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Simulation Methods in the Thermal Assessment of Wooden and Vernacular Houses

Revisão dos Métodos de Simulação Computacional na Avaliação Térmica de Casas de Madeira e Vernaculares

Revisión de los Métodos de Simulación Computacional en la Evaluación Térmica de Casas de Madera y Vernaculares

Thermal Performance of the Built Environment/ Desempenho térmico do ambiente construído/ Desempeño Térmico del Ambiente Construido

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Abstract

The aim of this study is to investigate the thermal performance of timber and vernacular buildings, analyzing how their construction characteristics influence this performance under different climatic conditions. The methodology employs computational simulations review using tools such as EnergyPlus, DesignBuilder, and ANSYS FLUENT to assess variables such as material thermal properties and passive climate control strategies. The main results indicate that these buildings have efficient thermal performance, highlighting the potential of wood as a thermal insulator and vernacular solutions for adaptation to the local climate. The contribution of the study lies in the systematization of effective practices, promoting the more sustainable and efficient use of these construction typologies in the civil engineering sector.

Keywords: Thermal performance. Vernacular buildings. Timber houses. Computational simulations. Sustainability.

Resumo

O trabalho tem como objetivo investigar o desempenho térmico de edificações de madeira e vernaculares, analisando como suas características construtivas influenciam esse desempenho em diferentes condições climáticas. A metodologia emprega revisão de simulações computacionais, utilizando ferramentas como EnergyPlus, DesignBuilder e ANSYS FLUENT, para avaliar variáveis como propriedades térmicas dos materiais e estratégias passivas de controle climático. Os principais resultados indicam que essas edificações possuem um desempenho térmico eficiente, destacando o potencial da madeira como isolante térmico e das soluções vernaculares para adaptação ao clima local. A contribuição do estudo reside na sistematização de práticas eficazes, promovendo o uso mais sustentável e eficiente dessas tipologias construtivas no setor da construção civil.

Palavras-chave: Desempenho térmico. Edificações vernaculares. Casas de madeira. Simulações computacionais. Sustentabilidade.

Resumen

El trabajo tiene como objetivo investigar el desempeño térmico de edificaciones de madera y vernáculas, analizando cómo sus características constructivas influyen en dicho desempeño bajo diferentes condiciones climáticas. La metodología emplea simulaciones computacionales, utilizando herramientas como EnergyPlus, DesignBuilder y ANSYS FLUENT, para evaluar variables como las propiedades térmicas de los materiales y estrategias pasivas de control climático. Los principales resultados indican que estas edificaciones presentan un desempeño térmico eficiente, destacando el potencial de la madera como aislante térmico y de las soluciones vernáculas para adaptarse al clima local. La contribución del estudio radica en la sistematización de prácticas eficaces, promoviendo el uso más sostenible y eficiente de estas tipologías constructivas en el sector de la construcción civil.

Palabras clave: Desempeño térmico. Edificaciones vernáculas. Casas de madera. Simulaciones computacionales. Sostenibilidad.

Introduction

Vernacular architecture has attracted increasing interest in recent decades due to its climatic adaptability, energy efficiency, and low carbon emissions, characteristics that make it a practical and sustainable solution to current environmental challenges (Zhang et al., 2018; Nguyen, 2011). Vernacular buildings, designed based on traditional knowledge and the use of local materials, demonstrate effective architectural strategies for thermal comfort and energy efficiency, even in extreme climatic conditions. These constructions, often adapted to the local climate, utilize techniques such as natural ventilation, solar shading, and high thermal mass materials to moderate internal conditions and reduce dependence on mechanical cooling systems (Nguyen, 2011; Zune et al., 2020).

Wooden houses, in turn, stand out as a sustainable alternative in the construction sector. Wood, being a renewable resource, has thermal properties that favor insulation, contributing to environmental comfort and reducing energy consumption (Leskovar & Premrov, 2012; Danovska et al., 2022). However, challenges related to low thermal mass and vulnerability to moisture can compromise the thermal and structural performance of these buildings, especially in extreme climates (Adekunle & Nikolopoulou, 2016; Rahiminejad et al., 2024). For this reason, strategies such as the use of thermally activated building systems (TABS), cross ventilation, and improvements in thermal insulation have been investigated to optimize the performance of wooden constructions (Heidenthaler et al., 2021; Lozoya-Peral et al., 2023).

