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Faculdade de Engenharia Civil, Arquitetura e Urbanismo

ÍRIS MARIA COSTA FAJARDO WERNECK LOCHE

# DESEMPENHO TERMOENERGÉTICO E LUMINOSO DE EDIFÍCIOS DE ESCRITÓRIOS COM VARANDAS EM CLIMA SUBTROPICAL

# THERMAL, ENERGY AND DAYLIGHT PERFORMANCE OF OFFICE BUILDINGS WITH BALCONIES IN SUBTROPICAL CLIMATE

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Tese de Doutorado apresentada à Faculdade de Engenharia Civil, Arquitetura e Urbanismo da Universidade Estadual de Campinas para a obtenção do título de Doutora em Arquitetura, Tecnologia e Cidade, na área de Arquitetura, Tecnologia e Cidade.

Thesis presented to the Faculty of Civil Engineering, Architecture and Urban Design, of Universidade Estadual de Campinas in partial fulfilment of the requirements for the degree of Doctor in Architecture, Technology and Cities, in the area of Architecture, Technology and Cities.

**Orientadora: Profa. Dra. Leticia de Oliveira Neves**

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**UNIVERSIDADE ESTADUAL DE CAMPINAS**
**FACULDADE DE ENGENHARIA CIVIL, ARQUITETURA E URBANISMO**

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Campinas, 20 de junho de 2024

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# Resumo

O uso de varandas em climas tropicais tem o potencial de bloquear a radiação solar direta, reduzindo o consumo de energia com refrigeração e melhorando o conforto visual. As varandas, no entanto, também podem diminuir a disponibilidade de luz natural dentro do ambiente, afetando a satisfação e o bem-estar dos ocupantes. Do ponto de vista do desempenho da edificação, o projeto de varandas nem sempre é trivial e pode afetar o desempenho do edifício em múltiplos domínios. A complexidade de uma análise multiobjetivo para o projeto de varandas é evidenciada na literatura pela escassez de artigos científicos que exploram os efeitos do uso de varandas no desempenho do edifício considerando uma abordagem multiobjetivo. Em vista disso, o principal objetivo desta tese é fornecer recomendações projetuais de varandas para melhorar o desempenho de luminoso, térmico e energético de edifícios de escritórios multipavimentos que operam em modo-misto de ventilação. Um modelo de referência representando um edifício de escritórios e variações de parâmetros geométricos de varandas foram definidos com base em um banco de dados de edifícios de escritórios localizados na cidade de São Paulo, Brasil. Uma análise paramétrica foi utilizada para avaliar os efeitos dos parâmetros projetuais de varandas combinados com parâmetros geométricos da edificação no desempenho de edifícios de escritórios que operam em modo misto. Uma avaliação multiobjetivo foi realizada por meio de simulações computacionais de desempenho luminoso, térmico e energético, usando programas computacionais confiáveis para avaliar diferentes casos de projeto de varandas. Para melhor precisão dos resultados, simulações de Dinâmica de Fluidos Computacional (CFD), validadas com experimentos de túnel de vento, foram usadas para gerar dados de coeficiente de pressão; e ensaios de iluminação natural foram desenvolvidos para validar as simulações de desempenho luminoso. Os resultados das simulações, considerando as variações projetuais de varandas, foram avaliados para disponibilidade de luz natural e conforto visual, bem como para o desempenho térmico, energético e da ventilação natural. Os resultados foram cruzados para desempenho de luminoso, térmico e energético, e recomendações projetuais de varandas foram desenvolvidas para cada orientação solar de fachada e combinadas cuidadosamente com a largura da porta envidraçada. Uma combinação ótima, apresentando uma porta envidraçada de 3 metros de largura e uma varanda de 2 metros de profundidade, mostrou-se benéfica para todas as orientações de fachada e para todos os pavimentos do edifício. No entanto, a escolha do tipo de parapeito deve estar alinhada com a localização da varanda, que está diretamente correlacionada com a profundidade do ambiente. Esta combinação projetual de varanda garante níveis ótimos de disponibilidade de luz natural e melhora o conforto visual em até 14%, aumentando o desempenho termoenergético da sala de escritório em até 40%. Os resultados desta pesquisa são pioneiros em fornecer recomendações de projeto de varandas e oferecem informações valiosas para os projetistas de edifícios, destacando que as varandas não devem ser projetadas apenas como elementos decorativos de fachada ou espaços para serviços. Além disso, os métodos desenvolvidos nesta pesquisa podem ser aplicados por pesquisadores/projetistas em seus próprios estudos de caso.

**Palavras-chave:** varanda; modo misto de ventilação; escritório, desempenho luminoso; conforto visual; desempenho térmico; desempenho energético; otimização; recomendações projetuais.

# Abstract

The use of balconies in tropical climates holds the potential to block direct solar radiation, thereby reducing energy consumption for cooling and enhancing visual comfort. However, balconies may also diminish daylight availability within the room, affecting occupants' satisfaction and well-being. From a building performance perspective, balcony design is not always trivial and can affect building performance in multiple domains. The complexity in trade-offs of balcony design is evident in the literature, as scientific papers have scarcely explored the effects of the use of balconies on the building performance considering a multi-objective approach. Therefore, the main objective of this thesis was to provide balcony design recommendations to improve daylight, thermal, and energy performance of mixed-mode office buildings. A reference model representing a high-rise mixed-mode office building and possible variations of geometric parameters of balconies were defined based on a database of office buildings located in the city of São Paulo, Brazil. A parametric analysis was used to evaluate the effects of balcony and building design parameters on the reference model's performance. A multi-objective assessment was performed through building performance simulations (BPS) for daylight, thermal and energy performance, using reliable software tools to assess different balcony design scenarios. To improve accuracy, computer fluid dynamics (CFD) simulations validated with wind tunnel experiments were used to generate wind pressure coefficient data, and daylight experiments were developed to validate the daylight simulations. The trade-offs of balcony design were assessed for daylight availability and visual comfort, as well as for natural ventilation, thermal and energy performance. The results were cross-analysed for daylight, thermal, and energy performance and recommendations for balcony design were tailored to each façade orientation and thoughtfully combined with the glazed door width. An optimal combination, featuring a 3-meter-wide glazed door and a 2-meter-deep balcony, proved beneficial for all façade orientations across all floor levels. However, the choice of parapet type should align with the balcony's location, which is directly correlated with the room's depth. This balcony design combination ensures optimal levels of daylight availability and improves visual comfort by up to 14%, enhancing thermal and energy performance within the room by up to 40%. The results of this research study pioneer in providing balcony design recommendations and offer valuable information for building designers, highlighting that balconies should not be designed solely as decorative façade elements or spaces for building services. Additionally, the methods developed in this research can be applied by researchers/designers to their own case studies.


**Keywords:** balcony; mixed-mode ventilation; office; daylight performance; visual comfort; thermal performance; energy performance; optimisation; design recommendation

# List of publications during the doctoral program

I. **LOCHE, I.**; OLIVEIRA, K. P.; DURANTE, M.; FRACALANZA, B. C.; NEVES, L. O. Effects of balconies on the wind pressure coefficients of naturally ventilated high-rise office buildings. *In:* Symposium on simulation in architecture + urban design, 2020, Viena. **Anais** […]. SimAUD: *[S. l.]*, 2020.

II. SILVA, V. G.; **LOCHE, I**.; SAADE, M. R. M.; PULGROSSI, L. M.; FRANCESCHINI, P. B.; RODRIGUES, L. L.; PIMENTA, R. G.; NEVES, L. O.; KOWALTOWSKI, D. Operational and embodied impact assessment as retrofit decision-making support in a changing climate. *In:* Windsor Conference, 11., 2020, Windsor. **Anais** […]. The Windsor Conference: Windsor, 2020.

III. **LOCHE, I.**; NEVES, L. O. Efeitos do uso de varandas no desempenho térmico de salas de escritório em edifícios verticalizados. *In*: Encontro Nacional de Tecnologia do Ambiente Construído, 18., 2020, Porto Alegre. **Anais** […]. Porto Alegre: ANTAC, 2020.

IV. **LOCHE, I.**; NEVES, L.O. Efeitos das varandas no desempenho térmico, energético e luminoso de edificações: revisão sistemática da literatura. *In*: Encontro Nacional de Conforto no Ambiente Construído, 16., 2020, Palmas. **Anais** […]. Porto Alegre: ANTAC, 2021.

V. **LOCHE, I.**; SOUZA, B. C.; SPAETH, A. B.; NEVES, L. O. Decision-making pathways to daylight efficiency for office buildings with balconies in the tropics. **Journal of Building Engineering**, *[S. l.]*, v. 43, p. 1-24, 2021. DOI: 10.1016/j.jobe.2021.102596.

VI. SILVA, V. G.; SAADE, M.; NEVES, L. O.; **LOCHE, I**.; PULGROSSI, L. M.; SILVA, M. G. Sight beyond reach: Dynamic life cycle assessment to support resilient retrofit decision-making in a changing climate. *In*: NICOL, F.; RIJAL, H. B.; ROAF, S. (org.). **Routledge Handbook of Resilient Thermal Comfort**. *[S. l.]:* Routlege, 2022. cap. 25, p. 417-432.

VII. **LOCHE, I.**; BRE, F.; GIMENEZ, J. M.; LOONEN, R.; NEVES, L. O. Balcony design to improve natural ventilation and energy performance in high-rise mixed-mode office buildings. **Building and Environment**, *[S. l.]*, v. 258, p. 1-16, 2024. DOI: 10.1016/j.buildenv.2024.111636.

VIII. **LOCHE, I.**; LOONEN, R; NEVES, L. O. Balcony design recommendations to enhance daylight, thermal and energy performance of mixed-mode office buildings. **Energy and Buildings.** (Submitted - Under review)

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# 1. Introduction

In office buildings located in subtropical climates, the use of climate control systems is often necessary to ensure occupants' thermal comfort and productivity. In Brazil, office buildings accounted for 10% of the total energy consumption in 2022, representing a 2% increase when compared to 2010 (EPE, 2023). One of the reasons for it is the increased use of air-conditioning systems, driven by global warming and the occurrence of more frequent heatwaves (EPE, 2023), which highlights the importance of using passive design strategies, such as solar shading devices and natural ventilation, to enhance thermal performance and decrease energy consumption with cooling.

In hot climates of tropical and subtropical regions, combining mixed-mode ventilation (MMV) systems with solar shading strategies in office buildings can effectively reduce energy use for cooling (Mohammed, 2021). MMV systems enable indoor spaces to use natural ventilation during favourable outdoor conditions to maintain thermal comfort, thereby reducing reliance on air-conditioning for supplementary cooling (Brager, 2006); also improving indoor air quality (IAQ) and enhancing occupants' satisfaction and productivity (Arata; Kawakubo, 2022; Brager; Baker, 2009; De Oliveira; Rupp; Ghisi, 2021).

Balconies are protruding structures that can work as solar shading devices for buildings situated in tropical and subtropical climates. When wide and deep, they show a good potential in reducing undesirable direct solar radiation and diminishing cooling loads (Elgohary; Abdin; Mohamed, 2023; Ribeiro *et al*., 2024). From a building physics perspective, their design presents a complex challenge due to trade-offs between daylighting, thermal and energy performance. Regarding daylight performance, balconies can reduce glare, improving visual comfort (Al-Sallal; AbouElhamd; Dalmouk, 2018), but they may also hinder daylight availability within the room, leading to higher energy consumption with electric lighting (Gabrova, 2014; Ribeiro *et al*., 2024).

Since balconies are, usually, prominent elements on building façades, they influence airflow patterns and pressure distribution, affecting natural ventilation inside the building. This, in turn, directly influences building thermal and energy performance. Depending on the balcony geometry and the direction of prevailing winds, they can either improve or obstruct airflow, adding complexity to their design. (Bamdad *et al*., 2022; Cochran, 2020; Cui; Mak; Niu, 2014; Izadyar *et al*., 2020; Montazeri; Blocken, 2013; Omrani *et al*., 2017, 2015; Zheng; Montazeri; Blocken, 2020, 2021).

Commonly used in residential buildings, balconies are often desired by occupants, since they allow the development of multifunctional activities such as leisure, entertainment, and gardening (Peters; Halleran, 2021; Peters; Masoudinejad, 2022; Ribeiro; Ramos; Flores-Colen, 2020). Also in offices, the use of balconies is gaining popularity. A study in São Paulo, Brazil, for example, revealed that the incorporation of balconies in mixed-mode office buildings increased by 85% from 1995 to 2016 (Neves;

Melo; Rodrigues, 2019). This study, which compiled a comprehensive database of design parameters for mixed-mode office buildings in São Paulo, reveals that 23% of these buildings have exterior shading devices, of which 92% are balconies (Neves; Melo; Rodrigues, 2019).

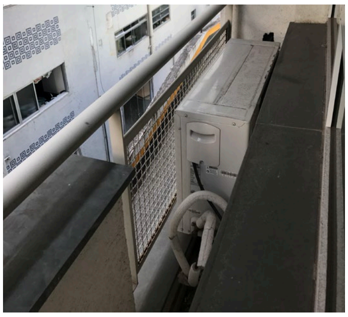
The increased use of balconies in mixed-mode office buildings is potentially linked to the popularization of split air-conditioning units, which require an outdoor space for housing the condenser unit. Balconies are a common choice for placing the condenser unit in high-rise buildings located in hot climates, following recommendations to place the condenser in well-ventilated areas for optimal heat dissipation and system efficiency (Abdullah; Barwari, 2022; Chow; Lin; Wang, 2000; Xue *et al*., 2007) (Figure 1). This trend presents an opportunity to advocate for the use of balconies in office buildings, as they could serve multiple purposes, such as accommodating building services, acting as shading control systems, and providing a pleasant transitional space between indoor and outdoor environments for occupants.

a) Balconies located on the short-axis façade

b) Balconies located on the long-axis façade

c) Balconies located on the short-axis façade

d) Office room with balcony



e) Balcony used as a service area to house the condenser unit in an office room

f) Office building façade with condenser unit in the balcony

**Figure 1.1:** Examples of mixed-mode office buildings with balconies in the city of São Paulo, Brazil available in the database.
Source: (Pereira, 2019)

Balcony design can also determine their utility and advantages for building occupants. A wide and deep balcony is more likely to be occupied, while a narrow and shallow balcony may be relegated to a non-occupied service area, leading to occupants' dissatisfaction (Li *et al*., 2023; Song *et al*., 2024). In São Paulo, the use of balconies is encouraged by the building code, as it exempts open balconies from being classified as built area if their dimensions per floor are less than 5% of the total site area (São Paulo, 2017). However, depending on the site area's size, it can lead to shallow and narrow balconies that are used as service spaces solely.

Balcony design is not always trivial and may affect building performance in multi-domains. Due to this complexity, there is a significant lack of research exploring the effects of balcony considering multi-objectives. A systematic literature mapping showed that the exploration of the simultaneous effects of balconies on natural ventilation and thermal comfort was conducted by Ai *et al*. (2011), Izadyar *et al*. (2020) and Omrani *et al*. (2017), employing CFD simulations and thermal comfort calculations. Ai et al. (2011) demonstrated that adding a balcony to the façade enhanced indoor air distribution, leading to improved thermal comfort. Aligned with these findings, Izadyar *et al*. (2020) showed that balconies between 2.5 and 3 m deep produced the best results in terms of indoor air distribution and thermal comfort in adjacent living rooms of residential buildings. Omrani *et al.* (2017) concluded that increasing the balcony depth led to a decrease in air speed. Moreover, the impacts of the balcony depth on thermal comfort were more pronounced in rooms relying on single-sided ventilation, compared to those employing cross-ventilation.

The impacts of balconies on daylight, thermal and energy performance were analysed concurrently in six studies (Dahlan *et al*., 2009a; Elgohary; Abdin; Mohamed, 2023; Li *et al*., 2023; Liu; Chen, 2017; Ribeiro *et al*., 2024; Yang; Li, 2022). The effects of balconies on thermal and daylight performance of residential rooms during summer were evaluated through surveys and field measurements by Dahlan *et al.* (2009), Yang and Li (2022) and Ribeiro *et al* (2024). Balconies were identified as effective elements for enhancing thermal comfort, although they reduced indoor daylight availability. Nevertheless, the results remained compliant with minimum daylight requirements (Dahlan *et al.*, 2009a; Yang; Li, 2022). Similarly, results from Ribeiro *et al.* (2024) demonstrated that rooms without balconies exhibited higher indoor temperatures during summer, with temperatures 4 °C higher than outdoor temperatures, whereas indoor spaces provided with open balconies on the South façade were 3 °C cooler. While apartments without balconies achieved higher illuminance levels compared to those with balconies, these values exceeded thresholds considered visually comfortable, and the presence of balconies helped regulate excessive daylight levels. Building performance simulations were conducted by Liu and Chen (2017), Li *et al.* (2023), and Elgohary, Abdin and Mohamed (2023) to optimise the balcony design for daylight and thermal performance. The three studies showed that balcony design should be aligned with the window-to-wall ratio (WWR). Liu and Chen (2017) suggested increasing the WWR from 50% to 75% and 100%, to allow a deeper balcony (3 m) without compromising daylight performance, enhancing the energy savings with cooling in residential buildings located in Taiwan. Li *et al*. (2023) recommended adjusting the WWR during balcony renovations to enhance both thermal and daylight performance in ancient residential buildings located in Beijing, China. A WWR of 50-60% with a 1.2-meter-depth balcony, for example, could improve indoor thermal comfort while meeting daylight requirements.

Elgohary, Abdin and Mohamed (2023) employed parametric design to determine optimal block arrangements and balcony shapes for designing residential buildings in Cairo. The authors suggest that the balcony depth should be designed in correlation with the WWR and based on the façade orientation. The WWR should vary according to each façade, in order to balance daylight penetration and glare, with the optimum percentage being 10% for the West, South, and East façades, and 60% for the North orientation. There are no benefits to thermal and energy performance in adding balconies to the North façade (considering Cairo's location above the equator line), except for architectural aesthetics or occupants' preferences. The design for the West façade could incorporate more vertical elements, while the South façade would require deeper balconies.

Current scientific literature predominantly focuses the analysis of balconies' performance on residential buildings (Bayazit; Kisakurek, 2023; Dahlan *et al*., 2009a; Duarte *et al*., 2023; Izadyar *et al*., 2020; Liu *et al*., 2021; Omrani *et al*., 2017; Peters; Masoudinejad, 2022; Ribeiro *et al*., 2024; Ribeiro; Ramos; Flores-Colen, 2020; Tungnung, 2020). This focus is evident in the comprehensive literature review conducted by Ribeiro *et al*. (2020) on the influence of balconies on the indoor environment of residential buildings, and in the ongoing discussion about the role of balconies in dwellings during the COVID-19 pandemic (Bayazit; Kisakurek, 2023; Duarte *et al*., 2023; Peters; Halleran, 2021; Peters; Masoudinejad, 2022; Säumel; Sanft, 2022). However, findings from daylight, thermal and energy performance of residential studies may have limited applicability to office buildings due to different occupancy schedules and internal loads, underscoring the necessity for research studies specific to the office typology. Moreover, balcony performance-based design is complex and correlated to other building design parameters. Possible consequences of design changes are not always trivial and could affect its performance in multiple domains.

## 1.1 Objectives

This research aimed to develop balcony design recommendations to optimise daylight, thermal and energy performance of mixed-mode office buildings in subtropical climates.

The **specific objectives** (SO) represent the objectives of the papers that compose this thesis, as follows:

SO1: Assessing both the existing knowledge and gaps in the literature regarding the influence of balcony design parameters on daylight, thermal and energy performance of buildings. (Chapter 2)

SO2. Evaluating the effects of balcony design parameters on the daylight performance of mixed-mode office buildings in subtropical climates. (Chapter 3)

SO3. Evaluating the effects of balcony design parameters on the natural ventilation, thermal and energy performance of mixed-mode office buildings in subtropical climates. (Chapter 4)

Chapters 2, 3, and 4 contribute to accomplishing the main objective, which is presented in Chapter 5.

## 1.2 Hypothesis and research questions

This research considered the hypothesis that balconies can enhance daylight, thermal and energy performance of mixed-mode office buildings.

In order to better clarify the research problem, the following research questions were developed:

- What are the effects of balcony design on daylight availability and visual comfort of mixed-mode office rooms in subtropical climates?
- What are the effects of balcony design on the natural ventilation, thermal and energy performance of mixed-mode office rooms in subtropical climates?
- Which combinations of balcony design parameters, combined with building design parameters, optimise daylighting, thermal efficiency, and energy performance simultaneously in office buildings in subtropical climates?

## 1.3 Thesis structure

This thesis comprises seven chapters and five appendices, as shown in Table 1.1. Chapters 2 to 5 and Appendix B present papers published or submitted to publication during the doctoral program. The papers were incorporated into this thesis using the same wording as originally published or submitted, with adjustments made to their layout for consistency within this document. As some references are redundant across the chapters, the references were compiled at the end of this thesis for conciseness, adopting NBR 10520 for citations (ABNT, 2023) and NBR 6023 for references (ABNT, 2018).

**Table 1.1:** Thesis chapters summary

| | | References | Status |
|---|---|---|---|
| **Chapters** | | | |
| **1** | Introduction | - | - |
| **2** | Literature review | LOCHE, I.; NEVES, L. O. Efeitos do uso de varandas no desempenho térmico de salas de escritório em edifícios verticalizados. *In*: Encontro Nacional de Tecnologia do Ambiente Construído, 18., 2020, Porto Alegre. **Anais** […]. Porto Alegre: ANTAC, 2020. | Published |
| **3** | Effects of the use of balconies on daylight performance | LOCHE, I.; SOUZA, B. C.; SPAETH, A. B.; NEVES, L. O. Decision-making pathways to daylight efficiency for office buildings with balconies in the tropics. **Journal of Building Engineering**, *[S. l.]*, v. 43, p. 1-24, 2021. DOI: 10.1016/j.jobe.2021.102596. | Published |
| **4** | Effects of the use of balconies on natural ventilation, thermal and energy performance | LOCHE, I.; BRE, F.; GIMENEZ, J. M.; LOONEN, R.; NEVES, L.O. Balcony design to improve natural ventilation and energy performance in high-rise mixed-mode office buildings. **Building and Environment**, *[S. l.]*, v. 258, p. 1-16, 2024. DOI: 10.1016/j.buildenv.2024.111636. | Published |
| **5** | Effects of the use of balconies on daylight, thermal and energy performance | LOCHE, I.; LOONEN, R; NEVES, L. O. Balcony design recommendations to enhance daylight, | Submitted in April 2024 (Under review) |

| | | | |
|---|---|---|---|
| | | thermal and energy performance of mixed-mode office buildings. **Energy and Buildings.** | |
| **6** | General discussions | - | - |
| **7** | Conclusions | - | - |
| **Appendices** | | | |
| **A** | Daylight simulations dataset | Appendix of Chapter 3 | - |
| **B** | Wind tunnel experiments | LOCHE, I.; OLIVEIRA, K. P.; DURANTE, M.; FRACALANZA, B. C.; NEVES, L. O. Effects of balconies on the wind pressure coefficients of naturally ventilated high-rise office buildings. *In:* Symposium on simulation in architecture + urban design, 2020, Viena. **Anais** […]. SimAUD: *[S. l.]*, 2020. | Published |
| **C** | Validation of CFD simulations | Appendix of Chapter 4 | - |
| **D** | Validation of daylight simulations | Appendix of Chapter 5 | - |

The thesis structure is shown in Figure 1.2 and is explained as follows.

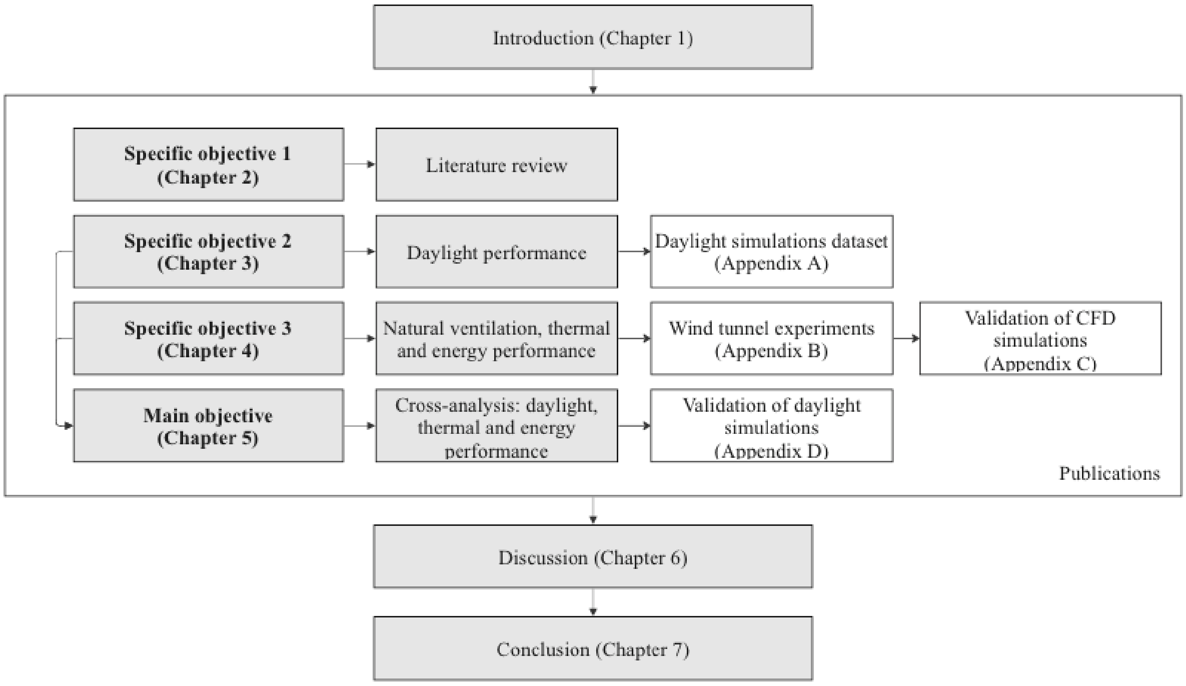



**Figure 1.2:** Thesis workflow

**Chapter 2** presents a systematic literature review about the effects of balconies on daylight, thermal and energy performance of buildings. This chapter addresses the first specific objective and identifies trends and gaps in the literature concerning this subject. The review also provides information regarding influential balcony design parameters and building design parameters that may affect daylight, thermal and energy performance of buildings, used to approach specific objectives 2 and 3, as well as this thesis' main objective.

**Chapter 3** presents an investigation of the effects of balcony design in the daylight performance of mixed-mode office buildings. This chapter approaches the second specific objective by creating successful combinations of building design parameters as well as important cut-off points for decision-making design, to achieve daylight efficiency in mixed-mode office buildings in São Paulo, Brazil. This chapter was developed in collaboration with Dr. Clarice Bleil de Souza and Dr. Benjamin Spaeth during a 5-month research internship at the Welsh School of Architecture, Cardiff University, United Kingdom.

**Chapter 4** presents an investigation of the effects of balcony design in the natural ventilation, thermal and energy performance of mixed-mode office buildings. This chapter approaches the third specific objective through an integrated method that involves computer fluid dynamics (CFD) and building performance simulations (BPS) to identify optimal balcony design solutions to enhance natural ventilation and reduce energy consumption for cooling in mixed-mode office buildings in São Paulo, Brazil. This chapter was developed in collaboration with Dr. Facundo Bre, Dr. Juan Marcelo Gimenez and Dr. Roel Loonen during an 18-month research internship at the Department of the Built Environment, Eindhoven University of Technology, Netherlands.

The main objective of the thesis is addressed in **Chapter 5**. Balcony design recommendations are developed to enhance daylight, thermal and energy performance of mixed-mode office buildings. This chapter was also developed in collaboration with Dr. Roel Loonen during the research internship at the Department of the Built Environment, Eindhoven University of Technology, Netherlands.

**Chapter 6** presents a discussion section that establishes connections between the results of Chapters 2, 3, 4, and 5. **Chapter 7** provides a comprehensive conclusion for all preceding chapters, including limitations, prospects for future studies, and highlighting the main contributions this thesis brings to the state-of-art.

**Appendix A** presents the dataset of daylight simulations developed in Chapter 3. **Appendix B** presents the wind tunnel experiments and **Appendix C** provides the validation of CFD simulations with the wind tunnel experiments, used to support the thermal and energy performance simulations conducted in Chapters 4 and 5. **Appendix D** presents the validation of the daylight simulations conducted in Chapter 5 through daylight experiments using scale models. Lastly, **Appendix E** presents the permissions to fully incorporate journal papers published and submitted to Elsevier into this thesis.

## 1.3 Consistency of terms across chapters

Throughout the period during which this study was conducted, we made adjustments to the terminology used in the chapters comprising this thesis. Consequently, Chapter 3 and Appendix B, published in 2021 and 2020, respectively, uses terminologies that differ from that used in Chapters 4 and 5, which were later submitted for publication in 2023 and 2024, respectively. These variations are outlined in Table 1.2 for clarity.

**Table 1.2:** Correspondence of terminologies used across chapters

| Terminology (Chapter 3 and Appendix B) | Correspondence (Chapters 4 and 5) | Meaning |
|---|---|---|
| Base case | Reference case | Model defined to represent a 'typical' mixed-mode office building without balconies located in São Paulo. This model serves as a performance benchmark to compare the balcony design propositions. |
| Scenarios | Design cases | Models with certain combinations of balcony design parameters used for the parametric analysis |
| Front-façade / Back façade | Short-axis façade | The model with and without balconies used in this study is a rectangular building, composed by a short-axis façade (11 m) and a long-axis façade (22 m). |
| Side façade | Long-axis façade | |
| Window width | Glazed door width | Width of the glazed door that opens to the balcony. |

# 2. Literature review

This chapter is the transcription of the following paper:

**Efeitos das varandas no desempenho térmico, energético e luminoso de edificações: Revisão sistemática de literatura**

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Published and presented at XVIII Encontro Nacional de Tecnologia do Ambiente Construído (ENCAC), Porto Alegre, 2020.

## Resumo

O sombreamento e a ventilação natural são estratégias de arquitetura passiva eficazes para garantir bom desempenho térmico de edificações em grande parte do território brasileiro. A varanda é um tipo de elemento de proteção solar que atua como um beiral para o pavimento inferior, reduzindo a incidência de luz solar direta, mas permitindo a entrada de luz refletida e difusa e a abertura de janelas para ventilação. Uma revisão sistemática da literatura foi desenvolvida com o objetivo de levantar o estado da arte sobre os efeitos das varandas no desempenho térmico, energético e luminoso de edificações e identificar tendências e lacunas de pesquisa sobre a temática em questão. Identificou-se, no estudo, um crescimento sobre a abordagem do tema nos últimos cinco anos, tendo como principal enfoque os efeitos da presença/ausência de varandas no desempenho térmico de habitações residenciais utilizando, como método, simulações computacionais. A revisão da literatura mostra a complexidade de cruzamento dos resultados para desempenho térmico, luminoso e energético em edificações providas de varandas, apontando a existência de uma interdependência entre as variáveis preditoras de maior influência nos resultados e, muitas vezes, relações negativas entre elas. Como trabalhos futuros evidencia-se, principalmente, a necessidade de estudos no tema para a tipologia de escritórios e da elaboração de diretrizes projetuais que colaborem nas decisões iniciais de projeto, de forma que a varanda possa ser utilizada em seu máximo potencial para promover desempenho térmico, energético e luminoso, concomitantemente.

**Palavras-chave:** varanda; desempenho térmico; desempenho luminoso; desempenho energético; revisão sistemática da literatura.

## Abstract

Shading and natural ventilation are effective passive strategies to assure thermal comfort in most part of the Brazilian territory. Balconies can be used as a solar shading device that behave as an eave to the lower floor, reducing the incidence of direct solar radiation, while allowing reflected and diffuse daylight and natural ventilation through windows openings. A systematic literature review was conducted aiming to present the state of the art about the effect of balconies on thermal, energy and daylight performance of buildings and identify trends and gaps in this subject. The systematic review indicated an increase in the number of publications in the last five years, showing, as a main focus, the analysis of the effect of balconies on the thermal performance of residential buildings, through computational simulations. This study shows the complexity in crossing the results obtained for thermal, daylight and energy performance in buildings provided with balconies, showing the interdependence of the independent variables and, often, negative relation between them. As future work, we identify the need of studies specifically for the office typology and to develop design guidelines for the early design stages, so balconies can behave to their full potential in providing thermal, daylight and energy performance concurrently.

**Keywords:** balcony; thermal performance; daylight performance; energy performance; systematic review.

## 2.1 Introdução

O consumo energético médio nacional de edificações dos setores residencial, comercial e público evidencia a crescente participação dos sistemas de ar-condicionado e de iluminação artificial na demanda energética (EPE, 2018). Diante disso, destaca-se a necessidade de projetos arquitetônicos adequados ao clima em que estão inseridos, visando a otimização do desempenho térmico, energético e luminoso. Estratégias passivas, como o sombreamento e a ventilação natural, são indicadas para a melhoria do desempenho térmico de edificações em grande parte do território brasileiro.

A varanda é uma estratégia passiva de arquitetura que, se adequadamente projetada e dimensionada, pode contribuir na melhoria do desempenho térmico, energético e luminoso de edificações e no bem-estar de seus usuários. Em edifícios multipavimentos, pode funcionar como um elemento de proteção solar para o pavimento inferior, reduzindo a incidência de luz solar direta enquanto permite a entrada de luz refletida e difusa e o uso de grandes aberturas para ventilação. Em relação à ventilação natural, pode interferir na taxa de renovação do ar, na direção do fluxo de ar e, dependendo do seu projeto e localização, pode agir como captadora ou como barreira do vento (Wong; Istiadji, 2003).

Por contribuir para o desempenho térmico da edificação, a varanda pode auxiliar na redução do consumo de energia com soluções artificiais de condicionamento (Brandão; Martins, 2008). Com relação à iluminação natural, pode reduzir o ofuscamento, melhorando o conforto visual, mas também reduzir a disponibilidade de iluminação natural no interior dos ambientes, podendo acarretar um maior consumo de energia pela utilização de iluminação artificial (Wong; Istiadji, 2003). A complexidade de cruzamento dos resultados para desempenho térmico, energético e luminoso reforça a necessidade de uma melhor compreensão de como as varandas e seus parâmetros geométricos afetam o desempenho das edificações, de modo a aproveitar ao máximo o seu potencial.

O papel da varanda na sensação de bem-estar dos usuários vem sendo evidenciado durante a pandemia de COVID-19, emergindo o debate sobre a importância desse elemento durante o confinamento global (Bournas, 2021; Peters; Halleran, 2021; Ribeiro; Ramos; Flores-Colen, 2020). De acordo com Peters e Halleran (2021), as varandas tornaram-se elementos ainda mais desejáveis e relevantes durante a pandemia, sendo utilizadas como ambientes de socialização, protestos, celebrações e promovendo uma janela para a vida pública. Estudos de avaliação pós-ocupação mostram a varanda como um espaço desejado pelos usuários que a associam à promoção do seu bem-estar físico e mental (Dahlan *et al*., 2009b; Wågø; Hauge; Støa, 2016; Xue *et al*., 2016a). Os usuários apreciam a experiência sensorial que a varanda oferece ao possibilitar a expansão das vistas para o exterior e o aumento no tamanho das aberturas, permitindo a criação de um espaço privativo de conexão com o ambiente externo (Wågø; Hauge; Støa, 2016).

## 2.2 Objetivo

Tendo em vista a crescente relevância do assunto em questão, este trabalho tem como objetivo levantar o estado da arte sobre os efeitos das varandas no desempenho térmico, energético e luminoso de edificações, assim como identificar tendências e lacunas de pesquisa sobre o tema.

## 2.3 Método

Utilizou-se como método de pesquisa a Revisão Sistemática da Literatura (RSL), que combina informações de estudos relevantes para responder a determinada pergunta de pesquisa a partir de um método científico. Para a realização da RSL utilizou-se o processo proposto por Jesson, Matheson e Lacey (2011), que propõe sua divisão em seis fases principais (Figura 2.1).

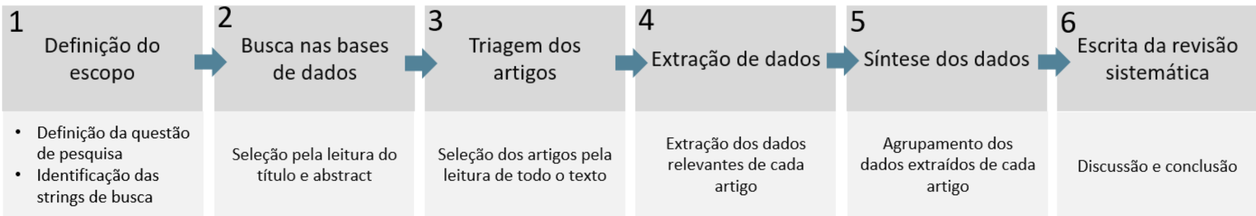



**Figura 2.1:** Processo de condução da RSL
Fonte: Os autores, adaptado de Jesson, Matheson e Lacey (2011)

Uma busca por artigos relevantes ao tema foi feita nas bases de dados Scopus e Web of Science, utilizando as seguintes *strings* de busca: *"daylight" OR "visual comfort" AND veranda OR balcony, e "thermal performance" OR "thermal comfort" OR "natural ventilation" AND veranda OR balcony*. Definiu-se que deveriam ser incluídos nos resultados da busca apenas os artigos que: a) tivessem as *strings* de busca no título, resumo ou palavras-chave; b) fossem redigidos em língua inglesa; c) fossem publicados nos últimos 20 anos (2001 a 2021). Como resultado deste primeiro filtro, foram encontrados 295 artigos. Uma segunda seleção foi feita excluindo os artigos por duplicidade e, a partir da leitura dos resumos e resultados, excluindo aqueles que não se enquadravam ao objetivo da pesquisa, como estudos com abordagem no desempenho acústico e estrutural das varandas. Após a seleção, 28 artigos foram selecionados para análise e desenvolvimento do presente trabalho.

## 2.4. Resultados

### 2.4.1 Análise bibliométrica da amostra

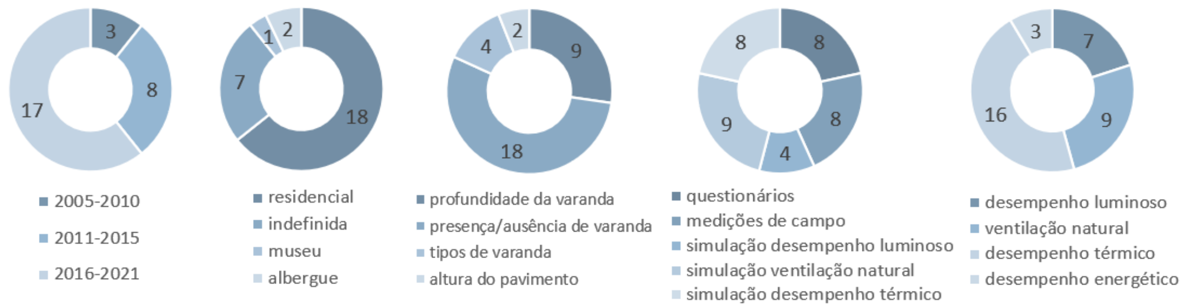
A categorização dos artigos por ano de publicação permitiu identificar que, no último quinquênio (2016-2021), a frequência de publicação aumentou 150% se comparado à soma das publicações dos anos anteriores, representando 61% das publicações (Figura 2.2a), o que indica o aumento do interesse em pesquisas sobre o tema nos últimos anos, tendo em vista o aumento da preocupação com as questões climáticas na última década (Fernandes *et al.*, 2020). Presume-se a tendência de um número crescente de publicações sobre a temática nos próximos anos, fomentado pelas discussões levantadas sobre a qualidade dos ambientes durante o confinamento global provocado pela pandemia de COVID-19, visto que o assunto foi abordado nas produções mais recentes sobre o tema (Bournas, 2021; Peters; Halleran, 2021; Ribeiro; Ramos; Flores-Colen, 2020).

