations on energy demand for cooling in hot arid climate. *SVU-International Journal of Engineering Sciences and Applications*, *3*(1), 8–20. https://doi.org/10.21608/svusrc.2022.119125.1028

Makhloufi, W. A., & Louafi, S. (2023). Parametric study for optimising building form and height: An approach toward net zero energy & carbon in buildings. *Tehnički Glasnik*, *17*(4), 501–507. https://doi.org/10.31803/tg-20221119182144

Marincu, C., Dan, D., & Moga, L. (2024). Investigating the influence of building shape and insulation thickness on energy efficiency of buildings. *Energy for Sustainable Development*, *79*, 101384. https://doi.org/10.1016/j.esd.2024.101384

Mba, E. J., Okeke, F. O., Oforji, P. I., Ozigbo, I. W., Emmanuel, E. C., & Ozigbo, C. A. (2024). *Impact of building plan shape on natural ventilation efficiency*. Proceedings of the 8th International Conference on Civil Engineering: ICOCE 2024, Singapore. *539*, pp. 355. https://doi.org/10.1007/978-981-97-5910-1_28

Mohsenzadeh, M., Marzbali, M. H., Tilaki, M. J. M., & Abdullah, A. (2021). Building form and energy efficiency in tropical climates: A case study of Penang, Malaysia. *City. Brazilian Journal of Urban Management*, *13*. https://doi.org/10.1590/2175-3369.013.e20200280

Mutani, G., Todeschi, V., Marta, C., & Andrea, R. (2020). *Urban-scale energy models:* Relationship *between urban form and energy performance*. 2020 IEEE 3rd International Conference and Workshop in Óbuda on Electrical and Power Engineering (CANDO-EPE), pp. 185–190. https://doi.org/10.1109/CANDO-EPE51100.2020.9337760

Noah, E. A., & Çağnan, Ç. (2021). A study of vernacular architecture in relation to sustainability: The Case of Northern Nigeria. *Near East University Faculty of Architecture Journal*, *3*(1), 21–35.

Notodipuro, P., & Mandala, A. (2022). The effect of building shape and orientation on energy use at sloped sites in tropical climates using sefaira. *ARTEKS : Jurnal Teknik Arsitektur*, *7*(7), 131–142. https://doi.org/10.30822/arteks.v7i1.1397

Nwalusi, D. M., Obi, N. I., Chendo, I. G., & Okeke, F. O. (2022). *Climate responsive design strategies for contemporary low-rise residential buildings in tropical environment of Enugu, Nigeria* IOP Conference Series: Earth and Environmental Science, *1054*(1). https://doi.org/10.1088/1755-1315/1054/1/012052

Ochedi, E. T., & Taki, A. (2022). A framework approach to the design of energy efficient residential buildings in Nigeria. *Energy and Built Environment*, *3*(3), 384–397.

Offor, J., & Emenike, A. (2019). Passive strategies for enhancing indoor comfort and air quality of high-density zones of South eastern Nigeria. *African Research Journal of the Environment*, *2*(1), 1–7. https://doi.org/10.36265/arejoen.2019.020101

Oh, M., & Kim, Y. (2019). Identifying urban geometric types as energy performance patterns. *Energy for Sustainable Development*, *48*, 115–129. https://doi.org/10.1016/j.esd.2018.12.002

Orçun, K. İ., & Onur, D. (2022). The impacts of early architectural design decisions on building performance. *International Journal of Digital Innovation in the Built Environment*, *11*(2), 1_21. https://doi.org/10.4018/IJDIBE.301245

Parry, C., & Strang, M. (2021). Airtightness and thermal bridging in buildings. *Environment*(3), 1–18. https://www.jstor.org/stable/27091017

Pathirana, S., Rodrigo, A., & Halwatura, R. (2019). Effect of building shape, orientation, window to wall ratios and zones on energy efficiency and thermal comfort of naturally ventilated houses in tropical climate. *International Journal of Energy and Environmental Engineering*, *10*(1), 107_120. https://doi.org/10.1007/s40095-018-0295-3

Pérez-Carramiñana, C., de la Morena-Marqués, A., González-Avilés, Á. B., Castilla, N., & Galiano-Garrigós, A. (2024). Influence of balcony thermal bridges on energy efficiency of dwellings in a warm semi-arid dry mediterranean climate. *Buildings*, *14*(3), 703. https://doi.org/10.3390/buildings14030703

Premrov, M., Žigart, M., & Žegarac Leskovar, V. (2018). Influence of the building shape on the energy performance of timber-glass buildings located in warm climatic regions. *Energy*, *149*, 496–504. https://doi.org/10.1016/j.energy.2018.02.074