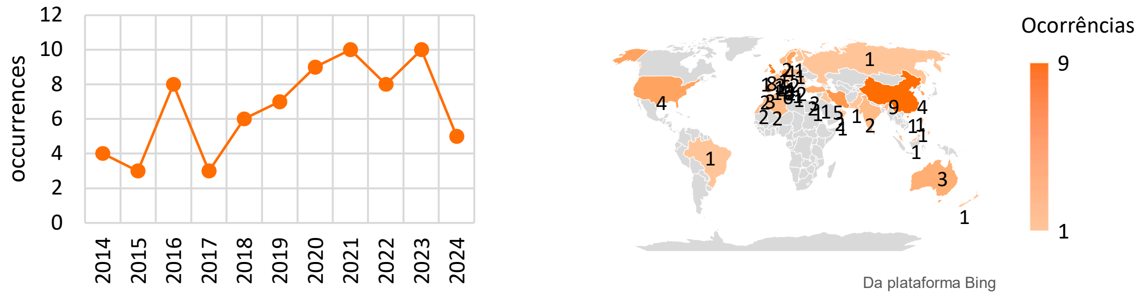
In recent years, advances in computational simulations have allowed detailed analyses of the thermal behavior of vernacular and wooden buildings. Tools such as EnergyPlus, DesignBuilder, and ANSYS FLUENT provide the possibility to evaluate complex variables, such as heat transfer, hygrothermal behavior, and performance of passive strategies (Crawley et al., 2001; Libralato et al., 2021). These methods are particularly important for identifying design solutions that meet the needs of thermal comfort and energy efficiency in different climatic contexts, as well as enabling the renovation of traditional buildings with lower environmental impact (Li et al., 2023; Lozoya-Peral et al., 2023).

Despite the potential of these approaches, there are still research gaps regarding the systematization of the simulation methods used to evaluate the thermal performance of vernacular and wooden buildings. Additionally, the diversity of climates, materials, and construction techniques requires a critical analysis of existing practices in order to identify effective and adaptable solutions for different scenarios (Zune et al., 2020; Maučec et al., 2021). In this context, this study aims to identify and analyze the most commonly used computational simulation methods to assess the thermal performance of wooden and/or vernacular houses, highlighting the specific parameters considered in these processes. Thus, it seeks to answer the following research question: what computational simulation methods are used to evaluate the thermal performance of wooden and/or vernacular houses, and what specific parameters are considered in this process?

Methodology

Articles published in peer-reviewed journals in English up to September 2024 were considered. The scientific database Scopus was utilized. The searches were conducted with a ten-year time window in the Scopus database. The keywords were defined to target the themes of computational simulation, thermal performance, and wooden and/or vernacular houses, using "AND" and "OR" as Boolean criteria for all descriptors. Therefore, the following string was used: (TITLE-ABS-KEY-AUTH (("Wooden Building" OR "Vernacular Building" OR "Timber Construction" OR "Traditional Architecture") AND (simulation AND ("Thermal Performance" OR "Thermal Comfort" OR "Energy Efficiency" OR "Heat Transfer" OR "Climate Adaptation")))), resulting in 73 scientific articles. Subsequently, the screening process began, categorizing by citation order and considering only articles published in journals, in English, and within the ten-year period. Figure 1 presents an overview of the search results.

Figure 1: Overview of the search results



Source: Authors (2024)

After categorization and the application of filters, the screening of documents was conducted through the reading of titles, abstracts, and keywords. Thus, for this screening, only articles addressing the research topic were selected, excluding studies that did not utilize the theme, as well as duplicate studies, resulting in 29 journal articles. The journals Energy and Buildings and Building and Environment from Elsevier led the publications on the topic, with six articles presenting 140 citations. The other journals are also from Elsevier, except for Environmental Science and Technology, which is from ACS Publications (Table 01).