A tipologia residencial foi a mais abordada nos estudos aqui analisados, representando 65% da amostra. A predominância dos estudos nessa tipologia deve-se ao fato de as varandas serem amplamente adotadas em residências unifamiliares e multifamiliares (Brandão; Martins, 2008; Peters; Halleran, 2021), embora o uso de varandas na tipologia de escritórios tenha crescido, como mostra o estudo de Manoel e Neves (2017), realizado para a cidade de São Paulo, que contabilizou um aumento de 85% no uso de varandas em edifícios de escritórios nos últimos 20 anos. Destaca-se, entretanto, a ausência de estudos nessa tipologia com enfoque específico em varandas (Figura 2.2b).

A categorização dos artigos por variável de saída analisada permitiu identificar que a maior parte dos artigos (55%) avalia apenas os efeitos da presença/ausência de varandas no desempenho do ambiente em estudo, sem incluir análises de aspectos relativos ao projeto das varandas. O segundo parâmetro mais avaliado, presente em 27% dos estudos, é a profundidade da varanda, seguido pelo tipo de varanda (tipo de peitoril e formato) e a altura do pavimento onde o ambiente com varandas está localizado, representando 12% e 6% dos artigos da amostra, respectivamente (Figura 2.2c). Com relação ao método adotado, destaca-se o uso de simulações (58% da amostra), seguido pela avaliação pós-ocupação por meio de questionários (21%) e por meio de medições em campo (21%) (Figura 2.2d).

Ao categorizar os artigos selecionados na RSL em objetivo do estudo, identificou-se uma maior quantidade de estudos sobre os efeitos das varandas no desempenho térmico (45% da amostra), seguido pelo enfoque na ventilação natural (26% da amostra), o que tem relação direta com o desempenho térmico da edificação. Isso deve-se ao fato de as varandas serem conhecidamente utilizadas como estratégia de sombreamento, contribuindo positivamente para o conforto térmico e diminuindo o consumo de energia com resfriamento (Omrani *et al.*, 2017). Uma menor quantia de estudos avaliou os efeitos das varandas no desempenho luminoso e energético de edificações, correspondente a 20% e 9%

da amostra, respectivamente. Uma parcela ainda menor, correspondendo a apenas dois artigos da amostra (7%), avaliaram os efeitos das varandas sobre o desempenho térmico e luminoso em conjunto, uma vez que a integração dessas duas variáveis aumenta a complexidade de análise de resultados (Ochoa *et al*., 2012) (Figura 2.2e).




a) Datas publicação b) Tipologia c) Variáveis de análise d) Método e) Objetivo do estudo

**Figura 2.2:** Classificação dos artigos selecionados na revisão sistemática da literatura

### 2.4.2 Efeitos das varandas no desempenho térmico e ventilação natural

O uso das varandas foi abordado na literatura como estratégia passiva para edificações situadas em diferentes localizações geográficas e climas, podendo ser utilizada como estratégia de sombreamento ou para aquecimento passivo, dependendo de sua configuração (Figura 2.3).


**Figura 2.3:** Classificação dos artigos por localização do estudo e tipo de estratégia passiva utilizada

A influência das varandas como elementos de sombreamento foi amplamente investigada na literatura devido ao seu conhecido potencial em reduzir a incidência de radiação solar direta e possibilitar amplas aberturas para ventilação natural. Ai *et al*. (2011a), Bhikhoo, Hashemi e Cruickshank (2017), Hashemi (2018), Kisnarini, Krisdianto e Indrawan (2018), Tungnung (2020) confirmaram, por meio de simulações computacionais, a varanda como potencial estratégia para sombreamento de edificações e, consequentemente, redução do sobreaquecimento de ambientes internos. Tungnung (2020) ao analisar uma edificação residencial localizada na Índia, identificou as varandas como espaços agradáveis de conexão entre o interior e o exterior, por apresentarem temperaturas mais amenas que o interior. Kisnarini, Krisdianto e Indrawan (2018), Hashemi (2018) e Bhikhoo, Hashemi e Cruickshank (2017) indicaram a contribuição da varanda para o decréscimo da temperatura de seu cômodo adjacente. Kisnarini, Krisdianto e Indrawan (2018) mostraram que o uso de varanda em uma edificação residencial localizada na Indonésia diminuiu em 1 ºC a temperatura interna do ambiente e, com a adição de dispositivos externos de sombreamento, a redução aumentou para 2 ºC. Hashemi (2018) e Bhikhoo, Hashemi e Cruickshank (2017) avaliaram o efeito das varandas na redução da probabilidade de superaquecimento dos ambientes internos. Ao analisar uma residência localizada na Uganda, Hashemi (2018) concluiu que a varanda reduziu em 50% o risco de superaquecimento. Bhikhoo, Hashemi e Cruickshank (2017) mostraram, para uma residência localizada na Tailândia, que a eliminação da varanda aumentou em 19,94% os dias anuais de superaquecimento. Os autores ressaltaram também a contribuição da ventilação natural na diminuição da probabilidade de superaquecimento, em especial pelo fato de as varandas possibilitarem o uso de grandes aberturas para ventilação natural.

O método dos estudos aqui analisados compreende avaliação pós-ocupação (medições de campo e questionários) e simulação computacional. Al-Absi, Abas e Baharum (2018), Arab, Hassan e Qanaa (2018), Dahlan *et al.* (2009a), Dahlan, Jones e Alexander (2011) avaliaram as influências das varandas na redução da temperatura de ambientes internos e na percepção de conforto térmico dos usuários de edificações localizadas na Malásia. Arab, Hassan e Qanaa (2018) realizaram medições nas fachadas de duas edificações residenciais e concluíram que, ao obstruir a incidência de radiação solar, as varandas reduziram a temperatura na superfície da fachada, contribuindo para o desempenho térmico do ambiente interno. Em concordância, as medições de campo realizadas por Dahlan, Jones e Alexander (2011) mostraram que os dormitórios sombreados por varandas apresentaram temperatura operativa 1,3 ºC abaixo dos valores medidos em dormitórios sem varandas. Em adição, Al-Absi, Abas e Baharum (2018) concluíram que, durante o pico de temperatura no interior da edificação, às 17 h, o ambiente sombreado por varandas apresentou temperatura 1,5 ºC inferior ao ambiente sem varandas quando as janelas de ambos os ambientes estavam abertas e 2,5 ºC inferior quando fechadas, mostrando a importância da ventilação natural em dissipar o calor do ambiente. Os estudos de Dahlan *et al*. (2009b) não identificaram mudanças significativas na medição de temperatura operativa dos ambientes com e sem varandas. No entanto, os autores identificaram, por meio de questionários, que os ocupantes de dormitórios sombreados por varandas mostraram-se mais satisfeitos com o conforto térmico do ambiente que os ocupantes de dormitórios não sombreados. Resultados semelhantes foram obtidos por

Dahlan, Jones e Alexander (2011). Ai *et al*. (2011b) combinaram análises em CFD e cálculos de voto médio estimado (*Predicted Mean Vote* – PMV) e porcentagem de pessoas insatisfeitas (*Predicted Percentage of Dissatisfied* – PPD) para investigar os efeitos das varandas no conforto térmico em um edifício de cinco pavimentos naturalmente ventilado localizado em região de clima tropical. Os resultados mostraram que, embora as varandas tenham reduzido a velocidade do ar no interior da edificação, sua presença melhorou o conforto térmico por aumentar a uniformidade da distribuição interna do ar.

Embora o uso das varandas tenha sido abordado majoritariamente como estratégia de sombreamento do ambiente, os estudos de Fernandes *et al*. (2015, 2020) e Grudzinska (2016) identificaram que o fechamento da varanda com elementos envidraçados permite sua atuação como estratégia de aquecimento passivo em edificações residenciais localizadas em climas frios. Fernandes *et al*. (2015, 2020) mostraram, por meio de medições em campo e questionários, que as varandas envidraçadas, ao serem estrategicamente posicionadas na orientação Sul, contribuíram para a entrada de radiação solar, aumentando o ganho de calor no ambiente interno em edificações residenciais localizadas à Norte de Portugal. Grudzinska (2016) comparou, por meio de simulação computacional, a eficácia do uso de varandas constituídas por materiais de alto e baixo isolamento térmico para promover a elevação da temperatura no ambiente interno de edificações residenciais situadas na Polônia. A varanda de alto isolamento mostrou-se mais eficaz, ao reduzir em 64,9% o número de dias com consumo energético para aquecimento, contra uma redução 32,1% resultante da varanda de baixo isolamento térmico, quando comparadas a um modelo sem varandas. Fernandes *et al.* (2015, 2020) e Grudzinska (2016) evidenciaram a importância de os elementos envidraçados de fechamento das varandas serem operáveis, para evitar o superaquecimento dos ambientes nos períodos quentes do ano, por meio do uso da ventilação natural. Adicionalmente, Fernandes *et al.* (2015, 2020) ressaltaram a importância de aliar a ventilação natural ao sombreamento das áreas envidraçadas da varanda. Os autores demonstraram a necessidade de uso de elementos fixos de sombreamento externo de modo a suprir, nos períodos sem ocupação, a falta de uma adequada operação de persianas e janelas.

Além dos fatores aqui destacados, a avaliação do desempenho térmico de edificações naturalmente ventiladas depende, em grande parte, do desempenho da estratégia de ventilação natural adotada. A existência de varandas nas fachadas das edificações modifica a distribuição da pressão dos ventos na envoltória, modificando o fluxo de distribuição de ar no interior da edificação (Ghadikolaei; Ossen; Mohamed, 2013). Entender os efeitos da presença de varandas na ventilação natural auxilia no desenvolvimento de projetos com maior desempenho térmico e energético, já que a ventilação natural interfere diretamente nesses aspectos (Ghadikolaei; Ossen; Mohamed, 2013; Izadyar *et al*., 2020). Alguns artigos selecionados na RSL abordaram os efeitos das varandas na ventilação natural, avaliando aspectos como o tipo de estratégia de ventilação natural, a direção de incidência dos ventos, a altura do pavimento onde a varanda está localizada, a presença/ausência de varandas na fachada e parâmetros geométricos da varanda como largura, profundidade e projeto de fachada, conforme detalhado a seguir.

a) Dimensionamento das varandas

O dimensionamento adequado das varandas em acordo com o tipo de estratégia de ventilação adotado pode potencializar o desempenho da ventilação natural em edificações (Ai *et al*., 2011b; Izadyar *et al*., 2020; Omrani *et al*., 2017). Omrani *et al*. (2017) investigaram os impactos da geometria das varandas comparando as estratégias de ventilação unilateral e cruzada em edifícios residenciais. Os resultados demonstraram que, para ambas as estratégias de ventilação, o aumento da profundidade das varandas (variações de 1 m a 4 m) ocasionou a redução da velocidade do ar no ambiente interno. Izadyar *et al*. (2020) estudaram os efeitos da profundidade das varandas na ventilação natural e no desempenho térmico de dormitórios residenciais ventilados unilateralmente. Os autores constataram que varandas de 2 m de profundidade provocaram uma distribuição interna do fluxo de ar heterogênea e instável, enquanto varandas mais profundas (2,5 m e 3 m) apresentaram maiores taxas de renovação de ar no ambiente interno, colaborando positivamente para o desempenho térmico. Em relação ao comprimento das varandas, Ai *et al*. (2011b) mostraram que a variação deste parâmetro trouxe variações insignificantes no desempenho da ventilação natural da edificação.

b) Inserção das varandas na fachada

Omrani *et al* (2017) identificaram que, para ambas as estratégias de ventilação natural (unilateral ou cruzada), uma varanda aberta e protuberante na fachada, oclusa apenas por um parapeito, proporciona melhor desempenho na ventilação natural do que uma varanda semifechada (oclusa por um parapeito e por paredes laterais). A adição de uma varanda aberta aumentou a velocidade do ar interno em até 80% em ambientes com ventilação unilateral e reduziu a velocidade do ar interno em ambientes com ventilação cruzada. Contudo, os melhores resultados obtidos para os ambientes com ventilação unilateral continuaram sendo inferiores aos resultados obtidos com ventilação cruzada, apresentando a velocidade do ar no interior do ambiente até duas vezes menor. Em contradição, Mirabi, Nasrollahi e Dadkhak (2020) concluíram que varandas semifechadas (oclusas por um parapeito e por paredes laterais) aumentaram a diferença de pressão entre as paredes opostas, aumentando a eficácia da ventilação natural no interior do ambiente quando comparadas às varandas abertas (protuberantes na fachada, oclusa apenas por um parapeito). Em relação ao tipo de peitoril das varandas, Kotani e Yamanaka (2007) identificaram que a distribuição da pressão do vento nas fachadas de um edifício de cinco pavimentos não apresentou modificações significativas na comparação entre varandas providas de peitoril opaco com gradil, sendo a distribuição de pressão mais impactada pela direção incidente dos ventos na fachada (0º, 90º e 180º).

c) Ângulo de incidência do vento nas aberturas

Os estudos disponíveis na literatura destacam a importância de orientar as aberturas da edificação em relação aos ventos predominantes para a potencialização da ventilação natural nos ambientes internos. Omrani *et al*. (2017), concluíram que o ângulo de incidência do vento nas aberturas de edificações providas de varandas é um parâmetro de maior influência no desempenho da ventilação natural do que as características geométricas das varandas. Os autores mostraram que, tanto para os ambientes com ventilação cruzada quanto para os ventilados unilateralmente, a velocidade do ar no ambiente interno foi superior para os casos com incidência do vento perpendicular às aberturas (0º) e inferior para os casos com incidência do vento paralela às aberturas (90º). No entanto, Mohamed (2017) identificou que, quando a incidência do vento ocorre perpendicular às aberturas (0°), o uso de varandas provocou o crescimento das taxas de ventilação natural em 99% para ambientes com ventilação unilateral contra uma redução de 44% para ambientes com ventilação cruzada. De maneira oposta, a incidência do vento oblíqua às aberturas (45°) provocou um aumento de 38% nos ambientes com ventilação cruzada contra uma redução de 39% para os ambientes ventilados unilateralmente.

d) Altura do pavimento

Cui, Mak e Niu (2014) identificaram que, em uma edificação de dez pavimentos, a presença de varandas melhorou o desempenho da ventilação natural nos pavimentos intermediários (4º ao 6º). Ai *et al*. (2011a) chegaram à mesma conclusão ao analisarem ambientes com ventilação cruzada localizados em uma edificação de cinco pavimentos, mostrando que a presença de varandas aumentou o desempenho da ventilação natural nos pavimentos intermediários e diminuiu sua eficácia nos pavimentos superior e térreo. No entanto, para ambientes ventilados unilateralmente, a adição de varandas reduziu o desempenho da ventilação natural nos pavimentos intermediários.

### 2.4.3 Efeitos das varandas no desempenho luminoso

Os estudos selecionados na RSL avaliaram os efeitos da presença de varandas e de sua profundidade na disponibilidade de luz natural e probabilidade de ofuscamento nos ambientes, utilizando como método de estudo simulações de desempenho luminoso e avaliação pós-ocupação (questionários e medições em campo).

Kim e Kim (2010a) e Liu e Chen (2017) mostraram, por meio de simulações computacionais, que o aumento da profundidade das varandas pode diminuir a disponibilidade de iluminação natural dentro do ambiente. Adicionalmente, os estudos de Kim e Kim (2010a) e de Liu e Chen (2017) identificaram a profundidade das varandas como o parâmetro de maior impacto no desempenho luminoso do ambiente interno. Kim e Kim (2010a) mostraram que varandas mais profundas (1,5 m, 3 m e 6 m de profundidade) reduziram o valor médio do fator de luz do dia em 46%, 70% e 90%, respectivamente, em relação a um modelo sem varandas, em análise realizada em um edifício de tipologia indefinida com varandas localizadas no átrio central. Em consonância, Liu e Chen (2017), ao analisarem uma edificação residencial localizada em Taiwan, sugeriram que aberturas menores deveriam ser associadas a varandas pouco profundas, de modo a evitar um desempenho luminoso insatisfatório do ambiente interno.

Com relação ao conforto visual e à probabilidade de ofuscamento, Al-Sallal, AbouElhamd e Dalmouk (2018) mostraram que a presença de uma varanda profunda (3 m) foi capaz de reduzir o ofuscamento no ambiente interno de 81% para 0%, quando comparado ao mesmo ambiente sem varanda. A análise foi realizada via simulação computacional, tendo como base a métrica dinâmica de análise Exposição Solar Anual (*Annual Sunlight Exposure* – ASE). Kim e Kim (2010b) também demonstraram a importância das varandas na promoção do conforto visual do ambiente interno ao investigarem uma prática comum nas edificações residenciais coreanas, que consiste na eliminação das varandas para incorporação de sua área ao cômodo adjacente. Ao remover o sombreamento proporcionado pela varanda, os autores indicaram que a transmitância do vidro deveria ser reduzida para valores abaixo de 0,54, de forma a promover o mesmo nível de conforto visual oferecido por uma varanda de 1,8 m de profundidade. Liu e Chen (2017) identificaram que, para uma edificação isolada (sem interferência do entorno), a altura do pavimento em que o ambiente provido de varandas se localiza apresenta impactos insignificantes no desempenho luminoso do ambiente interno.

Bournas (2021), Dahlan *et al*. (2009b) e Xue *et al*. (2016) basearam-se em avaliações pós-ocupação para avaliar os efeitos das varandas no desempenho luminoso de edificações por meio de questionários e medições em campo. Os resultados foram complacentes com os resultados das simulações de desempenho luminoso encontrados na literatura, confirmando que as varandas reduzem a incidência de iluminação natural no ambiente interno, mas melhoram o conforto visual. Bournas (2021) comparou o comportamento dos moradores de apartamentos com e sem varandas de seis edificações residenciais localizadas na Suécia. O autor identificou que a presença de varandas não exerceu influência no acionamento da iluminação artificial durante o dia. O estudo de Dahlan *et al*. (2009b), realizado em albergues estudantis localizados na Malásia, identificou que 78% dos ocupantes de dormitórios sem varandas mostraram-se satisfeitos com a iluminação natural, contra 60% dos ocupantes de dormitórios com varandas. As medições em campo, realizadas em dormitórios localizados no primeiro pavimento e orientados a Norte, ecoaram os resultados dos questionários, indicando que a presença de varandas reduziu em três vezes o nível de iluminação natural, medido através da métrica razão de iluminação natural (*daylight ratio*). Não obstante, os dormitórios com varandas continuaram apresentando *daylight ratio* complacente com os níveis mínimos de iluminação exigidos pela legislação local, o que explica a baixa diferença entre o número de usuários satisfeitos com os níveis de iluminância dos dormitórios com e sem varandas, obtido pelos questionários aplicados.

Xue *et al*. (2016a) e Dahlan *et al*. (2009b) analisaram o comportamento dos usuários na operação de elementos internos de sombreamento em apartamentos residenciais com e sem varandas. De acordo com Xue *et al*. (2016a), os usuários consideram que as varandas proporcionam pouca privacidade, induzindoos a fechar as cortinas com mais frequência do que usuários de dormitórios sem varandas, aumentando, por consequência, a necessidade do uso de iluminação artificial. Em contradição, de acordo com Dahlan *et al*. (2009b) os moradores de dormitórios com varandas raramente fecham as cortinas, devido à percepção de que seus quartos não possuem iluminação natural suficiente, enquanto os moradores de dormitórios sem varandas disseram fechar as cortinas com mais frequência em função do ofuscamento provocado pela falta de proteção solar.

### 2.4.4 Efeitos das varandas no desempenho energético

O desempenho energético de uma edificação está diretamente relacionado ao seu desempenho térmico e luminoso, que irão definir a demanda energética por aquecimento, resfriamento e iluminação artificial dos ambientes. Os estudos de Liu e Chen (2017), Grudzińska (2016) e Nikolic *et al*. (2020) investigaram, por meio de simulações computacionais, os efeitos das varandas no desempenho energético de edificações residenciais.

Liu e Chen (2017) analisaram o efeito da profundidade das varandas no desempenho termoenergético de uma edificação localizada em Taiwan e concluíram que, quanto mais profunda a varanda, maior a energia economizada no uso de ar-condicionado. Ao relacionarem a profundidade das varandas com o tamanho das aberturas das janelas, os autores indicaram que varandas mais profundas devem ser associadas com aberturas maiores. Para um cenário de percentual de abertura na fachada de 50%, os autores sugeriram o uso de varandas de 2,5 m de profundidade para reduzir o consumo energético anual em 22% em comparação a uma edificação sem varandas. Para um percentual de abertura na fachada de 75% ou 100%, os autores sugeriram o uso de varandas com 3 m de profundidade, de forma a reduzir o consumo energético anual em 30%. Grudzińska (2016) comparou a eficácia do uso de varandas de alto e baixo isolamento térmico na redução da demanda energética para aquecimento de edificações residenciais situadas na Polônia. Quando comparada a uma residência sem varandas, a varanda de alto isolamento mostrou-se mais eficaz em reduzir a demanda energética, atingindo até 30% de redução no ambiente da própria varanda e até 90% no cômodo adjacente. Já a varanda de baixo isolamento atingiu até 15% de redução no ambiente da varanda e até 70% de redução no cômodo adjacente. Nikolic *et al*. (2020) investigaram, por meio de simulações computacionais, como a profundidade das varandas impacta no consumo energético para aquecimento, resfriamento e iluminação artificial em edificações residenciais localizadas na Sérvia. Os autores indicaram a profundidade da varanda correspondente ao melhor cenário de redução do consumo energético, para cada orientação solar: 2,6 m para a fachada leste, 0,7 m para a fachada sul, 2,4 m para a fachada oeste e 0,4 para a fachada norte. A redução da incidência direta de radiação solar diminuiu a demanda energética para resfriamento em 44,15% enquanto o consumo energético com aquecimento e iluminação artificial aumentou em 16,33% e 4,98%, respectivamente, em comparação a uma edificação sem varandas. O consumo total de energia da edificação reduziu em 7,12%.

### 2.4.5 Lacunas de pesquisa e indicação de trabalhos futuros

Dentre os trabalhos levantados que trataram dos efeitos das varandas no desempenho luminoso, 50% utilizaram simulações computacionais como método de estudo. No entanto, apenas o estudo de Al-Sallal, AbouElhamd and Dalmouk (2018)utilizou métricas dinâmicas de análise dos resultados. As métricas dinâmicas são consideradas mais eficientes do que as métricas estáticas por considerarem as condições reais do céu presentes nos arquivos climáticos. Dessa forma, destaca-se a necessidade de mais estudos que avaliem os efeitos das varandas no desempenho luminoso por meio de métricas dinâmicas de análise, como *Daylight Autonomy* (DA), *Annual Sunlight Exposure* (ASE), *Spatial Daylight Autonomy* (sDA) e *Useful Daylight Illuminance* (UDI). Além disso, outros parâmetros de projeto da edificação devem ser considerados na abordagem do desempenho luminoso de edifícios providos de varandas, como a transmitância visível do vidro, o tamanho da abertura das janelas e a profundidade do ambiente, sendo que, o último não foi abordado em nenhum dos estudos da amostra selecionada.

Não foram identificados estudos que abordem os efeitos das varandas no desempenho térmico, luminoso e/ou energético para a tipologia de edifícios de escritórios. A necessidade de estudos específicos para esta tipologia é evidenciada tendo em vista características específicas da tipologia, como o período de ocupação, por exemplo, que difere significativamente entre edifícios residenciais e edifícios de escritórios. Outro exemplo é o nível mínimo de iluminância exigido pela NBR ISO/CIE 8995 (ISO, 2002), que é mais elevado para salas de escritórios (mínimo de 300 lux) do que para ambientes residenciais (mínimo de 100 lux). Outros fatores que diferem entre ambas as tipologias e que influenciam na avaliação do desempenho térmico e energético do ambiente são a densidade de ocupação, a carga térmica de equipamentos internos e o isolamento térmico da vestimenta dos usuários. Assim, evidencia-se a necessidade de estudos que abordem os efeitos do desempenho térmico, energético e luminoso para a tipologia específica de escritórios.

A maior parte dos estudos aqui analisados compararam a presença e a ausência de varandas no desempenho de edificações habitacionais, em especial com enfoque em desempenho térmico. Dessa forma, evidencia-se a importância de estudos que avaliem, simultaneamente, o desempenho térmico, energético e luminoso de varandas em edificações, bem como os impactos de sua geometria. É importante ressaltar também a necessidade de estudos nesta vertente que indiquem diretrizes de projeto que auxiliem os projetistas nas tomadas de decisão nas etapas iniciais de projeto, visando a inserção das varandas nas edificações tendo em vista seu máximo potencial para contribuir no desempenho térmico, energético e luminoso.

## 2.5 Conclusões

Este artigo apresentou uma revisão sistemática da literatura sobre os efeitos das varandas no desempenho térmico, energético e luminoso de edificações, com o intuito de identificar tendências e lacunas de pesquisa sobre o tema. Como tendências, evidencia-se um aumento do interesse pelo tema, indicado pelo crescimento do número de publicações nos últimos cinco anos. Evidencia-se também a abordagem majoritária dos efeitos das varandas no desempenho térmico de edificações residenciais, realizadas por meio de simulações computacionais. As principais variáveis preditoras analisadas consistem na presença/ ausência de varandas, seguida pela sua profundidade.

Evidencia-se, na revisão da literatura aqui empreendida, a complexidade do cruzamento de análises dos efeitos das varandas sob o enfoque em desempenho térmico, energético e luminoso, devido ao fato de que cada abordagem apresenta parâmetros específicos, que podem ser interdependentes e apresentar relações positivas ou negativas. De fato, as pesquisas aqui analisadas confirmam a existência de potenciais conflitos que precisam ser melhor explorados. O aumento da profundidade das varandas, por exemplo, pode aumentar o conforto visual ao reduzir a probabilidade de ofuscamento, mas também diminuir a disponibilidade de iluminação natural no ambiente interno, aumentando o consumo energético com iluminação artificial. Pode também ocasionar a redução da velocidade do ar no ambiente interno, causando interferência direta no seu desempenho térmico. Por outro lado, pode reduzir a incidência direta de radiação solar, reduzindo o sobreaquecimento do ambiente interno.

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# 3. Effects of the use of balconies on daylight performance

This chapter is the transcription of the following paper:

**Decision-making pathways to daylight efficiency for office buildings with balconies in the tropics**

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## Abstract

Daylight in the indoor environment is directly influenced by the building surroundings, envelope and its shading devices, such as balconies. Despite their potential in contributing to increase shaded periods and, at the same time, act as a daylight distribution system, balconies are not designed to their full potential when used in office buildings and the literature lack studies that investigate the effect of balconies on their luminous performance. This study aims to explore this niche: the integration of balconies to the design of office buildings in the tropics, in order to improve their daylight performance. The research method was based on a parametric design approach in combination with daylight simulations, while combining a systematic analysis with a data mining algorithm. The study revealed successful combinations of building design parameters as well as important cut-off points for design decision-making to achieve daylight efficiency in typical mixed-mode office buildings in the city of São Paulo, Brazil. Results provided multiple design routes to achieve successful performance targets showing that, if properly dimensioned, balconies could be an efficient shading device and daylight diffuser. As a key contribution, successful combinations of design parameters that allow deeper balconies to yield better Useful Daylight Illuminance levels were identified. Further details about when balconies stop influencing daylight performance results as well as when an increase in balcony depth becomes beneficial to performance were reported in attempt to develop design guidelines for the early design stages for office buildings in São Paulo.

**Keywords:** Office building, Balcony, Visual comfort, daylight performance, decision-making, data mining

## 3.1 Introduction

This study aimed to identify decision-making pathways to design efficient balconies for office buildings in the tropics, considering improving indoor daylight conditions in the climate of the city of São Paulo (Brazil). Balconies are common architectural features in residential and hospitality buildings used for several purposes which span from having a semi-private outdoor space, which can afford social activities, over urban greenery, and farming in multi-storey buildings, up to providing 'immersive' experiences to unique outdoor sceneries. From a building physics perspective, balconies are powerful shading devices. With larger depths and widths, they demonstrate great potential in increasing diffuse daylight into office spaces while reducing undesirable direct solar radiation with the effect of diminishing cooling loads commonly present in the tropics.

However, despite their large potential in contributing to well-being, sustainability and comfort, balconies are not used to their potential in office spaces in the tropics. In São Paulo, for instance, they tend to be shallow (normally 0.5 m depth) and primarily used to accommodate air conditioning condensers from split unit systems, rather than thought as a multipurpose and multi-functional façade element. More than half (56%) of the office buildings in São Paulo are supplied with split air conditioning systems, locally controlled, and metered (i.e. per room) with a mixed-mode regime (Acesse Buildings, 2016). They are office rooms rented by small companies, in a market scenario of medium-rise buildings with small office floor plans and mixed-mode operation systems, in opposition to wide open plan office buildings, which usually consists of non-operating curtain-wall façade systems.

This study aimed to explore the integration of balconies to the design of office buildings using a parametric design approach in combination with daylighting simulations. It did not see balconies in isolation but as an element of façade design. Therefore, it focuses on unfolding the most important combination of design parameters to be used in the early design stages for balconies to become efficient shading devices and daylight diffusers in a 'typical' mixed-mode office building in São Paulo. The richness of parametric design possibilities was explored via an extensive systematic analysis of simulation results in combination with the application of a datamining technique to show pathways of successful parametric combinations towards achieving different sets of daylight targets for comfort and well-being.

## 3.2 Background

Daylight has a positive impact on human well-being, particularly in workplaces, leading to better productivity and higher employee satisfaction (Knoop *et al*., 2020; Turan *et al*., 2020). Besides its human health benefits, the daylight is monetarily valued, providing energy savings with electric lighting, and impacting the real estate market, mainly in dense urban environments. According to Turan *et al*. (2020) in Manhattan, NY, tenants are willing to pay up to 6% more for office rooms with high daylight access over those with low daylight access. Daylight is therefore a fundamental component to achieve indoor wellbeing, energy efficiency and sustainability, stated through building regulations, urban zoning policies and green building certifications, which determine targets for building daylight performance.

Daylight performance can be evaluated through different daylight metrics. Static daylight measures, widely criticised throughout the literature (Mardaljevic *et al*., 2012; Reinhart; Mardaljevic; Rogers, 2006; Tregenza; Mardaljevic, 2018), are still being adopted as a performance measure for daylighting in building regulations such as the Brazilian to provide guidelines for lighting in residential buildings (ABNT, 2013) and workplaces (ISO, 2002). Despite the fact that there is still no consensus on a metric that should replace the daylight factor, it is commonly agreed in the literature that Climate-Based Daylight Modelling (CBDM) (IES LM 83-12, 2012; Mardaljevic *et al*., 2012), which uses real sun and sky conditions from standard weather files to quantify daylight and visual performance, could be the most suitable approach to assess daylight availability and distribution.

Daylight in an indoor environment is directly influenced by the building envelope and its shading devices, which are used to avoid glare and improve visual comfort, but also decrease the incidence of direct daylight in interior spaces (Glassman, 2015; Kim; Kim, 2010a). Balconies are horizontal overhanging structures enclosed by walls or parapets that behave as an eave to the lower floor, reducing the incidence of direct solar radiation, while allowing the penetration of reflected and diffuse light (Xue *et al*., 2016). Investigations about the effects of balconies on the luminous performance of office buildings have not been sufficiently explored yet. A systematic literature review identified that 62% of the papers on the subject investigated residential and hotel buildings. Moreover, also 62% used computer simulation tools as part of their methods, but only 12% used CBDM daylight metrics. The parameters analysed include the façade’s Window-to-Wall Ratio (WWR), the glazing’s visible transmittance, the balcony’s configuration (width, depth, parapet material and solar orientation), the room’s depth and the floor height.

Results presented by Al-Sallal, AbouElhamd and Dalmouk (2018), Kim and Kim (2010a) and Gábrova (2014) through daylight simulations showed that the presence of balconies increased daylight uniformity and decreased glare and illuminance levels in the indoor environment. Gábrova (2014) stated that the use of balconies increased daylight uniformity up to 55% inside the room. Al-Sallal, AbouElhamd and Dalmouk (2018) showed that a 3-meters wide balcony was able to eliminate glare inside the room. Kim and Kim (2010a) stated that balconies 3 and 6-meters deep decreased illuminance levels by 18% and 46%, respectively. Gábrova (2014) showed that balconies 0.75, 1.0, 1.25 and 1.5-meters deep decreased illuminance levels by 20%, 25%, 30% and 35%, respectively.

Xue *et al*. (2016) and Dahlan *et al*. (2009b, 2009a) investigated the impact of balconies on the luminous performance of residential buildings through field measurements and questionnaires applied to the occupants. Their results complied with daylight simulation results found in the literature, confirming that balconies reduce direct daylight incidence and increase visual comfort in indoor spaces. Regarding the balcony's parapet material, Dahlan *et al*. (2009a) showed that balconies with an opaque parapet provided higher levels of visual comfort than balconies with glazing parapet. Liu and Chen (2017) pointed out the WWR as an outstanding parameter in daylight performance for buildings with balconies, indicating that the smaller the WWR the shallower the balcony should be in order to avoid a negative impact on the indoor daylight availability. As to the window glazing properties, Kim and Kim (2010b) stated that, in order to provide the same visual comfort as a balcony does, the glazing visible transmittance should be lower than 0.54. Liu and Chen (2017) pointed out the floor level as the parameter with lower impact on the luminous performance of indoor environments, when considering an isolated building with balconies.

To the best of authors' knowledge, there are no studies that investigate the effect of balconies on the luminous performance of office buildings, perhaps because balconies are seen as a space of no use in commercial environments. Yet, the use of balconies in office buildings has been growing in recent years. In the city of São Paulo, Brazil, 23% of the mixed-mode office buildings are provided with exterior shading devices, of which 92% are balconies (Manoel; Neves, 2017). Between 1995 and 2015 alone, the use of balconies has increased by 85%, potentially related to the increasing use of split air-conditioning units, which demand an outdoor area to allocate the condenser (Neves; Melo; Rodrigues, 2019). This can be seen as an opportunity to promote the use of balconies in office buildings as they could be justified as a space to accommodate building services as well as act as a daylight and shading control system.

Already overheated by internal gains, office buildings need to minimise incident solar radiation and annual sunlight exposure to reduce cooling energy consumption, particularly in the tropics (CBCS, 2014). Balconies can offer possibilities to increase shaded periods and, at the same time, act as a daylight distribution system due to their special configuration, which can block direct sunlight but potentially contribute to increase reflected daylight. Seeing balconies as an architectural element to reduce overheating and at the same time act as a potential daylight system distributor, this study focused on exploring what balcony configuration together with window design parameters could improve daylight performance and contribute to reduce overheating in office buildings in São Paulo. The study was undertaken in a 'typical' mixed mode office building in São Paulo and simulation results were classified using systematic analysis in combination with a decision tree algorithm.

## 3.3 Methodology

The research design used in this study was threefold: It started by defining and parameterizing a 'typical' mixed-mode office building for the city of São Paulo based on a dataset of surveyed buildings developed by Neves, Melo and Rodrigues (2019) and Pereira and Neves (2018). Daylight simulations were then undertaken for a dataset of 6,360 combinations of parameters using specific weather data for São Paulo (latitude: 23°32'56" South, longitude: 46°38'20" West, altitude 800 m). CBDM metrics and relevant performance thresholds were specified to enable comparability and classification of daylight results. In the second stage, results were systematically analysed to identify effective combinations of parameters, with specific attention to the role of balconies, to reach the prescribed thresholds for daylight performance. In the third stage, results were mined and grouped using a decision tree algorithm to increase the number of successful combinations of design parameters to achieve daylight performance thresholds. Combining stages two and three would provide enough breath for designers to reach daylight performance targets in the early design stages, when simulation is potentially expensive and unavailable. The proposed research design was depicted in Figure 3.1 and further detailed in the following subsections.

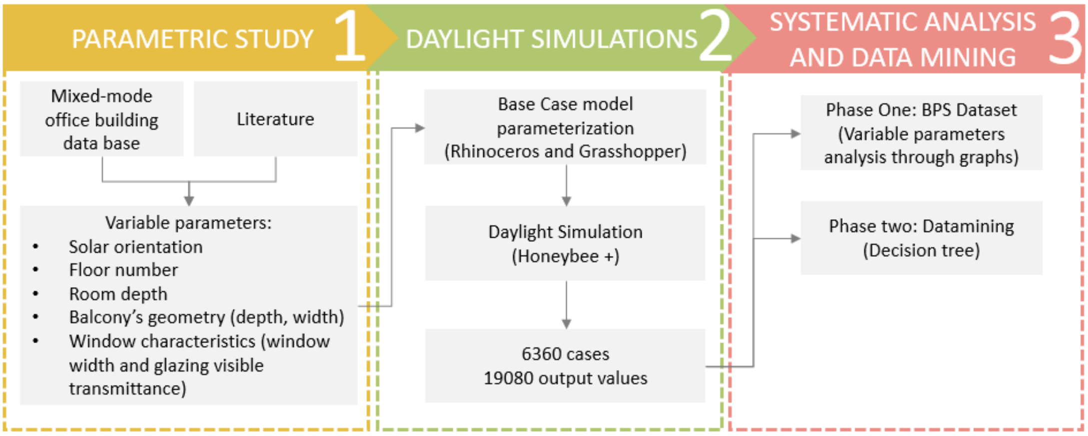



**Figure 3.1:** Research design workflow

### 3.3.1 Parametric study

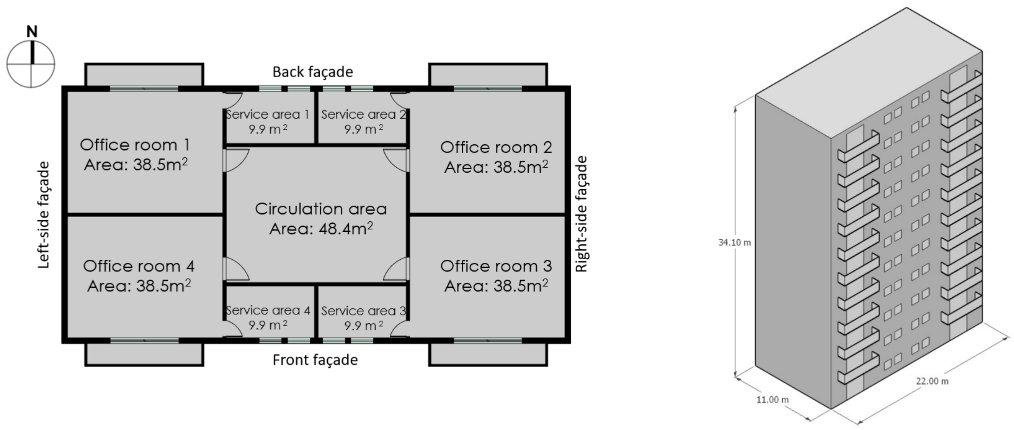
According to Neves, Melo and Rodrigues (2019) and Pereira and Neves (2018) , mixed-mode office buildings located in the city of São Paulo (Brazil) are mostly medium-rise buildings with multiple office units per floor (four to five units, in most cases), served by operable windows and individual air-conditioning systems, both manually operated in a concurrent mode. Each unit is normally a different tenancy, and most office buildings have no building facilities manager.

