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THE DIGITAL AND THE SOUTH: QUESTIONINGS VOL. 1

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PROJECT

BRIDGING THE GAP:
EMPIRICAL VS. SIMULATION IN GREEN FACADE MODELING
REDUZINDO A BRECHA:
EMPÍRICO VS. SIMULAÇÃO NA MODELAGEM DE FACHADAS VERDES

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Abstract

This paper examines the transformative role of digital simulation tools in architectural design, focusing on the implementation and performance evaluation of green facades in the Global South, particularly Chile. In alignment with the theme The Digital and the South: Questionings, the study highlights how digital simulations enable a critical re-evaluation of sustainable technologies within the unique climatic, social, and urban challenges of southern regions. By addressing the performance gap – the discrepancy between theoretical design and empirical building performance – this research explores how digital tools can bridge this divide, providing essential insights that are otherwise challenging to achieve in unique climatic and urban contexts. This study examines how digital modeling can bridge this gap by providing a deeper understanding of green facades' environmental and energy impacts in different urban microclimates. Using a mixed methodology that combines case studies, empirical measurements, and advanced digital simulations, the research evaluates the potential of green facades to enhance urban climate resilience and energy efficiency. Results indicate that the effectiveness of these facades varies significantly based on local climatic conditions and site-specific characteristics, underscoring the need for tailored architectural solutions to optimize performance. By refining simulation models to capture complex environmental interactions, this paper contributes to more accurate and effective sustainable design strategies, positioning digital simulation as a critical tool for adapting architectural practices to the distinct realities of the Global South.

Keywords: Digital simulation, Green facades, Performance gap, Empirical analysis, Analytical design

1   Introduction

As cities in the Global South expand and evolve, the need for sustainable architectural solutions becomes increasingly urgent, driven by rapid urbanization and the escalating impacts of climate change. This region, characterized by diverse climatic conditions and socioeconomic constraints, faces unique challenges that demand innovative approaches to building design. These challenges are intensified by extreme climatic conditions and fast urban development, which necessitate solutions that are not only visually appealing but also functionally effective in enhancing energy efficiency and climate resilience. Integrating green infrastructures, mainly green facades, into urban architecture is among the most promising solutions to these challenges. Green facades offer a way to improve building performance while addressing environmental issues such as urban heat islands and energy consumption.

Research on green facade technologies has predominantly occurred in the Northern Hemisphere, leading to a gap in context-appropriate studies for the Global South, particularly Chile. According to a review by Mela and co-authors (2023), Europe has been the leading geographic location for research on vertical gardens, representing 51% of all publications, followed by Asia with 31%, Oceania with 7%, South America with 6%, and North America with 5%. In South America, most of the research has been conducted in Argentina and Brazil, with a smaller portion in Chile. This geographical concentration underscores the pressing need for more research in the Southern Hemisphere, where climatic conditions differ significantly from those in the North, and tailored solutions are required to address specific environmental challenges.

To bridge this gap, integrating infrastructures like green facades and green walls into architectural designs has become increasingly recognized (Su et al., 2024). These green systems not only contribute to the aesthetic and psychological well-being of urban environments but also play a pivotal role in addressing critical environmental issues such as urban heat islands and energy consumption (Bakhshoodeh et al., 2022; Fu et al., 2022). By leveraging digital simulation tools, architects can optimize the integration of these green infrastructures into building designs, ensuring that they maximize their environmental benefits and contribute effectively to the overall sustainability of urban developments.

In the context of The Digital and the South: Questionings, this paper positions digital simulation as a critical tool that empowers architects to respond to unique environmental challenges. The effectiveness of digital modeling tools in forecasting building performance depends significantly on user expertise. Despite their potential benefits, practical implementation often fails due to a persistent gap between theoretical design and actual performance, exacerbated by the limited use of advanced simulations in practice (Dwyer, 2013), commonly known as the performance gap. This gap, particularly prevalent in sustainable architecture, can lead to actual energy consumption exceeding predicted

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levels by substantial margins, sometimes by as much as 483% (Bai et al., 2024). Further complicating practical application is caused by the lack of standardized criteria for designing and implementing alternative infrastructures like green walls (Ascione et al., 2020).

This paper explores how digital simulation models are transforming the architectural design process in the Global South by bridging the gap between intuitive design and empirical performance evaluation. It examines the barriers to adopting these technologies and the potential for these tools to facilitate the design of energy-efficient, climate-responsive buildings that address the specific environmental conditions of the region. By focusing on the case of vertical green facades in Chile, this study aims to demonstrate the practical benefits and enhanced performance outcomes achievable through advanced simulation tools, thereby positioning digital technology as an indispensable resource in the sustainable architectural practices of the Global South.

1.1   Green Facade and Digital Modeling

The study of green infrastructure, particularly green facades, has advanced considerably over the past two decades, driven by the need to enhance urban microclimates and improve building efficiencies (Bustami et al., 2018). These advancements are marked by significant methodological developments, where computational simulations have emerged as a crucial tool that enables architects and urban planners to model and analyze the thermal effects of green facades, optimizing their designs to maximize environmental and energy benefits. Early pioneering research, like the one conducted by Stec, Van Paassen, and Maziarz (2005), utilized parametric simulations to assess the shading capacity of plants on double-skin facades, providing valuable insights into their comparative efficacy against traditional solutions like blinds (Ip et al., 2010).