Table 1: The five most cited articles on the topic

Title	Authors	Journal	Citations
Building microclimate and summer thermal comfort in free-running buildings with diverse spaces: A Chinese vernacular house case	Du, Bokel e Dobbelsteen (2014)	Building and Environment	140
Thermal comfort, summertime temperatures and overheating in prefabricated timber housing	Adekunle e Nikolopoulou (2016)	Building and Environment	100
Environmental Impact of Buildings - What Matters?	Heeren, et al. (2015)	Environmental Science and Technology	97
Predictive rule-based control to activate the energy flexibility of Norwegian residential buildings: Case of an air-source heat pump and direct electric heating	Clauß, et al. (2019)	Applied Energy	82
Improvement of thermal inertia effect in buildings using shape stabilized PCM wallboard based on the enthalpy-temperature function	Wi, Chang, e Kim (2020)	Sustainable Cities and Society	72

Source: Authors (2024)

The five most cited articles present various simulation methods to evaluate the thermal performance of wooden and vernacular houses. Two of them use computational fluid dynamics (CFD) to analyze the thermodynamic efficiency of solar towers (KIM et al., 2024) and the effectiveness of windcatchers (CHOHAN et al., 2024). Others investigate the hygrothermal performance of wooden basements (RAHIMINEJAD et al., 2024), wood impregnation with phase change materials (PCM) (GRZYBEK et al., 2024), and thermal comfort in traditional buildings (LAMRANI et al., 2023), employing numerical and experimental simulations. One study explores energy retrofit strategies in a vernacular house on the Mediterranean coast of Spain (LOZOYA-PERAL et al., 2023), focusing on improvements in thermal insulation and natural ventilation. The parameters considered include air temperature (KIM et al., 2024; CHOHAN et al., 2024; RAHIMINEJAD et al., 2024; SALAMEH et al., 2023), air velocity (KIM et al., 2024; CHOHAN et al., 2024), and relative humidity (CHOHAN et al., 2024; RAHIMINEJAD et al., 2024), highlighting the importance of integrating passive solutions and energy retrofit strategies. This methodological diversity enriches the understanding of thermal performance and emphasizes the need for continuous research for more efficient construction practices and thermal comfort in vernacular environments.

Computational Simulation Methods for Assessing Thermal Performance in Vernacular Houses

The results of the literature review reveal the diversity of approaches and software used to simulate the thermal performance of vernacular constructions. Dynamic thermal simulation is a fundamental methodology that allows for the analysis of thermal behavior over time, considering numerous climatic variables. He et al. (2023) emphasizes that the use of EnergyPlus is crucial for this analysis, as it enables a detailed assessment of the interactions between traditional climatic strategies and the thermal comfort of occupants, as well as the energy efficiency of buildings. Adekunle (2019) highlights that this software is widely recognized for its ability to model energy consumption and thermal performance of buildings, allowing for detailed analyses under various climatic conditions. These studies also incorporated thermal performance simulations using tools like DesignBuilder, which is based on the EnergyPlus calculation engine.

Complementing this approach, Zune et al. (2020) adopt Integrated Environmental Solutions (IES), specifically the ApacheSim module, which models heat transfer processes. This tool allows for detailed simulations of internal temperatures in different construction scenarios, contributing to the understanding of how architectural features influence thermal performance. Additionally, computational fluid dynamics (CFD) simulations, conducted with ANSYS FLUENT software, are essential for understanding air flow in buildings (Zune et al., 2020). These simulations are highly significant for analyzing natural ventilation and thermal comfort, especially in roofs, where temperature distribution can vary significantly.

The research also shows that the authors applied a methodological approach that combines field measurements and computational simulations to assess the thermal performance of two types of wooden buildings. Ni et al. (2023) conducted experiments on a scaled model of the buildings, allowing for observation of thermal performance under controlled conditions, while Grygierek et al. (2020) used OpenStudio to perform simulations on a multi-zone model of a naturally ventilated single-family house. This research focused on comparing wooden and brick constructions, allowing for a detailed analysis of differences in terms of energy demand, life cycle cost, and thermal comfort.