A database with a sample of 153 surveyed case studies of mixed-mode office buildings in São Paulo (Neves; Melo; Rodrigues, 2019) was used as a reference to create a representative of 'typical' mixed-mode office room model, which was used as a base case to develop the parametric study proposed in this research. This corresponds to 10% of offices of this type in São Paulo and was considered a representative sample to extract typical features. The selection of the sample took into consideration the following criteria: small office rooms, excluding wide open plan office buildings (which usually consists of non-operating curtain wall façade systems); individual air-conditioning systems, consisting of independent outdoor air units per office room (excluding central systems, which usually corresponds to fully air-conditioned buildings); office buildings built between 1995 and 2016.

The geometry and envelope design parameters were chosen according to the highest frequency values, for categorical variables, and the mean values, for continuous variables, from the database. The indoor surfaces' reflectance was defined according to ISO/CIE 8995-1 (ISO, 2002) and the ground surface reflectance according to IES LM 83-12 approved method (IES LM 83-12, 2012). The base case characteristics are shown in Table 3.1 and illustrated in Figure 3.2.

**Table 3.1:** Base case model characteristics

| **Parameter** | **Value** |
|---|---|
| Building orientation (longitudinal axis) | North - South |
| Number of floors | 11 |
| Office room shape | Normally rectangular |
| Office room area | 38.5 $m^2$ (5.5 m x 7 m) |
| Office room height (floor-to-ceiling) | 2.75 m |
| Wall thickness | 0.25 m |
| **Balcony's parapet type / height** | Opaque parapet / 1.1 m |
| External wall and balcony's external surface reflectance | 0.30 - dark colour |
| Internal wall and balcony's internal surface reflectance | 0.5 |
| Room's and balcony's floor reflectance | 0.2 |
| Ceiling reflectance | 0.7 |
| Ground surface reflectance (albedo) | 0.1 |




a) Floor plan b) Building axonometric

**Figure 3.2:** Base case model

The literature suggests that balconies, window features and their configurations impact the luminous performance of indoor environment (Al-Sallal; AbouElhamd; Dalmouk, 2018; Liu; Chen, 2017). Specifically, balcony's geometry (depth, width, and location), window characteristics (window width and glazing visible transmittance), building's solar orientation and floor height were also considered as important variables in daylight performance of buildings with balconies. The abovementioned parameters were therefore selected as the main parameters to be used in a sensitivity analysis in the base case building. Table 3.2 illustrates the range of variation used for these parameters based on the database from Pereira and Neves (Neves; Melo; Rodrigues, 2019).

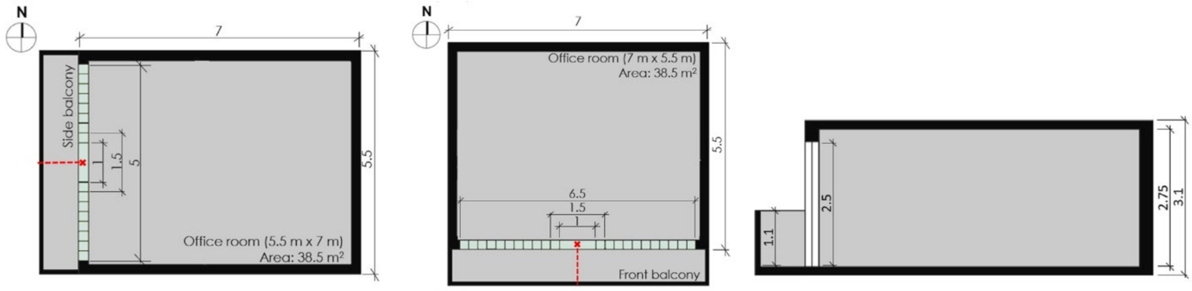
**Table 3.2:** Base case variable parameters

| **Parameter** | **Value** |
|---|---|
| Balcony depth | 0.0 m (no balcony) / 0.5 m / 1.0 m / 1.5 m / 2.0 m |
| Room's width and depth | Side façade (5.5 m width and 7 m depth) / front façade (7 m width and 5.5 m depth) |
| Balcony width | Ratio of balcony width to window width (0.5, 1.0, 2.0) |
| Glazing visible transmittance | 0.88 (clear glass) / 0.48 (laminated glass) |
| Window width | 1.0 m to 6.5 m (increments of 0.5 m) for the front façade<br>1.0 m to 5.0 m (increments of 0.5 m) for the side façade |
| Office room solar orientation | North / South / West / East |
| Floor number | Upper floor (10th floor – 30.1 m height) / middle floor (6th floor – 18.6 m height) / lower floor (1st floor – 3.1 m height) |

Balcony and room's geometry were selected based on the most common dimensions found in the database of Pereira and Neves (2018). According to Pereira and Neves (2018), the 0.5 m depth balconies are designed to house the outdoor air conditioning units, while balconies used as a liveable area, connecting indoor and outdoor spaces, are usually 1 m to 2 m deep (Figure 3.3). The room configuration shows that the office spaces from the selected sample tend to be small and normally used by 2 to 3 people. Parametric variations were applied to the four basic orientations to illustrate their effect in daylight conditions for a lower, middle and top floor. The window width, one of the most impacting parameters on daylight performance, was varied from 1 m up to 5 m (representing a fully glazed façade). Thus, increments of 0.5 m were used to iterate between the minimum and maximum scenarios. Windows and balconies were always considered as central to the room, increasing its width symmetrically for both sides (Figure 3.4).

(a) Office building with balconies (b) Office room with balcony (c) Balcony used to house the condenser unit

**Figure 3.3:** Examples of office buildings with balconies
Source: Pereira (2019)




a) Office room floor plan: side balcony

b) Office room floor plan: front balcony

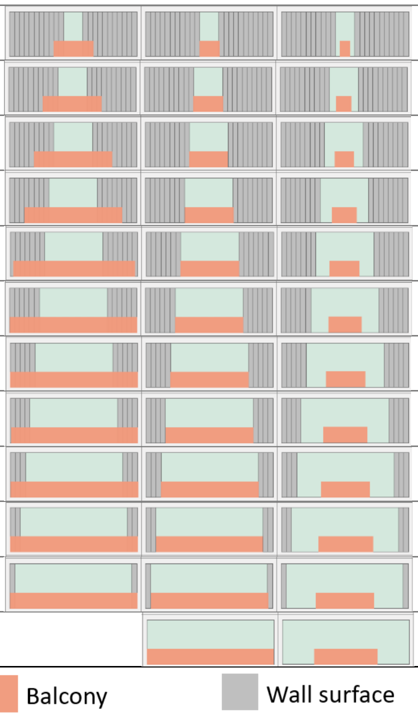
c) Office room section

**Figure 3.4:** Office room dimensions

The ratio of balcony width to window is proposed to evaluate the impact of the balcony's width and the corresponding window width, as illustrated in Table 3.3. This variable represents a façade compositional rule based on a central axis symmetry, enabling the investigation of apertures in connection with their corresponding daylight systems. This parameter allowed to simplify the number of cases when varying balcony's width and facilitated results comparison. Even though ratios 2 and 1 are considered more usual in the building façades, the 0.5 ratio was also selected to have its performance evaluated as a possible design scenario, despite not being commonly found in practice.

**Table 3.3:** Ratio of balcony width to window width

| **Window width (m)** | **Ratio of balcony width to window width** | | |
|---|---|---|---|
| | 2 | 1 | 0.5 |
| 1 | | | |
| 1.5 | | | |
| 2 | | | |
| 2.5 | | | |
| 3 | | | |
| 3.5 | | | |
| 4 | | | |
| 4.5 | | | |
| 5 | | | |
| 5.5 | | | |
| 6 | | | |
| 6.5 | | | |




### 3.3.2 Daylight simulations

The plug-in Grasshopper (Mcneel, 2020) was used to model the base case geometry, which consists of the entire building, as shown in Figure 3.2. Daylight simulations were run in Honeybee+ (Roudsari; Pak, 2013), a plug-in for Grasshopper that connects the Rhinoceros' shape parameterization with Radiance and Daysim for daylight simulation. To perform the simulations, the 2-phase Radiance-based method was used. The Radiance input parameters were chosen through Honeybee+ based on the simulation complexity, which was set as "medium complexity" due to the number of simulated cases (Table 3.4). The grid configuration and sky density were set according to the IES LM 83-12 approved method (IES LM 83-12, 2012). Simulations were run without any urban surrounding to assess daylight scenarios with the worst condition for direct incident solar radiation.

**Table 3.4:** Radiance input parameters

| Parameter | Value |
|---|---|
| Ambient bounces (ab) | 5 |
| Ambient divisions (ad) | 15,000 |
| Ambient resolution (ar) | 64 |
| Ambient super-samples (as) | 2,048 |
| Ambient accuracy | 0.2 |
| Work plane | Grid size: 0.5 m<br>Height: 0.8 m<br>Offset from the walls: 0.5 m |
| Sky density | Reinhart sky |

Three climate-based metrics were used to assess the daylight performance of the office room and its design variants: Useful Daylight Illuminance (UDI), Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). The UDI is defined as the annual occurrence of illuminances across the work plane that are within a range considered "useful" by occupants, when artificial lighting is not necessary. For office buildings, the UDI useful range was identified by Mardaljevic *et al*. (2012) as being 300-3000 lux, with the upper value considered a good proxy for excessive illuminance. The sDA is a measure of daylight illuminance sufficiency for a given area, reporting a percentage of floor area that exceeds a 300-lux illuminance level for more than 50% of annual working hours (8 am to 6 pm). The sDA was ranked in the following daylight sufficiency levels, according to IES LM-83 (2012) : preferred daylight sufficiency (must meet or exceed 75% of the analysis area), nominally accepted daylight sufficiency (must meet or exceed 55% of the analysis area), not accepted (sDA does not meet the minimum required value of 55% of the analysis area). The ASE describes the potential for visual discomfort and determines unsatisfactory visual comfort when its result is over 10% for daylit spaces (IES LM 83-12, 2012). This metric can also be used as a proxy for overheating, as it means the percentage of the year each point in space receives direct solar radiation.

The ASE and sDA metrics were reported together to provide a meaningful first-level understanding on how a space is expected to perform, since sDA sets a minimum value for daylight sufficiency but not any indication of an excess thereof whereas ASE sets a maximum value to prevent visual discomfort.

Daylight simulations were performed considering the occupancy period from 8 am to 6 pm, as suggested by IES LM 83 (2012), with no user interference, i.e. considering the worst-case scenario with no blinds. This setting is the same as the one from the Brazilian energy efficiency regulation (INMETRO, 2020) which also considers an occupancy period 10 h per day, without a lunchtime break. The weather file used to perform the simulations was a Typical Meteorological Year (TMY), based on weather data from the years 2000-2010, available in an EnergyPlus weather file (epw) format for the city of São Paulo, Brazil (LABEEE, 2018). A cross combination of all the seven parametric variations described in Table 2 were combined into 6,360 simulations, meaning all design solutions were explored. Thus, simulation outputs for the three aforementioned daylight metrics comprised a total of 19,080 results.

### 3.3.3 Post-processing and data mining

Simulation post-processing was divided into two large steps (Figure 3.5). Initially a systematic analysis in the extensive dataset presented in the Appendix A was undertaken, starting with a sensitivity analysis of each parameter in the three CBDM (Section 3.4.1), followed by unfolding interesting pairwise combinations for design decision-making (Section 3.4.2). Further explorations specifically on identifying the role of balconies in daylight performance were undertaken via a combination of results from the sensitivity analysis, the pairwise comparisons and the information contained in the Appendix A, from which general rules were extracted and discussed (Section 3.4.3).

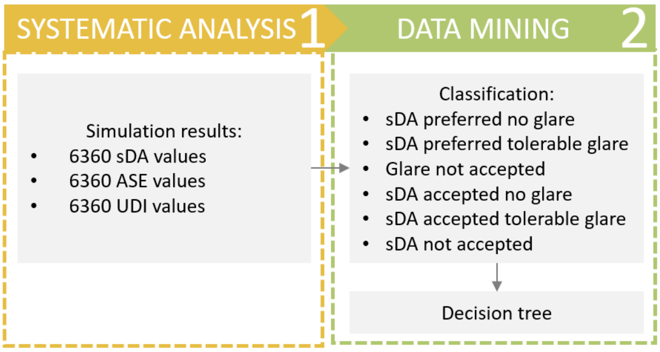



**Figure 3.5:** Results analysis diagram

Simulation results were grouped into six classes, for sDA and ASE only, using a data mining process so full patterns of successful combinations of design parameters could be quickly retrieved to aid design decision-making (section 4.4). Simulation results contained one nominal (solar orientation) and six numeric attributes (floor level, room depth, glazing visible transmittance, ratio of balcony width to window width, window width and balcony depth). Classes for nominal and numeric variables were described in Table 3.5, with a respective traffic light system indicating results practical suitability. The UDI metric was used specifically to further qualify cases in which the sDA was convergent above the threshold.

**Table 3.5:** Data classification

| sDA | | ASE | | Class |
|---|---|---|---|---|
| numeric | nominal | numeric | nominal | |
| Higher or equal to 75% | Preferred | 0% | No glare | sDA preferred no glare (green) |
| | | Equal or lower than 10% | Tolerable glare | sDA preferred tolerable glare (yellow) |
| | | Higher to 10% | Glare | Glare not accepted (red) |
| Lower than 75% and higher or equal to 55% | Accepted | 0% | No glare | sDA accepted no glare (yellow) |
| | | Equal or lower than 10% | Tolerable glare | sDA accepted tolerable glare (orange) |
| | | Higher to 10% | Glare | Glare not accepted (red) |
| Lower than 55% | Not accepted | 0% | No glare | sDA not accepted (red) |
| | | Equal or lower than 10% | Tolerable glare | |
| | | Higher to 10% | Glare | |

Decision tree was considered the best data mining option to illustrate successful routes through combinations of parameters which would lead to sDA and ASE respectively above and below thresholds established in section 3.2 and further detailed in Table 3.5. Decision trees popularly known as 'recursive divide and conquer' data mining methods, select the best attribute among a set of alternatives to produce routes with maximum information gain. They start by statistically selecting the attribute for a root node, to then creating branches for each possible value and splitting instances into sub-sets, recursively repeating this process until each instance belongs to a class. The widely applied J48 algorithm (Witten; Frank; Hall, 2014) was used as a classifier for the decision tree and could hierarchically organise 6,360 instances creating clear paths to achieve the desirable classes. The algorithm is based on a top-down strategy and uses information gain to measure the amount of information provided by each attribute as a basis to determine which one best splits the dataset at each step (Witten; Frank; Hall, 2014) The data mining process was undertaken in WEKA (Witten; Frank; Hall, 2014), and the decision tree which provided simultaneously a satisfactory level of accuracy and complexity, achieving an 85% correctly classified instances was discussed in section 4.4, with its configuration synthesised in Figure 3.6. Successful end nodes of the decision tree are highlighted using the traffic light system proposed in Table 3.5, so designers can visualize the best routes to achieve performance.

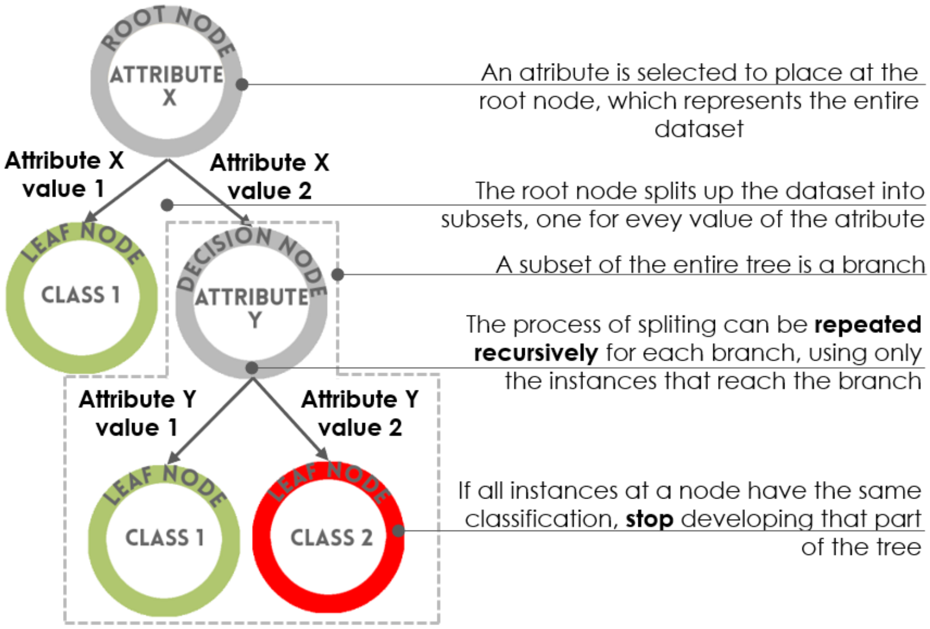



**Figure 3.6:** Decision tree configuration
Source: the authors, based on information provided by Witten; Frank and Hall (2014)

## 3.4 Results and discussion

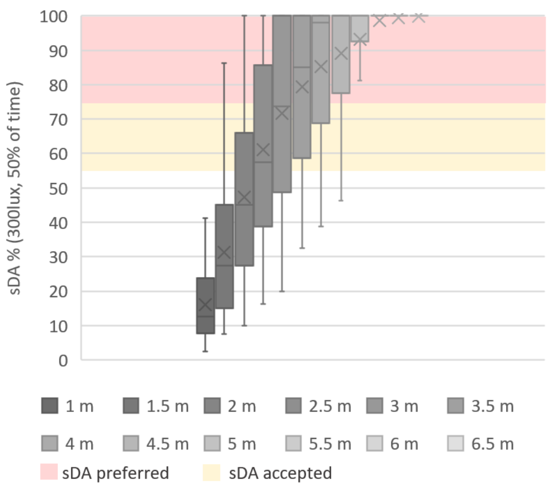
### 3.4.1 Sensitivity analysis

Box plots were used to evaluate the sensitivity of each design parameter in sDA and ASE considering the thresholds illustrated in Table 3.5. UDI graphs were plotted when necessary to verify sDA results, especially when compressed around the upper threshold (sDA = 100%). Box plots for each parametric variation were presented with different shades of grey, with the cross illustrating the mean and the line within the box illustrating the median. The discussion attempted to extract relevant information for design decision-making, i.e. to gauge the impact of specific design parameters in daylight performance as well as to identify relevant dimensions to achieve specific performance thresholds.

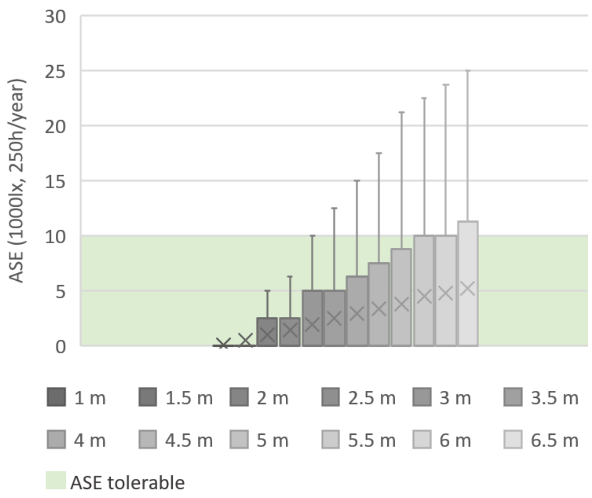
a) Window width

Window width seems to be the determinant parameter on office rooms' daylight performance. These findings echo the results shown by Al-Sallal *et al*. (2018) and Liu and Chen (2017). All cases with windows width between 5 m and 6.5 m reached the sDA preferred class together with more than 50% of the cases with windows widths between 3.5 m and 4.5 m (Figure 3.7a). Cases with narrow windows (1 m and 1.5 m width) presented the best potential to prevent glare (Figure 3.7b) by keeping ASE results close to null but all windows up to 3 m width still complied with ASE below 10% as well as 75% of windows with up to 6 m width. UDI results confirmed that the room's daylight performance was directly proportional to the window width (Figure 3.7c) and indicated that windows with widths above 5.5 m provided nearly the same performance results (see three light grey box plots from Figure 3.7c). This was partially confirmed by the ASE figures which showed almost 3/4 of results falling within the 10%

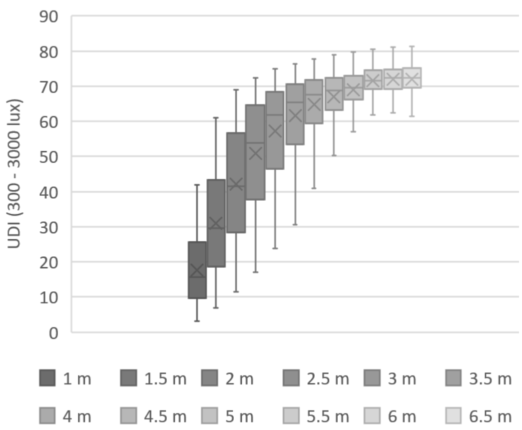
threshold, meaning windows above 6.5 m width would require more careful attention with regards to shading design.




(a) sDA




(b) ASE

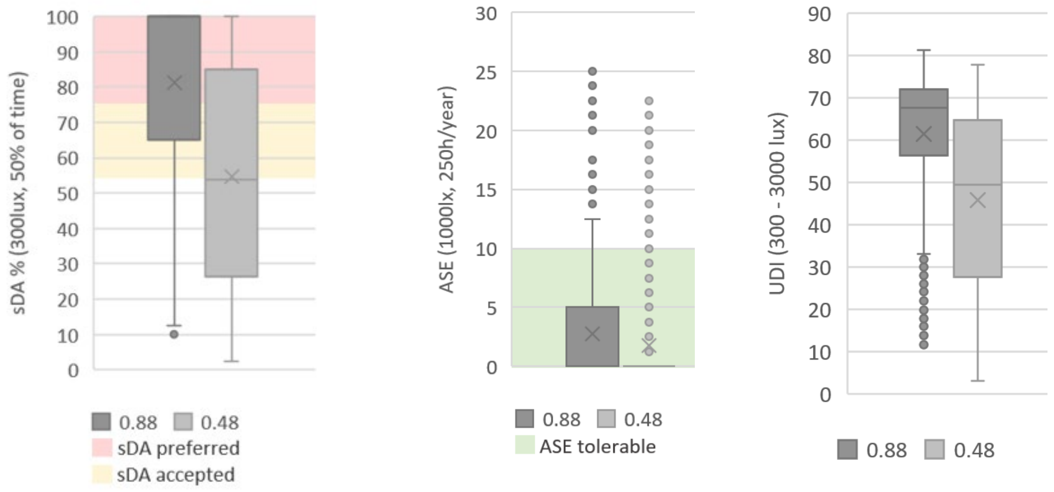



(c) UDI

**Figure 3.7:** Dataset results for the window width

b) Glazing visible transmittance

While the majority of the cases (62%) with clear glass (Glazing visible transmittance =0.88) achieved the sDA preferred class, this class was reached by only 24% of the cases with laminated glass (glazing visible transmittance = 0.48) (Figure 3.8a). However, the glazing visible transmittance showed less impact on ASE than on sDA results. While 80% of the cases with laminated glass were classified as ASE=0%, 68% of the cases with clear glass achieved this threshold (Figure 3.8b), with more than 3/4 of cases with this type of glass falling within the ASE 10% threshold. UDI results confirmed sDA ones but showed that results for clear glass have an even higher impact on performance when compared to results for laminated glass (Figure 3.8c).

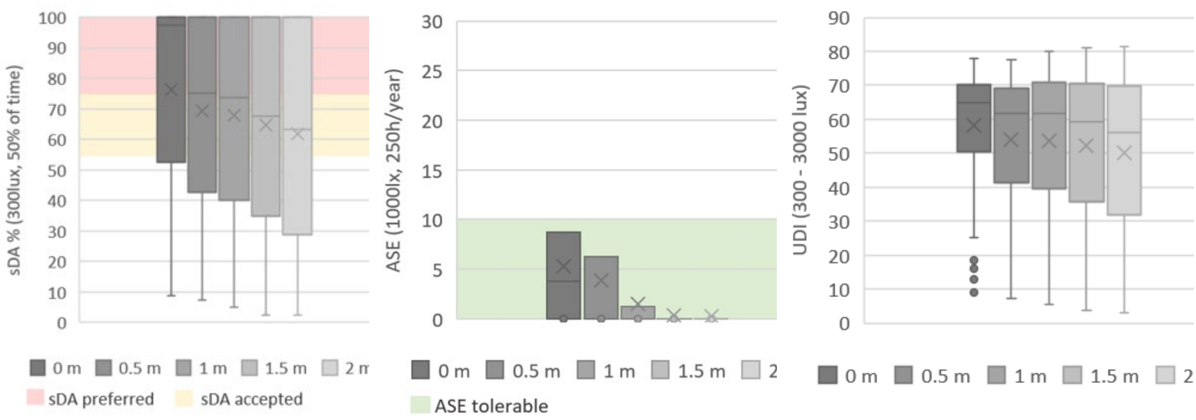



(a) sDA (b) ASE (c) UDI

**Figure 3.8:** Dataset results for the glazing visible transmittance

c) Balcony depth

Figure 3.9 illustrates the decrease in daylight illuminance levels resulting from the increase in balcony depth, as confirmed by Liu and Chen (2017), Gábrova (2014) and Kim and Kim (2010b). Figure 3.9a, however, illustrated an interesting cut-off point for design decision-making as balcony depths below 1.0 m had, in the majority of cases, sDA values falling within the preferred threshold whereas balcony depths above 1.0 m would tend to have sDA values falling, on average, within the accepted threshold. As expected from Al-Sallal, AbouElhamd and Dalmouk (2018), Kim and Kim (2010a), Gábrova (2014), Xue *et al*. (2016) and Dahlan *et al*. (2009a, 2009b), the addition of balconies was determinant in reducing the ASE (Figure 3.9b). However, this study identified that balconies deeper than 1.5 m will achieve null ASE and therefore are optimum to avoid glare and overheating due to direct solar radiation. UDI results (Figure 3.9c) confirmed sDA ones, also showing that the upper UDI limit is not affected by the balcony depth, since the 3rd quartile is roughly the same for all cases.

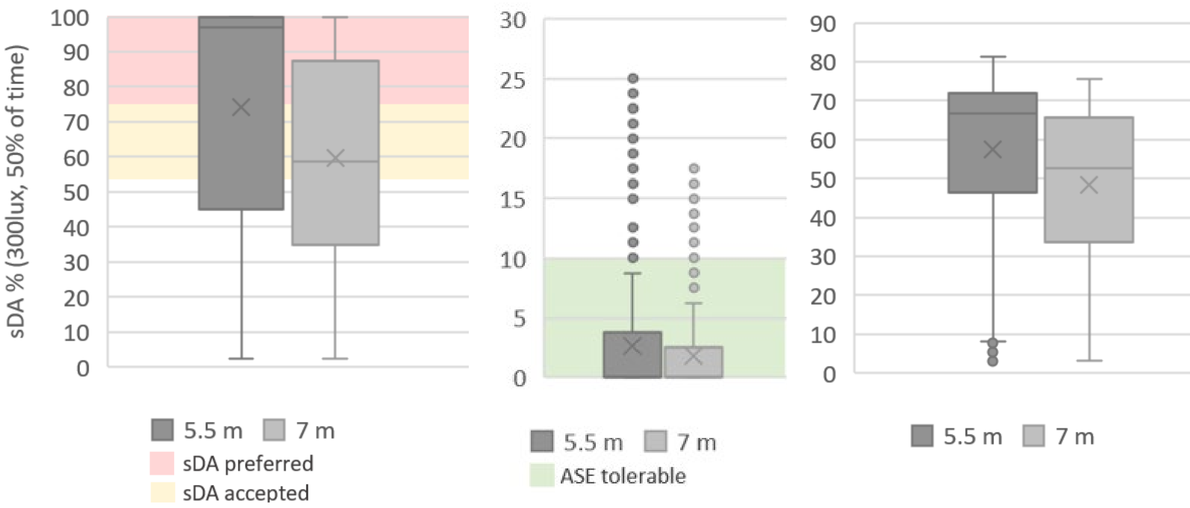



(a) sDA (b) ASE (c) UDI

**Figure 3.9:** Dataset results for the balcony depth

d) Room's width and depth

Room width and depth were investigated simultaneously by changing balcony and window positions from the front and back façades to side façades, as displayed in Figure 3.4, reflecting the most common floor plan proportions for mixed-mode office spaces in São Paulo (Pereira; Neves, 2018). As confirmed by Gábrova (2014), results clearly showed that the shallower the room, the better the daylight performance. More than 50% of the front balcony cases (room depth 5.5 m) were classified as sDA preferred, while only 29% of the side balcony cases (room depth 7 m) achieved this threshold. UDI levels confirmed sDA values for shallower rooms showing however, that room depth does not really affect the shape of the distribution curve as average cases will have a UDI of 55% for shallower rooms and 45% for deeper rooms (Figure 3.10c). ASE results were however not significantly different as the vast majority of cases for both configurations fell within the 10% threshold (Figure 3.10b), none of them with means in the null category.

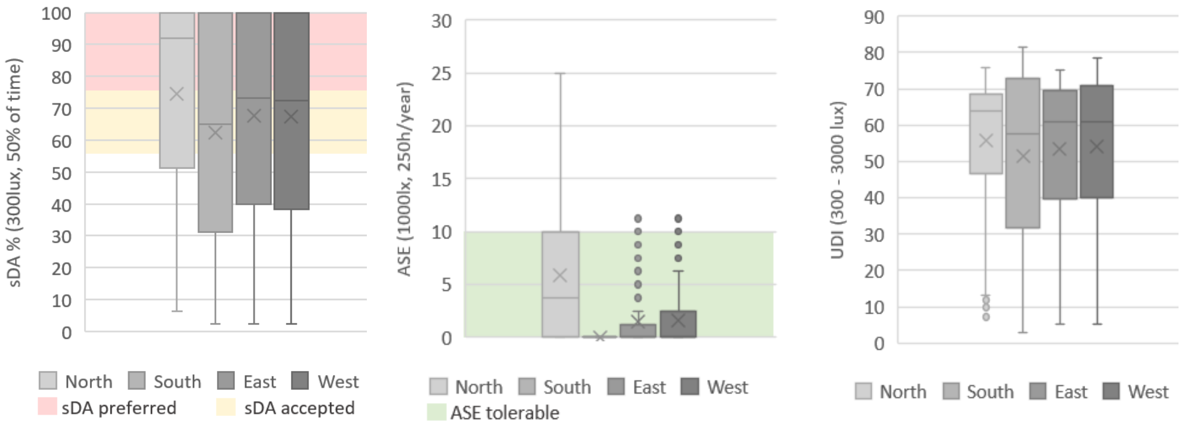



a) sDA b) ASE c) UDI

**Figure 3.10:** Dataset results for the room depth

e) Solar orientation

In the Southern tropical climate, the North and the South façades receive, respectively, the highest and the lowest amount of direct and diffuse solar radiation during the year. Thus, the office room facing North showed the highest daylight levels (Figure 3.11a) but also the highest probability of glare (Figure 3.11b). More than 50% of the North-oriented rooms were classified as having preferred sDA level and tolerable glare from ASE. As to the UDI level, the North-oriented office rooms presented higher results for the 1st quartile, the median and the mean values, if compared to the other solar orientations, showing the potential for the North orientation to achieve the best daylight performance (Figure 3.11c). In opposition, the South-oriented rooms showed the best results for ASE and the lowest mean and median values for sDA and UDI, with mean and median values for the former barely achieving the acceptable threshold. The West and East façades exposed similar daylight performance to each other. The mean and median values for both solar orientations were classified as sDA acceptable and ASE tolerable, although the West façade resulted in higher levels of ASE, possibly due to the fact that the number of occupied hours in the afternoons is higher than in the mornings.

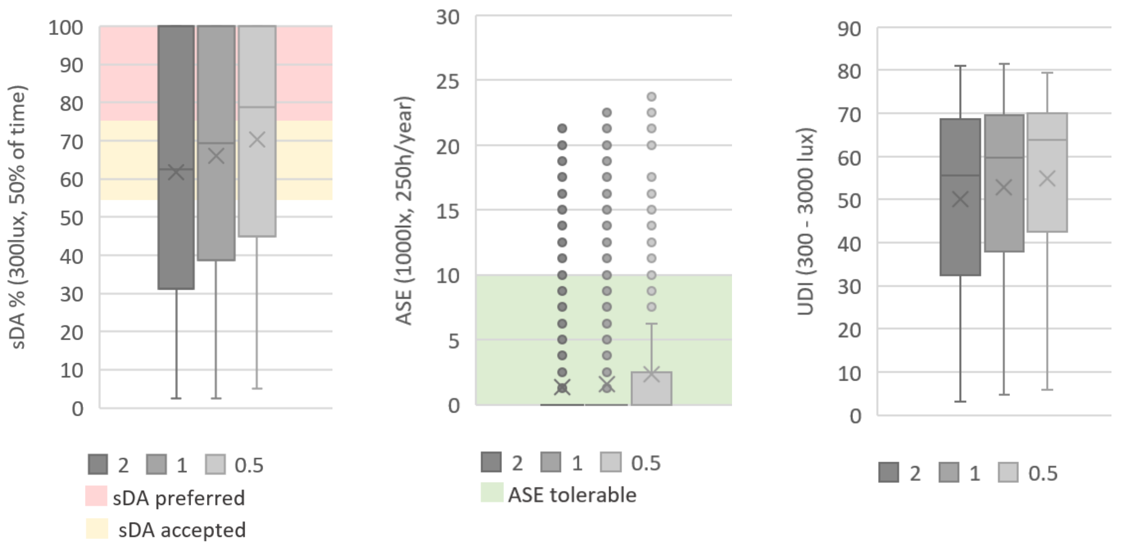



a) sDA b) ASE c) UDI

**Figure 3.11**: Dataset results for the solar orientation

f) Ratio of balcony width to window width

The use of balconies wider than the windows (ratio of balcony width to window width = 2) decreased the daylight performance (Figure 3.12a) but also prevented glare (Figure 3.12b), echoing results found by Kim and Kim (2010a), Gábrova (2014), Al-Sallal, Abouelhamd and Dalmouk (2018). The ratio of balcony width to window width of 1 and 2 showed similar performance for ASE, with most part of the cases classified as null, reinforcing the importance of having balconies with full window width. UDI results again confirmed sDA ones in terms of how ratio of balcony width to window width affect not only the average figures but also their distribution (Figure 3.12c).




(a) sDA (b) ASE (c) UDI

**Figure 3.12:** Dataset results for the Ratio of balcony width to window width

g) Floor level

Results from daylight simulations indicated that the floor level was the parameter with least impact on the room's daylight performance (Appendix A), findings echoed by Liu and Chen (2017), likely to be related to the fact that the building was simulated without any urban surroundings. Higher floors indicated a small increase in sDA and UDI in relation to lower floors possibly due to the albedo setting. The presentation of box plots for this parameter was therefore deemed unnecessary.

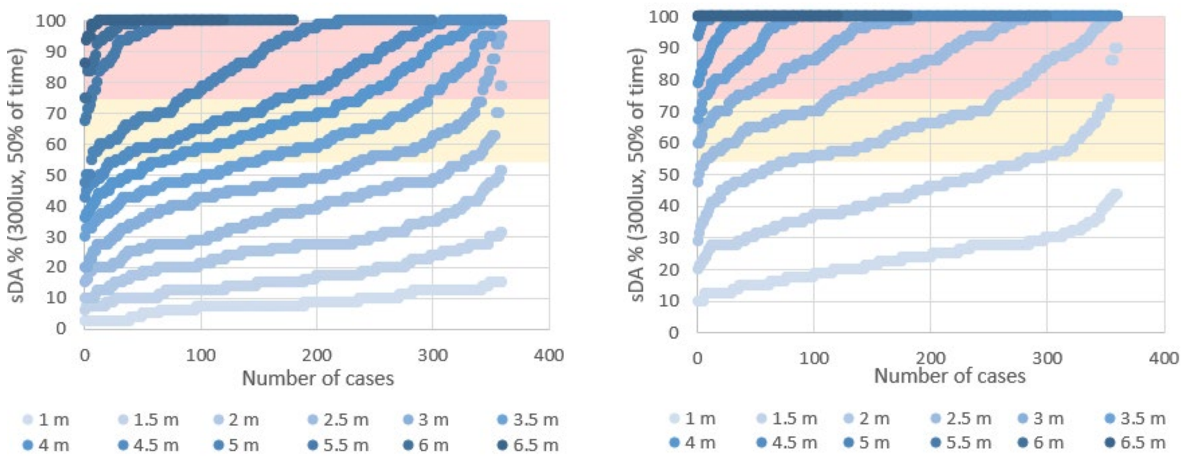
Nevertheless, in the case of densely built urban neighbourhoods, results would differ between higher, intermediary and lower floors. However, the development of suitable urban environments to undertake these experiments is still open to discussion as cities, especially in Brazil, have a very heterogeneous urban context meaning multiple types of geometric combinations for building height and lower floor configurations can be expected, making it difficult to extract typical cases to standardise the simulation of surrounding buildings.

### 3.4.2 Unfolding interesting pairwise combinations

To further extract relevant information for design decision-making, parameters were also analysed in pairs. Scatterplots were used to depict the most relevant pairwise comparisons, i.e. the ones from which it was possible to extract cut-off points for both parameters in relation to different performance thresholds. This section explored pairwise comparisons for the sDA metric only as ASE and UDI did not reveal any information different than the one received from the box plots. The analysis is focused on daylight illuminance sufficiency and does not include excessive illuminance (glare probability) or overheating probability issues.

a) Window width and glazing visible transmittance

When plotting window width against glazing visible transmittance it is possible to see that all windows wider than 4 m with clear glass achieved the sDA preferred threshold, whereas only windows wider than 6 m with laminated glass achieved this same threshold (Figure 3.13).