Despite these advancements, the architectural field has not fully embraced the techniques associated with green facades. Current tools often fail to integrate the complex interactions between green facades and the broader urban environment (Bakhshoodeh et al., 2022). This gap highlights the necessity for more accurate and effective hygrothermal models that can consider these factors, providing more precise and practical predictions about the impact of green facades in urban contexts. Ascione and co-authors (2020) emphasize the need for comprehensive data to enhance design decisions, particularly regarding plant selection and climatic response, which are crucial for green wall performance. Digital tools facilitate scenario modeling to predict performance, thus addressing the performance gap by allowing decisions based on empirical data and enhancing design reliability and environmental impact.

The current state of the art in studying the hygrothermal impact of green facades relies on a fusion of methodologies, including computational simulations, experimental analysis, and case studies. These approaches allow the exploration of multiple scenarios and configurations, where parameters such as the cavity depth between the green facade and the wall, vegetation density, and building orientation are varied to identify the most energy-efficient configurations. Computational simulations are exceptionally fundamental in studying the thermal performance of green facades. They allow for the recreation of multiple scenarios to assess the impact of these systems in different contexts, predicting the thermal behavior of green facades and their influence on the energy consumption of buildings (Bagheri et al., 2021).

Experimental analyses provide essential data to complement these simulations. These experiments, conducted in controlled environments and actual buildings, involve measuring surface and surrounding air temperatures using temperature and humidity sensors to monitor the thermal performance of green facades in real-time (Bakhshoodeh et al., 2022). This empirical data is critical for validating and refining simulation models to predict real-world outcomes better, thus contributing to more reliable and effective design practices. Case studies in specific urban contexts further contribute to understanding the impact of green facades in actual operational conditions. These studies consider variables such as local climate, urban density, and architectural configuration, offering vital insights for adapting designs to specific conditions in the Global South. The combination of computational simulations, experimental analyses, and case studies has laid a solid foundation for understanding the thermal performance of green facades. However, a considerable gap remains in the availability and application of effective hygrothermal models (Ascione et al., 2020). This gap raises essential questions about why architecture has not fully adopted these techniques despite their proven efficacy, highlighting the need to bridge the gap between theoretical design and actual performance.

1.2   Green Facades in Chile

The need for tailored solutions in the Global South becomes particularly evident when examining the implementation of green facades in regions like Chile. While the potential of green facades to address environmental challenges such as urban heat islands and energy consumption is well-recognized globally, their effectiveness is highly dependent on local climatic conditions and the specific characteristics of each site.

Since 2016, more specific studies have emerged in Chile, mainly focused on green roofs (Reyes et al., 2016). Other studies have examined the application of green roofs on large retail surfaces in Santiago and other climates, concluding that they are more efficient in controlling cooling loads than conventional roof insulation (Vera et al., 2018). Additionally, two models for calculating green roof performance have been validated against experimental measurements, with Santiago included as a reference city (Vera et al., 2019).

For vertical green solutions, modeling studies have explored the capacity of green roofs and living walls to mitigate particulate matter (PM 2.5) in Santiago and other cities worldwide, concluding that implementing green roofs with 50-75% coverage and 25% living walls could reduce particulate matter by over 7% in the city (Viecco et al., 2021). Green roof models have also been adapted to analyze living walls in Santiago, evaluating their thermal performance on retail surfaces and finding that green roofs can reduce cooling demands by up to 15%. In comparison, living walls can achieve up to a 25% reduction, with potential combined reductions of up to 37% (García et al., 2022).

Double-skin green facades have been integrated into Chilean architecture for decades. The Consorcio Building (1990), designed by architects Enrique Browne and Borja Huidobro, is an example of the integration of vegetation into the building, demonstrating its high potential for application in Chile's climate. Similar examples exist with varying degrees of success concerning the growth and adaptation of plant species used to enhance building thermal comfort. Nonetheless, the application of these solutions has often been based on the intuition and intentions of the architects rather than on a deep understanding of their energy potential. In a study involving in situ temperature and relative humidity measurements within the air chamber of this building and three others, the thermal control effects considered attributes of such facades in the literature were fully confirmed. These effects include temperature inversions in the chamber compared to the exterior, with maximums of -8°C during the day and +5°C at night, and relative humidity inversions of +15% during the day and -5% at night, leading to increased temperatures at night (Vásquez et al., 2020).

However, implementing green facades in Santiago has been sporadic and often motivated more by aesthetic considerations than by a deep understanding of their energy potential. Examples like the Consorcio Building (1990) and the MBA Building at the Pontifical Catholic University of Chile (2007), illustrated in Figure 1, stand out for their intuitive design and aesthetic focus but lack prior evaluation to ensure energy efficiency. That underscores a broader issue: not all vertical green facade solutions are equally effective across different climates and urban conditions, highlighting the importance of tailoring these systems to specific environmental conditions.