Puri, U. (2021). Influence of building shape on area to volume ratio and thermal loads in warm climate - Case of Itahari, Nepal. *International Journal of Engineering Research and*, *10*(1), 231–235. https://doi.org/10.17577/IJERTV10IS010084

Ragab, A. (2022). The influence of buildings proportions and orientations on energy demand for cooling in hot arid climate. *SVU-International Journal of Engineering Sciences and Applications*, *3*(1), 8–20. https://doi.org/10.21608/svusrc.2022.119125.1028

Rahmani, M., & Al-Sallal, K. (2019). *Impact of building form on energy performance in new school models*. 16th IBPSA International Conference, Rome, Italy. pp. 5123_5129. https://doi.org/10.26868/25222708.2019.210309

Ran, J., Xiong, K., Dou, M., Zhong, H., Feng, Y., Tang, M., & Yang, Z. (2022). Effect of window openable area and shading on indoor thermal comfort and energy efficiency in residential buildings with various operating modes. *Atmosphere*, *13*(12), 2020. https://doi.org/10.3390/atmos13122020

Remon, L. (2019). The effect of building geometric shape and orientation on its energy performance in various climate regions. *GEOMATE Journal*, *16*(53), 11_119. https://geomatejournal.com/geomate/article/view/2660

Sokar, L., Brakez, A., & Sobhy, I. (2023). A scientific process for a sustainable architectural design: A case study of a rural pavilion in a hot semi-arid climate. *Journal of Building Engineering*, *79*, 107816. https://doi.org/10.1016/j.jobe.2023.107816

Song, J., & Sun, S. (2021). *Research on architectural form optimization method based on environmental performance-driven design*. Proceedings of the 2020 DigitalFUTURES: The 2nd International Conference on Computational Design and Robotic Fabrication, Shanghai, China. pp. 217–228. https://doi.org/10.1007/978-981-33-4400-6_21

Song, S., Leng, H., Xu, H., Guo, R., & Zhao, Y. (2020). Impact of urban morphology and climate on heating energy consumption of buildings in severe cold regions [Article]. *International Journal of Environmental Research and Public Health*, *17*(22), 1–25, Article 8354. https://doi.org/10.3390/ijerph17228354

Taştemir, İ. A., Koymen, E., & Yasa, E. (2024). A geometry-based decomposition method for energy prediction in early design stages of residential buildings. *Open House International*, *50*(3), 452–469. https://doi.org/10.1108/OHI-05-2024-0178

The Archspace. (n.d.). *Form in architecture – An important element of design*. The Archspace. Retrieved March 6, 2025 from https://thearchspace.com/an-important-element-of-design-form-in-architecture/

Umar, G. K., Yusuf, D. A., & Mustapha, A. (2019). Theory and design for the contemporary residential building: A case study of Kano Metropolis, North-Western part of Nigeria. *International Journal of Innovative Environmental Studies Research*, *7*(1), 1–8.

Umaru, N., Adamu, S., Bello, M., & Jolaoso, A. B. (2022). Review of selected features of hausa vernacular architecture, case study of Dakali and Zaure in Jos, Plateau State, Nigeria. *ARTEKS: Jurnal Teknik Arsitektur*, *7*(3), 421–432.

Vasilenko, N. A. (2019). *Parametric optimization of an architectural object's form as a method to improve its energy efficiency*. IOP Conference Series: Materials Science and Engineering, *552*(1), pp. 012027. https://doi.org/10.1088/1757-899X/552/1/012027

Vidmar, J. (2019). *How can using form factor reduce energy consumption of buildings?* AgiliCity. Retrieved 8th March 2025 from https://modelur.com/use-form-factor-to-reduce-energy-consumption-of-buildings/

Viganò, G. S. M., Rugani, R., Marengo, M., & Picco, M. (2024). Assessing the impact of climate change on building energy performance: A future-oriented analysis on the UK [Article]. *Architecture*, *4*(4), 1201–1224. https://doi.org/10.3390/architecture4040062

Whole Building Design Guide. (n.d.). *Form*. National Institute of Building Sciences. Retrieved March 6, 2025 from https://www.wbdg.org/resources/form

Yadav, N., & Kumar, P. (2022). Energy-positive rectangular office building - a study of high rise, mid rise and low rise buildings. *Tuijin Jishu/Journal of Propulsion Technology*, *43*(4). https://doi.org/10.52783/tjjpt.v43.i4.1760

Yao, J., Huang, Y., & Cheng, K. (2021). Coupling effect of building design variables on building energy performance. *Case Studies in Thermal Engineering*, *27*, 101323. https://doi.org/10.1016/j.csite.2021.101323

Yip, S., Athienitis, A., & Lee, B. (2021). Early stage design for an institutional net zero energy archetype building. Part 1: Methodology, form and sensitivity analysis. *Solar Energy*, *224*, 516–530. https://doi.org/10.1016/j.solener.2021.05.091

