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RESEARCH ARTICLE

Development of a Conceptual Heat-Transfer Framework for Roof-Induced Solar Heat Performance in Warm-Humid Residential Buildings in Owerri, Nigeria

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ABSTRACT

Residential buildings in warm-humid tropical environments are increasingly exposed to overheating due to intense solar radiation, elevated humidity, and urban thermal intensification. Within the building envelope, roof systems constitute the primary pathway of solar heat gain because of their direct and prolonged exposure to solar radiation. Despite this significance, roof selection in many developing urban environments remains largely influenced by aesthetics, cost, and construction convenience rather than thermal performance considerations. This paper develops a conceptual heat-transfer framework for evaluating roof-induced solar heat performance in warm-humid residential buildings using Owerri, Nigeria, as a tropical case context. The study adopts a conceptual analytical approach grounded in heat-transfer theory, building physics, and climate-responsive architectural principles. The framework identifies key variables influencing roof thermal behaviour, including roofing material properties, roof colour, geometry, slope, orientation, attic ventilation, and ceiling insulation characteristics. Dynamic thermal indicators such as decrement factor, time lag, attic–indoor thermal gradient, and temperature difference ratio are identified as suitable parameters for tropical roof-performance evaluation. The paper concludes that integrating building physics and dynamic thermal assessment into architectural design is essential for climate-responsive residential development and sustainable housing performance in warm-humid environments.

Keywords: *Building physics; Roof systems; Solar gain; Heat transfer; Thermal performance; Owerri*

1. INTRODUCTION

Architecture has historically been guided by the classical Vitruvian ideals of firmness, function, and beauty, with considerable emphasis placed on visual expression, symbolism, spatial order, and formal composition. For centuries, the quality of buildings was interpreted largely through artistic, cultural, and functional lenses, while measurable environmental performance remained secondary within many mainstream architectural traditions. However, growing concern regarding climate change, urban overheating, rising building-energy demand, and occupant well-being has progressively transformed the priorities of contemporary architectural and urban-development practice. Buildings are increasingly evaluated not only by their aesthetic and functional qualities but also by their environmental and thermal performance outcomes (de Wilde, 2014).

Contemporary developments in building science and climate-responsive architectural theory increasingly conceptualise buildings as dynamic environmental systems whose envelopes continuously regulate exchanges of heat, air, moisture, radiation, and energy between internal and external environments (Givoni, 1998; Olgyay, 2015; Hens, 2017; de Wilde, 2014; Santamouris, 2016). Consequently, the building envelope is increasingly recognised not merely as a formal architectural element but as a critical environmental moderator that significantly influences indoor thermal comfort, building energy performance, occupant well-being, and sustainability outcomes (Olgyay, 2015; Givoni, 1998; de Wilde, 2014; Santamouris, 2016). This transition has progressively repositioned building physics from a secondary technical consideration to a fundamental component of climate-responsive architectural practice, environmental building performance, and sustainable design decision-making (Olgyay, 2015; Givoni, 1998; Hens, 2017; de Wilde, 2014).

Within this evolving professional context, the growing emphasis on measurable environmental performance has increasingly expanded the influence of environmental engineers, building-services specialists, sustainability consultants, and other technical disciplines within the built environment, thereby reinforcing the need for architects to engage more deeply with building science and environmental performance evaluation (de Wilde, 2014; Hens, 2017; Kibert, 2016; Altomonte et al., 2014). Contemporary built-environment research further demonstrates that sustainable building delivery increasingly depends on interdisciplinary collaboration involving architecture, environmental science, engineering, public health, and urban planning (Ye et al., 2023). Similarly, climate-responsive and net-zero building development now requires integrated design approaches in which environmental-performance expertise plays a central role (Vakeva-Baird, 2025). Consequently, knowledge of heat transfer, thermal behaviour, and building physics has become essential not only for achieving sustainable and energy-responsive buildings but also for sustaining the architect's professional relevance within contemporary climate-responsive practice, where environmental performance increasingly constitutes a major criterion of design evaluation (de Wilde, 2014; Santamouris, 2020).

