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Daylight Dynamics: A Preliminary Analysis of Radiation and Illuminance in Future Climate Scenarios

Dinâmica da Luz Natural: Uma Análise de Radiação e Iluminância em Cenários Climáticos Futuros

Dinámica de la Luz Natural: Un Análisis Preliminar de Radiación e Iluminancia en Escenarios Climáticos Futuros

Área 6: Iluminação Natural e Artificial / *Iluminación Natural y Artificial / Daylighting and Electric Lighting*

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Abstract

Accelerated urbanization and climate change have significantly impacted the availability and dynamics of daylight, particularly in densely built urban areas, influencing thermal conditions, energy efficiency, and human well-being. These impacts are directly related to variations in direct and diffuse solar radiation, illuminance levels, and surface temperatures. This study investigates these changes in a simulated urban model using Rhinoceros 3D, Grasshopper, and Ladybug Tools, considering current and future climate scenarios (2080) in an urban block in Porto Alegre, Brazil, a city with a subtropical climate. The simulation results were compared to analyze how climate change and urbanization affect the availability of natural light over time. The findings indicate increases in direct radiation and illuminance, with variations in exposure depending on building orientation. The conclusions highlight the need to integrate natural light into urban planning, adopting strategies to promote resilient and healthy environments.

Keywords: Urban lighting. Climate change. Adaptive design. Urban planning.

Resumo

O crescimento urbano acelerado e as mudanças climáticas impactam significativamente a disponibilidade e dinâmica da luz natural, especialmente em áreas urbanas densas, afetando condições térmicas, eficiência energética e bem-estar humano. Esses impactos estão diretamente relacionados às variações na radiação solar direta e difusa, nos níveis de iluminância e nas temperaturas de superfície. Esse estudo investiga essas mudanças em um modelo urbano simulado, utilizando Rhinoceros 3D, Grasshopper e Ladybug Tools, considerando cenários climáticos atuais e futuros (2080) em um quarteirão urbano de Porto Alegre, cidade com clima subtropical. Os resultados das simulações foram comparados para analisar como as mudanças climáticas e a urbanização afetam a disponibilidade de luz natural ao longo do tempo. Os achados indicam aumentos na radiação direta e iluminância, com variações na exposição segundo a orientação das edificações. As conclusões ressaltam a necessidade de integrar a luz natural no planejamento urbano, adotando estratégias para promover ambientes resilientes.

Palavras-chave: Iluminação urbana. Mudanças climáticas. Design adaptativo. Planejamento urbano.

Resumen

El crecimiento urbano y el cambio climático impactan significativamente la disponibilidad y dinámica de la luz natural, especialmente en áreas densas, afectando condiciones térmicas, eficiencia energética y bienestar humano. Estos impactos se relacionan con variaciones en la radiación solar directa y difusa, niveles de iluminancia y temperaturas de superficie. Este estudio investiga estos cambios en un modelo urbano simulado con Rhinoceros 3D, Grasshopper y Ladybug Tools, considerando escenarios climáticos actuales y futuros (2080) en una manzana urbana de Porto Alegre, ciudad de clima subtropical. Se compararon los resultados de las simulaciones para analizar cómo el cambio climático y la urbanización afectan la disponibilidad de luz natural en el tiempo. Los hallazgos indican aumentos en la radiación directa e iluminancia, con variaciones en la exposición según la orientación solar. Las conclusiones destacan la necesidad de integrar la luz natural en la planificación urbana, adoptando estrategias para promover entornos resilientes y saludables.

Palabras clave: Iluminación urbana. Cambio climático. Diseño adaptativo. Planificación urbana.

Introduction

Global urbanization is expected to add 2.2 billion people to cities in the coming decades, particularly in developing nations, raising concerns about sustainability and environmental impact (United Nations Environment Programme, 2020). In Brazil, urbanization and technological progress have driven construction growth, with metropolitan areas becoming dense economic hubs (Terra de Oliveira, 2017). This densification exacerbates urban overheating and regional climate change, especially where urban planning is inadequate (Monteiro *et al.*, 2021). Climate change is a major urban challenge, particularly in highly industrialized and densely populated cities, which face extreme weather, heatwaves, and deteriorating air quality. Addressing these issues requires adaptive urban strategies to enhance sustainability and resilience (Creutzig *et al.*, 2016; Sharifi, 2019).