Zankar, R., El-Kaaki, L., & Fares, J. (2022). Design challenges of solving circular geometry in residential buildings. *Architecture and Planning Journal (APJ)*, *28*(1), 1–23. https://doi.org/10.54729/BZXI2461

Zhao, S., Si, J., Chen, G., Shi, H., Lei, Y., Xu, Z., & Yang, L. (2023). Research on passive design strategies for low-carbon substations in different climate zones. *Processes*, *11*(6), 1814. https://doi.org/10.3390/pr11061814

Zhu, S., Ma, C., Wu, Z., Huang, Y., & Liu, X. (2024). Exploring the impact of urban morphology on building energy consumption and outdoor comfort: A comparative study in hot-humid climates. *Buildings*, *14*(5), 1381. https://doi.org/10.3390/buildings14051381

Zhuravchak, R., Nord, N., & Brattebø, H. (2022). The effect of building attributes on the energy performance at a scale: an inferential analysis. *Building Research & Information*, *50*(6), 662–680. https://doi.org/10.1080/09613218.2022.2038537

Resume

Mark Alegbe is a registered Architectural Technologist with the Nigerian Institute of Architects (NIA) and an emerging specialist in low-carbon construction. He holds a Distinction MSc in Climate Resilience and Environmental Sustainability in Architecture (CRESTA) from the University of Liverpool, a First-Class BSc in Architecture from Ambrose Alli University, and earlier Distinctions in Architectural Technology from Nuhu Bamalli Polytechnic. His research interests span embodied carbon assessment, building optimisation, life-cycle impact analysis, and sustainable construction, supported by several peer-reviewed publications and conference contributions. Mark is skilled in energy performance modelling and life-cycle analysis, using tools such as DesignBuilder, EnergyPlus, and leading LCA platforms. He is currently expanding his expertise through advanced study in Construction Management at Liverpool John Moores University, deepening his understanding of how sustainable construction principles integrate across the full building lifecycle.

Hammed Nasiru is a PMP-certified Project Manager and Architect with expertise in architectural design and construction project management. He began his academic journey with a Higher National Diploma in Architectural Technology from Auchi Polytechnic, Edo State and went on to earn a BSc in Architecture from Bells University of Technology, Ota, Nigeria. In 2023, he received a grant from the "Architecture Is Free" Foundation to support the construction of a community school in Makoko, Lagos and is currently leading efforts to equip the school's library through additional grant opportunities. His dedication to sustainable development was further recognised in 2025 when he was selected for the United Nations SDGs Advocate Programme (Cohort 6), focusing on SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action) and SDG 15 (Life on Land). Passionate about climate education and community engagement, his professional interests include sustainable construction, climate-resilient architecture and socially responsive design.

John Lekwauwa Kalu is a Lecturer in Architectural Technology at Auchi Polytechnic, Edo State, Nigeria. He has a strong record of academic and professional contributions to the built environment. He holds a Master's degree in Architecture from the University of Nigeria (UNN) and a certification in Flexible and Blended Education from the Commonwealth of Learning, following his bachelor's degree in architecture from Abia State University. With over six years of academic experience, he has undertaken significant academic leadership responsibilities, serving as Faculty Examination Officer and contributing as a committee member to the strategic expansion of the Faculty of Environmental Studies at Auchi Polytechnic. His earlier five-year practice in the construction industry further strengthened his expertise in design and project delivery. Highly proficient in Building Information Modelling (BIM), his interests lie in sustainable architecture, construction

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Laurence Chukwuemeka is an Architect and General Manager of a leading architectural firm in Abuja, Nigeria, where he directs building and construction projects with a focus on design excellence, technical innovation and effective project delivery. He holds both a Bachelor's and master's degree in architecture from the University of Nigeria (UNN) and is currently advancing his expertise as a PhD candidate in Architecture at Abia State University. With extensive professional experience, he has successfully overseen complex projects from concept through construction, integrating architectural design, planning and project management to achieve high-quality outcomes. His leadership skills are demonstrated through managing multidisciplinary teams and ensuring client satisfaction in diverse projects. Laurence's expertise spans architectural design, building construction, project management and strategic leadership, reflecting his capacity to bridge academic knowledge with industry practice. His current doctoral research is focused on advancing architectural innovation and sustainable solutions within the built environment.

Nnamdi Diribe is an Architectural Practitioner with a degree in Architecture and currently practicing within the Nigerian built-environment sector. His work focuses on technical design, environmental responsiveness, and evidence-based architectural solutions, supported by strong capability in architectural drafting and design documentation. His professional interests span spatial design, construction detailing, and performance-driven architecture, with an active commitment to applying research-informed thinking to everyday practice.