These concerns are particularly significant within warm-humid tropical environments where buildings operate under persistent thermal stress conditions. Elevated atmospheric humidity, intense solar radiation, and limited nocturnal heat dissipation frequently combine to produce severe indoor overheating conditions. Among all building-envelope components, roofs are especially important because they are typically the most exposed surfaces to incident solar radiation, thereby contributing substantially to solar heat gain and increased indoor cooling loads during daytime periods (Farhan et al., 2021; Tong et al., 2014). In warm-humid tropical environments, lightweight metallic roofing systems are widely used in residential construction because they are compatible with contemporary lightweight building practices and can be installed efficiently under rapid urban-development conditions (Szokolay, 2014). However, such roofing systems possess thermophysical characteristics that strongly influence building thermal behaviour. Metallic roof materials generally exhibit relatively high thermal conductivity and low thermal mass, thereby enabling rapid absorption and transmission of solar heat under intense tropical solar exposure (Incropera et al., 2007; Santamouris, 2016). Consequently, roof systems play a critical role in determining attic heat accumulation, indoor thermal conditions, and overall building energy performance within warm-humid climates.

In Nigeria and similar tropical regions, aluminium and coated metal roof systems have become increasingly common in residential construction due to their adaptability to contemporary construction practices and lightweight structural systems (Olotuah & Adesiji, 2005). However, these materials often permit rapid solar heat transfer into attic and indoor environments because of their relatively high thermal conductivity and limited thermal-storage capacity. Although ceiling systems may provide some degree of thermal attenuation, many residential buildings continue to experience substantial roof-induced thermal stress under persistent tropical solar exposure (Ho et al., 2024; Viljoen & Hugo, 2024). Contemporary building-envelope research demonstrates that real environmental performance is strongly influenced by transient thermal response, solar fluctuation, thermal inertia, decrement behaviour, and time-dependent heat-transmission processes (Pisello et al., 2016; Khaleghi & Karatas, 2023). Solar radiation within warm-humid climates fluctuates continuously throughout the day, generating periodic thermal waves that propagate through roof assemblies before influencing indoor thermal conditions. Roof systems should therefore be interpreted as dynamic thermal assemblies rather than static construction components.

Although roof systems constitute one of the most thermally exposed components of residential buildings in warm-humid tropical climates, roof selection and evaluation in many developing urban environments continue to be influenced primarily by aesthetics, construction convenience, and economic considerations rather than dynamic thermal-performance behaviour. Consequently, many lightweight residential roof systems remain poorly adapted to tropical climatic conditions, thereby contributing to excessive attic heat accumulation, indoor overheating, thermal discomfort, and increased cooling-energy demand.

Furthermore, many conventional approaches to roof thermal assessment continue to rely on simplified steady-state assumptions that inadequately represent the transient and cyclic nature of solar heat transfer under real tropical environmental conditions. Such approaches often fail to capture important thermal-response characteristics including heat attenuation, thermal delay, decrement behaviour, and periodic heat-flow dynamics that significantly influence indoor thermal conditions in lightweight roof assemblies. In addition, despite growing emphasis on environmental performance within the built environment, architectural discourse and residential-development practice in many tropical contexts still demonstrate limited integration of building physics and dynamic heat-transfer principles into roof-design evaluation and climate-responsive housing development. This situation creates a conceptual and professional gap between architectural design practice and contemporary environmental-performance demands within the built environment.

This paper aims to develop a conceptual heat-transfer framework for understanding roof-induced solar heat performance in warm-humid residential buildings while repositioning building physics as a central component of contemporary climate-responsive architectural practice. The objectives of the paper are to:

i. discuss the thermodynamic mechanisms through which conductive, convective, and radiative heat-transfer processes influence solar heat movement through residential roof assemblies in warm-humid climates;

ii. identify the physical and design characteristics of roof systems that influence solar heat absorption, storage, attenuation, and transmission within residential buildings;

iii. discuss the conceptual relevance of dynamic thermal-performance indicators such as decrement factor, time lag, attic–indoor thermal gradient, and temperature difference ratio for evaluating roof thermal behaviour under cyclic climatic forcing conditions;

iv. explore the theoretical relationship between roof thermal performance, indoor environmental quality, cooling-energy demand, and climate-responsive housing design in tropical urban environments; and

v. propose a conceptual framework integrating building physics, heat-transfer theory, and climate-responsive architectural design within contemporary residential-development practice.

