Evaluating the influence of convective heat transfer coefficient on the carbon footprint of a service building in Morocco

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Abstract. This study examines how the convective heat transfer coefficient impacts the carbon footprint of a service building situated in Morocco. This coefficient is pivotal in shaping the thermal efficiency of buildings, influencing energy consumption and environmental impact. Through simulations and analyses, we evaluate the extent to which variations in this coefficient affect overall energy efficiency and carbon emissions. Our analysis, based on specific climate data for Morocco and detailed architectural and operational parameters of a typical service building, reveals significant annual deviations. Heating energy fluctuates by up to ±48%, and cooling energy varies by up to ±32%. Furthermore, our findings demonstrate that the carbon footprint of electricity consumption for heating and cooling can vary by as much as ±31% of total CO2 emissions annually. Optimizing the convective heat transfer coefficient emerges as a critical strategy for reducing the carbon footprint, underscoring its importance in sustainable building design. These results offer valuable insights for architects, engineers, and policymakers seeking to enhance building performance and minimize environmental impact within the unique climate conditions of Morocco.

1 Introduction

1.1 Rationale and goals

The building sector is one of the largest consumers of energy worldwide and a significant contributor to global greenhouse gas emissions[1]. In the context of Morocco, a country with a growing service industry and an increasing demand for energy-efficient buildings, understanding the factors that influence energy consumption and carbon footprint is crucial[2]. One critical aspect of building energy performance is the convective heat transfer coefficient (CHTC), which plays a pivotal role in thermal comfort and energy efficiency[3].

This study aims to evaluate the influence of the convective heat transfer coefficient on the carbon footprint of a service building in Morocco. By analysing how variations in the CHTC affect the overall energy consumption and subsequent carbon emissions, we can

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identify strategies to optimize building design and operation for reduced environmental impact. The research involves detailed simulations to provide insights into the relationship between CHTC and the carbon footprint, offering valuable guidance for architects, engineers, and policymakers in the Moroccan context and beyond.

Understanding this relationship is particularly important for Morocco, given its climatic conditions and the country's commitments to sustainable development and carbon reduction targets. This study not only contributes to the academic discourse on energy efficiency in buildings but also provides practical recommendations for improving the sustainability of service buildings in Morocco.

1.2 Literature review

The impact of building energy efficiency on the global carbon footprint has been a focal point of environmental research for decades. As buildings account for a substantial portion of energy consumption and CO2 emissions, understanding the mechanisms that influence their thermal performance is critical. The convective heat transfer coefficient (CHTC) is one such mechanism that significantly affects a building's thermal dynamics and energy usage.

The convective heat transfer coefficient is a measure of the heat transfer between a building’s surfaces and the surrounding air. It plays a crucial role in determining the thermal comfort and energy requirements of buildings. The study conducted by Mirsadeghi et al[4]. explores the calculation models for exterior convective heat transfer coefficients used in Building Energy Simulation programs. It examines the factors considered by each model, elucidating their strengths and limitations. Through a case study, the research highlights significant deviations observed up to 30% in annual cooling energy demand and 14% in hourly peak demand for well-insulated buildings. These findings underscore the uncertainties inherent in current models and emphasize the critical need for accurate simulations. This is crucial for predicting cooling demands precisely and assessing related performance indicators like indoor temperature and comfort. Meanwhile, Obyn et al[5]. observed that despite notable variations in calculated CHTC values, their impact on energy demands at the room scale is minimal. They note that while CHTC expressions have minor implications for HVAC design in lightweight structures, they notably affect heavier structures. The authors suggest that constant CHTC values are generally acceptable, despite occasional fluctuations, which can lead to up to a 9.1% difference in heating demand compared to formulations sensitive to temperature changes. Additionally, they found that sophisticated formulations for CHTC, termed "mixed expressions," offer limited advantages in the construction industry.