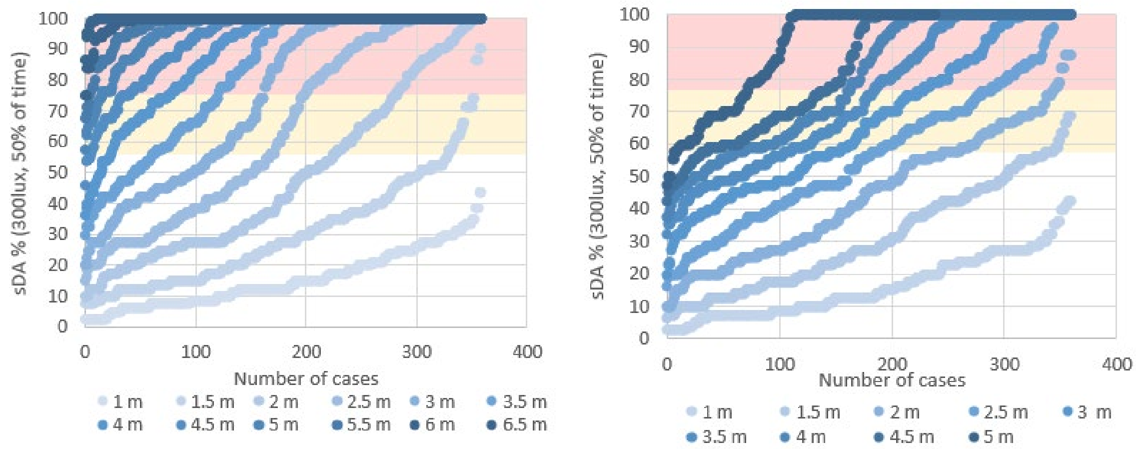



(a) Glazing Tvis 0.48 (b) Glazing Tvis 0.88

**Figure 3.13:** Scatter plots for sDA per window width

b) Window width and room depth

All the 5.5 m-deep rooms achieved preferred sDA thresholds when having windows wider than 5.5 m, whereas the 7 m-deep rooms did not achieve the preferred sDA threshold 100% of the time, even with a fully glazed facade (Figure 3.14).

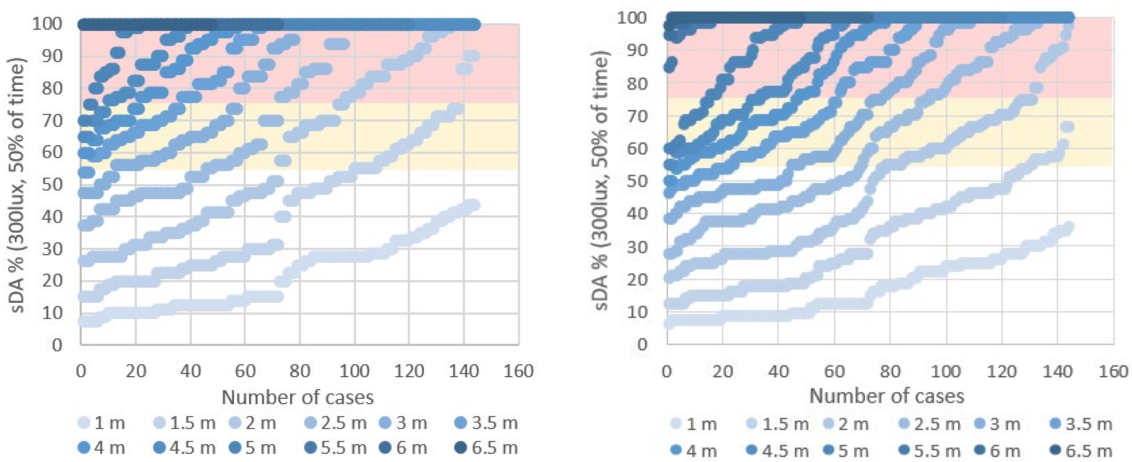



(a) Room depth = 5.5 m (b) Room depth= 7 m

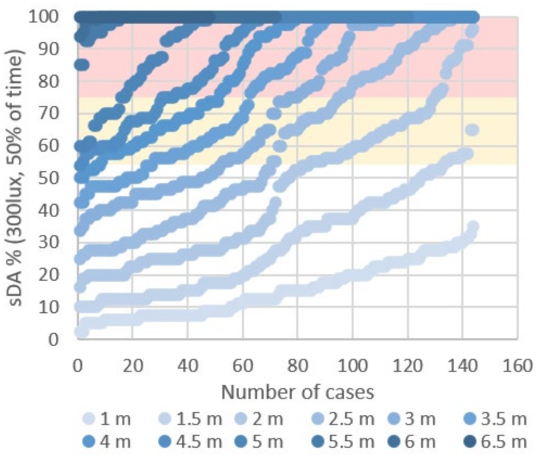
**Figure 3.14:** Scatter plots for sDA per window width

c) Window width and balcony depth

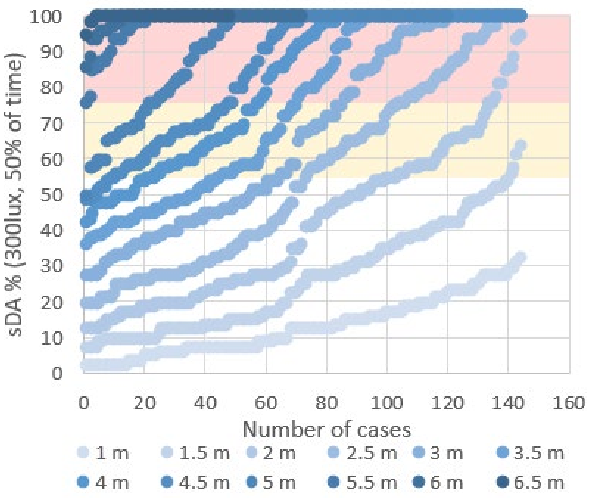
This pairwise combination showed that the deeper the balcony, the narrower the difference between sDA values falling within the preferred and acceptable thresholds. Figure 3.15 illustrated that when no balconies are present, the preferred threshold was achieved for all the scenarios with a 5 m width window whereas only a 3.5 m width window was necessary to achieve the acceptable one. Adding a balcony of 0.5 m and 1 m depth did not affect the window width needed to achieve the preferred threshold but did push the minimum width to achieve the accepted threshold to 4 m and 4.5 m, respectively. For balconies deeper than 1 m, for every increment of 0.5 m in depth, the distance between the preferred and acceptable thresholds seemed to remain constant.



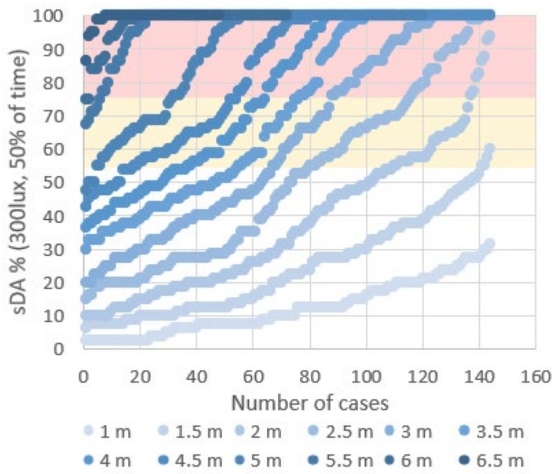

(a) Balcony depth = 0 m (without balconies) (a) Balcony depth = 0.5 m




(c) Balcony depth = 1 m




(d) Balcony depth = 1.5 m

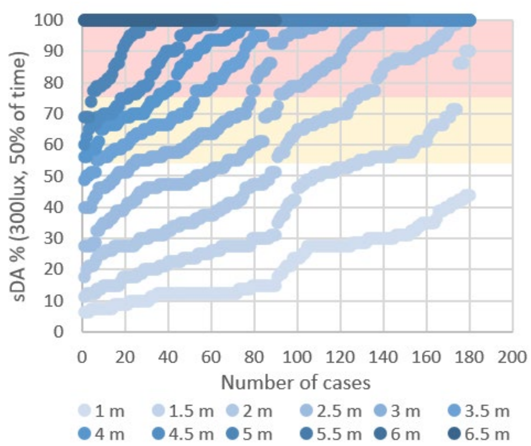



(e) Balcony depth = 2 m

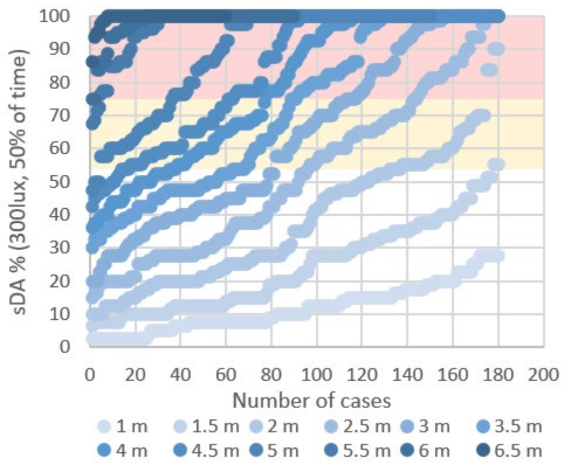
**Figure 3.15:** Scatter plots for sDA per window width

d) Window width and solar orientation

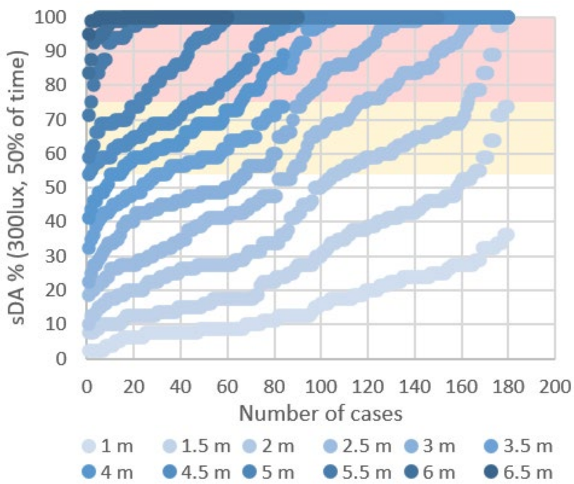
This pairwise combination, illustrated in Figure 3.16, showed that for the North orientation, the preferred sDA threshold was achieved for all scenarios with a 5 m window width whereas a 4 m window width was enough for all scenarios to achieve at least the acceptable sDA threshold. For the South façade, the preferred and acceptable thresholds were achieved with window widths of respectively 6 m and 5 m for all scenarios. The East and West orientations exhibited window width differences 0.5 m apart for all scenarios to achieve the preferred and acceptable thresholds.



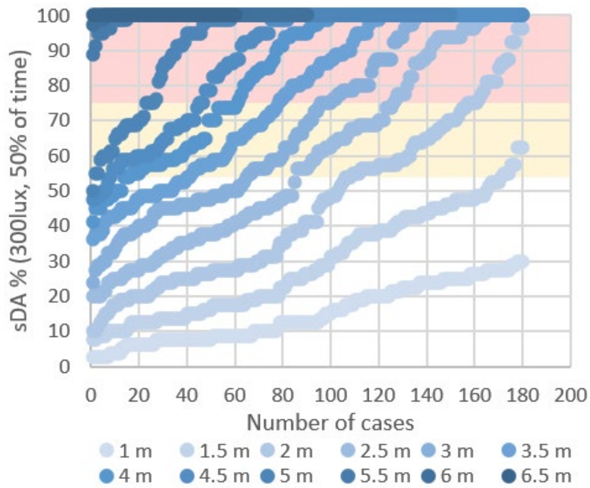

a) North




b) South




c) East




d) West

**Figure 3.16:** Scatter plots for sDA per window width

### 3.4.3 Extracting general rules

Results from section 3.4.1 showed the sensitivity of CBDM to each design parameter explored in this study when analysed in isolation, whereas results from section 3.4.2 attempted to unfold interesting pairwise combinations of parameters to examine how they, together, influenced sDA in particular. Whereas section 3.4.1 indicated that window width was potentially the most important parameter to achieve the targets, this was confirmed by the pairwise comparisons which showed that interesting thresholds could be identified when combining this parameter with the others. This section examined the summaries from section 3.4.1 and 3.4.2 in conjunction with Appendix A and attempted to provide general rules useful to designing medium rise mixed-mode office buildings in São Paulo, with or without balconies.

Table 3.6 shows general rules for window widths to achieve the sDA preferred threshold, for any balcony depth (from 0 m to 2 m) and ratio of balcony width to window width (0.5, 1 and 2) considered in this study. Window widths were established as a function of solar orientation, room depth and glass visible transmittance. The North façade contained the path to success with minimum dimensions, whereas the South orientation presented the worst-case scenario, needing the largest window widths for balconies to be used without affecting daylight performance. East and West orientations with shallow rooms and clear glass needed both 3 m window widths to achieve the preferred threshold but behaved differently when the room depth increased, and the glass visible transmittance decreased. No configuration achieved the preferred threshold when the room depth was 7 m and laminated glass was used.

**Table 3.6:** Rules to achieve preferred sDA for any balcony configuration

| Solar orientation | Room depth (m) | Glass Tvis | Window width to achieve sDA preferred threshold (m) |
|---|---|---|---|
| North | 5.5 | 0.88 | >= 2.5 |
| | | 0.48 | >= 4.5 |
| | 7.0 | 0.88 | >= 3.0 |
| | | 0.48 | - |
| South | 5.5 | 0.88 | >= 3.5 |
| | | 0.48 | >= 6.0 |
| | 7.0 | 0.88 | >= 4.0 |
| | | 0.48 | - |
| East | 5.5 | 0.88 | >= 3.0 |
| | | 0.48 | >= 6.0 |
| | 7.0 | 0.88 | >= 3.5 |
| | | 0.48 | - |
| West | 5.5 | 0.88 | >= 3.0 |
| | | 0.48 | >= 5.0 |
| | 7.0 | 0.88 | >= 4.0 |
| | | 0.48 | - |

Table 3.7 suggests the window width above which using deeper balconies improved UDI figures, i.e. when balconies were considered effective daylight diffusers. Deeper balconies could be particularly difficult to be used in the South façade and would improve performance only when used in shallow rooms with clear glass. It is important to notice that deeper balconies would never improve daylight performance of any configuration using laminated glass (Tvis = 0.48), therefore these values were not added to Table 3.7.

**Table 3.7:** Rules to achieve the same UDI for any balcony configuration and to improve UDI using deeper balconies.

| Solar Orientation | Room depth (m) | Glass Tvis | Window width above which UDIs improve with deeper balconies (m) |
|---|---|---|---|
| **North** | 5.5 | 0.88 | >= 3.5 |
| | 7.0 | | >= 4.0 |
| **South** | 5.5 | | >= 5.0 |
| | 7.0 | | - |
| **East** | 5.5 | | >= 4.5 |
| | 7.0 | | >= 4.5 |
| **West** | 5.5 | | >= 4.0 |
| | 7.0 | | 5.0 |

### 3.4.4 Data mining: Relevant combinations of design parameters to improve daylight performance.

Sections 3.4.1 to 3.4.3 showed limitations in further detailing causal relationships and extracting more specific rules when undertaking a systematic analysis. Therefore, this section focused on expanding this analysis to improve the search for successful routes towards sDA and ASE respectively above and below thresholds, through the use of data mining. As previously detailed in the methodology, Figure 3.17 depicted successful end nodes for a decision tree, produced by the J48 algorithm, using a traffic light system (discussed previously in Table 3.5), so designers could visualize the best routes to achieve any desired performance.

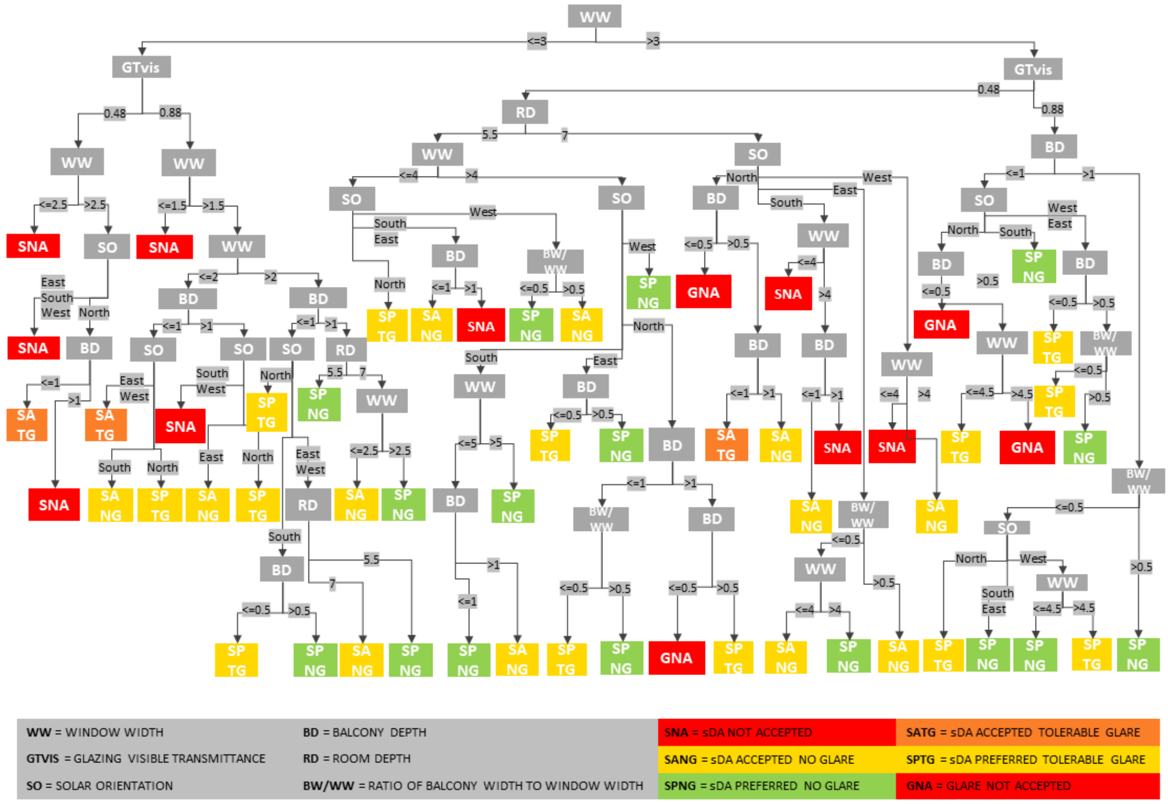



**Figure 3.17:** Decision tree

The decision tree from Figure 3.17 was achieved after multiple experiments in WEKA. Different decision tree settings were investigated altering the number of objects, to control complexity. A minimum number of objects of 3, yielded a confidence factor as high as 97%. However, these settings resulted in highly complex trees, with 298 end nodes, difficult to parse through and complex to be analysed. The tree displayed in Figure 3.17 provided simultaneously a satisfactory level of correctly classified instances (85%) and complexity and was achieved with the following settings: pruned, number of folds set to 3 and minimum number of objects set to 30. Decision tree paths led to 57 end nodes, from which 28% of them were highly successful (sDA preferred no glare), whereas 23% of them led to unacceptable results (both glare not accepted and sDA unacceptable) and should therefore be avoided. Thus, 77% of nodes were within the acceptable and/or tolerable thresholds and therefore yielded valid decision-making paths to be pursued.

Results depicted by the decision tree and summarised in Table 3.8, show general rules for which combination of parameters are likely to yield preferred sDA with no glare as well as which combinations of parameters should be avoided as they lead to either sDA or glare at not acceptable levels. Design parameters which do not belong to a specific rule marked as '-'. This table contains 29 rules from which 12 display combinations which should be avoided with the remaining ones listed deemed as highly successful. However, it is important to notice that window widths smaller than 3 m are not allowed by the São Paulo Building Regulation (1978), despite showing acceptable results. This means, in principle, non-listed combinations should lead to the achievement of acceptable targets, bearing in mind the classification correctness of 85%.

**Table 3.8:** Rules extracted from the decision tree

| Class | Window width (m) | Glazing Tvis | Solar orientation | Balcony Depth (m) | Room depth (m) | Ratio of balcony width to window width |
|---|---|---|---|---|---|---|
| **sDa preferred no glare** | > 2 to <= 3 | 0.88 | East or West | <=1.0 | 5.5 | - |
| | >2 to <= 3 | 0.88 | South | =1.0 | - | - |
| | >2 to <=3 | 0.88 | - | >1.0 | 5.5 | - |
| | = 3 | 0.88 | - | >1.0 | 7.0 | - |
| | > 3 | 0.88 | South | <=1.0 | - | - |
| | > 3 | 0.88 | West and East | =1.0 | - | >0.5 |
| | > 3 | 0.88 | - | >1.0 | - | >0.5 |
| | > 3 | 0.88 | South or East | >1.0 | - | - |
| | >3 to <= 4.5 | 0.88 | West | >1.0 | - | - |
| | > 4 | 0.48 | East | - | 7.0 | <=0.5 |
| | > 3 to <=4 | 0.48 | West | - | 5.5 | <=0.5 |
| | >4 to <=5 | 0.48 | South | <=1.0 | 5.5 | - |
| | >4 | 0.48 | East | >0.5 | 5.5 | - |
| | >4 | 0.48 | West | - | 5.5 | - |
| | >4 | 0.48 | North | <=1.0 | 5.5 | >0.5 |
| | >5 | 0.48 | South | - | 5.5 | - |
| | >5 | 0.48 | South | - | 5.5 | - |
| **sDA not accepted** | <=1.5 | 0.88 | - | - | - | - |
| | <=2.5 | 0.48 | - | - | - | - |
| | =3 | 0.48 | South, East or West | - | - | - |
| | <=3 | 0.48 | North | > 1.0 | - | - |
| | <=2 | 0.88 | South or West | >1.0 | - | - |
| | >3 <=4 | 0.48 | South or West | >1.0 | 7.0 | - |
| | >4 | 0.48 | South | > 1.0 | 7.0 | - |
| | >3 <=4 | 0.48 | South or East | >1.0 | 5.5 | - |
| **Glare not accepted** | >3 | 0.88 | North | <=0.5 | - | - |
| | >4.5 | 0.88 | North | <=1.0 | - | - |
| | >3 | 0.48 | North | <=0.5 | 7.0 | - |
| | >4 | 0.48 | North | <=0.5 | 5.5 | - |

Table 3.8 can be understood as a summary of more specific rules of thumb for parametric combinations to be used when pursuing preferred sDA as well as those to be avoided as they yield not acceptable sDA and glare. In addition, it also enables one to derive the following general design recommendations for office buildings with balconies in São Paulo:

- Avoid windows in the North façade which contain balconies shallower or equal to 1 m and window widths higher or equal to 3.0 m as they tend to result in not acceptable glare.
- Avoid combinations with clear glass and windows narrower or equal to 1.5 m as they tend to cause not acceptable sDA.
- Avoid scenarios with laminated glass and windows narrower or equal to 2.5 m as they tend to result in not acceptable sDA.
- Pay special attention to window width when designing balconies with more than 1.0 m depth and using laminated glass so sDA values would not go below accepted level.

Interestingly, Table 3.8 showed how the ratio of balcony width to window width and the room depth can play a tricky role in pathways to success. This is because in 70% of the successful paths from Table 3.8 the ratio of balcony width to window width was not relevant in classifying the instances as sDA preferred. However, in 17% of the paths this variable needed to be higher than 1, whereas in the remaining 13% it needed to be lower or equal to 0.5. With regards to room depth, in 53% of the paths the 5.5 m depth was classified as highly successful, but it was possible to see this parameter did not play a role in 35% of the pathways to success and that 12% of the cases with room depths of 7 m still yielded highly successful results.

## 3.5 Conclusion

This paper discussed the use of balconies in medium-rise mixed-mode office buildings in the tropics by exploring decision-making pathways to achieve daylight efficiency and reduce incident solar radiation. Balconies, assumed to be an efficient shading device as well as a daylight diffuser, were assessed in combination with different window configurations via parametric studies coupled with daylight simulations for a 'typical' mixed-mode office building in São Paulo. Guidelines considering preferred and accepted sDA, as well as preferred and accepted ASE were extracted considering daylight sufficiency and probability of glare, in separation and simultaneously, in addition with the UDI metric to formulate rules and relevant combinations of design parameters useful to the early design stages.

The following main results and recommendations which come out of this study were:

- Window width and glazing visible transmittance were always essential parameters to achieve preferred and acceptable sDAs and ASE as well as UDIs, reinforcing what was already indicated in the literature. However, this study showed throughout the systematic analysis and confirmed through the decision tree – the window width as the root node and the glazing visible transmittance as the second node – that these two parameters are the most important ones in achieving daylight performance.

- Window width, when combined with any other parameter, produced relevant thresholds for design decision-making. This was particularly evident in the pairwise comparisons displayed in section 3.4.2, which all referred to window width, as well as conclusive Tables 3.6 and 3.7, in which window width was written as a function of solar orientation, glazing visible transmittance and room depth. It was also evident, from the decision tree, that the window width was constantly used as a design parameter to create new decision nodes, as well as from Table 3.8, in which this parameter was written as a function of all the others.
- The systematic analysis was very useful to identify relevant parameters and parametric combinations which would yield successful sDAs and UDIs but not very successful to detect combinations of design parameters to achieve preferred and acceptable ASEs.
- The systematic analysis produced cut-off points after which balcony configurations stopped influencing the achievement of preferred sDAs (Table 3.6). Although results in Table 3.6 did not consider glare, they were still a good indicator of which window widths to use with each solar orientation, room depth and glazing visual transmittance to achieve preferred sDAs with any type of balcony configuration.
- The systematic analysis produced information about which combinations of design parameters for which deeper balconies would yield better UDIs (Table 3.7). Contrarily to Table 3.6, this table embedded information on the upper illuminance threshold (3000 lx) when recommending window widths as function of orientation, transmittance and room depth and therefore can be seen as complementary to information contained in Table 3.6.
- The datamining complemented the findings from the systematic analysis. In particular, Table 3.8 provided more detailed information on how to achieve preferred performance with the inclusion of ASEs, also indicating parametric combination pathways to be completely avoided.

Future studies could address limitations of this study such as including different positioning of balconies in relation to windows, as this study only addressed balconies centred to window widths; addressing alternative material properties such as balconies with visible transmittance and different reflectance setting; increase the number of parameters related to glazing visible transmittance and room depths to include outliers from the database (Neves; Melo; Rodrigues, 2019; Pereira; Neves, 2018), to test a wider spectrum of possibilities and increase design variety. Future work could also assess how these parametric combinations are affected by a densely populated urban context which could possibly be favourable in achieving preferred ASEs but would likely jeopardize the achievements of preferred sDAs.

**Acknowledgments**

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# 4. Effects of the use of balconies on natural ventilation, thermal and energy performance

This chapter is the transcription of the following paper:

**Balcony design to improve natural ventilation and energy performance in high-rise mixed-mode office buildings**

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## Abstract

Balconies have the potential to promote airflow and regulate solar heat gain, which can reduce energy usage for cooling in buildings. However, designing these elements can be challenging due to complex trade-offs for natural ventilation and energy performance, highlighting the need for advanced simulation tools to guide balcony design decisions. This study aims to evaluate the impacts of balcony design on natural ventilation and thermal and energy performance in high-rise mixed-mode office buildings in São Paulo, Brazil. To this end, an integrated method that involves computational fluid dynamics (CFD) and building performance simulations (BPS) is developed to identify optimal solutions. Through this method, the performance of 40 balcony designs is studied, comprising diverse alternatives for three balcony design parameters (width, depth, and location on the façade). Furthermore, the research is performed considering the balcony effects on two façade orientations (north and south), two wind incidences (windward and leeward), and three floor levels (upper, medium, and lower floors). Results are analysed through a sensitivity analysis, percentage of change and cross-analysis. The findings indicate that narrow and shallow balconies (2 m x 0.5 m) are the best design option for the south façade; they enhance natural ventilation and reduce energy consumption for cooling across all floor levels and balcony locations. Conversely, for the north, sun-facing façade, it is recommended to use wide and deep balconies (5 m x 2 m) to reduce solar gains and associated energy consumption for cooling, despite potential limitations in natural ventilation.

**Keywords:** Natural ventilation, Thermal performance, Mixed-mode, Office building, Balconies.

## 4.1 Introduction

In tropical regions, the use of mixed-mode ventilation (MMV) systems combined with shading strategies can be effective in reducing energy consumption for cooling in office buildings (Mohammed, 2021). The MMV system allows spaces to rely on natural ventilation when outdoor conditions are favourable for maintaining indoor thermal comfort while using air conditioning only for supplemental cooling (Brager, 2006). The incorporation of fixed shading elements, such as balconies and overhangs, can further enhance thermal performance and extend periods when the building operates with natural ventilation, improving indoor air quality (IAQ) and increasing occupants' satisfaction and productivity (Arata; Kawakubo, 2022; Brager; Baker, 2009; De Oliveira; Rupp; Ghisi, 2021).

The incorporation of balconies in office buildings' façades has been increasing, potentially related to the popularization of split air-conditioning units, which demand an outdoor area to allocate the condenser unit. Balconies are a common choice for placing the condenser unit in high-rise buildings located in hot climates, driven by façade aesthetics and the recommendation to position the condenser in well-ventilated areas for efficient heat dissipation and system efficiency (Abdullah; Barwari, 2022; Chow; Lin; Wang, 2000; Xue *et al*., 2007). A study conducted in São Paulo, Brazil, showed that the use of these elements in mixed-mode office buildings increased by 85% from 1995 to 2016, representing 23% of the buildings with this typology (Neves; Melo; Rodrigues, 2019). This trend can be seen as an opportunity to promote the use of balconies in office buildings, as they could be justified as a space to accommodate building services as well as act as a shading control system (Figure 4.1).

a) Office with balcony

b) Balcony used as service area to house the condenser unit

c) Office building façade with condenser unit in the balcony

**Figure 4.1:** Examples of mixed-mode office buildings with balconies in the city of São Paulo, Brazil
Source: Pereira (PEREIRA, 2019)

Despite the increasing use of balconies in office buildings, current literature predominantly focuses on their impacts on the indoor performance of residential buildings (Bayazit; Kisakurek, 2023; Dahlan *et al*, 2009a; Duarte *et al*., 2023; Izadyar *et al*., 2020; Liu *et al*., 2021; Omrani *et al*., 2017; Peters; Masoudinejad, 2022; Ribeiro *et al*., 2024; Ribeiro; Ramos; Flores-Colen, 2020; Tungnung, 2020). This emphasis is evident in the comprehensive literature review conducted by Ribeiro *et al*. (2020) regarding the impact of balconies on the indoor environment of dwellings, and in the ongoing debate on the role of balconies in residential buildings during the COVID-19 pandemic (Bayazit Solak; Kisakurek, 2023; Duarte *et al*., 2023; Peters; Halleran, 2021; Peters; Masoudinejad, 2022; Säumel; Sanft, 2022). However, findings from thermal and energy performance of residential studies may have limited applicability to office buildings due to different occupancy schedules and internal loads, underscoring the necessity for research specific to the office typology.

Balconies can serve as efficient fixed solar shading devices, reducing the direct solar radiation and significantly improving thermal conditions in adjacent rooms (Fernandes *et al*., 2015; Ribeiro; Ramos; Flores-Colen, 2020). However, since balconies are prominent elements on building façades, they also influence airflow patterns and pressure distribution, affecting natural ventilation inside the building. Depending on the balcony geometry and wind incidence, they can either enhance or obstruct the airflow, which adds complexity to its design (Bamdad *et al*., 2022; Cochran, 2020; Cui; Mak; Niu, 2014; Izadyar *et al*., 2020; Montazeri; Blocken, 2013; Omrani *et al*., 2017, 2015; Zheng; Montazeri; Blocken, 2020, 2021).

The influence of the balcony design on natural ventilation performance has been thoroughly investigated in the literature using computational fluid dynamics (CFD) simulations. These studies considered balcony design parameters, such as the presence and absence of balconies (Ai *et al*., 2011a, 2011b; Montazeri; Blocken, 2013; Zheng; Montazeri; Blocken, 2021), balcony depth (Izadyar *et al*., 2020; Karimimoshaver *et al*., 2023; Mohamed *et al*., 2014; Omrani *et al*., 2017; Tao *et al*., 2023; Zheng; Montazeri; Blocken, 2021), parapet type or height (TAO *et al*., 2023; ZHENG; MONTAZERI; BLOCKEN, 2021), balcony width (Karimimoshaver *et al*., 2023; Tao *et al*., 2023), Balcony Type (Mirabi; Nasrollahi; Dadkhah, 2020; Omrani *et al*., 2017; Ribeiro *et al*., 2024), and the position of the balconies, considering their placement in the middle, on the left or on the right side of the façade (Ai *et al*, 2011a; Karimimoshaver *et al*., 2023; Ghadikolaei; Ossen; Mohamed, 2020). The impacts of balcony design parameters on the natural ventilation performance were found to be dependent on other factors, such as wind incidence (Ai *et al*., 2011a, 2011b; Mirabi; Nasrollahi; Dadkhah, 2020; Mohamed *et al*., 2014; Montazeri; Blocken, 2013; Omrani *et al*., 2017), floor level (Ai *et al*., 2011b; Mirabi; Nasrollahi; Dadkhah, 2020; Mohamed *et al*., 2014; Montazeri; Blocken, 2013; Zheng; Montazeri; Blocken, 2021) and natural ventilation strategy (single-sided or cross ventilation) (Ai *et al*., 2011a, 2011b; Jin *et al*., 2016; Omrani *et al*., 2017).

Existing literature regarding the effects of balconies on thermal and/or energy performance has mostly focused on comparing the presence and absence of balconies, primarily examining a single balcony design. These studies have employed post-occupancy research methods, including interviews with occupants (Bayazit; Kisakurek, 2023; Chan; Chow, 2010; Dahlan *et al*., 2009a; Duarte *et al*., 2023; Fernandes *et al*., 2015; Säumel; Sanft, 2022), in-situ measurements (Dahlan *et al*., 2009a; FERNANDES *et al*., 2015; Omrani *et al*., 2017; Ribeiro *et al*., 2024) and building performance simulations for case studies, validated with indoor measurements (Liu *et al*., 2021; Tungnung, 2020). The literature has scarcely explored the impacts of balcony design on thermal and energy performance of buildings. This could be due to the complexity of evaluating multi-domain implications of protruding façade elements using solely building performance simulation (BPS). For example, the automatic calculation of wind pressure coefficients is incorporated in a simplified manner within BPS AirFlow Network tools, mostly restricted to rectangular-shaped buildings with no additional architectural elements on the façades (Bre; Gimenez, 2022).

Two studies specifically investigated the impact of balcony design on building thermal and energy performance. Liu and Chen (2017) and Nikolic *et al*. (2020) explored the effects of balcony depth in naturally ventilated residential buildings using BPS. Liu and Chen (2017) found that deep balconies (3 m) associated with a high window opening factor (75% to 100%) resulted in improved thermal comfort and a 30% reduction in energy consumption for cooling. Nikolic *et al*. (2020) identified optimal balcony depths for different solar orientations, revealing that reductions in direct solar radiation led to a 44% decrease in cooling demand. Yet, these studies overlooked the effects of balcony design variation on the wind pressure coefficients, likely by using simplified data automatically generated by the BPS software.

The literature has scarcely explored the simultaneous effects of balconies on natural ventilation and thermal performance, since it substantially increases the complexity of the analysis. Notably, three studies conducted by Ai *et al*. (2011a), Izadyar *et al*. (2020) and Omrani *et al*. (2017) employed CFD simulations and thermal comfort calculations to evaluate the associated impacts of balconies on thermal comfort and natural ventilation. Ai *et al*. (2011a) demonstrated that adding a balcony to the façade enhanced indoor air distribution, leading to improved thermal comfort. Aligned with these findings, Izadyar *et al*. (2020) showed that balconies between 2.5 and 3 m deep produced the best results in terms of indoor air distribution and thermal comfort in adjacent living rooms of residential buildings (Izadyar *et al*., 2020). Omrani *et al*. (2017) concluded that increasing the balcony depth led to a decrease in air velocity. Moreover, the impacts of the balcony depth on thermal comfort were more pronounced in rooms relying on single-sided ventilation, compared to those employing cross-ventilation.

Therefore, this study aims to provide optimal balcony design configurations to improve natural ventilation, thermal and energy performance in mixed-mode office buildings. This study employed an integrated approach involving computational fluid dynamics (CFD) and building performance simulations (BPS), not yet used to evaluate the impacts of balconies on building performance. Four balcony design parameters (width, depth, and location on the facade) will be tested, considering different facade orientations, wind directions, and floor levels, to derive valuable information for building designers.

## 4.2 Methods

The methodology for this study is unfolded in four key steps. First, we defined a "typical" mixed-mode office building, from which we developed a representative model without balconies and design cases with balconies, with variations in three balcony design variable parameters (location on the façade, width and depth) (step 1). Subsequently, validated Computational Fluid Dynamics (CFD) simulations were conducted to generate wind pressure coefficients ($\overline{C_P}$) for the reference case without balconies and for the design cases (step 2). Building performance simulations were executed for 40 design cases with balconies and for the reference case (step 3). The results were analysed through a sensitivity analysis, and the percentage change compared to the reference case was calculated for the air change rate and for the cooling thermal loads (step 4). By cross-analysing the obtained results, valuable insights are provided for designing balconies to enhance natural ventilation, thermal and energy performance in high-rise mixed-mode office buildings. The proposed methodology is illustrated in Figure 4.2 and is further detailed in the following subsections.

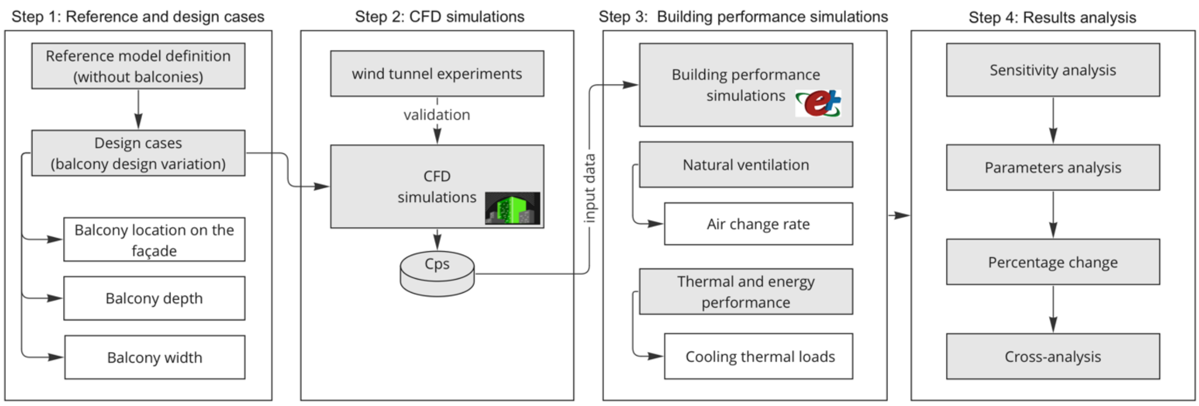
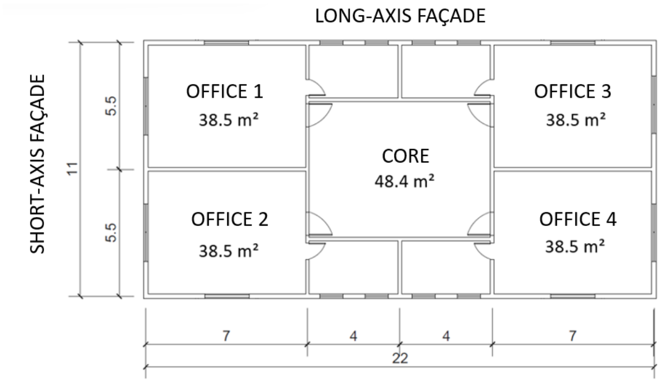



**Figure 4.2:** Methodology workflow

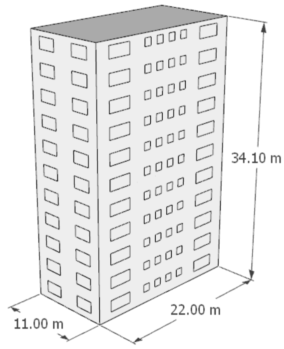
### 4.2.1 Representative building model and design cases

A representative building model was created to depict a “typical” mixed-mode office building without balconies in São Paulo, Brazil. The building geometry and envelope characteristics were based on the mean values of continuous variables and the highest frequency values of categorical variables from a real building database (Neves; Melo; Rodrigues, 2019). The database contains envelope design and construction information from 153 surveyed case studies of mixed-mode office buildings built between 1995 and 2016 in the city of São Paulo, Brazil.