Daylight is a fundamental architectural design element, shaping spatial experience, energy efficiency, and sustainability. Its strategic use involves optimizing openings, building orientation, and reflective surfaces to enhance natural illumination and strengthen the connection between occupants and the environment. Beyond energy efficiency, daylight significantly impacts health, well-being, and productivity. Human factors must be prioritized, as they influence user comfort, economic productivity, and energy savings (Gentile *et al.*, 2014). Research highlights its role in regulating hormones and circadian rhythms (Boyce, 2010). Modern daylighting solutions must balance user needs with low-carbon, net-zero-energy goals (Boer *et al.*, 2022). In new constructions, careful daylight design, solar control, and views are essential to achieving these objectives (Gentile *et al.*, 2022).

The growing concern about climate change has led to the widespread use of future weather files to assess urban temperatures, energy efficiency, and building performance in future scenarios (Guan, 2009). These studies provide valuable insights into climate impacts on energy consumption and thermal performance. However, research gaps remain regarding how future conditions will affect solar radiation, visible light availability, and interactions with urban geometry. Urban daylight simulations help address these challenges by predicting daylight behavior and informing strategies to optimize availability and efficiency. Studies have successfully applied parametric and climate-based daylight modeling tools, such as Rhinoceros 3D, Grasshopper, and Ladybug Tools, to evaluate daylighting strategies (Jakica *et al.*, 2017; Dogan *et al.*, 2021; Roudsari & Pak, 2013). These tools simulate solar radiation, illuminance, and surface temperatures, making them useful for assessing current and future conditions (Davidson, 2024; Ladybug Tools, 2024). Radiance and EnergyPlus provide complementary insights on light penetration and thermal performance but depend on high-quality input data and require significant computational resources (Dubois & Blomsterberg, 2011; Jin *et al.*, 2020). Despite these limitations, simulations remain essential for climate-responsive urban design (Machard *et al.*, 2020; Rodrigues, Fernandes & Carvalho, 2023).

Additionally, daylight reduces energy use while improving well-being and visual experience, reinforcing its role in sustainable development (Oakley, Riffat & Shao, 2000). Beyond visual benefits, inadequate daylight disrupts circadian rhythms, causing sleep disturbances, depression, and other health issues (Shishegar & Boubekri, 2016; Wirz-Justice, Skene & Münch, 2021). Light also regulates biological processes like hormone levels and blood circulation, underscoring its importance for human health (Logan & McClung, 2019).

Furthermore, daylight reduces building energy use while positively impacting occupant well-being and visual experience, emphasizing its multifaceted role in sustainable development (Oakley, Riffat & Shao, 2000). Beyond its visual benefits, insufficient daylight disrupts circadian rhythms, contributing to sleep disorders, depression, and other health issues (Shishegar & Boubekri, 2016; Wirz-Justice, Skene & Münch, 2021). Light also regulates key biological processes, such as hormone levels and blood circulation, highlighting its critical role in human health (Logan & McClung, 2019).

In summary, urbanization and climate change pose complex challenges that require sustainable solutions. As a dynamic resource, daylight enhances energy efficiency, health, and city resilience. Integrating daylight into architectural and urban planning can help address these challenges while promoting sustainable development and improving quality of life.

Objectives

This study aims to provide insights into diffuse daylight across various periods by investigating direct and diffuse radiation and illuminance factors. By implementing simulations utilizing present-day weather files and future-representative weather files, the research seeks to compare the simulation results and analyze the effects of urbanization on direct daylight.