Moreover, research by Zheng et al[6]. proposes a method to adjust CHTC considering mutual building shielding effects. It collects data from 51 green energy-saving residential buildings in China and categorizes them into typical arrays using the K-means method. Computational fluid dynamics (CFD) simulations compare CHTC ratios between buildings in arrays and individual buildings across various wind speeds. The study determines that CHTC in arrays ranges from 24% to 77% of that in isolated buildings, with different array types exhibiting unique CHTC characteristics. The adjusted CHTC values are used to calculate the energy consumption of buildings within arrays, highlighting potential savings compared to standalone buildings. Meanwhile, Obyn et al[7]. employed experimental and CFD methods to evaluate how building porosity affects exterior CHTCs. Onsite measurements confirmed the accuracy of the CFD simulations, which analysed ten different building configurations under two wind directions. The findings revealed significant discrepancies between the CFD-derived CHTCs and those predicted by EnergyPlus models, with variations of up to three times, resulting in potential deviations in cooling loads of up to 19%.

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The existing literature underscores the significance of the convective heat transfer coefficient in influencing building energy performance and carbon footprint. While substantial research has been conducted globally, there is a need for more focused studies in the Moroccan context. This review highlights the critical areas where further research is needed and sets the stage for evaluating the specific impact of CHTC on the carbon footprint of service buildings in Morocco. By bridging this gap, the current study aims to contribute valuable insights and practical recommendations for enhancing the sustainability of Moroccan buildings.

2 Methodology

2.1 Meteorological data

As part of this investigation, a thorough examination will be carried out in Rabat, Morocco. [Fig. 1] refers to the pattern of meteorological data changes observed throughout the different seasons. We acquired the meteorological data using the Meteonorm software.

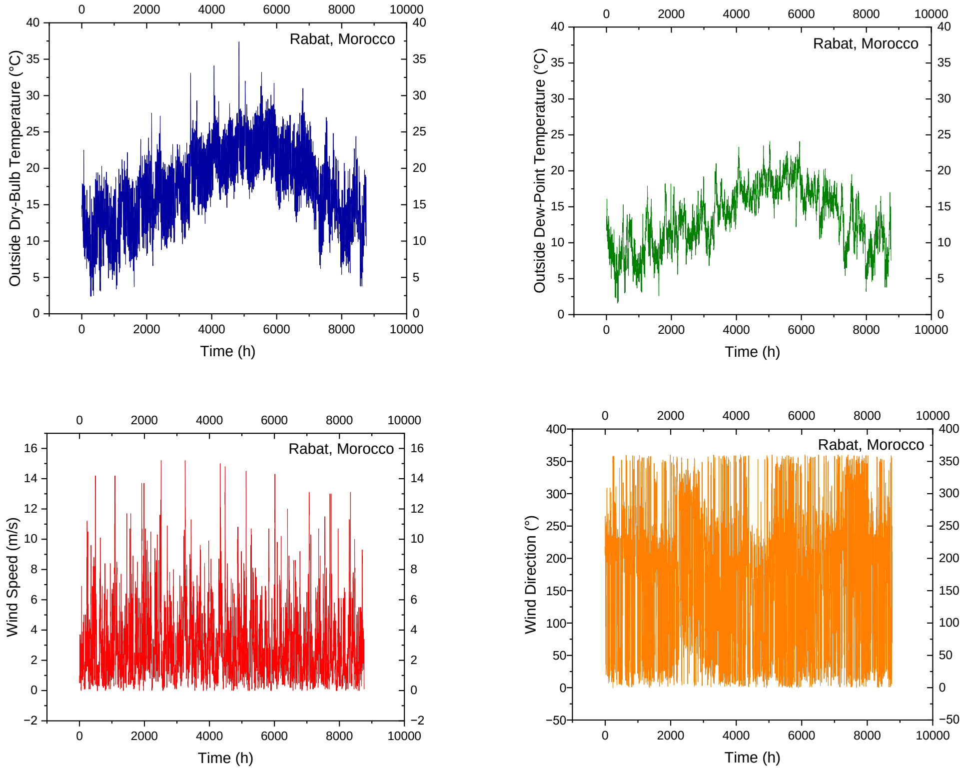

Fig. 1. Meteorological data fluctuations over a typical year of weather in Rabat, Morocco.

Rabat, Morocco experiences a Mediterranean climate characterized by distinct seasons. Summers are typically hot and dry, with occasional heatwaves. Autumn brings milder temperatures, while winters are mild and wet. Spring sees gradual warming and decreasing rainfall. The city's coastal location moderates its climate, with occasional breezes from the Atlantic Ocean influencing local weather patterns throughout the year.

2.2 Building description

The service building in question has two main floors: the ground floor and another floor above it, and there is an atrium (a large open space with a skylight) that is part of the building's design, as illustrated in [Fig. 2].