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Fig. 1: Right: The Consorcio Building (1990), Santiago, Chile. Photo by Nico Saieh (2009). Source: ArchDaily, 2009. Available at: https://www.archdaily.cl/cl/02-14392/edificio-consorcio-sede-santiago-enrique-browne-borja-huidobro. Left: MBA Building PUC (2007). Source: Puentes UC, 2019. Available at: https://www.uc.cl/temas/mba-uc/pagina2.

For instance, a study of a direct green facade in a warm, humid climate in China showed significant exterior facade temperature reductions of 20.8°C and interior reductions of 7.7°C. However, an indirect green facade in the same location only recorded modest temperature reductions of 3.1°C (Chen et al., 2013). In contrast, in the dry, high-radiation climate of Santiago, Chile, indirect green facades have shown impressive temperature differentials of -8°C and a +30% relative humidity inside the cavity compared to the outside (Vásquez et al., 2020). This example illustrates how the suitability and effectiveness of different green systems vary according to climate and site-specific conditions. In Chile's dry climates, such as the Central and Northern zones, double-skin green facades are particularly well-suited due to high solar potential and low humidity, which allow the air chamber influenced by the plant's evapotranspiration to function under optimal conditions. Additionally, in colder conditions with low solar radiation, double-skin green facades help to keep the walls warmer, with the air chamber acting as an additional insulator, reducing heat loss and decreasing the need for interior heating (Bakhshoodeh et al., 2022). This dual thermal performance facilitates energy savings in both heating and cooling, making these facades highly adaptable to the seasonal and daily temperature fluctuations typical in areas with high thermal oscillation, such as Chile's Central and Northern zones.

2   Methodology

This study aims to demonstrate digital tools' predictive capabilities in assessing green facades' thermal behavior, establishing their viability as integral components of the architectural design process. The methodology encompasses both empirical data collection from existing buildings and advanced digital simulations, providing a robust framework for analysis.

2.1   Data Collection from Case Studies

The empirical data were sourced from four buildings with green facades in Santiago, Chile. These buildings, examined in the paper Hygrothermal Potential of Applying Green Screen Façades in Warm-dry Summer Mediterranean Climates (Vásquez et al., 2020), offer a varied set of facade orientation, species, and plant maturity. This diversity enables a comprehensive analysis of different green facade configurations.

Temperature and relative humidity were measured outside and inside the cavities behind the green facades during the summer using Voltcraft DL-121TH Data Logger Thermohygrometers. These sensors were positioned at three distinct heights within each facade cavity (0.5m, 1.5m, and 2.5m from the monitoring floor) to capture detailed vertical profiles of thermal and moisture conditions. Data were collected over five days in March 2019, aligning with the peak foliage density in Chile's summer season, when office spaces are in regular use and plant leaves are at their fullest. This period was selected to maximize the representativeness of cooling and shading effects, although further studies could expand to different seasons to explore annual variations. Measurements were taken at one-minute intervals to capture dynamic thermal and humidity shifts, offering granular data to understand facade performance throughout each day.

2.2   Digital Simulation

Parallel to the empirical data collection, digital simulations were conducted using EnergyPlus software with custom routines developed in the Grasshopper platform in Rhinoceros 3D (version 7.3.21039.11201) and interfaced through Climate Studio (version 1.9.8389.21977) for enhanced simulation control. This hygrothermal model integrates conventional heat transfer equations and plant evapotranspiration, predicting how these processes impact the ambient temperature and the facade's evaporative potential.

The model includes the following variables and simulation components:

- **Incident solar radiation**: Estimated using solar geometry, cloud cover conditions, and facade orientation to calculate realistic sunlight exposure on the facades.

- **Foliage density**: The Leaf Area Index (LAI) was used to estimate solar transmittance through foliage, converting the density of the vegetation layer into a quantifiable shading factor.

- **Thermal and optic properties**: The optical characteristics of the green facades were represented using a custom Radiance material adapted to approximate the shading effects of climbing plants, following the consensus within current literature (Larsen et al., 2015). Although this simplification overlooks different plant species' specific thermal and optical properties, it provides a practical baseline.

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A three-dimensional model of the building envelope and vegetation layer was also constructed to accurately represent thermal behavior. The Big Leaf Method treated the plant layer as a single, uniform solar screen covering the entire facade (Larsen et al., 2015). This approach, widely recognized in current research, facilitates a streamlined representation of shading effects without the complexity of individual leaf characteristics. The model excludes substrate thermal contributions, as these were considered negligible.

The advanced hygrothermal model calculates the cooling potential of double-skin green facades by incorporating the thermal effects of vegetation as an additional element in the building's thermal balance. This balance includes sensible heat release, latent heat absorption during water phase changes, and a small portion of the energy used in photosynthesis. The model is based on a series of state-of-the-art equations linked to create a computation engine, drawing references from studies by Allen, Pereira, Raes, and Smith (1998), Stec, van Paassen and Maziarz (2005), Susorova, Angulo, Bahrami and Brent (2013), Larsen, Filippín and Lesino (2015), among others.