Methodology

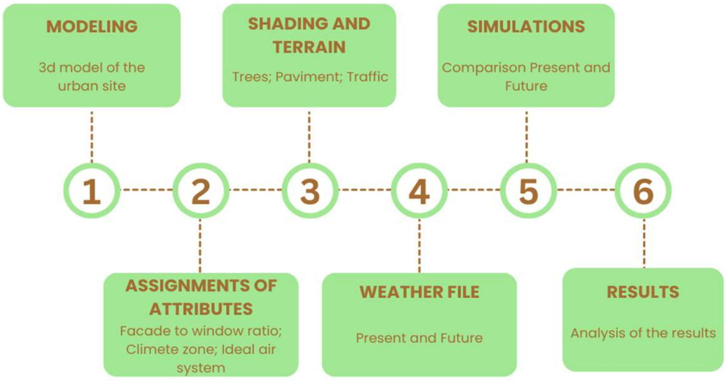
This study utilized Rhinoceros 8.3 software, Grasshopper, and Ladybug Tools applications. Rhinoceros 3D is a three-dimensional modeling software, and Grasshopper is a graphical algorithm editor integrated with its modeling tools (Davidson, 2024). Ladybug connects 3D Computer-Aided Design (CAD) interfaces to validated simulation engines. As a preparatory step, the study selected the location and weather files (present-day and future-representative) to provide accurate data inputs for environmental simulations.

The site is situated on Ernesto da Fontoura Street, located in the fourth district of Porto Alegre, Brazil, a neglected area with urban gaps, empty lots, and sparse green spaces. They are the reason for the extreme surface temperature of this zone, being the primary incentive for selecting this street. The site comprises seventeen buildings with different programs, including residential, commercial, offices, and mixed use, with some plants being considered in the simulations.

EPW (EnergyPlus Weather) data from INMET (Instituto Nacional de Meteorologia) from 2021 was used for present-time simulations and as the foundation dataset for creating the future weather file representing the conditions of 2080. The future EPW file was generated through the 'Future Weather Generator,' a Java application that morphs hourly EPW files to align with future climate change scenarios, compatible with dynamic simulation programs like EnergyPlus. The future weather file should be the worst-case scenario for 2080 to ensure that the simulations capture the largest differences between current and future weather files.

The article utilized a 3D model created in Rhinoceros configured for compatibility with Ladybug Tools, using the Ladybug, Honeybee, and Dragonfly applications (Ladybug Tools, 2024). The study was conducted in five steps (Figure 1), starting with an examination of solar radiation and illuminance, attempting to find future potential compared to the present.

Figure 1 - Methodology diagram



Source: Authors (2024)

Step 1 - Modeling: The process involved utilizing a DWG file from the municipal website for the area's floor plan. In Grasshopper, floor heights and the number of floors for each building were determined. A field survey aligned the digital models with current on-site conditions. Porto Alegre's ASHRAE climate zone is classified as 2A - hot and humid, information used to select the construction set of the buildings, with materials selected from the Honeybee software. The urban site consists of 18 buildings, ranging in height from 1 to 5 floors, each with a floor-to-ceiling height of 3 meters (figure 2).

Figure 2 – Location and 3D model of the urban site, 2024.

Source: Authors (2024)

Step 2 - Assignments of Attributes: In this phase, the model underwent an attribute assignment process. Each building was allocated specific programs, considering the proportion of windows on the facades. On-site verification and Google Maps analysis determined the building programs and window ratios as a percentage of the facade. The model includes eleven residential buildings, one office building, four commercial buildings, and two mixed-use buildings, with window ratios determined to be 20% of the facades.

Step 3 - Shading and terrain: Field analysis included evaluating the positions of local trees, detailing the diameter of their canopies and overall height. Terrain characteristics were defined through an evaluation of both its geometry and the albedo (reflectivity) of the pavement, influencing shading and daylight dynamics.

Step 4 - Weather File: The simulation depended on EPW data from INMET from 2021, processed through the 'Future Weather Generator' for the future weather file a tool developed in Portugal. The analysis used future weather data aligned with the Intergovernmental Panel on Climate Change's (IPCC) most pessimistic scenario, characterized by high emissions and limited mitigation efforts, leading to intensified extreme weather (Masson-delmotte *et al.*, 2021). This selection aimed to evaluate the urban environment, accounting for diverse climatic conditions in the study.

Step 5 – Simulations: The final step was performing complete simulations on the whole urban model. Detailed simulations included the sky matrix simulation, utilizing Radiance's gendaymtx command to compute radiation for each sky dome segment, executed using both current and projected future weather data files. The one-year simulation investigated the behavior of the model's radiation, including hourly Direct Normal Radiation and hourly Diffuse Horizontal Radiation. The outcomes were displayed through a three-component dome graph of Total Radiation, Direct Radiation, and Diffuse Radiation in KWh/m².