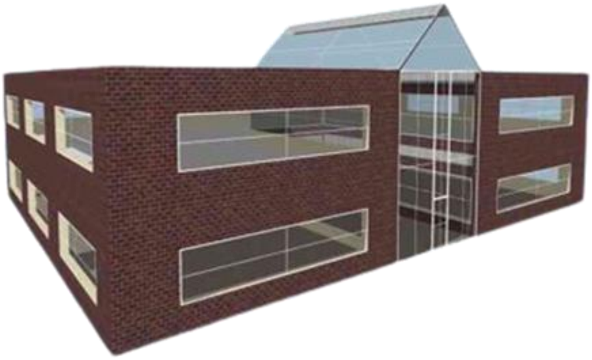

Fig. 2 Three-dimensional views of a typical service building.

To ensure the efficiency of the building envelope, which is crucial for maintaining thermal comfort and energy efficiency within the structure, careful consideration must be given to the selection of materials, following the Technical Guide to Thermal Insulation of Buildings in Morocco. The construction details are consolidated in [Tab. 1].

Table 1. Description of typical service building constructions.

Constructions	Area (m²)	U-value (W/m².K)
Roof	427,3	0,710
Wall	500,9	0,737
Floor	425,4	0,681
Ground	475,1	0,705
Glazing	373,7	2,429

This study will focus on the ground floor and the floor above it, conducting a detailed examination of their activity status in relation to several factors such as occupancy, heating, and cooling, as outlined in [Tab. 2].

According to the Moroccan Thermal Construction Regulations, the yearly cooling and heating requirements necessary to maintain a temperature between 20°C and 26°C for the reference service building fall within the thermal comfort range.

Table 2. The overall activity status of the service building.

Activity	Occupancy	Heating	Cooling
	Density: 0.12 people/m²	COP: 1.00	COP: 2.50

Schedule	Until: 07:00, 0, Until: 08:00, 0.25, Until: 09:00, 0.5, Until: 12:00, 1, Until: 14:00, 0.75, Until: 17:00, 1, Until: 18:00, 0.5, Until: 19:00, 0.25, Until: 24:00, 0,	Until: 05:00, 0.5, Until: 19:00, 1, Until: 24:00, 0.5,	Until: 05:00, 0, Until: 19:00, 1, Until: 24:00, 0,

2.3 Physical model

The modeling and analysis of building structures, along with simulations, were conducted using the DesignBuilder software suite. Wall simulations employed the Conduction Transfer Functions (CTFs) method, a state-space approach implemented in EnergyPlus.

The fundamental formulations of the thermal model in mathematical terms are based on heat transfer balances. The equation for the exterior wall surface is shown in [Eq. 1],

$$Q_{\mathrm{solr}} + Q_{\mathrm{LWR}} + Q_{\mathrm{conv}} + Q_{\mathrm{cond}} = 0 \qquad (1)$$

where Q_{solr} denotes the heat flux attributable to both direct and diffuse solar radiation, characterized by short wavelengths, Q_{LWR} represents the net exchange of the flux of long-wave (thermal) radiation interacting with the ambient air and environment, Q_{conv} indicates the exchange of convective flux with the ambient outdoor air and Q_{cond} represents the heat flux due to conduction into the exterior wall.

EnergyPlus offers various methods to calculate the values for exterior convection coefficients. The primary options, summarized in [Tab. 3], include the Simple, TARP, DOE-2, and Adaptive convection algorithms.

Table 3. Modeling options for exterior convection coefficients.

Algorithms	Description	Validation
Simple	The simple algorithm calculates the exterior heat transfer coefficient based on surface roughness and local surface windspeed.	The coefficients are directly sourced from Walton 1983[8].
TARP	TARP, known as the Thermal Analysis Research Program, incorporates relationships derived from laboratory tests on flat plates to include both natural convection and convection induced by wind.	The algorithm is utilizing the assumptions provided by Walton 1983[8], while the forced convection component depends on a correlation established by Sparrow 1979[9].