This study is justified by the increasing need to integrate building physics and heat-transfer principles into architectural thinking and residential-development practice within tropical environments. The paper contributes to contemporary discourse on climate-responsive architecture by providing a conceptual framework through which roof-induced thermal behaviour may be interpreted using dynamic heat-transfer principles rather than simplified steady-state assumptions

2. LITERATURE REVIEW

Growing concern regarding climate change, urban overheating, rising cooling-energy demand, and indoor environmental quality has intensified interest in the thermal performance of building-envelope systems. In warm-humid tropical climates, roofs are particularly significant because they receive the greatest intensity of direct solar radiation and therefore constitute major pathways for heat transfer into buildings (Santamouris, 2020; Hens, 2017). Consequently, roof thermal behaviour strongly influences indoor thermal conditions, occupant comfort, and cooling-energy demand within residential buildings.

Lightweight metallic roofing systems such as aluminium and stone-coated metal sheets are widely used in tropical residential construction because they are affordable, lightweight, durable, and easy to install. However, such systems frequently exhibit high thermal conductivity and low thermal inertia, thereby enabling rapid absorption and transmission of solar heat into attic and indoor spaces (Asan, 2006; Akbari & Levinson, 2016). This condition contributes significantly to indoor overheating within warm-humid environments.

This section of the paper reviews the theoretical, conceptual, and empirical literature relating to roof thermal performance, building physics, heat-transfer processes, and dynamic thermal behaviour of roof systems in warm-humid tropical climates. The chapter further identifies gaps in existing knowledge that justify the present study.

Theoretical Framework

This framework is anchored in Systems Theory and Ecological Modernisation Theory. Systems Theory and Ecological Modernisation Theory jointly provide the theoretical basis for the study. Systems Theory explains the dynamic interaction between roof systems and climatic conditions, while EMT emphasises environmentally responsive approaches for improving thermal performance and sustainability. Together, the theories support the investigation of how roof systems influence indoor thermal conditions within warm-humid tropical environments.

Systems Theory

Systems Theory conceptualises buildings as open environmental systems continuously interacting with surrounding climatic conditions through exchanges of heat, air, moisture, and radiation (Bertalanffy, 1968; Hens, 2017). Within this framework, roof systems function as environmental subsystems that receive climatic inputs such as solar radiation, ambient temperature, humidity, and wind, while producing measurable thermal outputs reflected in attic and indoor temperatures (Olgyay, 2015; de Wilde, 2014).

The theory is relevant to roof thermal-performance studies because thermal behaviour results from interactions among roof materials, roof geometry, attic conditions, ceiling systems, and external climatic forcing (Asan, 2006; Hens, 2017). Consequently, thermal indicators such as decrement factor, time lag, and attic–indoor thermal gradient may be interpreted as outputs of dynamic environmental interactions occurring within the roof system (Barrios et al., 2012; Hens, 2017).

Ecological Modernisation Theory

Ecological Modernisation Theory (EMT) argues that environmental challenges may be mitigated through technological innovation, scientific advancement, policy reform, and environmentally responsive design strategies rather than through opposition to modernisation itself (Mol & Sonnenfeld, 2000; Spaargaren & Mol, 1992). Within architecture and the built environment, the theory supports the integration of sustainability, energy efficiency, and environmental performance into building design and construction practices (Hajer, 1995; Guy & Farmer, 2001).