The selected mixed-mode office building comprises 11 floors. Each floor consists of four open-plan offices with a floor-to-ceiling height of 2.75 m, connected by a central core (see Figure 4.3). Each office room is equipped with a service area that includes a small toilet and kitchen/pantry, with two small windows (1 m x 1 m). The windows in the office room correspond to a window-to-wall ratio of 25% and are centrally positioned along the horizontal axis on both external walls, allowing cross ventilation between adjacent façades. The mixed-mode strategy consists of cross ventilation on adjacent façades, and individual air-conditioning systems installed in each office room, with independent outdoor and indoor units. The building in this study was considered isolated, i.e., without surrounding buildings.




(a) Floor plan




(b) Building axonometric

**Figure 4.3**: Representative building model.

The window in the façade where the balcony was located was modified to become a balcony door, measuring 2.0 m x 2.10 (width x height). The parapet height of the balconies was fixed at 1.1 m, while three balcony geometric design characteristics were selected as variable parameters. Their values were defined to represent feasible possibilities, considering practical achievability and typical construction practices obtained from the real building design characteristics in the database (Neves; Melo; Rodrigues, 2019).

a) Balcony location: short-axis façade or long-axis façade.
b) Balcony depth: 0.5 m, 1.0 m, 1.5 m, or 2.0 m.
c) Balcony width: 1.0 m, 2.0 m, 3.0 m, 4.0 m, or 5.0 m.

The combination of balcony designs, in addition to a reference case without balconies, led to 41 case studies. Figure 4.4 provides examples of these case studies from each design parameter.

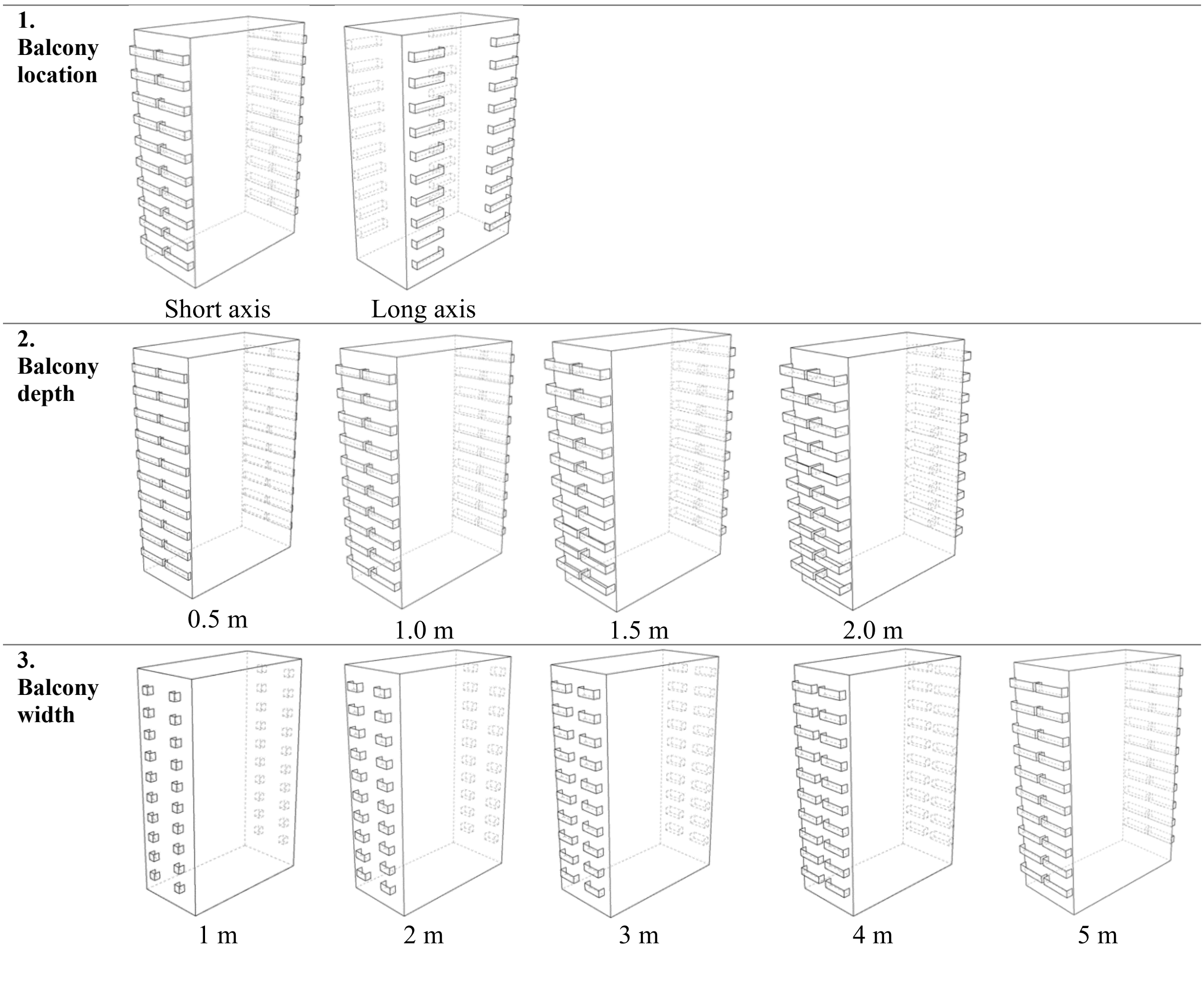



**Figure 4.4:** Example of design cases for each variable parameter.

### 4.2.2 CFD simulations

The present study has chosen the cloud-based platform CpSimulator (Gimenez; Bre, 2023) as the CFD tool. The platform encompasses a collection of tools designed to automate the complete workflow of ABL simulations and acquire comprehensive wind flow data in urban environments with surrounding buildings. This numerical toolkit encompasses the generation of the computational domain, the meshing procedure, the solution stage, and the post-processing of the results. These processes are introduced in (Gimenez; Bre, 2023) but a concise description of their main functionalities and set-up is included in this section.

The accuracy of the platform was successfully validated for several case studies using wind tunnel experimental data, including high-rise buildings with balconies (Bre; Gimenez, 2022). However, in Appendix C, further comparisons were performed against experimental data for three building designs representative of the case studies addressed in this work.

The platform processes geometric data, creating a regular polygonal computational domain with sizes based on best practice guidelines for building-to-boundary distances and blockage ratios (Figure 4.5).

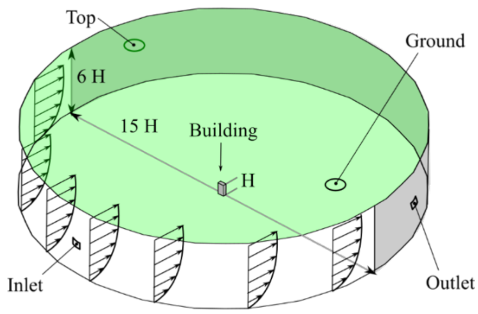



**Figure 4.5:** Computational domain for the CFD simulations

Automated refinement determines reference cell size (DX) and characteristic lengths for accurate meshing. Recursive refinement maintains aspect ratios, with prismatic layers near buildings for perpendicular grid lines. Mesh quality is ensured via skewness, non-orthogonality, and undetermined cell limits, conforming to finite volume method (FVM) principles. The robust tool consistently generates high-quality meshes, particularly hexahedral cells, enhancing numerical solution quality in complex cases; see references (Bre; Gimenez, 2022) and (Gimenez; Bre, 2022) for further details of the meshing procedure. To verify grid independence, Appendix C also studies the sufficiency of the spatial discretization generated by the automatic procedure of the CpSimulator platform.

Horizontally homogeneous atmospheric boundary layer flow (HHABL) was used to derive the boundary conditions for the velocity $U$, the turbulent kinetic energy ($k$), and the specific dissipation ($\omega$) (Bre; Gimenez, 2022). The inlet flow follows the log-law profile as:

Horizontally homogeneous atmospheric boundary layer flow (HHABL) was used to derive the boundary conditions for the velocity and the turbulent variables (Bre; Gimenez, 2022). The inlet flow follows the log-law profile as:

**Equation 1:**

$$U(z) = \frac{u_*}{\kappa}\ln\left(\frac{z+z_0}{z_0}\right), \quad k(z) = \frac{{u_*}^2}{\sqrt{\beta^*}}, \quad \omega(z) = \frac{u_*}{\kappa\beta^*(z+z_0)}, \text{with} \quad u_* = \kappa\frac{U_H}{\ln(\frac{H+z_0}{z_0})}$$

where $\kappa$ is the von Karman's constant, $\beta^*$ is a closure coefficient in the k-$\omega$ SST model, $z_0$ is the aerodynamic roughness length of the building terrain equal to 0.446838 m, and the reference wind velocity $U_H$ is 21 m/s at building height H of 34.1 m. The Auto-fitting module of the CpSimulator platform (Bre; Gimenez, 2022) was used to fit these parameters to match the ABL found in the wind tunnel investigation, see Appendices B and C. This wind profile—which in the roughness classification (Wieringa, 1992) corresponds to suburban terrain— is the inflow condition used in all scenarios. The shear stress at the top boundary, combined with a compatible wall function on the ground, guarantees the HHABL condition throughout the upstream domain. Building surfaces were considered smooth, where an automatic near-wall treatment by shifting between the viscous and logarithmic sub-layer formulations was used for turbulent fields. A summary of the boundary conditions employed is shown in Table 1. Given the cylindrical shape of the computational domain used, the boundary conditions at the vertical planes of the external bounds, i.e., Inlet or Outlet, are selected by comparing the orientation of the normal vector to the plane with the direction of the incident wind. This procedure enables using only one mesh per case study when several wind incidence angles are analysed.

**Table 4.1:** Summary of the boundary conditions employed.

| **Boundary** | **Velocity** | **Pressure** | **Turbulence** |
|---|---|---|---|
| **Inlet** | HHABL | Zero gradient | HHABL |
| **Outlet** | Outflow | Outflow | Outflow |
| **Ground** | No-slip | Zero gradient | HHABL wall function |
| **Top** | Shear stress | Zero gradient | Zero gradient |
| **Building** | No-slip | Zero gradient | Hybrid wall function |

The time-averaged RANS equations are solved using an implicit, segregated, three-dimensional FVM. Regarding turbulence modelling, an enhanced k-ω SST model for the accurate prediction of urban wind flow was employed (Gimenez; Bre, 2023). Pressure-velocity coupling was solved with the SIMPLE algorithm. The running procedure begins the simulation by initialising the velocity and turbulent fields for the inlet conditions everywhere. The initial relaxation is gradually deactivated, and first-order discretisation schemes are replaced with second-order discretisation schemes. The iterative solution process is repeated until the normalised residuals for pressure, velocity components, and turbulent fields each have decreased by five orders of magnitude It should be emphasised that the RANS equations yield time-averaged solutions. Pressure, velocity, and turbulent kinetic energy will henceforth refer to these mean fields. The time-averaged wind pressure coefficient $C_P$ at a point $x_i$ on the facade is defined as:

**Equation 2:**

$$C_P = \frac{p(x_i) - p_0}{\frac{1}{2} U_H^2}$$

where the static reference pressure far away from any disturbance is $p_0$ = 0 m²/s².

Finally, the surface-averaged pressure coefficient on a given surface of area Ω was obtained as:

**Equation 3:**

$$\overline{C_P} = \frac{1}{\Omega} \int_{\Omega} C_p \, d\Omega$$

A total of twelve CFD simulations were conducted for each design case and for the reference case. Each simulation corresponds to a different wind incidence ranging from 0º to 360º, with a step size of 30º. This implies a cumulative count of 492 simulations, i.e., 40 design cases and one reference case versus

12 wind incidences. In average, each case study requires a mesh of 1.6 M cells and each CFD simulation demands around 2 h, running in a four-core processor. In every simulation, the $\overline{C_P}$ on each building opening (i.e., window), were computed. As the Reynolds number independence criterion applies (Lin *et al.*, 2021), these data are regarded as representative of the range of wind speeds examined in the building performance simulations.

### 4.2.3 Building performance simulations (BPS)

Building performance simulations were performed with EnergyPlus software to assess the influence of the balcony design on the natural ventilation and thermal and energy performance of the representative model. The construction materials, internal loads (occupancy, electric lights, and equipment), occupancy schedule, natural ventilation, and air-conditioning system settings were considered as shown in Table 4.2.

**Table 4.2:** Building performance simulation input parameters.

| | Parameter | Input value | Reference |
|---|---|---|---|
| **Construction materials** | Glazing thermal transmittance | 5.7 W/m². K | (Neves; Melo; Rodrigues, 2019) |
| | Glazing SHGC | 0.87 | |
| | Wall thermal transmittance (Mortar 0.025 m + concrete block 0.032 m + air gap 0.17 m + concrete block 0.032 m + mortar 0.025 m) | 2.38 W/m². K | (ABNT, 2022) |
| | Wall thermal capacity | 258.6 kJ/m². K | |
| | Wall solar absorptance | 0.61 | (Neves; Melo; Rodrigues, 2019) |
| **Internal loads** | Lighting power density | 14.1 W/m² | (INMETRO, 2020) |
| | Equipment | 15 W/m² | |
| | Occupancy | 10 m²/person | |
| **Schedule** | Occupancy schedule | Weekdays 8 am to 6 pm | |
| **Natural ventilation system** | Natural ventilation strategy | Cross ventilation on adjacent façades | (Neves; Melo; Rodrigues, 2019) |
| | Window opening factor (or openable window area) | 0.41 (Top-hung window frame) | |
| | Window dimensions | 25% window-to-wall ratio | |
| | Balcony door opening factor | 0.45 (two-panel sliding door) | |
| | Balcony door dimensions | 2.0 x 2.10 (width x height) | |
| **Air-conditioning system** | Cooling setpoint | 24 °C | (INMETRO, 2020) |
| | Heating setpoint | 20 °C | |

The electric lights were not automated and set as “always on” during occupied hours. The internal doors were assumed to always be closed. The natural ventilation (window operation) was modelled with the multizone Airflow Network (AFN) model. To accurately implement the AFN model approach, the wind pressure coefficient values ($\overline{C_P}$), generated for the 40 balcony design variations (as detailed in Section 2.2) were used as input data for the AFN models. This ensured that the impact of the balcony design was correctly considered in terms of wind pressure distribution on the building envelope. The window discharge coefficient was set at 0.6, which corresponds to the averaged value of standard window shapes (Jones *et al.*, 2016).

The air-conditioning system was modelled using an ideal load air system, considering the outdoor airflow rate as 27 $m^3$/h.person (0.0075 $m^3$/s.person), according to the Brazilian Health Surveillance Agency (ANVISA, 2003). The mixed-mode ventilation system was automated based on the ASHRAE 55-2020 adaptive model (ASHRAE, 2020). This approach was supported by De Oliveira; Rupp; Ghisi (2021) and Deuble and De Dear (2012), which showed that the ASHRAE adaptive comfort model was suitable for mixed-mode buildings, being more adherent to real users' behaviour than the static Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) model. Furthermore, De Oliveira; Rupp; Ghisi (2021) showed that the 80% acceptability threshold from the adaptive model aligns closely with the actual thermal acceptability reported by occupants in three mixed-mode office buildings located in a humid subtropical climate. The Energy Management System (EMS) was used to set up the MMV automation system, as illustrated in Figure 4.6. The windows were modelled as a binary function, i.e., fully open or fully closed (1/0), with no variations in the opening size.

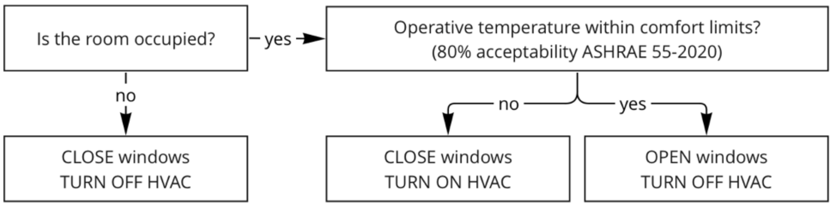
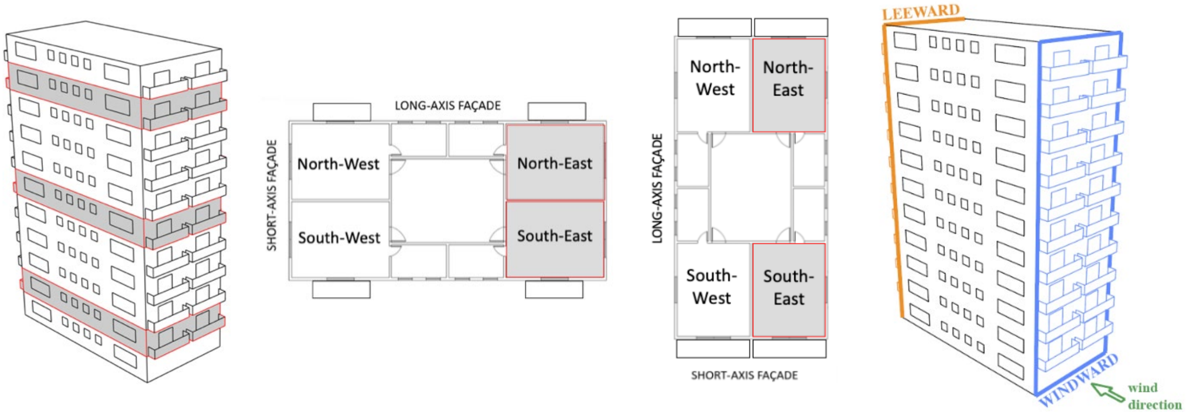



**Figure 4.6:** The modelling approach employed in the Energy Management System (EMS) of EnergyPlus

Balcony design variations were analysed considering a low level (first floor), an intermediary level (fifth floor), and a high level (ninth floor); see Figure 4.7a. To assess the effects of the balcony design on thermal and energy performance, two offices per floor were selected, with balconies located on the north or south façades; see Figure 4.7b. The natural ventilation analysis was performed considering windward or leeward wind incidences; see Figure 4.7c. To this end, the hourly results of air change rates run over a one-year period were filtered to identify instances when the wind incidence was perpendicular to the south façade (specifically at 90 degrees), based on the information available in the weather file.



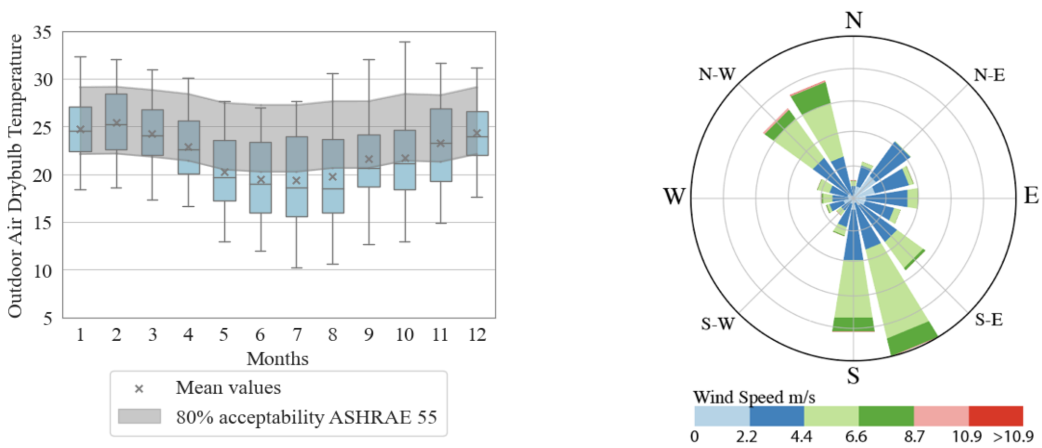

a) 1st, 5th, and 9th floors analysed

b) Office rooms analysed, with balconies located on the north and south façades

c) Windward and leeward façades analysed.

**Figure 4.7:** Building parameters selected to analyse the design cases.

The annual building simulations were performed using a typical meteorological year, which was derived from the period between 2007 and 2021 (TMYx.2007-2021) (Bre *et al*., 2021; LABEEE, 2018) in São Paulo, Brazil. São Paulo is located at latitude 23° 32′ South and longitude 46° 38′ West, at an altitude of 800 m. Its climate is classified as humid subtropical (Cfa), according to the Köppen-Geiger climate classification (Beck *et al*., 2018) (Figure 4.8).




(a) Outdoor temperatures, highlighting the ASHRAE 55-2020 adaptive model 80% acceptability threshold.

(b) Predominant wind incidence and speed.

**Figure 4.8:** São Paulo weather conditions during occupied hours (8 a.m. – 6 p.m.) according to the weather file used in the simulations

Regarding the building performance indicators, we examined the air change rate, measured in air changes per hour (ACH) in each office, assessed during periods when windows were open and air conditioning was off, and the cooling thermal loads (kWh/m$^2$.year) to calculate the energy demand required to cool an office per square meter throughout a year, computed when windows were closed, and the air conditioning was on.

Since the building operates on a mixed-mode ventilation strategy, cooling thermal loads were considered a representative metric for both thermal and energy performance, as decreasing the energy demand for cooling implies improved thermal conditions inside the office room. According to ASHRAE 90.1 (2010) the demand for cooling surpasses the one for heating in the city of São Paulo, presenting 4011 Cooling Degree Days (CDD10) and only 248 Heating Degree Days (HDD18). Therefore, heating thermal loads were disregarded, as they were irrelevant to the analysed climate. Results for all the balcony design variations were compared with the reference case (i.e., without balconies) through the calculation of the percentage change in the air change rate and cooling thermal loads.

### 4.2.4 Sensitivity analysis

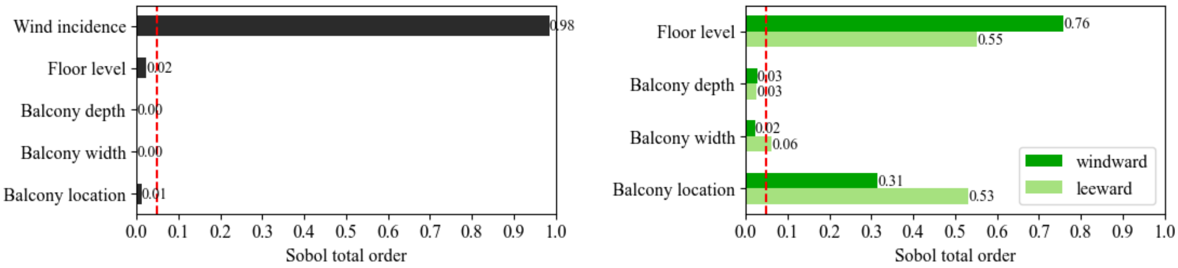
A sensitivity analysis (SA) was conducted to determine the most influential parameters on the building performance simulation indicators. The Sobol method was considered suitable for this analysis, since it quantifies the variance of the output considering the contribution of individual parameters and interaction effects among inputs (Saltelli *et al*., 2010; Wei, 2013). This approach helped to identify the parameters that require special attention for designing balconies for mixed-mode office buildings.

The sensitivity analysis was performed using the results from the building performance simulations, which were performed separately for the metrics of air change rate and cooling thermal loads. Saltelli's sample method was employed to generate the dataset for the sensitivity analysis, using continuous values (Saltelli *et al*., 2010). Since all variables in this study are discrete, the sampling method was adjusted by rounding the selected variable values to the nearest integer. The parameters that achieved a Sobol index above 0.05 were considered influential parameters for the building performance indicators. Additional sensitivity analyses were conducted individually for the most influential parameter identified in each metric, enhancing the analysis of results.

## 4.3 Results and discussion

### 4.3.1 Natural ventilation performance

The sensitivity analysis revealed that the wind incidence (windward or leeward) was the most influential parameter for the natural ventilation performance (Figure 4.9a), consistent with findings from Mohamed *et al*. (2014) and Mirabi *et al*. (2020) and Omrani *et al.* (2017). Therefore, two additional sensitivity analyses were conducted to analyse windward and leeward results separately (Figure 4.9b). The floor level ($1^{st}$, $5^{th}$, or $9^{th}$) and the balcony location (short- or long-axis) were identified as the most influential parameters for both windward and leeward façades.

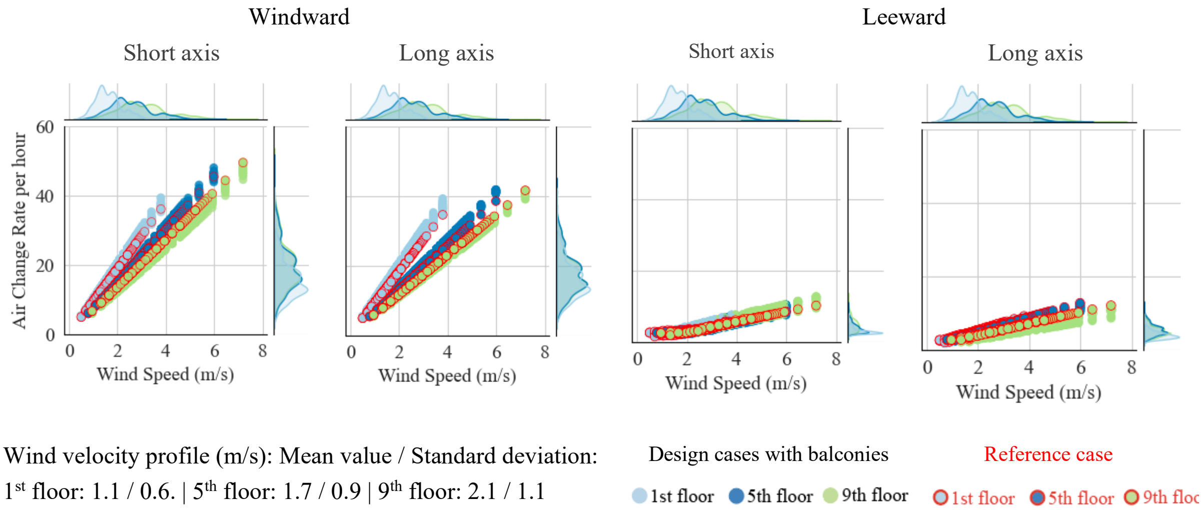



a) Sensitivity analysis for air change rate.

b) Sensitivity analysis for air change rate for the windward and leeward façades.

**Figure 4.9:** Sensitivity analysis results for natural ventilation

As the wind speed increased according to the height above the ground, the 9th floor mostly showed higher air change rate values than the 1$^{st}$ and 5$^{th}$ floors for the two wind incidences and two balcony locations. These findings complement the study conducted by Mohamed *et al*. (2014), which indicated that in windward conditions, the average air speed inside cross-ventilated rooms increased for higher floors. When the façade with balconies is windward, the design cases showed higher levels of air change rate (15 to 25 ACH) than when leeward (2 to 5 ACH) (Figure 4.10), as expected.




Wind velocity profile (m/s): Mean value / Standard deviation:
1$^{st}$ floor: 1.1 / 0.6. | 5$^{th}$ floor: 1.7 / 0.9 | 9$^{th}$ floor: 2.1 / 1.1

a) Air change rate per hour for offices located in the windward façade

b) Air change rate per hour for offices located in the leeward façade

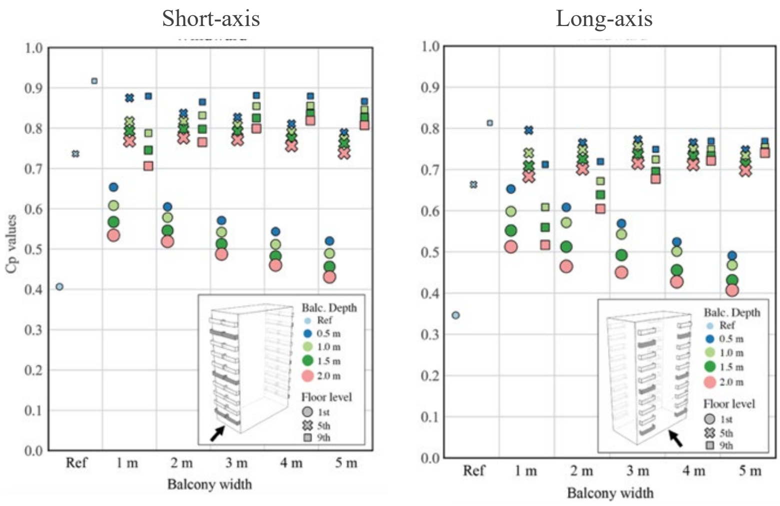
**Figure 4.10:** Impacts of the use of balconies considering the wind speed, wind incidence, and balcony location. In the margins, density curves show the frequency of occurrence in the outdoor wind speed (axis x) and in the air change rate (axis y).

The sensitivity analysis results also showed that the balcony geometry (depth and width) is a less influential parameter. This corresponds with the findings of Omrani *et al*. (2017), who demonstrated that the effects of balcony depth on the cross-ventilation performance were less sensitive compared to rooms with single-side ventilation. Nevertheless, the addition of balconies to the façade and the variations in the balcony dimensions notably impacted the natural ventilation performance in the office rooms when compared to the reference case, i.e., without balconies (Figure 4.10), showing the importance of further assessing the subject. Therefore, the following subsections analyse the wind pressure coefficient values, used as input data for the building performance simulations, and the percentage change (reduced or increased) in the air change rate by comparing the design cases with balconies with the reference case (without balconies).

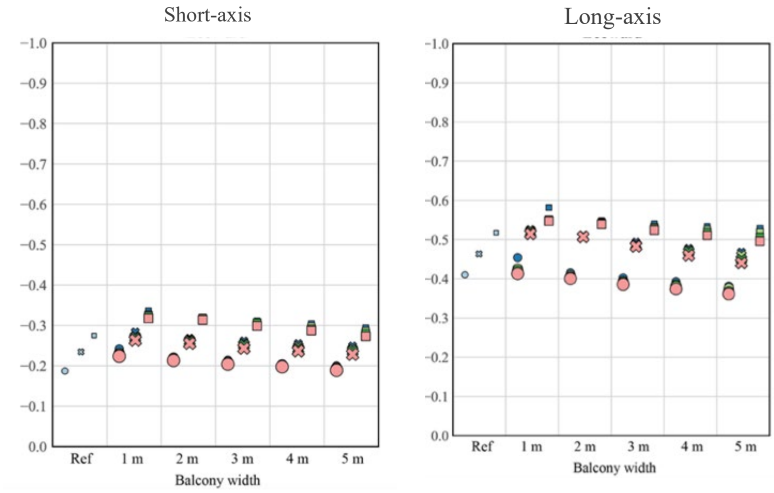
a) Impact of balcony location on the façade

The investigation regarding the balcony location on distinct façades (short axis or long axis), which has not yet been investigated in the literature, highlighted this parameter as more sensitive to natural ventilation than other balcony geometry parameters, such as the balcony width and depth. The addition of balconies to both short-axis and long-axis façades increased the complexity of the wind pressure distribution across the façade; see Figure 4.11. Design cases with balconies located on the short-axis façade showed higher air change rates than those located on the long-axis façade (Figure 4.10). This is due to the higher values of wind pressure coefficients on the narrow façade (short-axis) in contrast to the wide façade (long-axis); see Figure 4.11.

The use of balconies on the short-axis façade showed potential to improve the natural ventilation for the first and fifth floors when windward and for all the floors when leeward. When windward, the addition of balconies to the long-axis facade was also advantageous for the first and fifth floors, but not for the ninth floor, nor for any of the floors when facing the opposite direction. Moreover, when leeward the air change rates decrease compared to the reference case without balconies.; see Figure 4.10. These results emphasise the importance of considering the prevailing wind incidence, the floor level, and the building floor plan shape to set the balcony location on the façade and its dimensions.




a) **Windward** façade

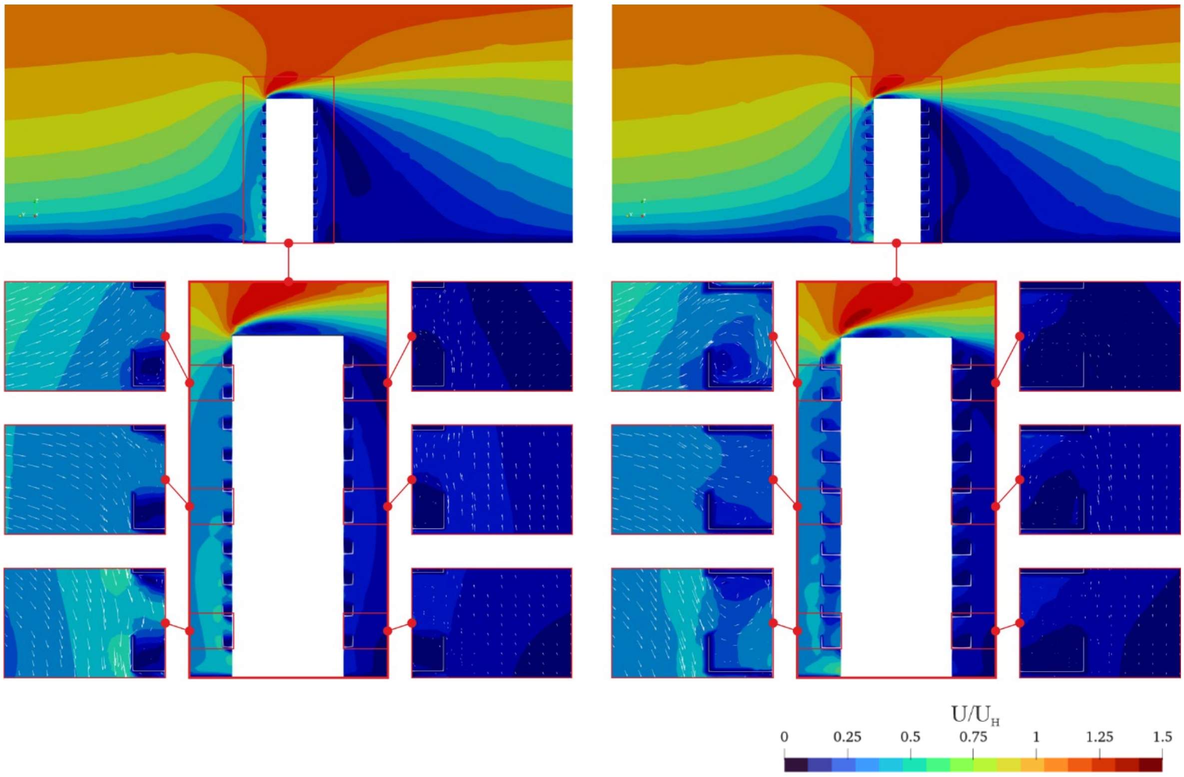



b) **Leeward** façade

**Figure 4.11:** Wind pressure coefficients results.

b) Impact of balcony dimensions on the outdoor airflow

As was observed in the previous section, larger (wider and deeper) balconies decrease the Cp differential between windward and leeward surfaces. To better understand this effect, Figure 4.12 shows the CFD results in the form of contours for $U/U_H$ and the detailed velocity fields around balconies for levels 1, 5, and 9, to assess the impact of balcony dimensions on the outdoor airflow. For this, we compare two extreme designs: one with a prominent balcony of 5 m in width and 2 m in depth, and the other with a small size of 1 m in width and 1 m in depth. Larger balconies reduce the reattachment lengths on the roof and the ground behind the building, which increases the pressure in these areas and lessens the separation bubble above the roof, according to the overview flow pattern. Upon examining various floor levels, the increased sheltering effect of larger balconies on windward surfaces becomes apparent, as does the amplified strength of vortexes inside their cavities, primarily on higher floor levels. Because of these two phenomena, broader and deeper balconies result in smaller pressure differences, making them less suitable for natural ventilation applications.



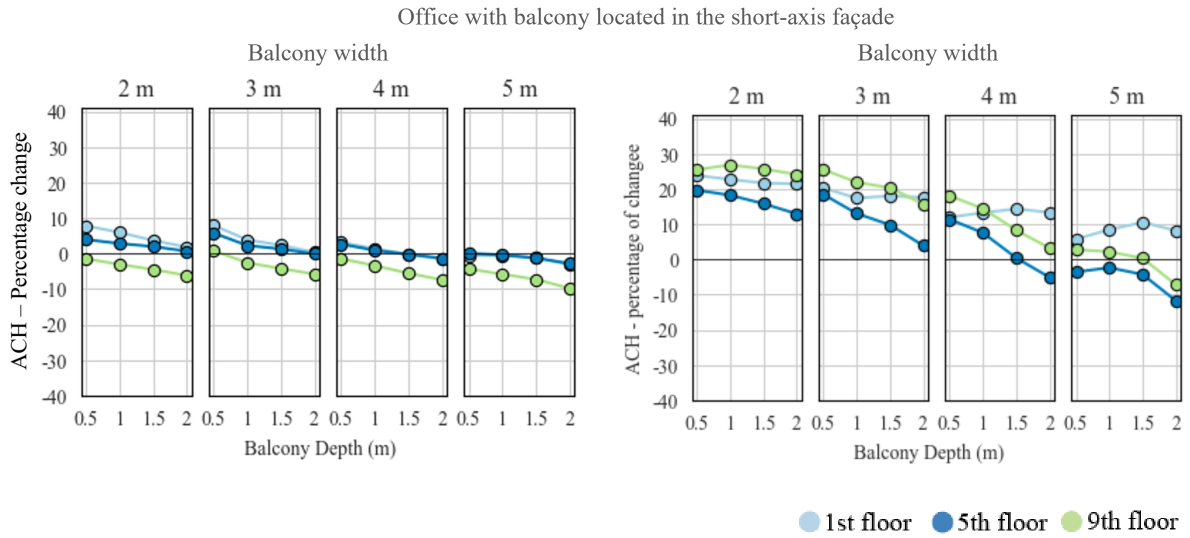

a) Balconies 1 m x 1 m (width x depth) b) Balconies 5 m x 1 m (width x depth)

**Figure 4.12:** Contours for $U/U_H$ and details of the velocity fields around balconies for levels 1, 5, and 9.

c) Influence of balcony dimensions on the indoor airflow

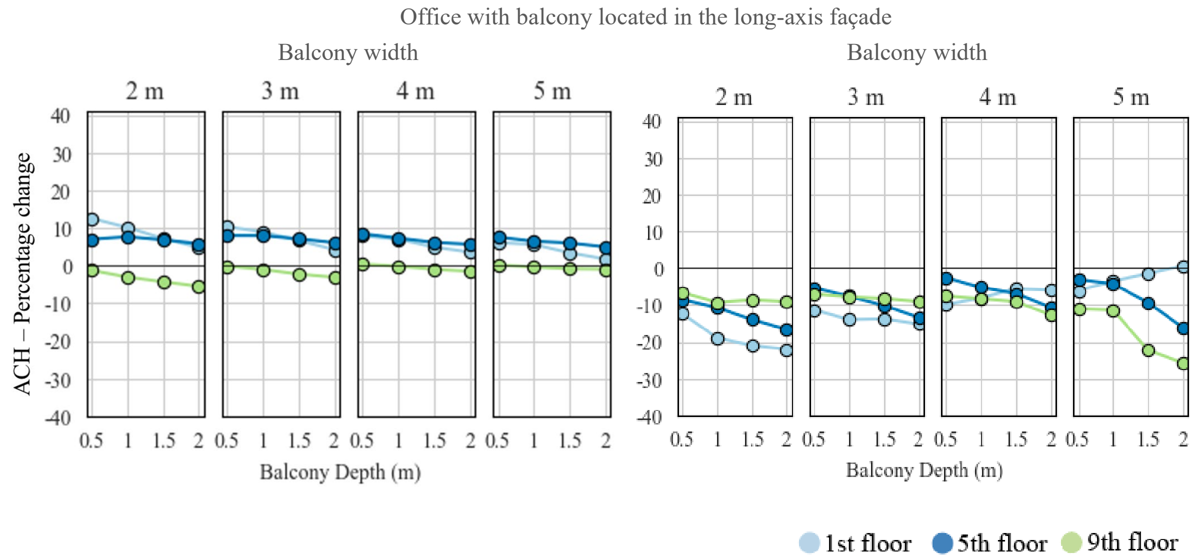
The influences of balcony dimensions (width and depth) were analysed regarding the balcony's location in the façade, the floor level, and the wind incidence. When the balcony is positioned on the short-axis façade, the best design option is narrow and shallow balconies (2.0 m x 0.5 m) for all floor levels and for both wind incidences (windward and leeward); see Figure 4.13. When facing windward, this same balcony dimension significantly improved the natural ventilation performance of office rooms on the 1st and 5th floors (up to 10% and 7%, respectively), with a minor 2% reduction in air change rates observed on the 9th floor compared to the reference case (without balconies). When facing leeward, it enhanced the natural ventilation performance of office rooms for all floor levels by up to 27%. Wider and deeper balconies diminished the natural ventilation potential of both leeward and windward façades; see Figure 4.13.