However, mathematical modeling also plays a significant role in thermal simulations. Polesek-Karczewska and Kardaś (2015) employ a one-dimensional model to simulate the pyrolysis of biomass in fixed-bed reactors. This model considers mass, momentum, and heat transfer, including moisture evaporation and pyrolysis gas convection. Modeling is crucial for predicting temperature distribution and heat flow, as well as the devolatilization dynamics of the material. Heidenthaler et al. (2021) perform static and dynamic simulations to assess the thermal performance of thermal storage systems in wooden structures, using HTflux software, which applies the finite element method. This methodology allows for the creation of two-dimensional geometric models that simulate heat transfer in different layers of materials, considering their specific thermal properties.

The combination of field measurements and numerical simulations, as demonstrated by Rahiminejad et al. (2024), provides a robust validation of the simulated models. The WUFI® Pro and WUFI® 2D programs were employed to analyze heat and moisture transfer in multilayer building components. Additionally, cost analysis and economic efficiency were explored by Soršak et al. (2014). The authors used the Passive House Planning Package (PHPP) to model the thermal performance of different envelope compositions. This approach allows for a detailed assessment of material combinations and their thermal efficiencies, considering variables such as the composition of external walls, roofs, floors, as well as the quality of glazing. Finally, simulation software such as EnergyPlus, IES, ANSYS FLUENT, WUFI, PHPP, and DesignBuilder play a vital role in analyzing the thermal performance of vernacular constructions. The combination of dynamic simulations, field measurements, and mathematical modeling provides a solid foundation for developing more efficient construction solutions adapted to local climatic conditions, promoting sustainability and thermal comfort in buildings.

Parameters Considered in the Simulation of Thermal Performance of Vernacular Buildings

The studies highlight the fundamental role of variables such as thermal conductivity, heat transfer coefficient, and envelope composition in optimizing energy performance. Additionally, the geometry of buildings and strategies for adapting to regional climatic conditions have been widely investigated as ways to reduce energy consumption and improve occupant comfort. He et al. (2023) investigated the thermal conductivity and heat transfer coefficient of materials such as adobe and earth roofs, highlighting how these properties affect the thermal efficiency of constructions. The comparison between wooden and concrete structures conducted by Heidenthaler et al. (2021) is also relevant, as it shows how material thickness and fluid temperature influence thermal performance, in addition to considering the spacing of embedded tubes, which directly impacts system efficiency. Soršak et al. (2014) emphasize the importance of the building envelope composition, analyzing different combinations of materials, such as external walls, slabs, and roofs. The evaluation of the heat transfer coefficient (U-value) is central to this study, as variations in the U-value of walls, roofs, and windows directly affect heat demand and energy efficiency.

Ni et al. (2023) investigated the thermal performance of wooden constructions with water-passing walls. The testing conditions included measurements of internal and external temperature and humidity during winter conditions, allowing for the assessment of thermal comfort through the calculation of the thermal comfort index (PMV). Goto et al. (2016) focused on the hygrothermal performance of wooden envelopes in subtropical conditions. Heat and moisture transfer simulations were conducted using thermal conductivity parameters of materials such as laminated wood panels and wood fiber insulation. Measurements of temperature and humidity at different depths of walls and roofs were essential to validate the simulation model.

El Azhary et al. (2021) focused on the thermal properties of construction materials, such as thermal conductivity, thermal resistance, and heat capacity, in dynamic simulations that evaluated the thermal performance of a vernacular building in arid climatic conditions. The analysis of different passive retrofit interventions, including thermal insulation and natural ventilation, demonstrated how these actions can improve energy efficiency and comfort in challenging climates. Žegarac Leskovar and Premrov (2011) analyzed the impact of window size on the energy efficiency of wooden buildings. The study included variations in the U-values of walls and the thermal properties of different wood panel systems, as well as window characteristics.

Lozoya-Peral et al. (2023) highlighted various energy rehabilitation strategies, emphasizing the importance of increasing thermal insulation of envelopes. Simulations showed that improving thermal insulation and solar control of windows, using movable shading devices, are fundamental for optimizing energy performance. Additionally, increasing window area and introducing enhanced natural ventilation, through ceiling fans, contributed to a significant reduction in cooling and heating requirements, achieving up to 87%. These interventions demonstrate how adjustments to the envelope and design of openings can positively impact energy consumption.