From the perspective of roof thermal performance, EMT supports the adoption of climate-responsive roof systems involving reflective roofing materials, insulation strategies, ventilation systems, and passive cooling approaches capable of reducing heat gain and improving indoor thermal conditions (Akbari & Levinson, 2016; Santamouris, 2020). The theory is therefore relevant to contemporary efforts aimed at improving environmental performance and reducing cooling-energy demand within tropical residential buildings (Hens, 2017; Santamouris, 2015).

Conceptual Review

Building Physics and the Contemporary Built Environment

Building physics provides the scientific basis for understanding how buildings interact with environmental forces such as heat, air, moisture, and solar radiation (Hens, 2017). Within architecture, it explains how building-envelope systems influence thermal comfort, energy demand, and environmental performance under varying climatic conditions (Incropera et al., 2007; Olgyay, 2015).

Contemporary environmental concerns have increasingly shifted architectural attention toward measurable building performance rather than purely visual and formal considerations. Buildings are therefore increasingly interpreted as thermodynamic systems whose envelopes regulate heat and energy exchange between indoor and outdoor environments (de Wilde, 2014).

Within warm-humid tropical climates, building physics is particularly important because roof systems constitute major pathways for solar heat gain. Consequently, understanding conductive, convective, and radiative heat-transfer processes is essential for developing climate-responsive and thermally efficient roof systems.

Climatic Context of Warm-Humid Tropical Environments

Warm-humid tropical climates are characterised by high temperatures, elevated humidity, intense solar radiation, and prolonged thermal stress (Olgyay, 2015; Oke, 1987). These climatic conditions frequently reduce indoor thermal comfort because high humidity limits evaporative cooling efficiency while continuous solar exposure increases heat accumulation on building surfaces and within indoor environments (ASHRAE, 2017; Santamouris, 2015).

Owerri, located in southeastern Nigeria, experiences a typical warm-humid tropical climate characterised by distinct dry and wet seasons. Urbanisation processes involving asphalt pavements, concrete surfaces, and widespread use of metallic roofing materials may further intensify local thermal conditions through urban heat island effects (Santamouris, 2020).

Within this climatic environment, roofs represent highly exposed building components because they receive prolonged solar radiation during daytime periods. Consequently, roof material properties, roof geometry, attic ventilation, and ceiling systems significantly influence indoor thermal conditions within residential buildings.

Heat Transfer in Roof Systems

Heat transfer within roof systems occurs through radiation, conduction, and convection (Incropera et al., 2007). These processes govern how solar heat is absorbed at roof surfaces, transmitted through roofing assemblies, and transferred into indoor spaces.

Radiative Heat Transfer: Solar radiation constitutes the primary source of thermal loading on roof surfaces in tropical climates. Roof colour, absorptivity, reflectivity, and emissivity influence the quantity of solar heat absorbed at the roof surface. Dark-coloured roofs generally absorb more solar radiation and therefore attain higher surface temperatures.

Conductive Heat Transfer: Heat absorbed at roof surfaces propagates through roofing materials by conduction. According to Fourier's law, conductive heat transfer depends on thermal conductivity, temperature difference, material thickness, and heat-flow area.

$q = -kA\frac{(T_2 - T_1)}{x}$ ………………………………………………………………… Equation 1

Where: q = rate of heat transfer; k=thermal conductivity; A= heat-flow area; T_2-T_1= temperature difference; and x=material thickness.

Lightweight metallic roof systems generally exhibit rapid thermal response because of their relatively high thermal conductivity.

Convective Heat Transfer: Convective heat exchange occurs between roof surfaces and surrounding air, particularly within attic spaces. Quantification of convective heat transfer is expressed as:

$q = hA(T_s - T_f)$ …………………………………………………………………Equation 2

where q =convective heat-transfer; A =surface area; T_s= surface area; T_S = surrounding air temperature. Poor attic ventilation may promote daytime heat accumulation and intensify downward heat transfer through ceiling systems.