When the balcony is located on the long-axis façade, the optimal design options are more case-dependant. When facing windward, the use of narrow and shallow balconies (2.0 m x 0.5 m) showed as the best design choice for the 1$^{st}$ floor, increasing air change rates by 12% compared to the reference case; see Figure 4.14. For the 5$^{th}$ floor, shallow balconies (0.5 m) are the best option, regardless of the balcony width, increasing air change rates by 8%. For the 9$^{th}$ floor, regardless of the balcony depth, the widest balconies (5.0 m) are the best option, since they not only enhance but also do not reduce the natural ventilation performance. As the balconies decrease the air change rates in the office rooms of all floor levels when facing leeward, adding balconies to the long-axis façade is not recommended when the prevailing winds throughout the year are unfavourable to natural ventilation.




a) Windward b) Leeward

**Figure 4.13:** Impacts of balcony design on the air change rate when located in the short-axis façade.




a) Windward b) Leeward

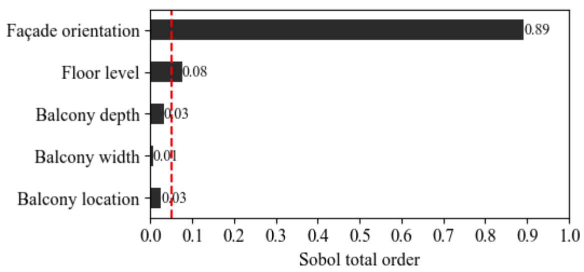
**Figure 4.14:** Impacts of balcony design on the air change rate when located in the long-axis façade.

The impacts of the balcony geometry on the natural ventilation performance of office rooms were complex and case-dependent, being highly related to the building floor plan proportion (long- or short-axis, for rectangular buildings), wind incidence (windward or leeward), and floor level (low, intermediate, or high level). When feasible, it is preferrable to orient office rooms based on the prevailing wind incidence, as those located on the windward façade exhibited superior natural ventilation performance. This observation aligns with findings by Omrani *et al*. (2017) and Mohamed *et al*. (2014), which indicate that the highest indoor wind speed is achieved when the façade is windward. The use of narrow and shallow balconies (2 m x 0.5 m) in narrow façades (short axis) showed to be efficient in improving the natural ventilation for the lower (first) and intermediate (fifth) floor levels when the wind incidence is either windward or leeward, compared to the reference case.

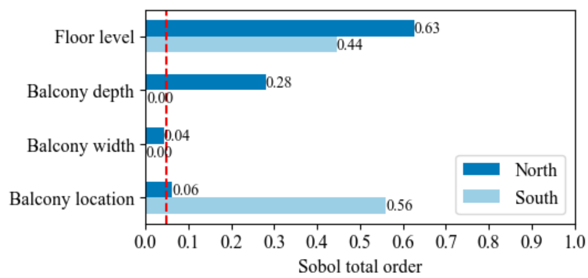
The outcomes of our study concerning the balcony depth align with results from Zheng *et al*. (2021), showing that increasing the balcony depth reduced the façade-averaged $\overline{C_P}$ values on the windward façade. They also echo findings from Mohamed *et al.* (2014) which demonstrated that a cross-ventilated room with deeper balcony (3 m) experienced lower ventilation rate and average indoor air velocity than a room with a 1.5 m deep balcony, thus compromising the balcony's efficiency as wind scoop. Nevertheless, research by Izadyar *et al*. (2020) conducted in a single-side ventilated residential apartment, revealed shallow balconies (0.85 m and 1.275 m deep) exhibited lower average indoor wind speed when compared with a 2 m deep balcony. This highlights the importance of considering ventilation strategy in balcony design. Furthermore, air change rates inside the office rooms were highly dependent on the wind pressure coefficients on the façades, reinforcing the need to use primary data as input for the building performance simulations.

### 4.3.2 Thermal and energy performance

The sensitivity analysis showed the façade orientation as the most influential parameter for thermal and energy performance (Figure 4.15a). Therefore, two additional sensitivity analyses were conducted to separately assess the results for when the balcony is on the south or north façades (Figure 4.15b). In both cases, the floor level was identified as a highly influential parameter, and the balcony width was identified as not influential. The balcony depth was considered influential only for the north façade, and the balcony location was considered influential only for the south façade.




a) Sensitivity analysis for cooling thermal loads



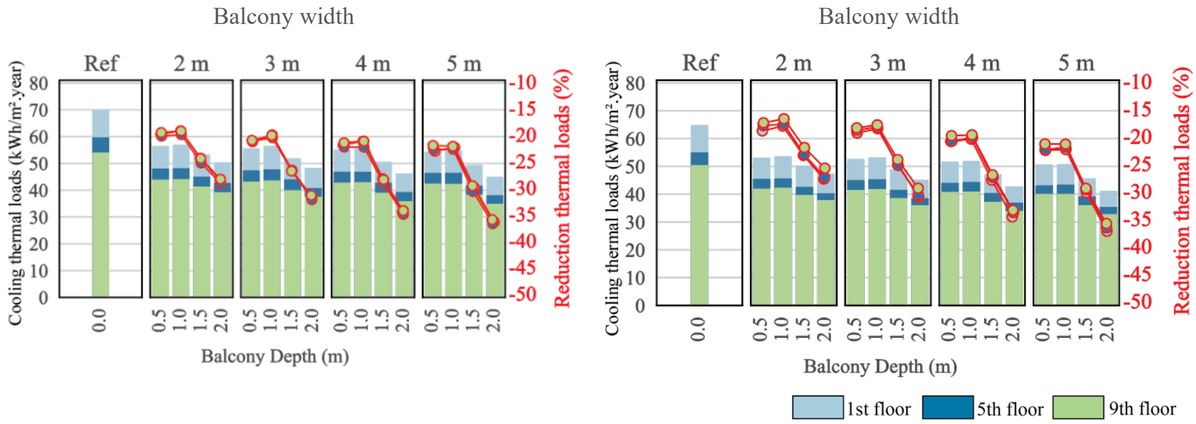

b) Sensitivity analysis for cooling thermal loads of offices with balconies on the north and south façades.

**Figure 4.15:** Sensitivity analysis for thermal and energy performance (cooling thermal loads).

To further assess and quantify the impacts of the balcony location on the façade and its dimensions on the thermal and energy performance of the office rooms, the percentage change of cooling thermal loads was calculated by comparing the different design case results with the reference case.

a) Impact of balcony location on the façade

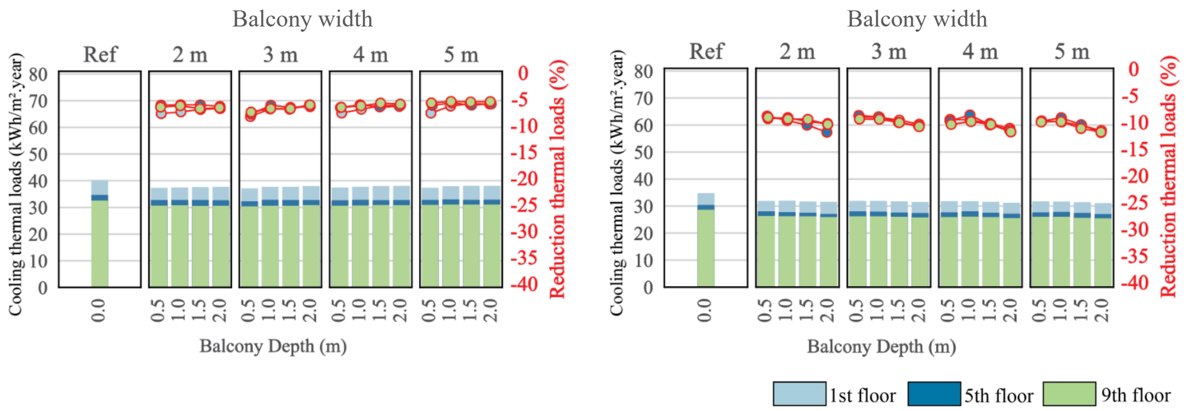
The addition of balconies to both long-axis and short-axis façades was proven to be an efficient design strategy to decrease energy use for cooling across all floor levels. These findings are aligned with existing literature, indicating that balconies can reduce solar heat gain and decrease temperatures in adjacent rooms (Dahlan *et al*., 2009b; Fernandes *et al*., 2015; Ribeiro *et al*., 2024). Although the 9$^{th}$ floor showed improved thermal performance due to higher natural ventilation performance, the percentual reduction in energy usage for cooling remained consistent across all floor levels, for both south and north façades. However, the addition of balconies was more efficient for design cases facing North, since this façade receives direct solar radiation throughout the year at south-latitude locations, such as São Paulo. Results showed a reduction in the cooling thermal loads of up to 37% for office rooms at the north façade and up to 10% for office rooms at the south façade for all floor levels, compared to the reference case; see Figures 4.16 and 4.17.




a) Office with balcony located on the short-axis façade

b) Office with balcony located on the long-axis façade

**Figure 4.16:** Impacts of balcony design on the office located in the north façade.




a) Office with balcony located on the short-axis façade

b) Office with balcony located on the long axis façade

**Figure 4.17:** Impacts of balcony design on the south façade.

b) Influence of balcony width and depth dimensions

The influences of balcony dimensions (width and depth) were analysed regarding the balcony's location in the façade, the floor level and the façade orientation. When positioned on the north façade, the widest and deepest balconies (5.0 m x 2.0 m) are the best design option for all floor levels and both balcony locations (short-axis and long-axis). In this case, increasing the balcony depth resulted in significant reductions in the cooling thermal loads, reaching up to 30% for balconies 1.5 m deep and up to 36% for balconies 2 m deep, compared to the reference case; see Figure 4.16. These findings are aligned with Fanger's thermal comfort calculations conducted by Izadyar *et al.* (2020), indicating deeper balconies enhanced the room thermal comfort. The balcony width had a minor effect, but still contributed to decreasing cooling thermal loads. For instance, increasing the balcony width from 2 m to 5 m reduced thermal loads from up to 30% to up to 36% across all the analysed floor levels and both balcony locations (short- and long-axis façades), compared to the reference case.

When positioned on the south façade, the balconies were less effective but still proved to be advantageous for thermal and energy performance. Thermal loads decreased by 5% and 10% across all floor levels when balconies were positioned on the short-axis and long-axis façades, respectively, when compared to the reference case; see Figure 4.17. Notably, the variation in balcony dimensions (width and depth) and their location on the façade (short and long axis) demonstrated similar thermal and energy performance results. This suggests that the balcony dimensions on the south façade can be more flexible.

### 4.3.3 Cross-analysis

Balancing trade-offs in balcony design to optimise natural ventilation and thermal and energy performance of mixed-mode office buildings was achieved through a cross-analysis of the results obtained through CFD and BPS. These trade-offs are pivotal when designing mixed-mode office buildings, as effective natural ventilation directly enhances thermal performance and saves energy by decreasing reliance on air conditioning systems.

Balcony design recommendations showed different trends for north and south façades, indicating that balconies should be designed according to the façade orientation. For the south façade, the use of narrow and shallow balconies (2 m x 0.5 m) emerged as the best design option for natural ventilation and thermal and energy performance. Since variations in balcony dimensions did not substantially impact the energy usage for cooling in offices situated on the south façade, reducing cooling thermal loads by 5% to 10%, depending on the balcony location and floor level, the most suitable balcony dimension for natural ventilation performance should be adopted. This contributes to reducing solar heat gains and thermal loads for cooling, while simultaneously enhancing natural ventilation by up to 28%, depending on the balcony location on the façade, wind incidence and floor level. Conversely, for the north façade, the use of deep and wide balconies is the best recommendation, resulting in reduction in cooling thermal loads by up to 36% for both analysed balcony locations on the façade and floor levels. Although this dimension may not be favourable for natural ventilation performance, potentially leading to a decrease in the air change rate by up to 25% depending on the balcony location on the façade, wind incidence and floor level, the notable benefits of enhancing thermal and energy performance could overcome this limitation. These results contribute to the literature in providing balcony design recommendations to simultaneously improve the natural ventilation, thermal and energy performance of mixed-mode office buildings.

## 4.4 Limitations and future studies

The balcony design recommendations provided in this study are based on predominant construction practices in São Paulo, Brazil, which were used to create the reference and design cases for this research. Future research could extend these cases to diverse building design contexts by incorporating scenarios with single-sided natural ventilation strategy, exploring variations in window opening factor, and considering the influence of surrounding buildings. Outdoor noise may also influence occupant behaviour, particularly in deciding whether windows are kept open or closed, as emphasized by Ribeiro *et al*. (2024). This aspect was not considered in the current mixed-mode strategy adopted for the building performance simulations.

The balcony design can also dictate how occupants will use this space. Literature shows that balconies are desirable by users, as it creates a connection between indoor and outdoor (Peters; Halleran, 2021; Ribeiro; Ramos; Flores-Colen, 2020). A wide and deep balcony is more likely to serve this purpose as an occupied space, while a narrow and shallow balcony is prone to be relegated to a non-occupied service area. Future research could assess the effects of balcony design on occupant satisfaction with the workplace, and how it may impact their productivity.

It is important to note that the reference case (without balconies) and the design cases (with balconies) analysed in this study are notional models, making physical measurements unfeasible. Future research could aim for empirical validation in buildings with balconies, thereby enhancing the findings and enabling to extrapolate our findings to other building design settings.

## 4.5 Conclusions

The present research introduced an integrated approach, combining computational fluid dynamics (CFD) and building performance simulation (BPS), to assess the effects of balcony design on the natural ventilation and thermal and energy performance of high-rise mixed-mode office buildings in São Paulo, Brazil.

The achieved results showed that the effect of balcony design on natural ventilation is complex and case-dependent. Thus, the use of wind pressure coefficients from primary data sources (e.g., CFD) is essential to ensuring accurate simulation results in natural ventilation modelling using BPS. This is especially mandatory for analysing buildings with prominent façade elements, such as balconies.

Balcony design can be challenging since different design options may have conflicting effects on the natural ventilation and thermal and energy performance of buildings. Narrow and shallow balconies (2 m x 0.5 m) were identified as the best balcony design for natural ventilation, while wide and deep balconies (5 m x 2 m) emerged as the best design for enhancing thermal and energy performance in offices on the north façade, across all floor levels and for both balcony locations (short-axis and long-axis façades). For the south façade, since it receives less direct solar radiation throughout the year, balcony dimensions had low impact on thermal and energy performance. Therefore, it is recommended to prioritise narrow and shallow balconies (2 m x 0.5 m) across all the floor levels, independently of the balcony location (short or long-axis façade), as this design predominantly favours natural ventilation.

The present research pioneers in providing balcony design recommendations to enhance natural ventilation, thermal and energy performance simultaneously for mixed-mode office buildings. The results obtained provide valuable information for building designers, emphasising that balconies should not be designed solely as decorative façade elements or spaces for building services. Conversely, they should be appropriately dimensioned to fully harness their potential as active contributors to improving natural ventilation and thermal and energy performance in high-rise mixed-mode office buildings.

## Acknowledgments

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# 5. Effects of the use of balconies on daylight, thermal and energy performance

This chapter is the transcription of the following paper:

**Balcony design recommendations to enhance daylight, thermal and energy performance of mixed-mode office buildings**

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## Abstract

The use of balconies in hot climates holds the potential to block direct solar radiation thus reducing energy consumption for cooling and enhancing visual comfort. However, balconies may also diminish daylight availability within the room, thereby affecting occupants' satisfaction and wellbeing. This study aimed to provide balcony design recommendations through a parametric analysis of various combinations of balcony design parameters (balcony depth, width, location on the façade, and parapet type), along with key building design parameters (façade orientation, floor level, and glazed door width), considering a multi-domain objectives assessment. The results demonstrate that balcony design can effectively enhance visual comfort, thermal performance, and energy efficiency while ensuring optimal daylight availability in office rooms located in subtropical climates. Recommendations for balcony design were tailored to each façade orientation and thoughtfully combined with the glazed door width. One optimal combination, featuring a 3-meter-wide glazed door and a 2-meter-deep balcony, proved beneficial for all façade orientations across all floor levels. However, the choice of parapet type should align with the balcony's location, which is directly correlated with the room's depth. The insights gained from this study offer valuable information for building designers, highlighting that balconies should not be designed solely as decorative façade elements or spaces for building services. Furthermore, the cross-analysis method developed in this study can be applied by researchers and designers to their own case studies.

**Keywords:** balcony, cross-analysis, daylight performance, thermal performance, energy performance, decision-making guidelines

## 5.1 Introduction

Balconies are spaces that connect indoor and outdoor areas, serving as fixed solar shading device for buildings located in hot climates. From a building physics perspective, their design presents a complex challenge due to trade-offs between daylighting, thermal and energy performance. Wide and deep balconies hold the potential to reduce direct solar radiation, reducing energy consumption for cooling (Mohammed, 2021) and improving visual comfort (Al-Sallal; Abouelhamd; Dalmouk, 2018; Gabrova, 2014). However, they may also cause a reduction in the amount of indoor daylight, which can increase the energy consumption for electric lighting and impact occupants' satisfaction and wellbeing (Gabrova, 2014; Loche *et al*., 2021).

Balconies are commonly used in residential buildings and often desired by occupants, since they allow the development of multifunctional activities such as leisure, entertainment, and gardening (Peters; Halleran, 2021; Peters; Masoudinejad, 2022; Ribeiro; Ramos; Flores-Colen, 2020). Also in offices, balconies are gaining popularity. For example, a study in São Paulo, Brazil, revealed that the use of balconies in mixed-mode office buildings increased by 85% from 1995 to 2016 (Neves; Melo; Rodrigues, 2019), which may be attributed to the growing popularity of split air-conditioning units, which require an outdoor space to house the condenser unit (Figure 5.1). Indeed, balconies are a popular option to house the condenser unit in high-rise buildings located in tropical climates, driven by considerations of both façade aesthetics and the recommendation to position the condenser in well-ventilated areas, in order to enhance heat dissipation and system efficiency (Abdullah; Barwari, 2022; Chow; Lin; Wang, 2000; Xue *et al*., 2007). This trend also represents an opportunity to promote the use of balconies in office buildings, as they can be used not only for accommodating building services but also as effective shading control systems, acting as a daylight diffusor and helping to decrease the energy consumption for cooling.

a) Office with balcony

b) Balcony used as service area to house the condenser unit

c) Office building façade with condenser unit in the balcony

**Figure 5.1**: Mixed-mode office buildings with balconies in the city of São Paulo, Brazil.
Source: Pereira (2019)

The complexity of balcony design in terms of building energy performance is highlighted in the literature, as most research studies focus on isolated objectives. A systematic literature mapping showed that the combined impacts of balconies on daylight, thermal and energy performance concurrently were analysed in six studies only (Dahlan *et al*., 2009a; Elgohary; Abdin; Mohamed, 2023; Li *et al*., 2023; Liu; Chen, 2017; Ribeiro; Ramos; Flores-Colen, 2020; Yang; Li, 2022). The effects of balconies on thermal and daylight performance of residential rooms during summer were evaluated through surveys and field measurements by Dahlan *et al*. (2009a), Yang and Li (2022) and Ribeiro *et al.* (2024). Balconies were identified as effective elements for enhancing thermal comfort, although they reduced indoor daylight availability. Nevertheless, the results remained compliant with minimum daylight requirements (DAHLAN *et al*., 2009a; YANG; LI, 2022). Similarly, results from Ribeiro et al. (2024) demonstrated that rooms without balconies exhibited higher indoor temperatures during summer, with temperatures 4°C higher than outdoor temperatures, whereas indoor spaces provided with open balconies on the South façade were 3°C cooler. While apartments without balconies achieved higher illuminance levels compared to those with balconies, these values exceeded thresholds considered visually comfortable, and the presence of balconies helped regulate excessive daylight levels.

Building performance simulations were conducted by Liu and Chen (2017), Li *et al*. (2023), and Elgohary, Abdin and Mohamed (2023) to optimise the balcony design for daylight and thermal performance. The three studies showed that balconies should be designed in correlation with the window-to-wall ratio. Liu and Chen (2017) suggested increasing the window-to-wall ratio from 50% to 75% and 100%, to allow a deeper balcony (3 m) without compromising daylight performance, enhancing the energy savings for cooling in residential buildings located in Taiwan. Li *et al*. (2023) recommended adjusting the window-to-wall ratio during balcony renovations to enhance both thermal and daylight performance in ancient residential buildings located in Beijing, China. A window-to-wall ratio of 50-60% with a 1.2-meter-depth balcony, for example, could improve indoor thermal comfort while meeting daylight requirements. Elgohary, Abdin and Mohamed (2023) employed parametric design to determine optimal block arrangements and balcony shapes for designing residential buildings in Cairo, Egypt. The authors suggest that the balcony depth should be designed in correlation with the window-to-wall ratio and based on the façade orientation. The window-to-wall ratio should vary according to each façade, in order to balance daylight penetration and glare, with the optimum percentage being 10% for the West, South, and East façades, and 60% for the North orientation. There are no benefits to thermal and energy performance in adding balconies to the North façade (considering Cairo's location in the northern hemisphere), except for architectural aesthetics or occupants' preferences. The design for the West façade can incorporate more vertical elements, while the South façade requires deeper balconies.

Current scientific literature predominantly focuses the analysis of balconies' performance on residential buildings (Bayazit; Kisakurek, 2023; Dahlan *et al*., 2009a; Duarte *et al*., 2023; Izadyar *et al*., 2020; Liu *et al*., 2021; Omrani *et al*., 2017; Peters; Masoudinejad, 2022; Ribeiro *et al*., 2024; Ribeiro; Ramos; Flores-Colen, 2020; Tungnung, 2020). This emphasis is evident in the comprehensive literature review conducted by Ribeiro *et al*. (2020) regarding the impact of balconies on residential buildings, and in the ongoing discussion regarding the significance of balconies in residential buildings during the COVID-19 pandemic (Bayazit; Kisakurek, 2023; Duarte *et al*., 2023; Peters; Halleran, 2021; Peters; Masoudinejad, 2022; Säumel; Sanft, 2022). Yet, conclusions drawn from studies examining the daylight, thermal, and energy performance of dwellings may not translate to office buildings, due to variations in occupancy schedules and internal loads, highlighting the need for research specifically focused on the office typology. Moreover, performance-based balcony design is complex and correlated to other building design parameters. Possible consequences of design changes are not always trivial and could affect its performance in multiple domains. Therefore, this study aims to provide a comprehensive assessment of combinations of balcony design parameters (balcony depth, width, location on the façade, and parapet type), along with key building design parameters (façade orientation, floor level, and glazed door width) to provide balcony design recommendations to promote the use of balconies as active contributors to enhancing daylighting, thermal and energy performance in mixed-mode office buildings located in subtropical climates.

## 5.2 Methods

The research method was divided into five steps, as illustrated in Figure 5.2 and further detailed in the following subsections.

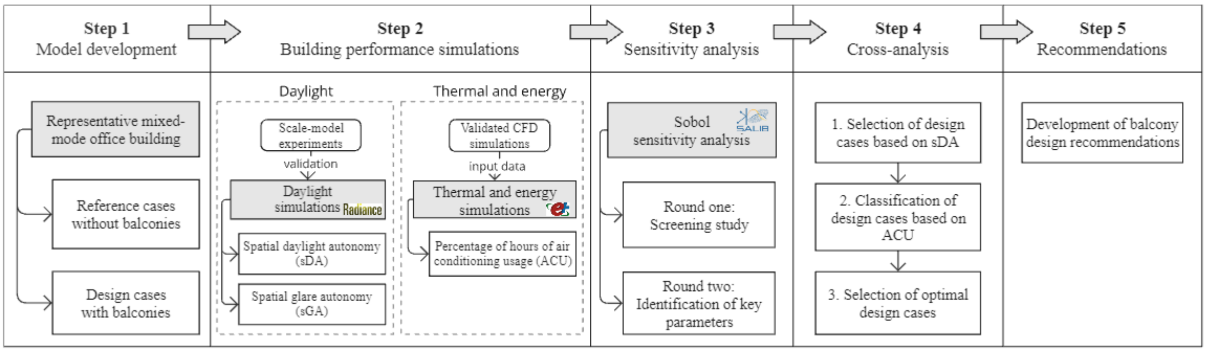
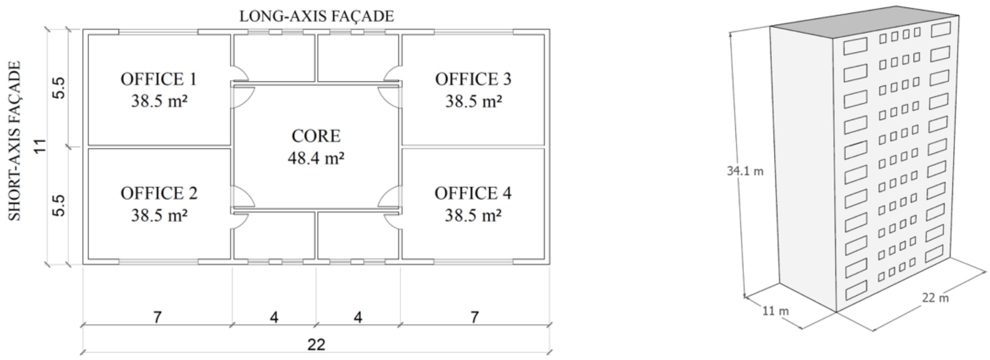



**Figure 5.2:** Methods workflow

### 5.2.1 Representative model development and variable parameters selection (Step 1)

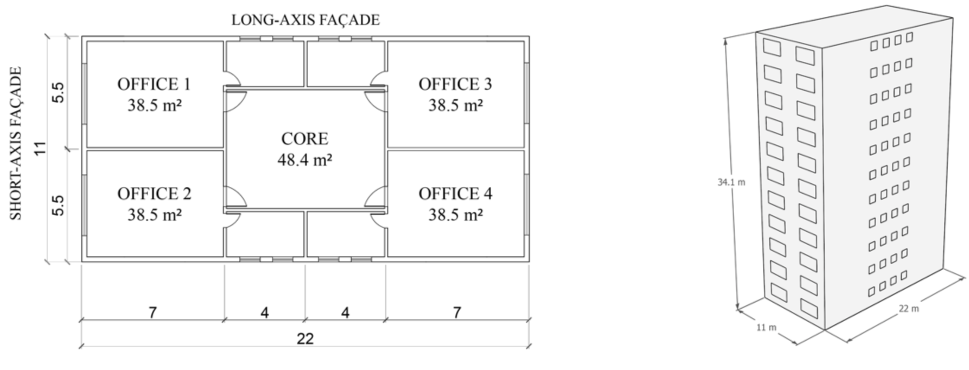
A representative model was defined to illustrate a 'typical' mixed-mode office building built in São Paulo, Brazil. Envelope design and construction information were extracted from a database containing information gathered from 153 surveyed case studies of mixed-mode office buildings built in São Paulo between 1995 and 2016 (Neves; Melo; Rodrigues, 2019). Considering that the lifespan of a building is on average 30-50 years (Andersen and Negendahl, 2023), the buildings in this database were considered a representative sample for extracting typical features. The design and envelope characteristics of the representative model were established based on the mean values of continuous variables and the highest frequency values of categorical variables from the database.

The representative model is composed of 11 floors, each one containing four cellular office rooms with a floor-to-ceiling height of 2.75 m, connected by a central core (Figure 5.3). Each office room has a service area that includes a small toilet and kitchen/pantry, with two small windows (1 m height x 1 m width x 1.5 m sill height). The windows in the office room are centrally positioned along the horizontal axis, with a window-to-wall ratio of 25%. Its position varies between the long-axis façade (Figure 5.3a) and the short-axis façade (Figure 5.3b), configuring two options of representative model. When the office window is located on the long-axis façade, the room is 7 m wide and 5.5 m deep. Conversely, when the window is located on the short-axis façade, the room is 5.5 m wide and 7 m deep. The mixed-mode strategy consists of natural ventilation and individual air-conditioning systems installed in each office room, with independent outdoor and indoor units. The representative model was analysed considering North/South and East/West solar orientations (Figure 5.4). The model was considered isolated, without surrounding buildings, and its location (São Paulo, Brazil) is characterized by latitude 23° 32′ South and longitude 46° 38′ West, at an altitude of 800 m. São Paulo's climate is classified as humid subtropical (Cfa), according to the Köppen-Geiger climate classification (Beck *et al.*, 2018) (Figure 5.5).




Floor plan Building axonometric

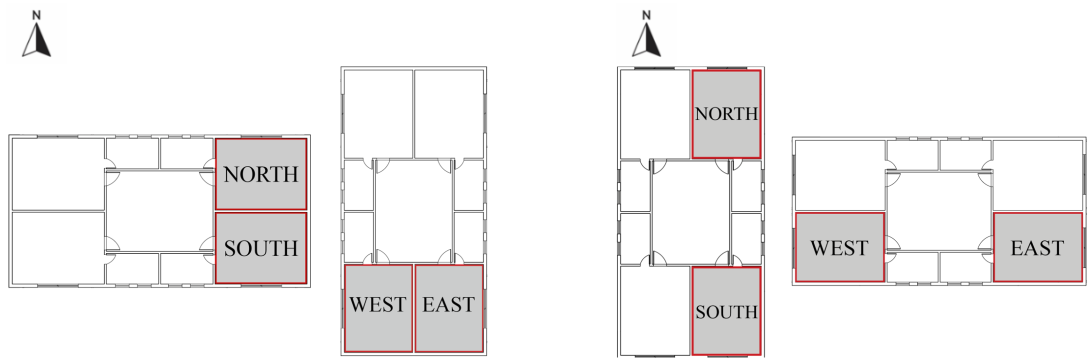
a) Office windows on the long-axis façade




Floor plan Building axonometric

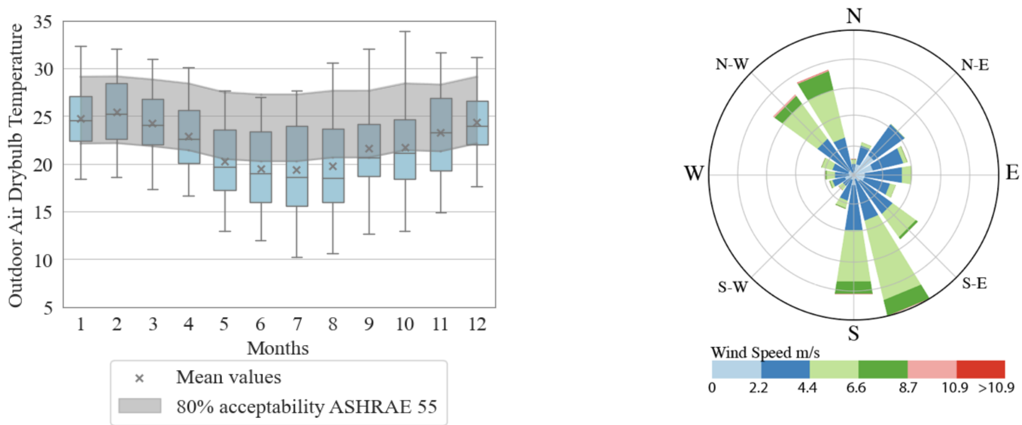
b) Office windows on the short-axis façade

**Figure 5.3:** Representative mixed-mode office building




a) Office windows on the long-axis façade b) Office windows on the short-axis façade

**Figure 5.4:** Office rooms analysed for each façade orientation




a) Outdoor air dry bulb temperature b) Wind incidence and speed

**Figure 5.5:** São Paulo weather conditions during occupied hours (8am - 6pm)

A first selection of design parameters to be varied was conducted based on the literature, considering parameters that could affect daylight, thermal and energy performance. The ranges were defined to represent feasible possibilities, considering practical achievability and typical construction practices, obtained from the real buildings database (Neves; Melo; Rodrigues, 2019) (Table 4.1). The combination of design parameters resulted in 768 design cases with balconies for daylight performance and 2,304 for thermal and energy performance. Some particularities are worth clarifying:

- The windows in the representative model without balconies were converted into sliding glazed doors in the design cases with balconies, with a height of 2.1 m and variable width.
- The impact of floor level is limited to thermal and energy performance, with no significant influence on daylight performance when the building is considered as isolated (Liu; Chen, 2017; Loche *et al.*, 2021). Consequently, it was considered as a fixed parameter for daylight assessment, with measurements conducted on the 5th floor only.

**Table 5.1:** First selection of variable design parameters

| | Parameter | Input values |
|---|---|---|
| **Envelope design parameters** | Office room's façade orientation | North / South / East / West |
| | Floor level (height above the ground) | 1st (3.1 m) / 5th (15.5 m) / 9th (27.9 m) |
| | Glazed door width (m) | 1.2 / 1.5 / 2.0 |
| **Balcony design parameters** | Location on the façade | Long-axis façade / short-axis façade* |
| | Parapet type | Glazed (clear glass) / opaque |
| | Balcony depth (m) | 0.5 / 1.0 / 1.5 / 2.0 |
| | Balcony width (m) | 2.0 / 3.0 / 4.0 / 5 .0 |

* This variation is in accordance with the representative office models shown in Figure 3: when the balcony is located in the long-axis façade, the glazed door is also located in the long-axis façade and the short-axis façade has no office windows (Figure 3a), and vice versa (Figure 3b).

A performance benchmark was developed to allow the evaluation of balcony design effectiveness compared to buildings with similar characteristics but without balconies. Reference cases were established by combining the same envelope design parameters as the design cases (Table 5.1) but removing the balconies.

### 5.2.2 Building performance simulations (Step 2)

Building performance simulations were carried out to assess daylight, thermal and energy performance of the design and reference cases, considering an occupancy period from 8 am to 6 pm (INMETRO, 2020). The weather file selected to perform the simulations was the typical meteorological year (TMY) from Congonhas, São Paulo, Brazil, which was derived from the period between 2007 and 2021 (TMYx.2007-2021) (BRE *et al.*, 2021; LABEEE, 2018).

a) Daylight simulations

To evaluate the daylight performance of the design and reference cases, daylight simulations were carried out using the Radiance software and validated with reduced-scale model daylight experiments. The daylight experiments and validation are further detailed in Appendix D. The simulations were performed for the office rooms, considering the workplane level at 0.8 m high, with a grid size of 0.5 m and 0.5 m offsets from the walls. The Reinhart sky was used, set according to the IES LM 83–12 approved method (IES LM 83-12, 2012). The reflectances of indoor and ground surfaces are detailed in Table 5.2.

**Table 5.2:** Daylight simulation input parameters

| Parameter | Input values | References |
|---|---|---|
| **External wall and balcony's external surface reflectance** | 0.3 | (Neves; Melo; Rodrigues, 2019) |
| **Internal wall and balcony's internal surface reflectance** | 0.5 | (ISO/CIE 8995-1, 2002) |
| **Room's and balcony's floor reflectance** | 0.2 | |
| **Ceiling reflectance** | 0.7 | |
| **Ground surface reflectance** | 0.1 | (IES LM 83–12, 2012) |

Two daylight performance indicators were chosen to evaluate the daylight availability and visual comfort on the work plane in the office room:

- Spatial Daylight Autonomy (sDA): percentage of floor area that exceeds a 300-lux illuminance level for more than 50% of occupied hours. To achieve the preferred daylight sufficiency, according to IES LM-83 (IES LM 83-12, 2012), sDA levels must meet or exceed 75% of the analysis area.
- Spatial Glare Autonomy (sGA): percentage of floor area that does not exceed the glare threshold (40% of Daylight Glare Probability (DGP) – considered as disturbing glare) for 95% of occupied hours.

b) Thermal and energy simulations

Thermal and energy performance simulations of the design and reference cases were carried out with EnergyPlus software. The construction materials, internal loads (occupancy, electric lights, and equipment), natural ventilation, and air-conditioning system settings were considered as shown in Table 5.3.