The spatial configuration and geometry of buildings are critical factors for air circulation and temperature distribution. Zune et al. (2020) explored different roof typologies and their effectiveness in natural ventilation, as well as modeling various geometries while maintaining constant internal volume. The organization of spaces, as discussed by He et al. (2023), is fundamental for optimizing air circulation and, consequently, the thermal comfort of occupants. Li et al. (2023) addressed the dimensions and proportions of buildings, analyzing the width-to-length ratio of constructions and depth. The window-to-wall ratio, which considers the proportion between the area of windows and the area of walls, was also discussed, as it influences natural light entry and thermal efficiency.

Maučec et al. (2021) considered variations in the geometry of constructions, insulation characteristics, glazing ratio, shading control, and internal temperatures. Simulations were conducted in three distinct climates (moderate, hot, and cold), focusing on energy demand for heating and cooling, allowing for a comprehensive assessment of energy performance in different climatic contexts. The evaluation of different building characteristics, such as floor height and window area, is crucial for optimizing the thermal performance of buildings.

The specific climatic conditions of the study regions are essential for the accuracy of the simulations. He et al. (2023) used climatic data from the Turpan region, including solar radiation, air temperature, and relative humidity, to assess the impact of these variables on thermal performance. Rahiminejad et al. (2024) complemented this approach by monitoring relative humidity and conducting temperature measurements at different depths and layers of the structure, considering the properties of materials such as CLT and XPS, and their moisture resistance.

Nguyen et al. (2011) collected climatic data for three regions (Hanoi, Danang, and Hochiminh), focusing on temperature, humidity, and solar radiation. The thermal simulations conducted allowed for assessing the performance of houses in relation to thermal comfort, highlighting the importance of considering local climatic conditions. Libralato et al. (2021) addressed the simulation of heat and moisture transfer, emphasizing the assessment of the risk of wood deterioration in building envelopes. The authors implemented heat and moisture transfer models, both with and without consideration of hysteresis, in various locations such as Bolzano, Copenhagen, and Hong Kong. The inclusion of climatic data, such as humidity and temperature, was fundamental for determining conditions that may lead to material deterioration over time. Adekunle and Nikolopoulou (2016) conducted a study that monitored internal temperatures in two prefabricated wooden buildings, assessing occupant thermal satisfaction. The dynamic thermal performance simulations, based on climatic data and internal measurements, allowed for an in-depth analysis of overheating.

Finally, the importance of integrating thermal properties of materials, spatial configuration, and climatic conditions in the planning and construction of energy-efficient buildings is observed. The use of traditional and innovative materials, combined with passive retrofit strategies, natural ventilation, and solar control, demonstrates significant potential to reduce energy consumption and improve thermal comfort in different climatic contexts. Additionally, considering geometric factors and adapting to regional specificities reinforces the need for tailored solutions for each type of building.

Conclusions

The analysis of computational simulation methods applied to the thermal performance of wooden and/or vernacular houses has revealed a wide diversity of approaches, reflecting the complexity and specificity of this field of study. Tools such as EnergyPlus, DesignBuilder, ANSYS FLUENT, and WUFI stand out for their capabilities to model dynamic interactions between climatic variables, thermal properties of materials, and architectural features. The most relevant parameters include thermal conductivity, heat transfer coefficient, heat capacity, air temperature, relative humidity, and strategies for ventilation and solar control, which are fundamental for understanding the thermal behavior of buildings in different climatic contexts. Furthermore, the integration of field measurements with numerical simulations reinforces the accuracy and reliability of the results, allowing for robust validations. The research highlights that adapting to regional climatic conditions, combined with the use of traditional materials and passive strategies, is essential for maximizing energy efficiency and thermal comfort. Thus, it is concluded that the continuous advancement of simulation methodologies and the incorporation of multidimensional approaches are fundamental for developing sustainable and adaptive solutions in the construction sector.

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