Dynamic Thermal Behaviour of Roof Systems

Roof systems in warm-humid climates operate under cyclic solar forcing and therefore exhibit dynamic rather than purely steady-state thermal behaviour (Asan, 2006; Hens, 2017). Consequently, dynamic thermal indicators provide more realistic representations of actual roof thermal performance. These indicators include the decrement factor, time lag, attic-indoor thermal gradient, and temperature difference ratio.

Decrement factor (DF) represents the attenuation of thermal-wave amplitude between attic and indoor environments. Lower values indicate greater attenuation of heat transfer into occupied spaces.

$DF = \frac{T_{indoor}}{T_{attic}}$ ………………………………………………………………… Equation 3

where, DF = decrement factor; A_{indoor} = indoor temperature amplitude; A_{attic} = attic temperature amplitude.

Time lag (TL), represents the delay between peak attic temperature and peak indoor temperature. A longer time lag generally indicates delayed heat transmission through roof assemblies.

$TL = t_{indoor\ max} - t_{attic\ max}$ ……………………………………………………………Equation 4

where, $t_{indoor\ max}$= time of maximum indoor temperature; $t_{attic\ max}$ = time of maximum attic temperature.

The attic–indoor thermal gradient represents the temperature difference between attic and indoor spaces. Larger gradients generally indicate stronger roof-induced heat transfer.

Temperature difference ratio (TDR) represents the proportion of thermal fluctuation transmitted from attic spaces into indoor environments. TDR is computed as:

$TDR = \frac{T_{attic,max} - T_{indoor,max}}{T_{attic,max} - T_{attic,min}}$ ……………………………………...…...…. Equation 5

where: TDR = Temperature Difference Ratio, $T_{attic,\ max}$ = maximum attic temperature during the monitoring period, $T_{indoor,\ max}$ = maximum indoor temperature during the same period, $T_{attic,\ min}$ = Minimum attic temperature during the same period.

This formulation expresses the maximum attic–indoor temperature separation as a proportion of the total attic temperature fluctuation. Lower TDR values indicate that indoor temperatures more closely follow attic temperatures, whereas higher values indicate greater thermal attenuation by the roof–ceiling assembly. Lower TDR values generally indicate improved thermal attenuation and better thermal responsiveness.

3. RESULTS AND DISCUSSION

Interpretive Implications of Dynamic Thermal-Performance Indicators in Warm-Humid Tropical Buildings

The thermal-performance indicators discussed above have important implications for indoor thermal conditions and climate-responsive roof design within warm-humid tropical environments. In general, lower decrement factors and lower temperature difference ratios are associated with greater attenuation of cyclic solar heat transfer through roof assemblies, thereby reducing the intensity of indoor thermal fluctuations and improving thermal comfort conditions (Asan, 2006; Barrios et al., 2012). Conversely, higher values may indicate stronger transmission of roof-induced heat into occupied spaces.

Similarly, longer time lags are generally considered thermally desirable in warm-humid climates because they delay peak heat transmission from roof surfaces into indoor environments. Roof assemblies capable of producing extended thermal delay may reduce immediate daytime overheating and improve indoor thermal moderation during periods of intense solar exposure (Hens, 2017; Givoni, 1998). Short time lags, by contrast, often indicate rapid conductive heat transmission through lightweight roof systems with limited thermal-storage capacity.

Attic–indoor thermal gradients also provide insight into the effectiveness of roof-ceiling systems in moderating downward heat transfer. Persistent or large attic–indoor temperature differentials may suggest inadequate thermal attenuation, insufficient attic ventilation, or limited ceiling insulation performance under tropical climatic forcing conditions.

Although universally fixed acceptable thresholds for these indicators remain difficult to establish because of variations in climate, roof configuration, occupancy patterns, and building materials, tropical building-envelope studies generally associate improved thermal performance with lower decrement-factor values, lower temperature difference ratios, longer time lags, and reduced attic-indoor thermal gradients. For parameters such as Decrement Factor (DF) and Temperature Difference Ratio (TDR), which are commonly expressed as ratios between 0 and 1, interpretive ranges can indeed be discussed conceptually for tropical roof-performance evaluation

Factors Influencing Roof Thermal Performance

Roof thermal performance is influenced by roofing materials, solar reflectivity, roof geometry, roof orientation, emissivity, attic ventilation, ceiling insulation, solar radiation, ambient temperature, humidity, and wind movement (Hens, 2017; Santamouris, 2020).