2.3   Validation and Comparison

The digital models were validated against empirical data collected over the five days, focusing on comparing temperature trends. Temperature and humidity data were averaged across the three vertically placed sensors for each case to create a single representative value for calibration. Finally, results from both the empirical measurements and the digital simulations were compared to evaluate the effectiveness of digital modeling in supporting architectural design. This comparison assessed the capability of digital tools to predict the passive cooling and heating effects observed empirically, with implications for optimizing green facade designs to maximize their thermal regulation potential in varying contexts.

3   Case Studies

The study includes four case studies, each representing a unique building type, orientation, and facade structure characteristics. Case 1 consists of a twelve-story high-rise university building oriented to the North-East. This building's green facade is supported by vertical profiling and horizontal wiring positioned 105 centimeters from the facade surface. The plant species used is *Jasminum grandiflorum* (Spanish jasmine), characterized by low-density foliage that offers minimal shading and protective coverage. The plants are installed in built-in planter boxes at the bottom of each floor, leading to an uneven growth pattern across the facade due to differing maturity levels. Vegetation maintenance is managed by building staff.

Case 2 focuses on a seventeen-story office building with a South-West orientation. Here, the facade is supported by horizontal and vertical profiles that follow the building's curved shape, maintaining a 120-centimeter distance between the building and the support structure. The plant species selected is *Parthenocissus quinquefolia* (Virginia creeper), which has medium-density foliage and more woody branches near the substrate. The plants are installed in built-in planter boxes at the bottom of every three floors, providing a moderate level of shading effectiveness and an average density compared to the other cases.

Case 3 examines a four-story university building oriented to the North. The green facade of this building is supported by vertical elements and horizontal wiring spaced 82 centimeters from the glazing. *Wisteria sinensis* (Chinese wisteria) is used here, known for its high-density foliage. However, the growth varied in height and covered only portions of the facade at the measurement time, as the plants were relatively newly installed. The plants are placed in built-in planter boxes at the bottom of every two floors, resulting in a distribution of non-uniform foliage.

Finally, Case 4 examines a three-story office building oriented to the North-West. This building's facade features a support structure consisting of pillars and expanded metal mesh positioned 70 centimeters from the building enclosure. *Parthenocissus quinquefolia* (Virginia creeper) is again the selected species, now exhibiting very dense foliage that covers the entire building height, reaching a thickness of at least 30 centimeters. Unlike the other cases, the plants are planted directly into the ground, which promotes robust growth and results in the densest vegetation coverage among the four cases.

Fig. 2: Top-left: Image of the facade and buffer zone of Case 1; Top-right: Image of the facade and buffer zone of Case 2; Bottom-left: Image of the facade and buffer zone of Case 3; Bottom-right: Image of the facade and buffer zone of Case 4. Source: Vásquez et al. (2020).
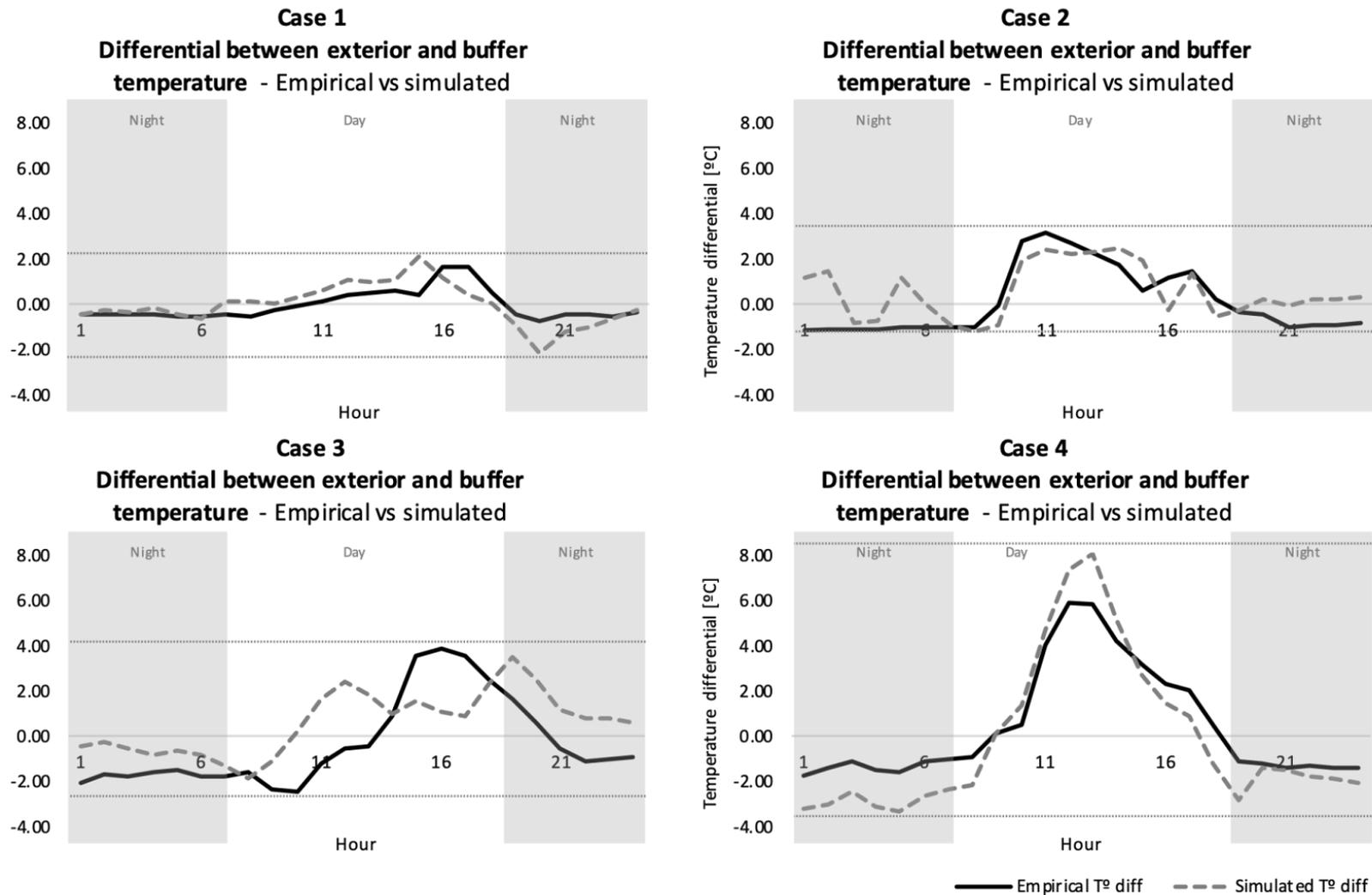
4   Results