DOE-2	The convection model utilized in DOE-2 incorporates elements from the Mobile Window Thermal Test (MoWiTT) model, which is based on experimental data, as well as the detailed convection models from BLAST.	The algorithm is directly provided and developed by Birdsall 1990[10], Yazdanian 1994[11], and Booten 2012[12].
Adaptive	This algorithm dynamically selects equations for (CHTC) to regulate heat transfer. The surface classification system comprises four distinct categories determined by the prevailing wind direction and heat flow orientations. As the model progresses, it bifurcates the equation into two parts, employing separate formulas for forced convection and natural convection, thereby increasing its complexity.	Beausoleil-Morrison 2000[13] introduced this algorithm, The individual (CHTC) equations for the outside face have been documented and validated by Sparrow 1979[9]; Yazdanian 1994[11]; Clear 2003[14]; Emmel 2007[15]; Palyvos 2008[16]; Blocken 2010[17]; Booten 2012[12].

The thermal equilibrium within the indoor environment is described by the equation presented in [Eq. 2],

$$Q_{\mathrm{LWX}} + Q_{\mathrm{SW}} + Q_{\mathrm{LWS}} + Q_{\mathrm{sol}} + Q_{\mathrm{conv}} + Q_{\mathrm{cond}} = 0 \qquad (2)$$

where Q_{LWX} denotes the net exchange flux of long-wave (thermal) radiation among the surfaces within the indoor environment, Q_{SW} represents the overall flux of short-wave radiation reaching surfaces from sources of illumination, Q_{LWS} denotes the radiation flux emitted by equipment within the designated area, Q_{cond} represents the heat conduction flux traversing through the interior wall, Q_{sol} denotes the solar radiation flux absorbed by the surfaces and Q_{conv} represents the convective heat flux toward the indoor air.

EnergyPlus provides various modeling options for interior convection coefficients. This input parameter is used to control the selection of models applied to surface convection on the interior face of all heat transfer surfaces in the model. The main options, including the Simple, TARP, and Adaptive convection algorithms, are summarized in [Tab. 4].

Table 4. Modeling options for interior convection coefficients.

Algorithms	Description	Validation
Simple	The Simple model uses constant heat transfer coefficients that differ depending on the surface orientation.	The coefficients are sourced immediately from Walton 1983[8].
TARP	The comprehensive model for natural convection determines the convective heat transfer coefficient based on both the surface orientation and the temperature gradient (ΔT).	The algorithm is directly sourced from Walton 1983[8].

Adaptive	This algorithm aims to select the most suitable equation for (CHTC) from the available options for a given surface at any given time.	The algorithm for the inside face covers 45 surface categories and offers 29 options for selecting (CHTC) equations as sourced from Walton 1983[8]; Alamdari and Hammond 1983[18]; Khalifa and Marshall 1990[19]; Fisher 1997[20]; Awbi and Hatton 1999[21]; Beausoleil-Morrison 2000[13]; Fohanno and Polidori 2006[22]; Karadağ 2009[23].

D. B. Crawley et al[24]. have documented and validated the individual operations of [Eq. 1.2]. The energy utilized by the heat pump condenser in cooling and heating mode is determined by the coefficient of performance (COP) specified in [Tab. 2]. This calculation is based on the individual operations of the equations as documented and validated by Richard Raustad[25].

3 Results and discussions

The presented results aim to assess the impact of the convective heat transfer coefficient on the carbon footprint of electricity consumption for heating and cooling in a service building in Rabat, Morocco. This analysis evaluates different options for exterior and interior convection algorithms.

3.1. Effects on heating and cooling energy demand

Based on [Fig. 3], the results show significant monthly variations, with heating energy fluctuating by up to ±44% and cooling energy varying by up to ±25%. The yearly analysis indicates even greater deviations, with heating energy fluctuating by up to ±48% and cooling energy varying by up to ±32% of the total electricity consumption.

These findings underscore the critical importance of accurately modelling convective heat transfer in building design and energy simulations to optimize energy management and efficiency, especially in climates similar to Rabat's.

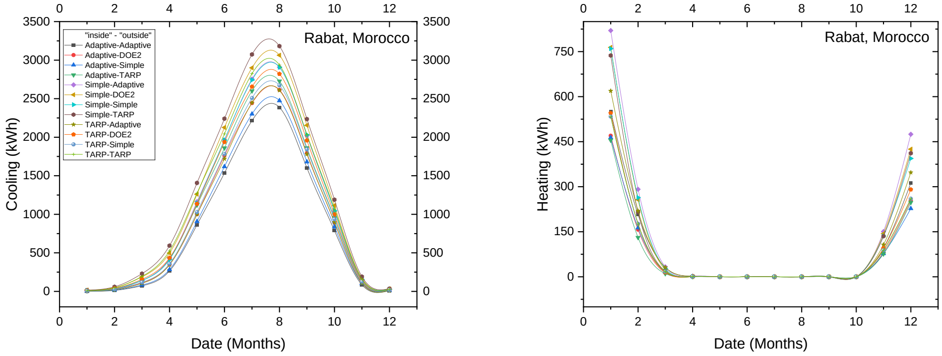

Fig. 3. Variations in the heating and cooling energy demand of a typical service building.