Material thermal conductivity influences the rate of heat transfer through roof assemblies, while roof colour, absorptivity, and reflectivity affect the quantity of solar radiation absorbed at roof surfaces (Incropera et al., 2007; Akbari & Levinson, 2016). Similarly, roof slope and orientation modify the angle, intensity, and duration of solar exposure, whereas attic ventilation and ceiling systems influence heat storage, dissipation, and attenuation within roof cavities before transmission into occupied indoor spaces (Asan, 2006; Hens, 2017). Consequently, roof thermal behaviour in warm-humid climates reflects the combined influence of material, geometric, environmental, and thermodynamic processes operating under cyclic solar forcing conditions (Santamouris, 2020; Olgyay, 2015).

Proposed Conceptual Heat-Transfer Framework for Roof-induced Solar Heat Performance

This paper adopts a systems-based conceptualisation derived from structural functionalism, which posits that any system comprises interrelated and interdependent parts whose interactions produce observable outcomes. Within this framework, understanding a phenomenon requires examining the components of the system, the functions they perform, and how they influence one another. Structural functionalism, therefore, operationalizes the theoretical underpinnings of Systems Theory and Ecological Modernization Theory (EMT) into a measurable structure that connects physical roof characteristics and design roof characteristics with quantifiable thermal performance outcomes.

The proposed framework, as shown in Figure 1, conceptualises roof systems as integrated environmental-performance assemblies involving interactions among climatic forcing conditions, roof physical characteristics, roof design characteristics, attic environmental conditions, ceiling insulation systems, and indoor thermal-response indicators.