Fig. 3: This graph displays the temperature differentials between the exterior and buffer zones throughout the day, segmented by hour, for each case study. It highlights the variations between night and day, comparing empirical measurements with simulations. Source: Authors, 2024.

Across all cases, the empirical data generally showed a pronounced cooling effect during the day due to evapotranspiration and a slight warming effect at night due to the plants' insulation properties (Fig 6). However, the magnitude of these effects varied considerably, influenced by the density and coverage of the foliage. While effective in capturing the general trends, the simulations often diverged in the specifics, particularly in cases with medium or irregular foliage density.

The discrepancies between simulated and empirical data highlight the need for adjustments in digital models, particularly regarding how plant characteristics are represented and how they interact with climatic variables. One part of these discrepancies can be attributed to the challenge of accurately representing the dynamic variability of vegetal material in simulations. Typically, these models simplify vegetal components into homogeneous and static conditions, which may not fully capture the nuanced behaviors of living plants as they respond to environmental changes. Improvements in these areas could enhance the predictive accuracy of simulations, making them more reliable tools in the architectural design process.

5   Discussion

5.1   Comparative Analysis of Simulation Accuracy and Performance

To assess the effectiveness of green facades through the lens of simulation accuracy compared to empirical measurements, a comprehensive regression analysis was conducted across four distinct case studies. The analysis, centered on the coefficient of determination, R^2, quantifies how well variations in empirical temperature measurements are accounted for by simulation models.
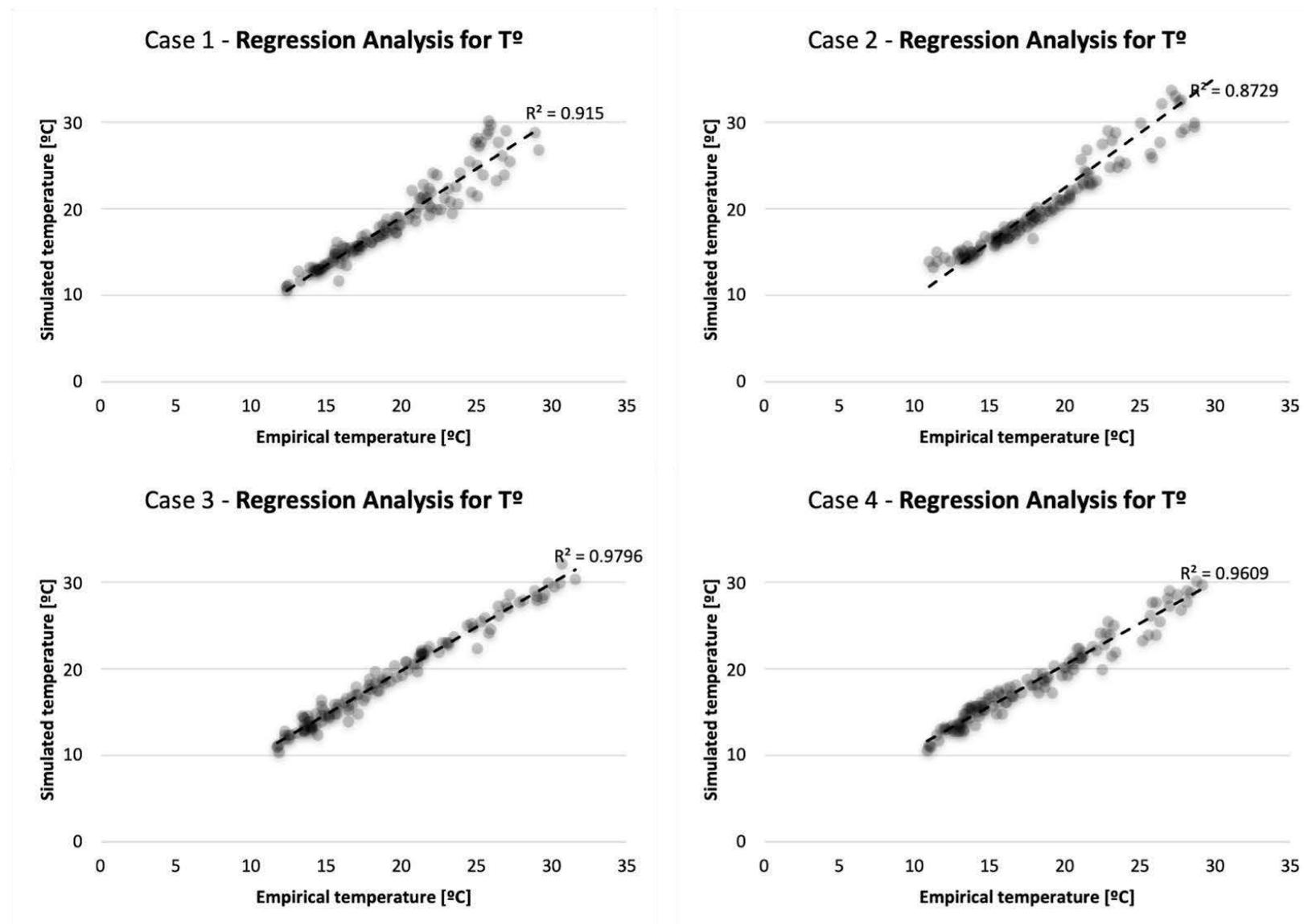