The convective heat transfer coefficient (CHTC) significantly impacts heating and cooling energy demand by influencing the rate of heat exchange between a building's interior surface and the exterior air. A higher CHTC increases heat transfer efficiency, leading to faster temperature changes in response to external conditions. In colder days, this can raise heating energy demand as heat is lost more quickly, while in warmer days, cooling energy demand increases as heat is gained more efficiently. Accurate modeling of CHTC is crucial for optimizing HVAC system performance, maintaining thermal comfort, and ensuring energy efficiency, particularly in regions with significant temperature variations.

3.2. Effects on the carbon footprint of electricity consumption

According to [Fig. 4], the annual analysis reveals more pronounced variations, showing that the carbon footprint of electricity consumption for heating and cooling in a service building can vary by as much as ±31% of a total CO2 emission.

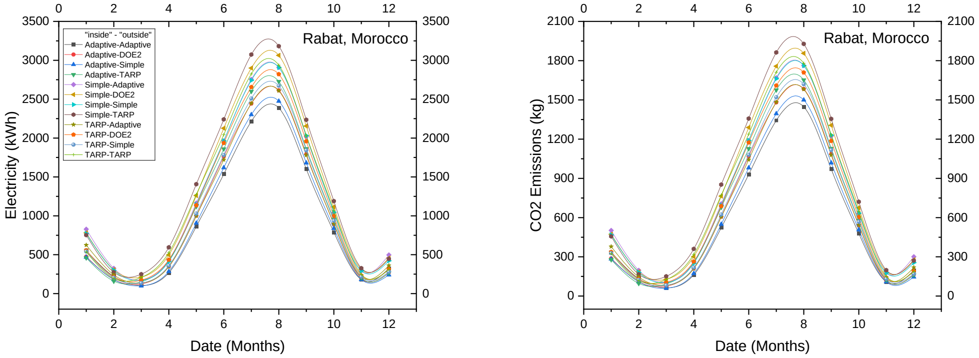

Fig. 4. Variations in the carbon footprint and electricity consumption of a typical service building.

CHTC plays a significant role in shaping the carbon footprint of electricity consumption in buildings. This coefficient influences the efficiency of heating and cooling systems, directly impacting energy demand. A higher CHTC enhances heat exchange between a building and its surroundings, necessitating increased energy use for maintaining indoor comfort. This heightened demand typically results in greater electricity consumption, which predominantly sourced from fossil fuels leads to higher carbon dioxide (CO2) emissions.

4 Conclusion

In conclusion, this study highlights the pivotal role of the convective heat transfer coefficient (CHTC) in shaping the energy demand and carbon footprint of electricity consumption for heating and cooling in service buildings, particularly in climates akin to Rabat, Morocco.

The research demonstrates that variations in CHTC can lead to significant fluctuations in both heating and cooling energy requirements, with potential yearly deviations of up to ±48% for heating and ±32% for cooling. Additionally, our research indicates that the annual variation in the carbon footprint of electricity consumption for heating and cooling can reach up to ±31% of the total CO2 emissions. These findings underscore the critical importance of accurately modeling CHTC in building design and energy simulations to optimize HVAC system performance, ensure thermal comfort, and enhance energy efficiency. Moreover, the study reveals that a higher CHTC increases the efficiency of heat exchange between a building and its environment, thereby influencing electricity consumption levels. Consequently, the increased demand for energy, largely sourced from fossil fuels, results in higher carbon dioxide emissions.

This analysis underscores the need for precise CHTC modeling to mitigate environmental impact and achieve sustainable building practices. By optimizing the convective heat transfer coefficient, stakeholders can effectively reduce both energy consumption and the associated carbon footprint, thereby contributing to global efforts toward environmental sustainability and climate resilience in building operations.

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