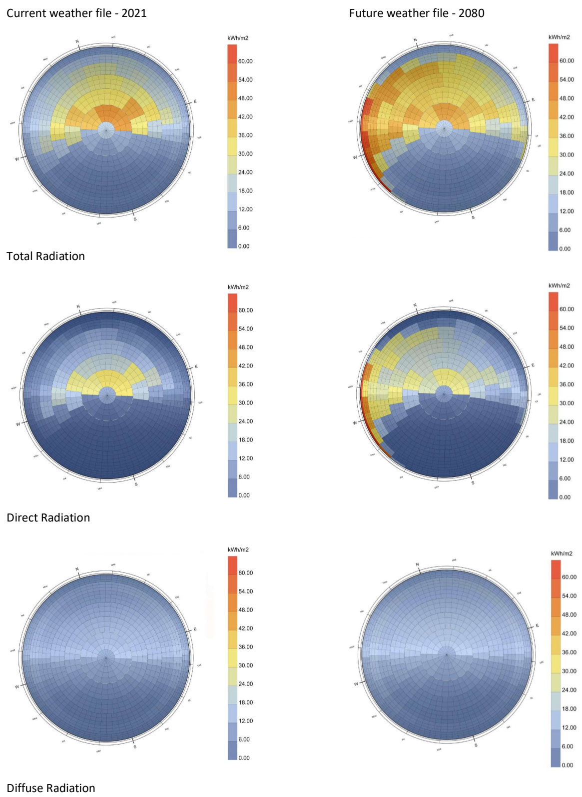
In parallel, the second simulation determined illuminance across the urban region based on Global Horizontal Illuminance, Diffuse Horizontal Illuminance, and Direct Horizontal Illuminance, measured over twelve months. This analysis generated a monthly breakdown of lux, and a comparative simulation projected these metrics into the future using the 2080 weather file.

This combined methodology, presented in visual representations and analytical reports, contributes to our understanding of the complex relationship between urbanization, climate change, and their various effects on the urban environment, providing insightful data on existing environmental trends and potential future trends.

Results

Based on current weather files, the analysis of radiation dynamics in the urban model involved the utilization of hourly Direct Normal Radiation and hourly Diffuse Horizontal Radiation. This approach extended our comprehension of solar radiation, clearly distinguishing between direct and diffuse sky radiation (Figure 3 - A). Similarly, an analysis was performed to illustrate how the urban area would respond in a scenario projected for 2080 (Figure 3 - B). In comparing both analyses, a substantial increase in Direct Radiation becomes apparent, along with a shift in orientation where higher values shift for the West orientation. While the difference in Diffuse radiation is not as significant as in Direct Radiation, there is still a noticeable increase in diffuse light when comparing both analyses.