**Table 5.3:** Building performance simulation input parameters.

| | Parameter | Input value | Reference |
|---|---|---|---|
| **Construction materials** | Glazing thermal transmittance | 5.7 W/m². K | (Neves; Melo; Rodrigues, 2019) |
| | Glazing SHGC | 0.87 | |
| | Wall U-value (Mortar 0.025 m + concrete block 0.032 m + air gap 0.17 m + concrete block 0.032 m + mortar 0.025 m) | 2.38 W/m². K | (ABNT, 2022) |
| | Wall thermal capacity | 258.6 kJ/m². K | |
| | Wall solar absorptance | 0.61 | (Neves; Melo; Rodrigues, 2019) |
| **Internal loads** | Lighting power density | 14.1 W/m² | (INMETRO, 2020) |
| | Equipment | 15 W/m² | |
| | Occupancy | 10 m²/person | |
| **Natural ventilation system** | Window opening factor (or openable window area) | 0.41 (Top-hung window frame) | (Neves; Melo; Rodrigues, 2019) |
| | Glazed door opening factor | 0.45 (two-panel sliding door) | |
| **Air-conditioning system** | Cooling setpoint | 24 °C | (INMETRO, 2020) |
| | Heating setpoint | 20 °C | |

The electric lights were set as “always on” during occupied hours, without any automation system. Natural ventilation was modelled using the multizone Airflow Network (AFN) model. To accurately implement the AFN model approach, wind pressure coefficient values (cp) were generated through CFD simulations, using the cloud-based platform CpSimulator as the CFD tool (Bre; Gimenez, 2022). The platform’s accuracy was successfully validated for various case studies, employing wind tunnel experimental data (Bre; Gimenez, 2022). Additionally, the CFD simulations were validated with wind tunnel experiments specifically conducted for the models from this study, as detailed in prior research conducted by the authors (Loche *et al*., 2024) (see Appendix B). A total of twelve CFD simulations were conducted for each variation in balcony design (balcony location, width and depth) and for the representative model without balconies. Each simulation corresponds to a different wind incidence angle ranging from 0º to 360º, with a step size of 30º. In every simulation, the Cp values of each building opening (i.e., window), were computed. These Cp values were then used as input data for the AFN models. This ensured that the impact of the balcony design was correctly considered in terms of wind pressure distribution on the building envelope.

The window discharge coefficient was set as 0.6, corresponding to the averaged value of standard window shapes (Jones *et al.*, 2016). The windows were modelled as a binary function, i.e., fully open or fully closed (1/0), with no variations in the opening size. The internal doors were assumed to be always closed. The air-conditioning system was modelled using an ideal loads air system, considering the outdoor airflow rate as 27 $m^3$/h.person (0.0075 $m^3$/s.person), according to the Brazilian Health Surveillance Agency (ANVISA, 2003).

The mixed-mode ventilation system was automated based on the ASHRAE 55-2020 adaptive model (80% acceptability) (ASHRAE, 2020). This approach was supported by De Oliveira; Rupp and Ghisi (2021) and Deuble and De Dear (2012), which showed that the ASHRAE adaptive comfort model was suitable for mixed-mode buildings, being more adherent to real occupants' behaviour than the static Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) model. Furthermore, De Oliveira; Rupp and Ghisi (2021) indicated that the 80% acceptability threshold from the adaptive model aligns closely with the actual thermal acceptability reported by occupants in three mixed-mode buildings, also located in a humid subtropical climate. The Energy Management System (EMS) functionality in EnergyPlus was used to set up the mixed-mode ventilation automation system, considering three situations:

1. During unoccupied hours: Closed windows, AC off.
2. During occupied hours and when indoor operative temperature is within the adaptive model thermal comfort limits (80% acceptability ASHRAE 55-2020): Opened windows, AC off.
3. During occupied hours and when indoor operative temperature falls outside the adaptive model thermal comfort limits (80% acceptability ASHRAE 55-2020): Closed windows, AC on.

The performance indicator Percentage of hours of air-conditioning usage (ACU) was used to assess both thermal and energy performance. This metric consists of the percentage of occupied hours per year during which the air-conditioning is operating for cooling the space. Lower values of ACU indicate enhanced thermal performance of the office, as the building relies on natural ventilation when the air-conditioning is not being used. The use of a heating system was disregarded, as their relevance to the analyzed climate was found to be negligible. According to ASHRAE 90.1 (2010) the demand for cooling surpasses that for heating in São Paulo, with 4011 Cooling Degree Days (CDD10) compared to merely 248 Heating Degree Days (HDD18).

### 5.2.3 Sensitivity analysis (Step 3)

Two rounds of sensitivity analysis were conducted. To reduce the number of design cases to be analysed, a screening study was carried out by running a first round of sensitivity analysis. The screening study aimed to identify the least influential envelope and balcony design parameters (defined in Table 5.1), to be assigned as fixed values. The Sobol method was deemed appropriate for this analysis as it quantifies the variance of the output, considering the contribution of individual parameters and the interaction effects among inputs (Saltelli *et al.*, 2010; Wei, 2013). The Saltelli's sampling method, that uses continuous values to perform the sample selection (Saltelli *et al.*, 2010), was employed to generate the dataset for the sensitivity analysis. Since all variables in this study are discrete, the sampling method was adjusted by rounding the selected variable values to the nearest integer. The results from the building performance simulations for thermal, energy and daylight performance were used to perform the analysis and the parameters that achieved a Sobol total index below 0.05 were considered as not influential for the performance indicators analysed.

A second round of sensitivity analysis was performed to identify the most influential parameters that should be carefully considered when designing mixed-mode office buildings. The second round was run based on the selected parameters from the screening study. Additional sensitivity analyses were conducted individually for the most influential parameter identified for each metric (sDA, sGA and ACU).

### 5.2.4 Cross-analysis (Step 4)

The cross-analysis was divided into three phases to assess the trade-offs between daylight, thermal and energy performance, aiming to select optimal balcony design solutions.

a) First phase: selection of design cases based on the daylight performance.
Design cases that did not achieve sDA levels classified as preferred (meeting or exceeding 75%) were considered as sDA fail and therefore excluded.

b) Second phase: classification of design cases based on the thermal and energy performance
Design cases with preferred daylight availability levels were classified according to their thermal and energy performance, separated into six ACU ranges: 0 – 4%, 5% – 9%, 10% – 14%, 15% – 19%, 20% – 24%, >=25%. This phase was performed considering office rooms located on the intermediate floor (5$^{th}$ floor).

c) Third phase: selection of optimal design cases.
Design cases that achieved daylight availability 'sDA preferred' and the lowest level of ACU were considered as optimal design cases. The optimal design cases were compared to the reference cases to calculate the percentage change (decrease or increase) in daylight availability (sDA), visual comfort (sGA), and thermal and energy performance (ACU). The percentage change was calculated considering

the optimal design cases' location on the lower floor (1st floor), intermediate floor (5th floor), and top floor (9th floor).

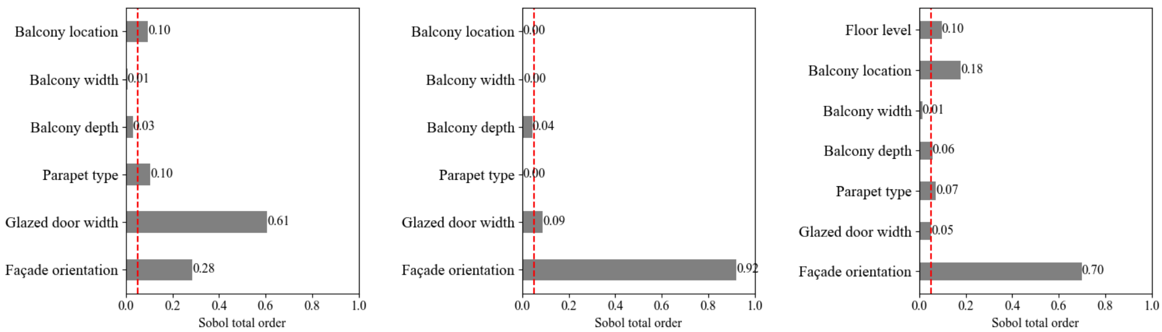
### 5.2.5 Balcony design recommendations (Step 5)

The systematic analysis guided the development of balcony design recommendations to improve daylight, thermal and energy performance of mixed-mode office buildings.

## 5.3 Results and discussion

### 5.3.1 Sensitivity analysis results

The screening study developed in the first round of sensitivity analysis identified the least influential envelope and balcony design parameters, in order to assign them as fixed values in the following optimisation rounds. Parameters that achieved a Sobol total index below 0.05 were considered as not influential for the performance indicators analysed. As a result from this analysis, the glazed door width emerged as the most influential parameter for daylight availability (Figure 5.6a) and the balcony width emerged as the least influential parameter for both daylight and thermal performance (Figure 5.6b and 5.5c). Design cases with glazed door widths of 1.2 and 1.5 m failed to meet the preferred Spatial Daylight Autonomy (sDA) levels and were excluded from further analyses. Therefore, we decided to broaden the variations in window width from 2 to 5 m, maintaining the balcony width the same size as the glazed door width.



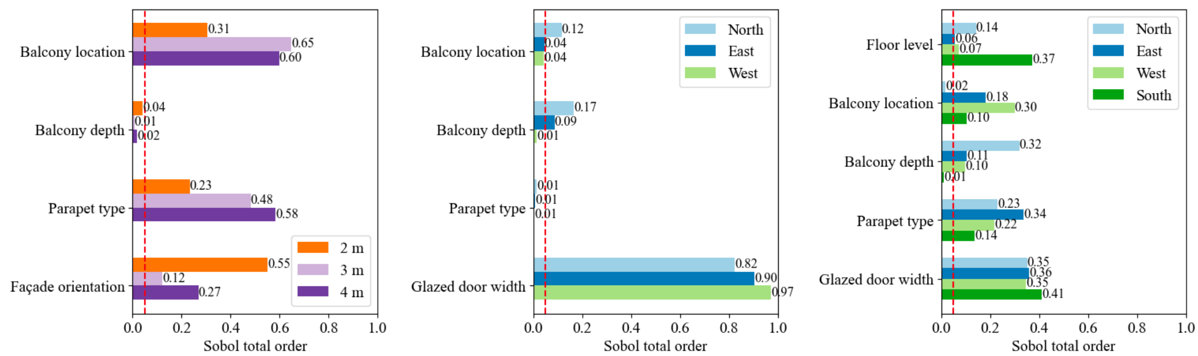

a) Daylight availability (sDA) b) Visual comfort (sGA) c) Thermal and energy performance (ACU)

**Figure 5.6:** First round of sensitivity analysis: Screening study

The most influential balcony design parameters, that should be carefully considered when designing mixed-mode office buildings, were identified in the second round of sensitivity analysis, which used the screening study results as input data. Results revealed the glazed door width as the most influential parameter for daylight performance and the façade orientation for visual comfort and thermal and energy performance (Figure 5.7). This suggests that balconies should be designed based on these key parameters. Therefore, additional sensitivity analyses were conducted individually for the most influential parameter identified for each metric (Figure 5.8).


a) Daylight availability (sDA)  b) Visual comfort (sGA)  c) Thermal and energy performance (ACU)

**Figure 5.7:** Second round of sensitivity analysis




a) sDA separated by glazed door width  b) sGA separated by façade orientation  c) ACU separated by façade orientation

**Figure 5.8:** Second round of sensitivity analysis separated by key parameters

Design cases featuring wider glazed doors (5 m) consistently achieved the preferred Spatial Daylight Autonomy level (sDA >= 75) for all façade orientations (Figure 5.8a). Design cases with balconies located on the South façade consistently achieved high levels of visual comfort (sGA) due to reduced solar radiation incidence throughout the year. Due to the lack of variability in sGA for the South façade and in sDA for 5-meters-wide glazed doors, they were both excluded from the sensitivity analysis (Figure 5.8a and 5.8b). In terms of daylight availability, design cases with narrower glazed doors (2 m) were primarily influenced by façade orientation, while those featuring wider glazed doors (3 m and 4 m) were predominantly affected by the location of balconies on the façade (short-axis and long-axis), which is directly correlated with variations in the room depth (Figure 5.8a). The balcony depth did not prove to be a significant factor influencing daylight availability, indicating that balconies can be designed with a flexible depth without causing substantial variations in daylight performance. The visual comfort was highly influenced by the glazed door width, with no impacts from the parapet type for all façade orientations. The balcony depth was identified as influential for visual comfort solely in the North and East façades, while the balcony location was considered influential for visual comfort only for the North orientation. Although the West façade faces similar solar radiation conditions as the East façade, the office occupancy schedule shows more hours of occupation in the afternoons than in the mornings.

This difference in occupancy patterns plays a large role in explaining why balcony depth was deemed more impactful for the East façade. Similar to visual comfort, thermal and energy performance were predominantly influenced by the glazed door width across all façade orientations. The balcony depth exhibited a significant impact on thermal and energy performance for the North façade, with no influence on the South façade.

The sensitivity analysis identified the window width as a crucial parameter influencing daylight performance, as an increase in the door glazing area increases daylight performance, but also decreases visual comfort, thermal and energy performance. The façade orientation was also identified as an important parameter, as different levels of solar radiation influence daylight, thermal and energy performance and, therefore, the efficiency of the balconies as shading systems. This implies that balconies should be designed according to their façade orientation and carefully combined with their glazed door width.

The results for the design and reference cases selected in the screening study were categorised and further analysed for each solar orientation, as shown in Figure 5.9. The visual comfort (sGA) showed to be highly correlated with thermal and energy performance (ACU) on the North, East, and West façades, since cases presenting improved visual comfort (high values of sGA) also demonstrated enhanced thermal and energy performance (low values of ACU), as illustrated in Figure 5.9a, 5.9b and 5.9c. However, design cases with enhanced thermal performance and visual comfort showed lower levels of daylight availability. This underscores the importance and emphasises the challenges of conducting a comprehensive cross-analysis to identify optimal balcony design solutions.

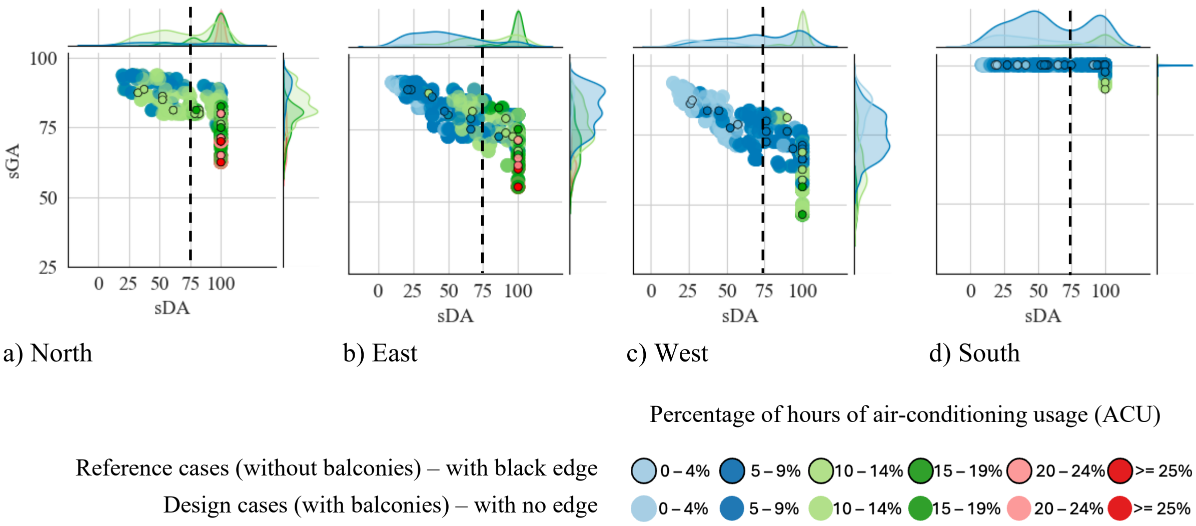



**Figure 5.9**: Results for daylight availability (sDA) and visual comfort (sGA) classified according to results for thermal and energy performance (ACU). Density curves in the margins display the frequency of occurrence of design cases for sDA values (x-axis) and sGA values (y-axis).

### 5.3.2 Cross-analysis results

Optimal design cases - that achieved the preferred sDA level (sDA ≥75) and the lowest levels of ACU - were identified through a cross-analysis. The results were analysed separately for each façade orientation, as this parameter was identified as the most influential for visual comfort and thermal and energy performance. First, the design cases were filtered based on their daylight performance: design cases that did not achieve sDA 'preferred' were excluded. The selected design cases, located on the 5th floor level, were then classified based on their ACU results. Design cases (with balconies) achieving the lowest levels of ACU were considered as optimal design solutions and were then compared to the reference cases (without balconies) to calculate the percentage change (improvement or decrease) for sDA, sGA and ACU.

a) North façade

Attaining the preferred level of Spatial daylight autonomy (sDA) was more feasible for the design cases situated in the North façade (Figure 5.10), since the studied location (near the tropic of Capricorn) consistently receives high solar radiation levels throughout the year. When balconies are located on the long-axis façade (room depth = 5.5 m), all design cases achieved the preferred sDA level. If the balcony is positioned along the short-axis façade (room depth = 7 m) and combined with a narrower glazed door (2 m), it is advisable to incorporate glazed parapets, regardless of the balcony depth, to achieve preferred levels of daylight availability in the office (Figure 5.10a). This recommendation is complementary to the study by Liu and Chen (2017) on residential apartment buildings located in Taiwan, which suggests that small windows should be associated with shallow balconies. Therefore, the use of glazed parapets could allow an increase in the balcony depth.

The lowest ACU level achieved by the design cases on the North façade, also ensuring optimal daylight availability, was 10% - 14%. In this façade, placing the balcony on the long-axis façade provides more flexibility of design, since the combination of narrower glazed doors (2 m) and opaque parapets provides flexibility in the balcony depth (0.5 to 2.0 m) while maintaining the same ACU level (10-14%). When narrower glazed doors (2 m) are paired with glazed balconies on the long-axis façade, a deeper balcony (2 m) is recommended. Design cases with a glazed door of 3 and 4 m wide on the long-axis façade should be combined with opaque and deeper balconies (2 m) to achieve the 10-14% ACU level. When balconies are positioned on the short-axis façade, only one design option met both preferred daylight availability and achieved 10-14% ACU: the combination of a 3-meter-wide glazed door and opaque and deeper balconies (2 m) (Figure 5.10b).

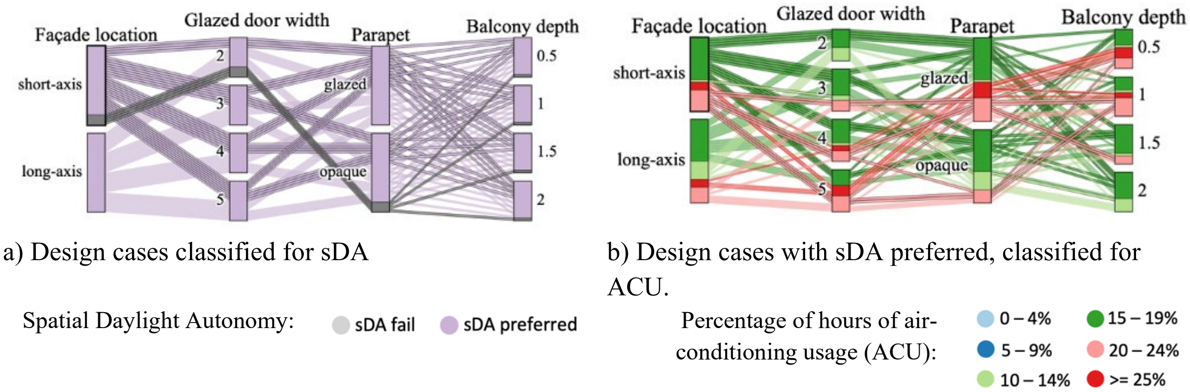
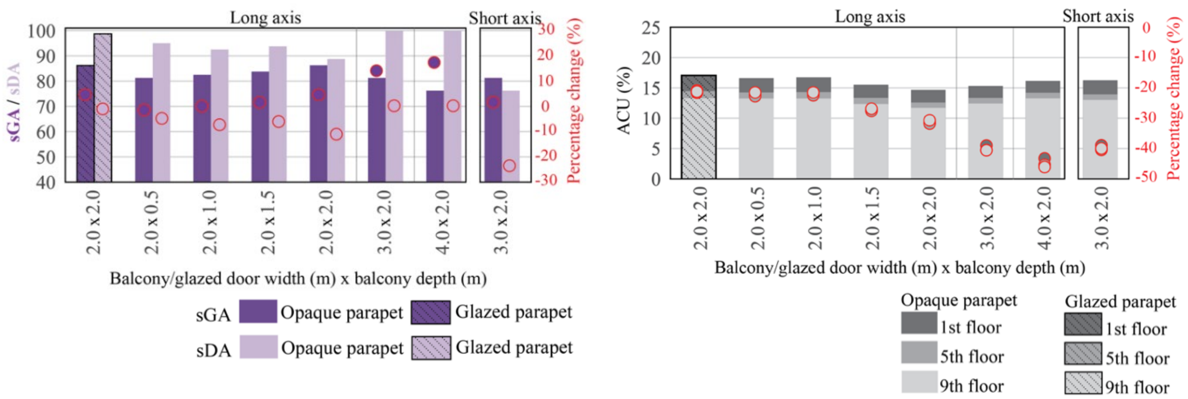



**Figure 5.10:** Classification of design cases with balconies located on the North façade for sDA and ACU.

Design cases with narrower glazed doors (2 m) situated on the short-axis façade, when combined with glazed and deeper balconies (2 m) or opaque and shallower balconies (0.5 and 1.0 m) showed, similarly, 20% decrease in ACU (Figure 5.10b). Design cases incorporating opaque and 2 meters-deep balconies for both long-axis and short-axis façades demonstrated a more substantial improvement in ACU and sGA for all glazed door width values, while concurrently maintaining desirable levels of daylight performance. This balcony configuration should be combined with 3 meters-wide glazed doors when located on the short-axis façade, improving ACU in 25% with no variations in sGA (Figure 5.11).

When located on the long-axis façade, opaque and deeper (2 m) balconies can be combined with a flexible choice of glazed door width, ranging between 2 and 4 m. Design cases with balconies located on the long-axis façade with wider glazed doors (4 m) exhibited the most significant percentage of change of ACU and sGA. This resulted in a 45% reduction in ACU and a 18% improvement of sGA in the office, when combined with opaque and deeper balconies (Figure 5.11). This design case demonstrated no change in daylight performance when compared to the reference case, as both achieved the highest sDA level (Figure 5.11a). While the percentage change remains consistent across all floor levels, offices situated on higher floors exhibit superior thermal and energy performance compared to those on lower levels. This difference can be attributed to the increased wind speed experienced on higher floors, resulting in enhanced natural ventilation performance (Loche *et al.*, 2024).




a) sDA and sGA

b) ACU

**Figure 5.11:** Percentage change for optimal design cases with balconies located on the North façade

b) South façade

The South façade receives low direct solar radiation levels throughout the year. Although this condition leads to a challenge in achieving preferred sDA levels, it also provides flexibility in balcony design for thermal and energy performance. When balconies are positioned on the long-axis façade, design cases featuring windows of 3 to 5 m width consistently attained the targeted level of daylight availability, regardless of the parapet type and balcony depth, highlighting the flexibility in balcony design for shallow rooms (room depth = 5.5 m). When balconies are situated on the short axis (room depth = 7 m), design cases featuring windows 3 and 4 m wide should be paired with glazed parapets, regardless of the balcony depth, to allow more daylight to penetrate in the office room and meet the preferred levels of daylight availability. Design cases with balconies on the short-axis façade and 5-meters-wide windows exhibit flexibility in balcony design, successfully attaining the preferred daylight availability levels regardless of parapet type and balcony depth (Figure 5.12a).

The lowest ACU level achieved by design cases on the South façade, also ensuring optimal daylight availability, was 5% - 9%. Design cases with balconies situated along the long-axis and 3-meters wide windows exhibit high flexibility in achieving a 5-9% ACU level, irrespective of the parapet type or balcony depth. Design cases with balconies located on the long-axis, combined with 4 and 5 meters-wide windows and opaque balconies, showed flexibility in balcony depth. However, if combined with glazed parapets, 4-meters-wide windows require balconies over 1 meter-deep, and 5 meters-wide windows require a 2 m balcony depth to achieve 5-9% ACU level (Figure 5.12b).

Design cases with balconies located on the short-axis featuring 3 meters-wide windows should be combined with glazed parapets, regardless of the balcony depth. Design cases with balconies on the short-axis provided with 4 meters-wide windows should also be combined with glazed parapets, but the balconies should be deep (1.5 or 2 m). When widening windows to 5 m, balconies located on the short-axis façade should be paired with opaque parapets and can have flexible balcony depth.

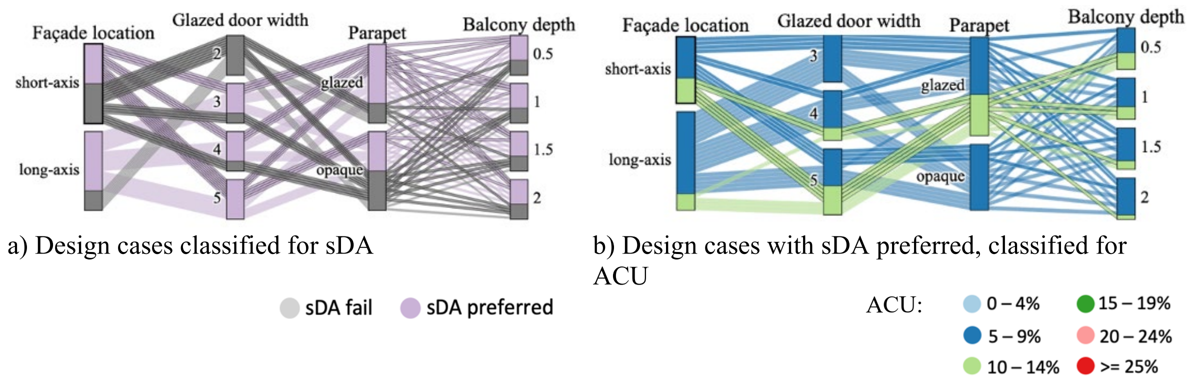
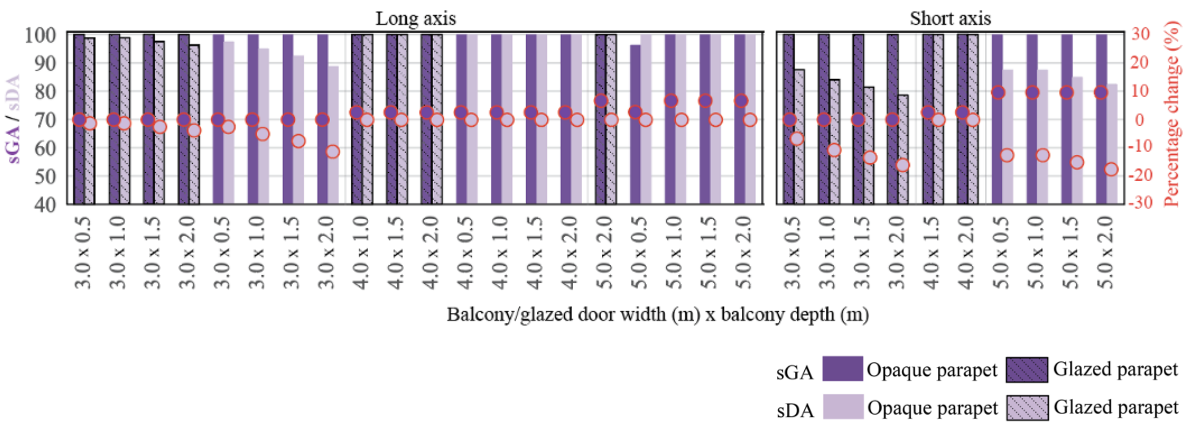
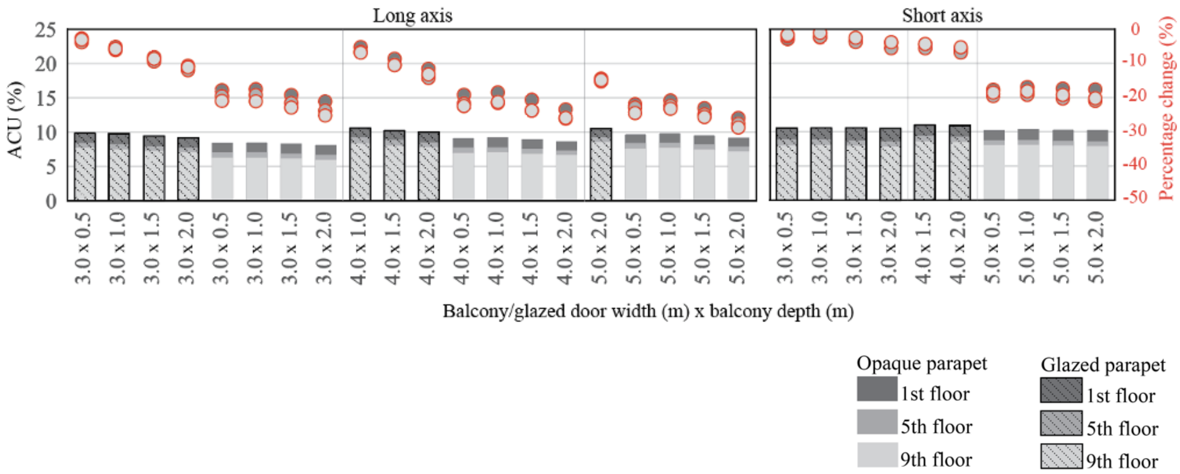



**Figure 5.12:** Classification of design cases with balconies located on the South façade for sDA and ACU

When positioned on the South façade the balconies were less effective but still proved to be advantageous for improving visual comfort by up to 10% and enhancing thermal and energy performance by up to 29%. The combination of opaque parapets and deep balconies proved efficient for thermal and energy performance on the South façade, reducing ACU values for all balcony locations and window widths by up to 28%, when compared to the reference cases. Design cases with balconies located on the long-axis façade, featuring wide windows (5 m), opaque parapets and balconies deeper or equal to 1 m also had their visual comfort improved by up to 8%, if compared to the reference cases without balconies. Design cases with balconies located on the short-axis façade and wide windows (5 m) saw improvements in visual comfort and thermal and energy performance by 10% and 20%, respectively, regardless of the balcony depth (Figure 5.13).




a) Optimal design cases for sDA and sGA



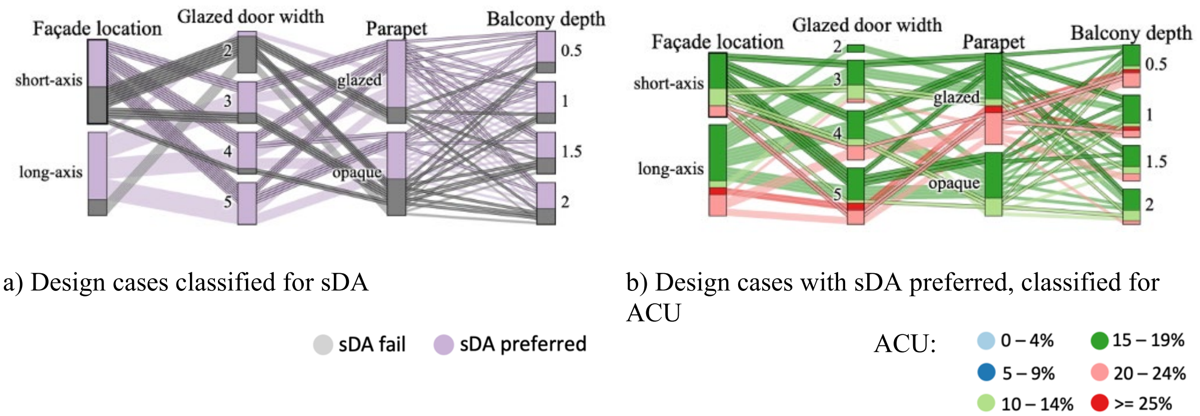

b) Optimal design cases for ACU

**Figure 5.13:** Percentage of change for optimal design cases with balconies located on the South façade

c) East and West façades

As seen in the results sections for North and South façades, results are very case-specific to solar orientation. For the East and West façades, we highlight here the main findings and the results charts (Figures 5.14 to 5.17).

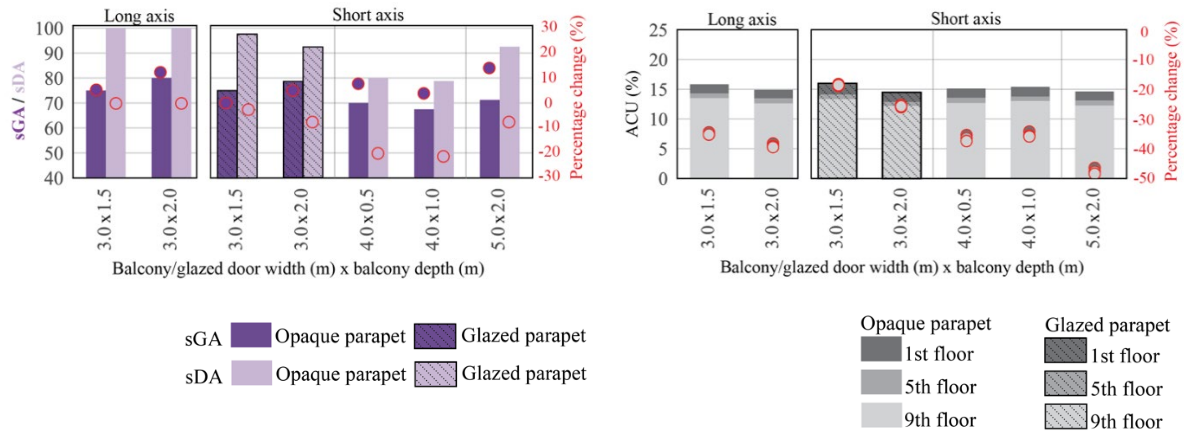
For the East and West façade (Figures 5.14-17), positioning the balconies along the short-axis façade (room depth = 7 m) has proven more advantageous compared to the long-axis façade (room depth = 5.5 m). As a result, a high number of design cases with balconies located on the short-axis façade achieved the lowest ACU level, falling within the 10-14% range. When balconies are situated on the short-axis façade facing East (Figure 5.14 and 5.15), the design case featuring a glazed door 5 meters-wide paired with opaque and deep balconies (2 m) demonstrated the highest performance improvement, reducing air conditioning usage by 48% during occupied hours and enhancing visual comfort by 14%, compared to the reference case without balconies.




a) Design cases classified for sDA

b) Design cases with sDA preferred, classified for ACU

**Figure 5.14:** Classification of design cases with balconies located on the East façade for sDA and ACU

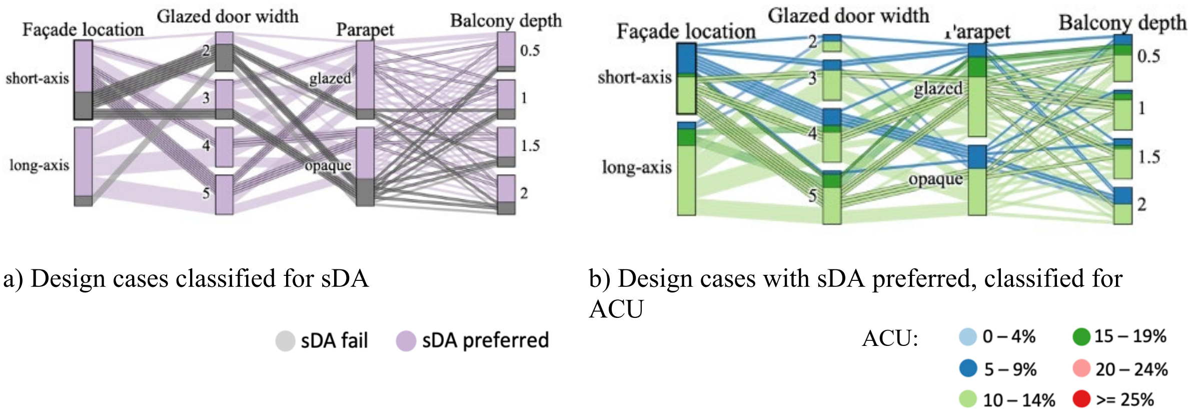



a) Optimal design cases for sDA and sGA

b) Optimal design cases for ACU

**Figure 5.15:** Percentage of change for optimal design cases with balconies located in the East façade

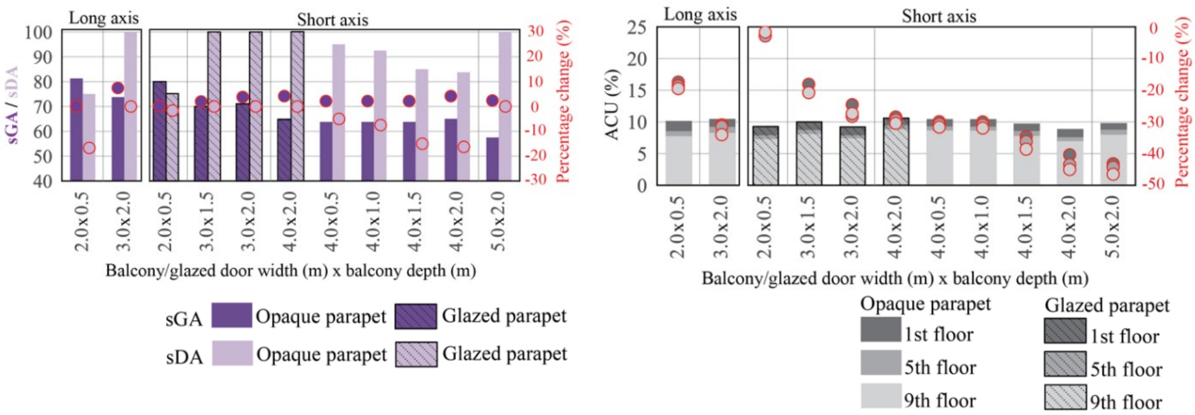
For the West façade (Figures 5.16 and 5.17), a greater number of design cases with balconies located on the short-axis façade achieved the lowest ACU level, falling within the 5-9% range. When balconies are located on the long-axis, they should be opaque, and their depth will depend on the glazed door width: a 2 meters-wide door should be paired with a shallow balcony, while a 3 meters-wide door should be paired with a deep balcony (2 m) to achieve preferred sDA and a 5-9% ACU level.




a) Design cases classified for sDA

b) Design cases with sDA preferred, classified for ACU

**Figure 5.16:** Classification of design cases with balconies located on the West façade for sDA and ACU




a) Optimal design cases for sDA and sGA

b) Optimal design cases for ACU

**Figure 5.17:** Percentage of change for optimal design cases with balconies located in the West façade

### 5.3.4. Balcony design recommendations

Balancing trade-offs in balcony design to optimise daylight, thermal and energy performance of mixed-mode office buildings was achieved through a parametric analysis and multi-objective assessment. Balcony design is not trivial, and changes in design parameters (both balcony and building) can have multi-domain impacts, since these interactions are complex and case-dependent. However, generally applicable recommendations are presented here, based on the results obtained in this research and related literature, which can be useful to provide insights to new construction and retrofit projects.

The results revealed that the same balcony design can be consistently applied across all floor levels (considering an isolated building, with no surrounding constructions). However, offices situated on higher floors will benefit from superior thermal and energy performance compared to those on lower levels. This advantage stems from the higher wind speeds experienced at higher floor levels, resulting in improved natural ventilation within spaces. This finding is consistent with studies conducted by Mohamed *et al*. (2014), which examined the influence of balconies on natural ventilation performance.

Façade orientation and glazed door width emerged as key parameters that should be considered when designing balconies. These findings align with previous research conducted by Liu and Chen (2017) and Elgohary, Abdin and Mohamed (2023) that demonstrated that combining the window-to-wall ratio with balcony depth can establish relevant thresholds for daylight and thermal performance. Additionally, Elgohary, Abdin and Mohamed (2023) also suggested that the balcony depth and window-to-wall ratio should be selected according to the façade orientation.