Fig. 4: This graph illustrates the values for each of the four case studies, indicating the accuracy of simulation models in predicting empirical temperature data. Source: Authors, 2024.

As shown in Figure 4, the R2 values reported in the study indicate generally strong model performance across all cases. Case 1 showed an R2 of 0.92, indicating that the simulations were highly predictive of the empirical data, capturing the thermal dynamics effectively. Case 2, with an R2 of 0.87, though slightly lower, still reflects a good level of accuracy, suggesting that even in less ideal conditions, the model performs robustly. Case 3 exhibited the highest predictive accuracy with an R2 of 0.98, demonstrating near-perfect alignment between the simulated and actual measurements. This level of precision suggests that with finely tuned model parameters, simulations can accurately reflect real-world outcomes under varying environmental conditions. Similarly, Case 4, with an R2 of 0.96, showed substantial model accuracy, confirming the simulations' reliability in scenarios with dense vegetation coverage.

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These results' consistently high values across different cases underline the effectiveness of these models in reproducing the temperature dynamics influenced by green facades. Thus, they support the idea that simulation models, when appropriate, provide an effective tool for predicting the impact of green facades.
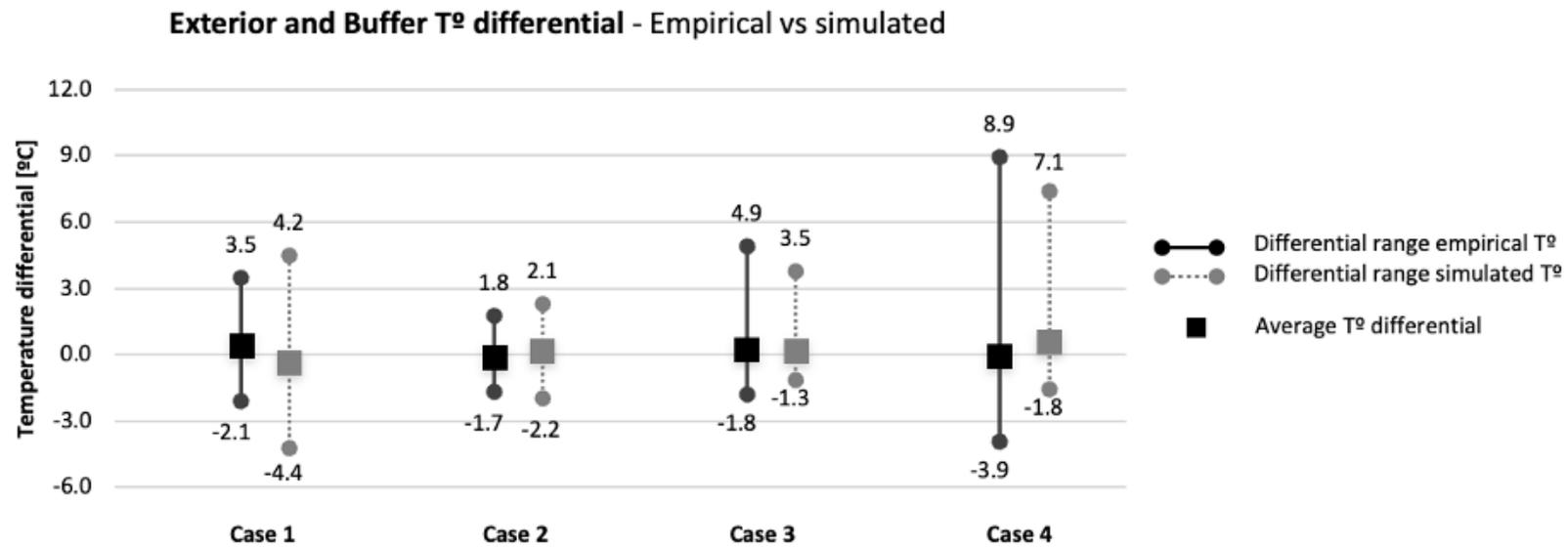