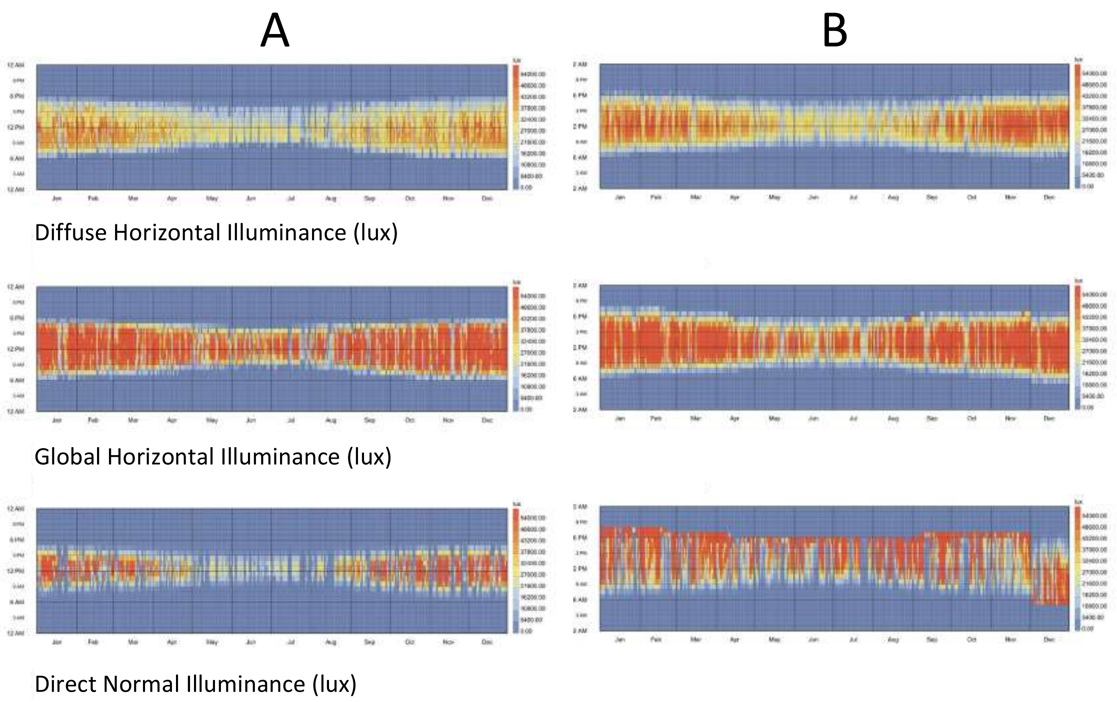
Figure 3 – A: Dome representation of Total Radiation, Direct Radiation and Diffuse Radiation in present weather file. B: Total Radiation, Direct Radiation and Diffuse Radiation in future 2080 weather file



Source: Authors (2024)

To enhance the comprehensiveness of the analysis, an additional simulation was made to illustrate illuminance variations across the study area. Global Horizontal Illuminance, Diffuse Horizontal Illuminance, and Direct Horizontal Illuminance were simulated across the twelve months of the year, utilizing the present weather file (Figure 4 – A). For comparison, all graphs were standardized with a maximum of 5400.00 Lux and a minimum of zero Lux, showcasing the correlation between average lux levels during specific hours of the day for each month. Subsequently, mirroring the simulation parameters, the same analysis was extended to the future weather file (Figure 4 – B). This approach facilitates a visible and comprehensive comparison between both analyses, providing further insights into the potential variations in illuminance under different climatic scenarios.

Figure 4 – A: Charts representation of Global Horizontal Illuminance, Diffuse Horizontal Illuminance, and Direct Horizontal Illuminance in present weather. B: Charts representation of Global Horizontal Illuminance, Diffuse Horizontal Illuminance, and Direct Horizontal Illuminance in future weather

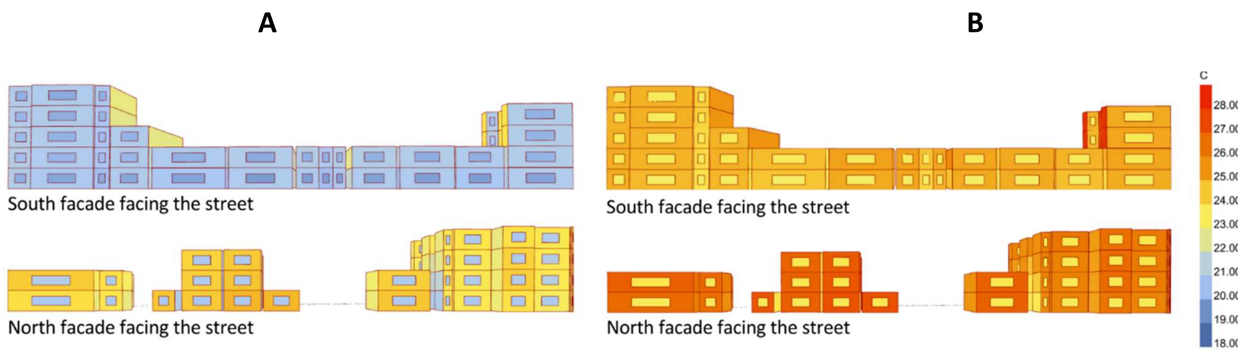


Source: Authors (2024)

This exploratory overall analysis sheds light on potential nuances in the effects of air pollution, aerosols, and climate change on diffuse light behavior. While these findings offer valuable insights, it's essential to approach them with the awareness that further, more in-depth studies may be needed to draw definitive conclusions.