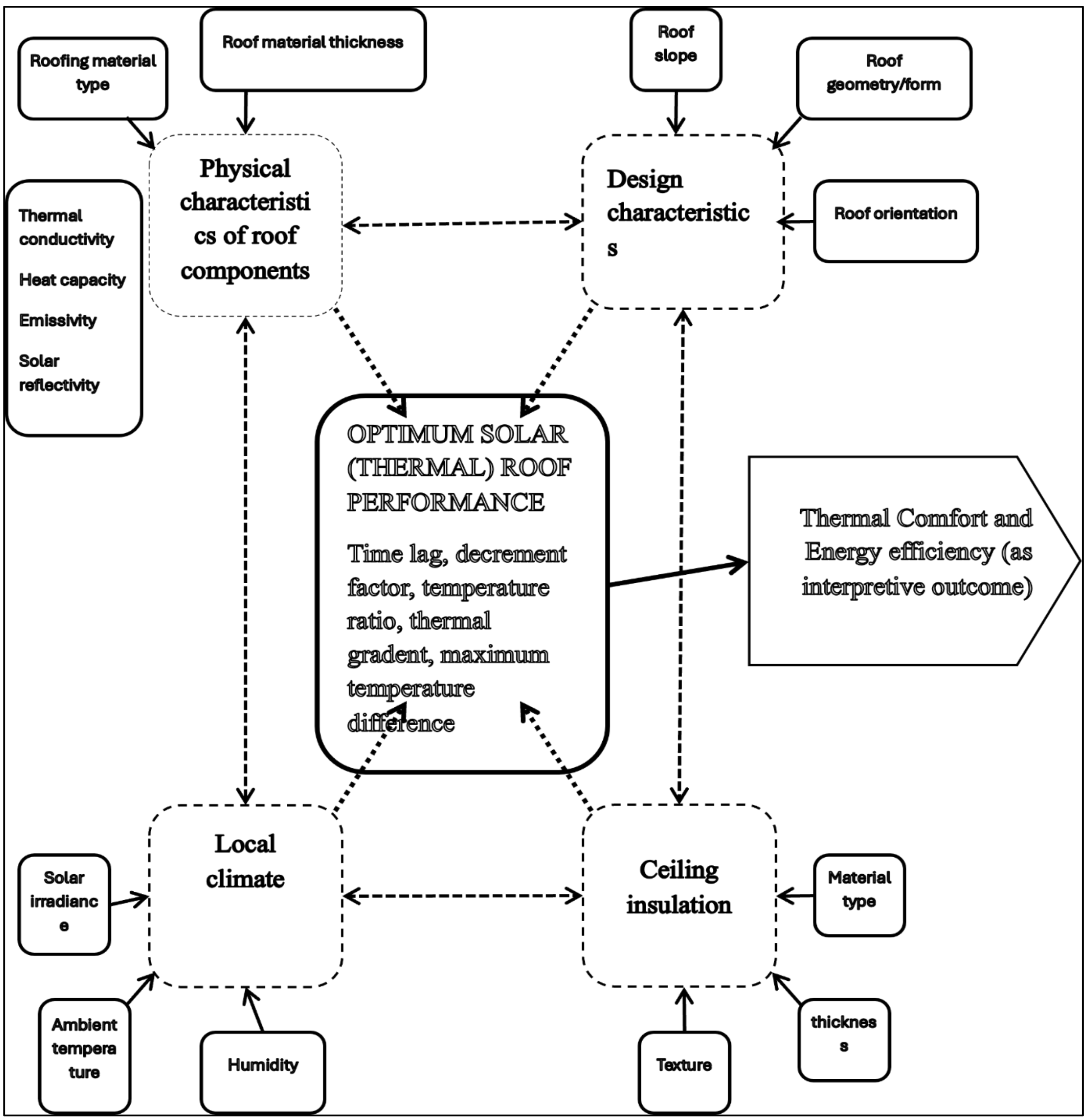

Figure 1. Proposed Conceptual Framework for Roof-induced Solar Heat Performance in warm-humid climates

Within this framework, solar radiation, ambient temperature, humidity, and wind conditions are theoretically understood to interact with roof material properties and geometric configurations in ways that may generate dynamic attic and indoor thermal behaviour.

The framework further proposes that evaluation of roof-induced solar heat performance within warm-humid climates may benefit from consideration of dynamic thermal indicators such as decrement factor, time lag, attic–indoor thermal gradient, temperature difference ratio, and indoor temperature variability.

Implications For Architectural Practice

First, architectural education and professional practice may increasingly benefit from integrating building physics into climate-responsive design processes. Roof systems may therefore require evaluation not only based on aesthetics, affordability, or construction convenience but also in relation to their potential thermal implications within tropical climatic conditions. Second, performance-oriented architectural practice may require architects to engage more actively with measurable environmental considerations. Understanding heat-transfer behaviour may strengthen the capacity of architects to participate meaningfully within environmental-performance evaluation and climate-responsive building design. Third, residential development regulations and building-approval systems within tropical urban environments may benefit from greater integration of roof thermal-performance considerations into climate-responsive housing policies and environmental planning frameworks.

4. CONCLUSION

This paper proposed a conceptual heat-transfer framework for understanding roof-induced solar heat performance within warm-humid residential buildings using Owerri as a contextual reference. Drawing upon building physics and heat-transfer theory, the study argued that roof systems may be more appropriately interpreted as dynamic thermal assemblies governed by conductive, convective, and radiative heat-transfer processes operating under cyclic climatic forcing conditions.The paper further argued that contemporary architecture is increasingly transitioning toward performance-oriented environmental practice in which measurable building behaviour constitutes an important component of professional relevance. Within this context, integrating building physics into architectural thinking may contribute to climate-responsive design, sustainable residential development, and broader environmental responsiveness within the built environment.

Finally, the proposed framework contributes to the theoretical repositioning of architecture as a scientifically informed and environmentally responsive discipline capable of engaging more effectively with the climatic and sustainability challenges confronting contemporary tropical urban environments.

5. COMPETING INTERESTS

None to declare.

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