Fig. 5: This graph displays the minimum, maximum, and average temperature differentials for each case study, contrasting empirical measurements with simulation predictions. Source: Authors, 2024.

While simulation models generally predict temperature trends accurately, there are notable variations in the precision with which they capture the extremes of temperature fluctuations. For instance, in Case 1, the simulation displayed a broader temperature differential range and a lower average than the empirical measurements, indicating a model tendency to overestimate the extreme effects of temperature moderation. These results contrast with Case 2, where the simulated values closely reflected the empirical data, suggesting that the model is quite effective in predicting the actual behavior of the green facade under those specific conditions. For Cases 3 and 4, the simulations underestimated both the minimum and maximum differentials compared to the empirical data, pointing to performance gaps in the model, particularly in its ability to capture the maximum cooling potential observed empirically. This discrepancy is especially evident in Case 4, where the simulation did not fully capture the empirical minimum differential but came close to the maximum, suggesting some limitations in accurately predicting the coldest buffer conditions.

These differences between the simulated and empirical data are clearly illustrated in Figure 5 in the temperature differential graph, which shows each case's minimum, maximum, and average values. The variability in simulation accuracy underscores the complexity of modeling interactions within green facades, which are influenced by factors such as vegetation density, moisture content, and local climatic conditions. These findings suggest a need for iterative refinement of simulation models, incorporating a deeper understanding of plant physiological properties and their interaction with the built environment.
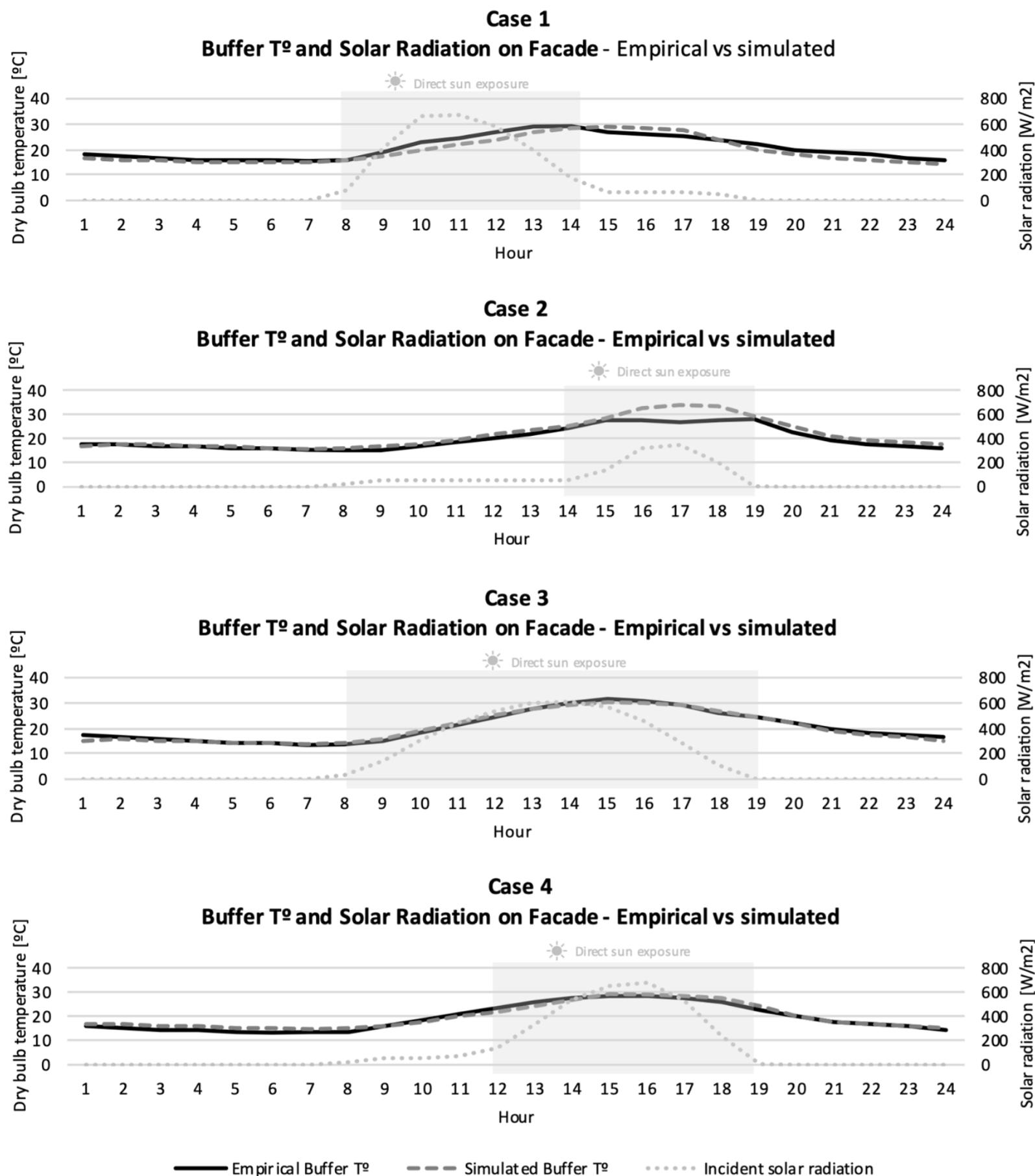
Fig. 6: This graph presents hourly buffer temperature and solar radiation data for four distinct cases, each with different facade orientations. It specifically highlights the hours of direct solar radiation on the facade, comparing empirical measurements with simulation. Source: Authors, 2024.