The significant increase in surface temperatures projected for 2080, as revealed by the simulation (Figure 7 – A and B), underscores the complex interplay between climate change and the built environment.

Figure 7 - A: Exterior surface temperatures using the present weather file. B - Exterior surface temperatures using the future weather file

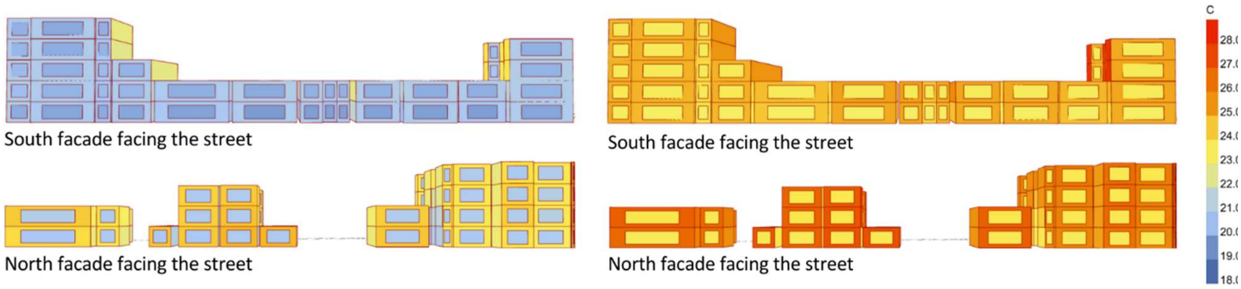


Source: Authors (2024)

This rise in surface temperatures can be correlated with the intensified solar radiation, particularly the increased Direct Radiation observed in the urban model. A new set of simulations was conducted to expand this analysis, increasing the window-to-facade ratio from 20% to 40% (Figures 8 – A and B).

Figure 8 - A: Exterior surface temperatures using the present weather file with a 40% window-to-facade ratio. B - Exterior surface temperatures using the future weather file with a 40% window-to-facade ratio

A B



Source: Authors (2024)

These updated results demonstrate an amplified sensitivity of surface temperatures and daylight dynamics to building design choices. Even though the visual differences may seem subtle, the results reveal an increase of up to 3.7°C in surface temperature variation under the present weather file and an additional 1.12°C under the future weather file. The higher window ratio not only intensified surface temperatures due to increased solar heat gain but also altered the behavior of daylight distribution, potentially impacting interior lighting conditions and cooling demands.

While not explicitly explored in the current analysis, the temperature surface simulations and daylight performance evaluations point to broader implications for human well-being, energy consumption, and environmental sustainability. The interconnected nature of these factors emphasizes the need for a holistic approach to urban planning and design, considering adaptive strategies for facade design, in the face of evolving climate conditions.

Conclusion

This study provides a nuanced understanding of the interplay between urbanization, climate change, and daylight dynamics through radiation and illuminance simulations. The findings highlight direct radiation and illuminance potential increases by 2080, emphasizing the critical role of building orientation and urban design in mitigating thermal and lighting challenges. These results reveal the environmental and architectural implications of evolving urban climates and underscore the importance of integrating adaptive design strategies to foster resilient and sustainable urban environments.

The illuminance simulations also illuminate the potential for optimizing daylight use to enhance human well-being, reduce energy consumption, and support green building practices. By linking climate-responsive urban planning with daylight strategies, this research lays the groundwork for more comprehensive investigations into the interconnection between urban form, sustainability, and human health. The current outcomes serve as a preliminary study, laying the groundwork for future, more comprehensive investigations that should build upon this preliminary analysis by incorporating more complex scenarios, such as the impact of vegetation, dynamic shading systems, and varying building typologies, to refine mitigation strategies further. Integrating social and behavioral dimensions could also provide a perspective on the role of daylight in promoting equitable and health-centered urban living. The current outcomes serve as a preliminary study, laying the groundwork for future, more comprehensive investigations.

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