5.2   Sensitivity to Environmental Variables

Notably, cases with dense foliage, such as Case 2 and Case 4, showed a more significant cooling effect and enhanced humidity control. That suggests that denser vegetation can create more substantial microclimatic alterations, which contribute to lowering temperatures and moderating humidity levels around the facades. In contrast, Case 1, which featured sparser vegetation, displayed less pronounced thermal and humidity effects. This case indicates that while green facades with sparse foliage can contribute to environmental control, their impact is considerably more limited than those with denser coverage.

This variation in performance across the case studies highlights the critical role of plant selection and design in the effectiveness of green facades. It suggests that to optimize the benefits of green infrastructure, particularly in climatic and urban conditions like those in the Global South, careful consideration of vegetation type and configuration is essential. For instance, selecting plant species with higher foliage density may be particularly advantageous in environments with desired more potent cooling effects.

Moreover, the findings underscore the need for tailored architectural solutions that consider local environmental factors. By integrating specific plant characteristics that align with the climatic conditions and architectural requirements of a building, designers can enhance the sustainability and energy efficiency of their projects. This approach not only improves the microclimate around buildings but also contributes to broader sustainability goals by reducing the need for mechanical cooling and enhancing the overall energy efficiency of the urban fabric.

Figure 6 presents buffer temperature and solar radiation data for four distinct cases with different facade orientations. The sensitivity analysis revealed that all green facades responded dynamically to environmental changes, particularly solar radiation and temperature. However, the extent of this responsiveness varied by the type of vegetation and its configuration. For instance, the dense foliage in Cases 2 and 4 provided more significant cooling and humidity control, while the sparser coverage in Case 1 resulted in less pronounced effects. This variation underscores the importance of plant selection and facade design in optimizing green infrastructure for specific climatic and urban conditions. It also highlights the need for tailored architectural solutions that consider local environmental factors to maximize the sustainability and energy efficiency of buildings in the Global South.

6   Conclusions

The exploration and incorporation of green facades within urban settings, particularly in the Global South, presents a transformative opportunity to address urban heat islands and enhance energy efficiency in building designs. This study has demonstrated the potential and variability of green facades in modifying microclimates through the dynamic interaction with environmental factors such as solar radiation and temperature. Key findings from this research underscore the significant impact that plant selection and facade orientation have on the performance of green facades. Dense vegetation in some case studies provided substantial cooling effects and humidity control, proving more effective in moderating internal and external microclimates than sparser vegetation configurations. It highlights the critical role of tailored design approaches considering specific local environmental conditions and architectural needs.

Addressing the Global South's unique challenges demands innovative simulation and design approaches. Digital simulation tools have shown considerable promise in accurately predicting the performance of green facades, as demonstrated across multiple case studies. These tools allow for precise adjustments in design parameters, facilitating the optimization of green facades to achieve maximum environmental benefits and energy savings. By incorporating these tools, architects, and students can better understand the dynamic interactions between architectural elements and environmental conditions, fostering a more analytical and responsive approach to design.

Nevertheless, the discrepancies observed between simulated results and empirical data highlight the need for continued refinement of these tools to accurately capture the complex interplay between the built environment and natural elements. These differences also reveal the limitations of the current variables used in the study, including the brief data collection period, specific species characteristics like foliage density and leaf decay cycles, and variations in planting conditions. Future improvements should advance simulation algorithms and incorporate a broader range of variables. Expanding data collection to different seasons could provide insights into annual variations in vegetation behavior and facade performance, ultimately enhancing model accuracy.

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In conclusion, continued research and the application of refined simulation models are essential to advancing our understanding and implementation of these systems and ensuring they meet the specific demands of diverse urban landscapes. This study contributes to the growing body of knowledge on green facades and sets a foundation for future research to bridge the gap between theoretical design and practical performance.

Acknowledgments

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