Adding balconies to all façade orientations was proven to be an efficient design strategy to decrease energy use for cooling across all floor levels. Nevertheless, balcony design recommendations showed different trends for different orientations. On the North and South façades, placing balconies along the long axis (room depth = 5.5 m) has proven more advantageous than positioning them along the short axis (room depth = 7 m), since shallower rooms are more likely to offer higher levels of daylight availability when paired with deep and opaque balconies. This finding is in line with the research conducted by Gabrova (2014) who suggested that increasing the depth of balconies in deep rooms impairs daylight levels. However, on the East and West façades the balconies on the short-axis (room depth = 7 m) were more advantageous. This is likely because balconies, as horizontal overhanging structures, are less effective for low angles of solar radiation, and deep rooms offer enhanced protection against solar radiations experienced in these orientations.

As the North façade has a higher risk of overheating, since direct solar radiation is received throughout the whole year, the use of opaque parapets and 2-meter-deep balconies are recommended, enhancing visual comfort by up to 18% and thermal and energy performance by up to 45%, while providing preferred levels of daylight availability, depending on the glazed door width and the balcony location. Deep balconies (2 m) are also the best choice for the East and West façades. The parapet type and the glazed door width should be correlated to the balcony location. When positioned along the long axis, a 3-meter-wide glazed door should be paired with an opaque parapet. This combination enhances visual comfort by up to 12% and reduces air-conditioning usage (ACU) by up to 39%. When the balcony is located on the short axis, an opaque parapet combined with windows 3 or 5 m wide can enhance visual comfort by up to 15% and reduce ACU by up to 45%.

The use of balconies on the South façade was not as effective in reducing air conditioning usage as other façade orientations, but it still demonstrated benefits. Depending on the width of the glazed door, the location of the balcony, and the type of parapet, air conditioning usage can be reduced by up to 28%, enhancing visual comfort by up to 10%. However, the depth of the balcony was found to have minimal influence, providing flexibility in choosing this parameter. This finding contradicts the study by Elgohary, Abdin and Mohamed (2023), who suggested that adding balconies to the North façade for residential buildings in Cairo (which, being above the equator, is equivalent to the South façade in this study) does not significantly improve thermal performance, except for enhancing aesthetics or meeting occupants' needs. According to the authors, Cairo lacks direct sunlight exposure on the North façade, whereas in São Paulo, direct sunlight exposure is somewhat reduced but still present.

The use of deep balconies was considered the best choice for north, east, and west façades, while the south façade allows flexibility in selecting balcony depth. For all façade orientations, deep balconies can be combined with flexibility in glazed door width, offering at least two options of combinations. The flexibility of glazed door width in all the façade orientations and the flexibility in balcony depth in the South façade allow designers to consider other factors in parameter selection, such as how occupants use the space. A wide and deep balcony is more likely to be occupied, while a narrow and shallow balcony may be relegated to a non-occupied service area, leading to occupants' dissatisfaction (Li *et al*., 2023; Song *et al*., 2024). In this study, the size of the balcony is linked to the width of the glazed door, so choosing wider windows also means having wider balconies. Wide and deep balconies can contribute to occupants' satisfaction (Song *et al*., 2024) and wide windows also enrich outdoor views, which is highly appreciated by occupants, enhancing their wellbeing (Abd-Alhamid; Kent; Wu, 2023).

Current standards and guidelines for building envelopes, which focus on parameters such as thermal properties and window-to-wall ratio, generally overlook the effects of balconies on the trade-offs among daylight, thermal, and energy performance. An exception in the São Paulo context is the building code, which encourages the use of balconies by exempting open balconies from being classified as built area if their dimensions per floor are less than 5% of the total site area (Prefeitura de São Paulo, 2017). However, depending on the site area's size, this regulation can lead to the construction of shallow and narrow balconies, neglecting the effects of balcony design on daylight, thermal, and energy performance. Additionally, the Brazilian standard for daylight performance, ABNT 15215-3 (2024), provides guidelines for window design based on room depth, glazing visible transmittance, façade orientation, and the use of blinds/curtains, but does not consider the impact of overhangs, such as balconies, on daylight availability and visual comfort within the room.

An optimal combination of glazed door width and balcony depth has been identified for use in all solar orientations: deep balconies (2 m) paired with a glazed door width 3 meters-wide. The balcony's parapet type used in this combination will vary depending on the balcony's location on the façade (Figure 5.18). For the North façade, an opaque parapet is recommended for both short and long axes. Glazed parapets are needed on South-facing façades if the balconies are along the short axis. This ensures that there is enough daylight in the office. For the long-axis façade, both opaque and glazed parapets can be used. However, the option with an opaque parapet reduces energy consumption for cooling by 23%, whereas the option with a glazed parapet only reduces it by 12%. For the East and West façades, glazed parapets are recommended for balconies on the short-axis façade, and opaque parapets for those on the long axis. This approach ensures optimal levels of daylight availability and improved visual comfort, thermal and energy performance within the room across all floor levels for all façade orientations.

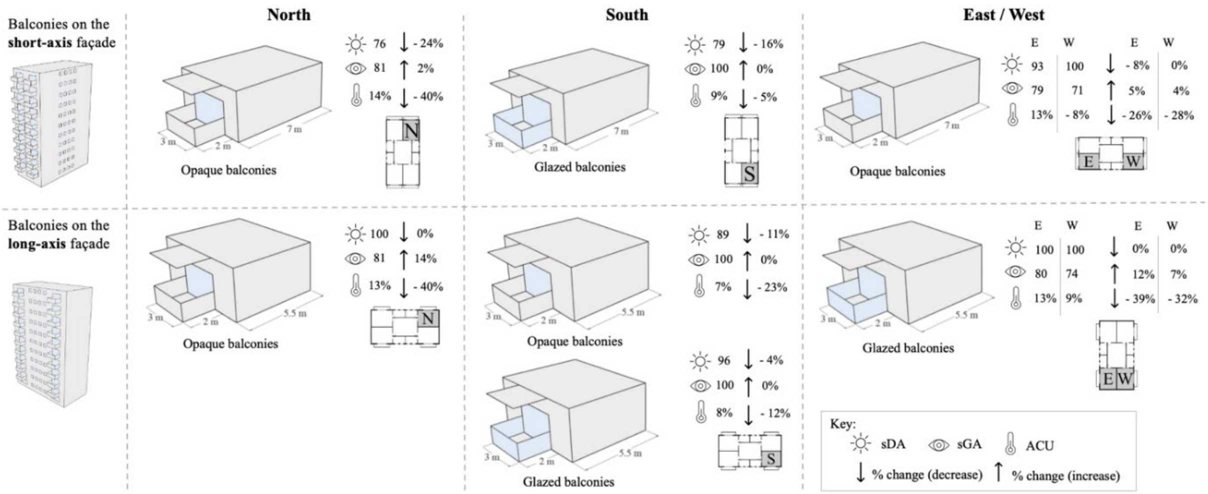



**Figure 5.18:** Optimal combination of glazed door width and balcony depth for all façade orientations, varying the parapet type according to the balcony location

## 5.4 Limitations and prospects for future studies

The main focus of this study was to promote balconies as efficient exterior shading devices, therefore we did not consider the use of other types of shading elements, such as interior blinds and curtains. The combination of balconies and interior shading devices may compromise the efficiency of balcony design recommendations in providing preferred levels of daylight availability within the office rooms. The outdoor noise was also a factor pointed out by Ribeiro *et al*. (2024) that may influence whether occupants keep windows open or closed, and this aspect was not accounted for in the current mixed-mode strategy adopted for the thermal and energy performance simulations. Future research could assess how occupant behaviour regarding window and blinds operation could affect daylight, thermal and energy performance in office buildings with balconies. Additionally, recent studies have highlighted the physical and mental well-being that balconies can bring to residential buildings (Bayazit; Kisakurek, 2023; Duarte *et al*., 2023; Peters; Halleran, 2021; Säumel; Sanft, 2022), and future studies could also investigate the benefits of balconies on occupants' satisfaction with the workplace in office rooms and how balconies may impact workers productivity.

The balcony design recommendations presented in this study are derived from prevalent construction practices in São Paulo, Brazil, which were used to create the reference and design cases. Considering additional parameters, such as varying reflectance values for balcony and building surfaces, as well as different glazing visible transmittance and solar heating gain coefficient for the glazed doors, could complement the findings of this study.

This study treated the reference and design cases as isolated buildings. Therefore, future research could also investigate the influences of surrounding buildings. It is important to note that the reference case (without balconies) and the design cases (with balconies) here analysed are conceptual models, making physical measurements unfeasible. Future research could focus on empirical validation in buildings with balconies, thereby enhancing the findings and enabling extrapolation to other building design settings.

## 5.5 Conclusions

This research performed a parametric analysis of balcony design parameters correlated with building design parameters to provide balcony design recommendation to improve daylight, thermal and energy performance of high-rise mixed-mode office buildings in São Paulo, Brazil. Balcony design was shown to be complex and case-dependent. The consequences of design modifications are not trivial and affect performance in multiple domains.

Results show that balcony design can effectively enhance visual comfort, thermal performance, and energy efficiency while ensuring optimal daylight availability in office rooms, for all façade orientations. Recommendations for balcony design, including balcony depth, parapet type, and balcony location, were tailored to each façade orientation and thoughtfully combined with the glazed door width. One optimal combination of a 3 meters-wide glazed door and a 2 meters-deep balcony was shown to be beneficial for all façade orientations across all floor levels. However, the parapet type should be chosen according to the balcony location, which is directly correlated to the room depth.

Given that certain balcony proportions (width/ depth) were identified as optimal design solutions to improve daylight, thermal and energy performance for all façade orientations analysed in this study, design guidelines for building codes and green buildings certifications should promote the use of such façade elements in office buildings, as long as they are properly designed according to the location and solar orientation.

The present research pioneers in providing balcony design recommendations to enhance daylight, thermal and energy performance simultaneously for mixed-mode office buildings. The findings offer valuable insights and guidance for architects and designers, emphasizing the importance of designing balconies not merely as decorative façade elements or spaces for building services. Instead, they should be dimensioned thoughtfully to maximize their potential as active contributors to improving visual comfort, thermal and energy performance, while maintaining preferred levels of daylight availability in high-rise mixed-mode office buildings. Also, the cross-analysis method developed in this study can be applied by researchers/designers to their own case studies.

## Acknowledgments

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# 6. General discussions

From a building performance perspective, changes in balcony design parameters are not always trivial and can affect building performance across multiple domains. Therefore, the main objective of this thesis, addressed by Chapter 5, was to develop balcony design recommendations to optimise daylight, thermal, and energy performance of mixed-mode office buildings located in subtropical climates. To support the attainment of the main objective, specific objectives were addressed in Chapters 2, 3, and 4. The results and discussions were presented separately for each chapter in this thesis. Therefore, this chapter provides a summary of the key discussions and contributions presented in each chapter. Table 6.1 provides a summary of the parameters analysed, the methodology employed, and the main contributions of each chapter.

**Chapter 2** aimed to achieve the first specific objective: *Assessing both the existing knowledge and gaps in the literature regarding the influence of balcony design parameters on daylight, thermal and energy performance of buildings.*

This specific objective was achieved through a systematic literature review. The key contribution of the literature review was the identification of trends, knowledge, and gaps regarding the impacts of the use of balconies on the thermal, energy and daylight performance. The review uncovered a notable increase in the number of publications focused on the role of balconies on building performance and occupants' well-being. This surge may be attributed to the increasing debate about climate change and further fuelled by the role of balconies in residential buildings during the COVID-19 pandemic (Bournas, 2021; Peters; Halleran, 2021). Furthermore, the literature review highlighted two notable gaps: the absence of papers addressing the use of balconies in office buildings and a scarcity of studies evaluating the effects of balcony design on building performance using a multi-objective approach, which significantly increases the complexity of the analysis. Although the literature review was concluded in 2021, Chapters 1, 4, and 5 provided an updated overview of the literature, incorporating publications released after 2021 into their introduction sections. Nevertheless, the identified gaps persist to the present day, and recent literature reinforced that performance-based balcony design is complex and correlated to other building design parameters, underscoring the significance of the present thesis in addressing and filling these research gaps.

**Chapter 3** aimed to achieve the second specific objective: *Evaluating the effects of balcony design parameters on the daylight performance of mixed-mode office buildings in subtropical climates.*

To achieve this goal, the impact of balcony design on daylight performance was assessed through a parametric design approach, which involved varying balcony design parameters (depth, width, and location on the façade) and building design parameters (façade orientation, glazed door width, glazing visible transmittance, and floor level). The key contribution of this chapter was the development of decision-making pathways to provide guidance to architects in designing efficient balconies to enhance daylight availability and visual comfort in office buildings located in tropical regions. To the best of authors' knowledge, this study pioneered in investigating the effects of balconies on the daylight performance of office buildings. Results showed that the glazed door width is a determinant parameter for daylight performance, echoing the results shown by Al-Sallal, AbouElhamd and Dalmouk (2018) and Liu and Chen (2017). When combined with any other parameter, the glazed door width produced relevant thresholds for design decision-making. Specific rules of thumb were derived to assist architects in the initial stages of design of office buildings with balconies, including:

- Avoiding placing windows on the North façade with balconies shallower than 1 m and glazed door widths exceeding 3.0 m to prevent unacceptable glare.
- Avoiding combinations involving clear glass and glazed doors narrower than 1.5 m to prevent unacceptable spatial daylight autonomy (sDA).
- Avoiding scenarios with laminated glass and glazed doors narrower than 2.5 m to prevent unacceptable sDA values.
- Giving particular attention to the glazed door width when designing balconies deeper than 1.0 m and using laminated glass to ensure sDA values remain above acceptable thresholds.

**Chapter 4** aimed to achieve the third specific objective: *Evaluating the effects of balcony design parameters on the natural ventilation, thermal and energy performance of mixed-mode office buildings in subtropical climates.*

This study pioneered in evaluating the impacts of balconies on natural ventilation, thermal and energy performance through a combined methodology using CFD analysis and building performance simulations (BPS). Through this method, the performance of 40 balcony design cases was studied, considering three balcony design parameters (width, depth, and location on the façade) combined with two façade orientations (North and South), two wind incidences (windward and leeward), and three floor levels (upper, medium, and lower floors). The key contribution of this chapter was the development of optimal balcony design recommendations to improve natural ventilation, thermal and energy performance in mixed-mode office buildings. Different trends were found for the North and South façades, indicating that balconies should be designed according to the façade orientation.

For the South façade, the use of narrow and shallow balconies (2 m x 0.5 m) emerged as the best design option for natural ventilation and thermal and energy performance. Since variations in balcony dimensions did not substantially impact the energy usage for cooling in offices situated on the South façade (reducing cooling thermal loads by 5% to 10%, depending on the balcony location and floor level), the most suitable balcony dimension for natural ventilation performance should be adopted. This contributes to reducing solar heat gains and thermal loads for cooling, while simultaneously enhancing natural ventilation by up to 28%, depending on the balcony location on the façade, wind incidence and floor level. Conversely, for the North façade, the use of deep and wide balconies is the best recommendation, resulting in reduction in cooling thermal loads by up to 36% for all floor levels and for both analysed balcony locations on the façade. Although this dimension may not be favourable for natural ventilation performance, potentially leading to a decrease in the air change rate by up to 25% (depending on the balcony location on the façade, wind incidence and floor level), the notable benefits of enhancing thermal and energy performance could overcome this limitation.

**Chapter 5** aimed to achieve the main objective: *Developing balcony design recommendations to optimise daylight, thermal and energy performance of mixed-mode office buildings in subtropical climates.*

To achieve this goal, a parametric analysis was conducted for various combinations of balcony design parameters (balcony depth, width, location on the façade, and parapet type), along with key building design parameters (façade orientation, floor level, and glazed door width). A multi-objective assessment was performed by employing building performance simulations (BPS) for daylight, thermal and energy performance. The wind pressure coefficient data generated through computer fluid dynamics (CFD) and validated with wind tunnel experiments (Chapter 4) were used as input data for the thermal and energy performance simulations. Daylight experiments using scale-models under real sky were developed to validate the daylight simulations and improve the reliability of the daylight data.

The results obtained demonstrate that balcony design can effectively enhance visual comfort, thermal and energy performance, while ensuring optimal daylight availability in office rooms, confirming this thesis hypothesis. Recommendations for balcony design were tailored to each façade orientation and thoughtfully combined with the glazed door width. The use of deep balconies was considered the best choice for North, East, and West façades, while the South façade allows flexibility in selecting balcony depth. The flexibility in balcony depth in the South façade allow designers to consider other factors in balcony design selection. In Chapter 4 we recommended the use of narrow and shallow balconies for the South façade, as it is beneficial to improve the natural ventilation performance. However, another factor that should be considered is that the balcony size can also dictate how occupants use the space. A wide and deep balcony is more likely to be occupied, while a narrow and shallow balcony may be relegated to a non-occupied service area, which could lead to occupants' dissatisfaction (Li *et al*., 2023; Song *et al*., 2024). Wide and deep balconies can contribute to occupants' satisfaction (Song *et al*., 2024), allowing windows to be wider and enriching outdoor views, which is highly appreciated by occupants, enhancing their wellbeing (Abd-Alhamid; Kent; Wu, 2023).

An optimal combination of glazed door width and balcony depth has been identified for use in all solar orientations: deep balconies (2 m) paired with a 3 meters-wide glazed door. The balcony's parapet type used in this combination will vary depending on the balcony's location on the façade (Figure 5.17 from

Chapter 5). For the North façade, an opaque parapet is recommended for both short and long axes. Glazed parapets are needed on South façades if the balconies are along the short axis. This ensures that there is enough daylight in the office. For the long-axis façade, both opaque and glazed parapets can be used. For the East and West façades, glazed parapets are recommended for balconies on the short-axis façade, and opaque parapets for those on the long axis. This approach ensures optimal levels of daylight availability and improved visual comfort, thermal and energy performance within the room across all floor levels and for all façade orientations

It is important to note the difference in the parameters analysed for the different chapters, which are described on Table 6.1. Chapters 3 and 5 focused on scenarios with single-sided ventilation, since including a window on the adjacent façade for cross-ventilation consistently resulted in the highest levels of daylight availability (sDA = 100), lacking variation in output values, and thus preventing the evaluation of the impacts of balconies on daylight availability. Conversely, chapter 4 focused on scenarios with cross-ventilation, as the variation in simulation outputs was higher than the ones for single-sided ventilation, making them more relevant to the analysis (Figure 6.1).

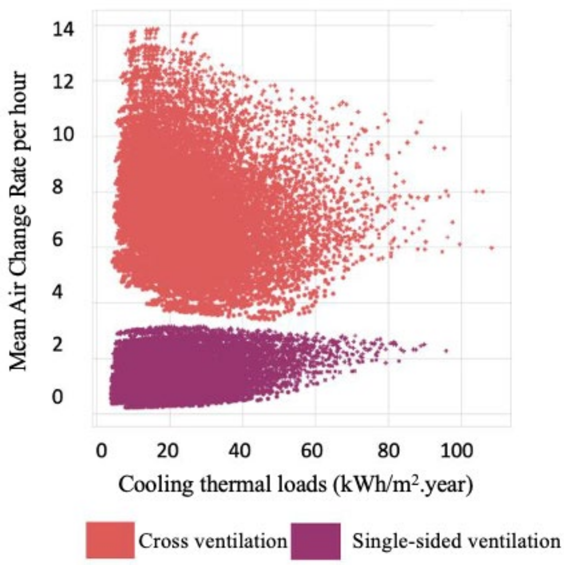



**Figure 6.1:** Design cases with cross-ventilation and single-sided ventilation

**Table 6.1:** Summary of analyses across chapters

| Chapter | Objective | Methods | KPIs | Variable parameters: Balcony design | Variable parameters: Building design | Variable parameters: Natural ventilation | Main contributions |
|---|---|---|---|---|---|---|---|
| **2** | **SO1:** Assessing both the existing knowledge and gaps in the literature regarding the influence of balcony design parameters on the natural ventilation, daylight, thermal and energy performance of buildings. | Systematic literature review | - | Presence/ absence of balconies, balcony depth, balcony type, parapet type | Floor level, wind incidence, glazing visible transmittance | Single-sided, cross-ventilation | Identification of knowledge and research gaps |
| **3** | **SO2:** Evaluating the effects of balcony design on the daylight performance of mixed-mode office buildings. | BPS (daylight simulations) | Spatial daylight autonomy (sDA) Useful Daylight Illuminance (UDI) Annual Sunlight Exposure (ASE) | Balcony depth, balcony width (ratio of balcony width to window width), location on the façade (room depth) | Floor level, façade orientation, glazed door width (ratio of balcony width to window width), glazing visible transmittance | Single-sided ventilation | Decision-making pathways for designing efficient balconies for office buildings in tropical regions |
| **4** | **SO3:** Evaluating the effects of balcony design on the natural ventilation, thermal and energy performance of mixed-mode office buildings. | Wind tunnel experiments, CFD analysis, BPS (thermal and energy performance simulation) | Air change rate Thermal loads for cooling | Balcony depth, width, and location on the façade | Floor level, façade orientation, wind incidence | Cross ventilation | Optimal balcony design configurations to improve natural ventilation, thermal and energy performance in mixed-mode office buildings |
| **5** | **Main objective:** Developing balcony design recommendations to enhance daylight, thermal and energy performance of mixed-mode office buildings | BPS (daylight, thermal and energy simulations) and scale-model daylight experiments | Spatial daylight autonomy (sDA) Spatial Glare Autonomy (sGA) (ACU) | Balcony depth, width, parapet type and location on the façade | Floor level, façade orientation, glazed door width | Single-sided ventilation | Balcony design recommendations to enhance daylight, thermal and energy performance |

**Key: SO:** Specific objective
**BPS:** (Building performance simulations)
**KPI:** (Key performance indicator)

# 7. Conclusions

The main objective of this thesis was to develop balcony design recommendations to enhance the daylight, thermal, and energy performance of mixed-mode office buildings. The thesis was structured into four main chapters. Chapters two to four addressed specific objectives and provided support for Chapter 5, which tackled the main objective of the thesis. This study confirms the hypothesis that a well-designed balcony can significantly enhance daylight, thermal, and energy performance of mixed-mode office buildings and provides recommendations for designing balconies as active contributors to improve the building's performance. The key conclusions are summarized as follows:

Chapter two addressed the **first specific objective** by conducting a systematic literature review, which assessed both the existing knowledge and gaps in the literature regarding the influence of balcony design parameters on daylight, thermal, and energy performance of buildings. The review highlighted that current scientific literature predominantly focuses the analysis of balconies' performance on residential buildings, while there is a notable lack of research studies in the office typology. Additionally, it emphasized that balcony design impacts building performance across multiple domains. Due to this complexity, there is a significant lack of research exploring the effects of balcony design considering multiple objectives. These gaps are therefore addressed in the subsequent chapters of this study.

Chapter three addressed the **second specific objective** by evaluating the effects of balcony design on the daylight performance of office buildings. A parametric design approach in combination with daylight simulations and a systematic analysis with a data mining algorithm, revealed successful combinations of building design parameters as well as important cut-off points for decision-making design to achieve daylight efficiency in mixed-mode office buildings in the city of São Paulo, Brazil. Results provided multiple design routes to achieve successful performance targets to design balconies as efficient shading devices and daylight diffusers.

Chapter four addressed the **third specific objective** by evaluating the effects of balcony design on the natural ventilation, thermal and energy performance of mixed-mode office buildings, through an integrated approach, combining computer fluid dynamics (CFD) and building performance simulations (BPS). Balcony design showed conflicting effects on the natural ventilation and thermal and energy performance of buildings. Narrow and shallow balconies (2 m x 0.5 m) were identified as the best balcony dimensions for natural ventilation, while wide and deep balconies (5 m x 2 m) emerged as the best dimensions for enhancing thermal and energy performance in offices on the North façade, across all floor levels and for both balcony locations (short-axis and long-axis façades). For the South façade, since it receives less direct solar radiation throughout the year, balcony dimensions had low impact on thermal and energy performance. Therefore, it is recommended to prioritise narrow and shallow balconies (2 m x 0.5 m) across all the floor levels, independently of the balcony location (short or long-axis façade), as this design predominantly favours natural ventilation.

Chapter five addressed the **main objective** of this thesis by developing balcony design recommendations to optimise daylight, thermal and energy performance of mixed-mode office buildings. In this chapter, a parametric analysis of balcony design parameters correlated with building design parameters was conducted to provide balcony design recommendations to improve daylight, thermal and energy performance of high-rise mixed-mode office buildings in São Paulo, Brazil. Balcony design can effectively enhance visual comfort, thermal performance, and energy efficiency while ensuring optimal daylight availability in office rooms, for all façade orientations. Recommendations for balcony design, including balcony depth, parapet type, and balcony location, were tailored to each façade orientation and thoughtfully combined with the glazed door width. One optimal combination of a 3 meters-wide glazed door and a 2 meters-deep balcony was shown to be beneficial for all façade orientations across all floor levels. However, the parapet type should be chosen according to the balcony location, which is directly correlated to the room depth.

## 7.1 Main contributions to science and society

This section highlights the scientific advancements achieved in this doctoral thesis, including main findings and methodologies that enrich the current knowledge about the effects of the use of balconies on daylight, thermal and energy performance in mixed-mode office buildings located in tropical climates.

This thesis fills an important gap in the literature by comprehensively analysing the effects of balcony design parameters, combined with building design parameters, on daylight performance (Chapter 3) and on natural ventilation, thermal and energy performance (Chapter 4), specifically for the office typology. Additionally, it contributes to the state-of-the-art by providing balcony design recommendations considering a multi-objective approach (Chapter 5).

The results obtained from this thesis provide valuable information for architects, emphasising that balconies should not be designed solely as decorative façade elements or service areas. Instead, they should be carefully designed as active contributors to improve daylight, thermal, and energy performance, thereby reducing energy consumption for cooling and electric lighting.

The outcomes of this study can be directly applied to buildings with similar geometry to those used as reference and design cases in this study and placed in comparable climate conditions. Additionally, the methodology employed in this study can be adapted by researchers and architects to other contexts, considering their respective case studies. Chapter 3 demonstrated that by employing a decision tree, designers can be guided toward successful pathways to identify effective solutions for achieving daylight efficiency and visual comfort in office spaces. Chapter 4 pioneered the evaluation of the effects of balconies on natural ventilation, thermal and energy performance by employing a combined approach of Computer Fluid Dynamics (CFD) analysis and Building Performance Simulation (BPS). It underscores the importance of considering the impact of balconies on wind pressure coefficients derived from primary data sources (e.g., CFD), which is essential for ensuring accurate simulation results in natural ventilation modeling using BPS. Lastly, the cross-analysis method utilized in Chapter 5 to select optimal design solutions proved to be an effective approach for addressing conflicting objectives.

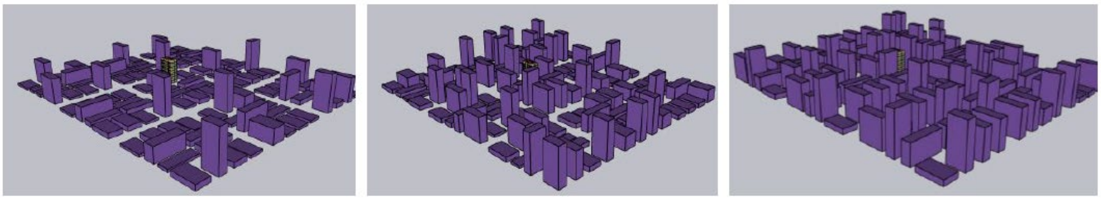
This research demonstrated that carefully designed balconies, combined with building design parameters, can successfully contribute to improve thermal performance, thereby reducing energy consumption with cooling while maintaining efficient levels of daylight performance in mixed-mode office buildings. Given that a deep (2 m) and wide (3 m) balcony was identified as the optimal balcony design solution for all façade orientations analysed in this study, design guidelines for buildings and green buildings certifications should promote the use of such façade elements in office buildings, while discouraging the use of shallow and narrow balcony design, prone to being solely used as service areas.

The nuanced understanding provided by this thesis regarding the effects of balcony design on daylight, thermal, and energy performance of mixed-mode office buildings contributes to the development of more sustainable office spaces, thereby contributing to the ongoing global goal and debate of reducing energy consumption in buildings and mitigating climate change.

## 7.2 Limitations and future studies

In this section, the limitations of this research study are outlined and prospects for future studies are suggested to overcome these limitations, as explained below.

a) **Impacts of surrounding constructions:** This study considered the reference and design cases as isolated buildings. Another manuscript is under development to also investigate the influences of surrounding buildings in mixed-mode office buildings provided with balconies. To analyse how the surrounding constructions impact the microclimate of mixed-mode office buildings with balconies, three hypothetical scenarios of surrounding constructions created by Herling (2023) will be used. The scenarios represent different construction densities in the city of São Paulo - low, medium, and high density (Figure 6.1). A 'typical' mixed-mode office building, provided with balconies on the long-axis façade measuring 2 m deep and 5 meters wide, will be analysed considering these surrounding scenarios. For results comparison, the same building without balconies will also be analysed, also considering the surrounding construction scenarios. This study is being performed in collaboration with the master student Rachel Herling[1] and the bachelor student Beatriz Gonçalves[2].



a) Low-density surroundings b) medium-density surroundings c) high-density surroundings

**Figure 7.1:** Surrounding scenarios used in the ongoing analysis

b) **Use of blinds/curtains and window operation:** The main focus of this study was to promote balconies as efficient exterior shading devices, therefore we did not consider the use of other types of shading elements, such as interior blinds and curtains. It is worth highlighting that the combination of balconies with interior shading devices may compromise the efficiency of balcony design recommendations in providing preferred levels of daylight availability within the office rooms. The outdoor noise may influence whether occupants keep windows open or closed, as pointed out by Ribeiro *et al*. (2024). Additionally, rain can prompt occupants to close the windows. These aspects were not accounted for in the current mixed-mode strategy adopted for the thermal and energy performance simulations. Future research could also assess how occupant behaviour regarding window and blinds operation could affect daylight, thermal and energy performance in office buildings with balconies.

c) **Occupant behaviour and well-being:** Recent studies have highlighted the physical and mental well-being that balconies can bring to residential buildings (Bayazit Solak; Kisakurek, 2023; Duarte *et al*., 2023; Peters; Halleran, 2021; Säumel; Sanft, 2022). Future studies could also investigate the benefits of balconies on occupants' satisfaction with the workplace in office rooms and how balconies may impact workers productivity.

d) **Uncertainties regarding fixed parameters:** The balcony design recommendations presented in this study stem from prevalent construction practices observed in São Paulo, Brazil, which served as the basis for creating the reference and design cases. Considering additional parameters, such as varying reflectance values for balcony and building surfaces, as well as different glazing visible transmittance and solar heat gain coefficient for the glazed doors, could enhance the comprehensiveness of the analysis. Additionally, exploring different balcony

[1] Master research project from the student Rachel Herling at FECFAU-UNICAMP. Research Project title: Impactos das alterações climáticas globais e urbanas no desempenho termoenergético de edifícios escritórios de modo misto. Supervised by Letícia de Oliveira Neves (Funded by CAPES)

[2] Undergraduate research project from the student Beatriz Mestre Matos Gonçalves at FECFAU-UNICAMP. Research Project title: Impactos do entorno construído no desempenho térmico e na ventilação natural de um edifício de escritórios com varandas. Supervised by Letícia de Oliveira Neves and co-supervised by Iris Maria C. F. W. Loche (Funded by PIBIC – CNPq).

positioning in relation to windows - beyond the scope of this study, which only examined balconies centred to glazed door width - and expanding room depths to encompass outliers from the database would enable a broader spectrum of possibilities to be tested, thereby increasing design variety to complement the findings of the analysis conducted in this study.

e) **Balcony enclosure with glass panels:** The balcony design recommendations in this study are intended for open balconies. However, in Brazil, it is common for occupants to enclose their balconies with glass panels, which may affect the effectiveness of these recommendations. Future studies should investigate the impact of enclosing balconies with glazed panels and propose regulations for this practice.

f) **Robustness of balcony design recommendations:** Uncertainties in occupant behaviour, changes in fixed parameters, and external factors like climate change can impact building performance. While various balcony design configurations might demonstrate similar performance in the conditions here analysed, they can manifest different levels of deviation in uncertain scenarios, thus affecting anticipated performance outcomes. Future studies could conduct robustness assessments of balcony design recommendations to effectively address these uncertainties.

g) **Validation and physical measurements:** The reference case (without balconies) and the design cases (with balconies) here analysed are conceptual models, making physical measurements unfeasible. Future research could focus on empirical validation in buildings with balconies, thereby enhancing the findings and enabling extrapolation to other building design settings.

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# Appendices

## Appendix A: Daylight simulations dataset (Appendix of Chapter 3)

In this dataset, the 6360 simulated cases, were derived from 7 variable parameters and three daylight metrics, leading to 19080 output values. To gather the large amount of data, a dataset with 32 graphs was created. Figure A.1 provides a graphic structure to improve legibility of results.

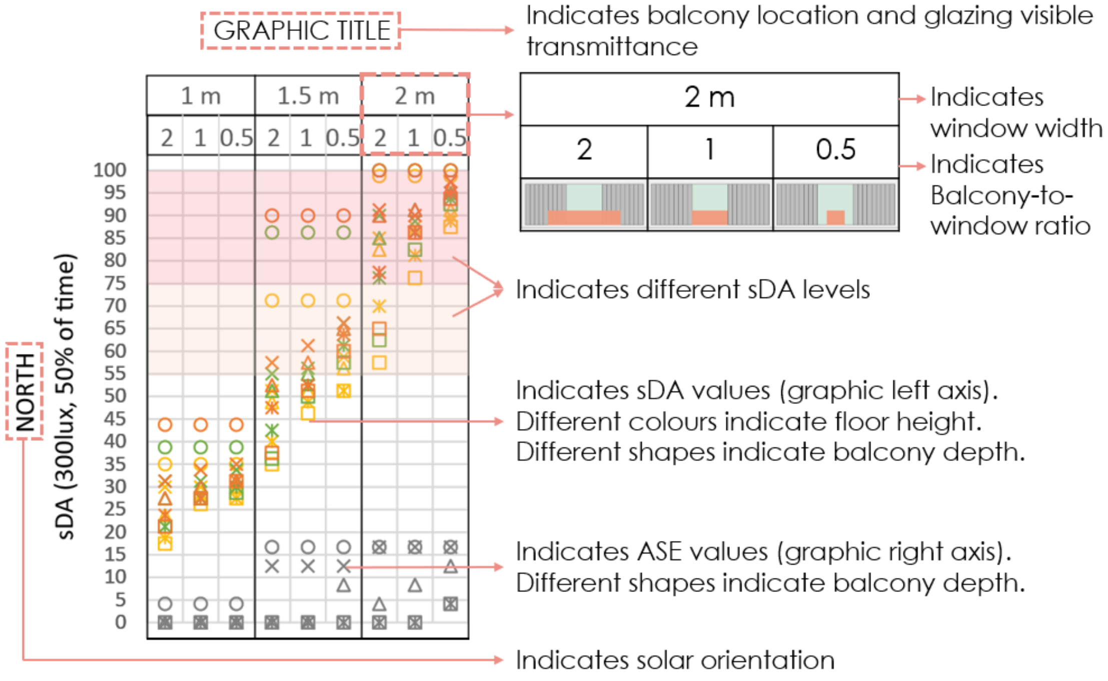


**Figure A.1:** Graphic structure to improve legibility of results

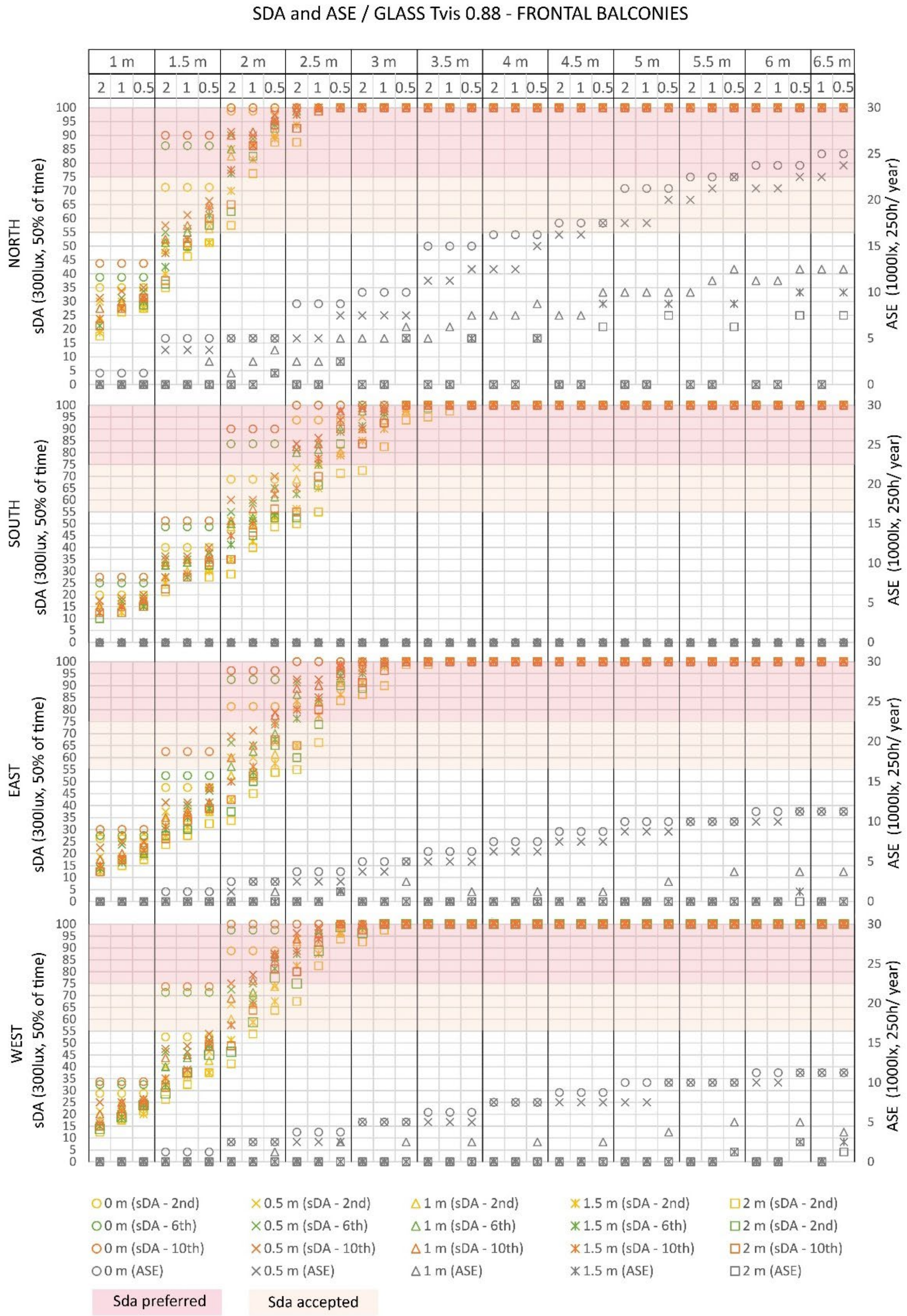


**Figure A.2**: Results for sDA and ASE - Scenarios with front balconies and clear glass (GTvis 0.88)

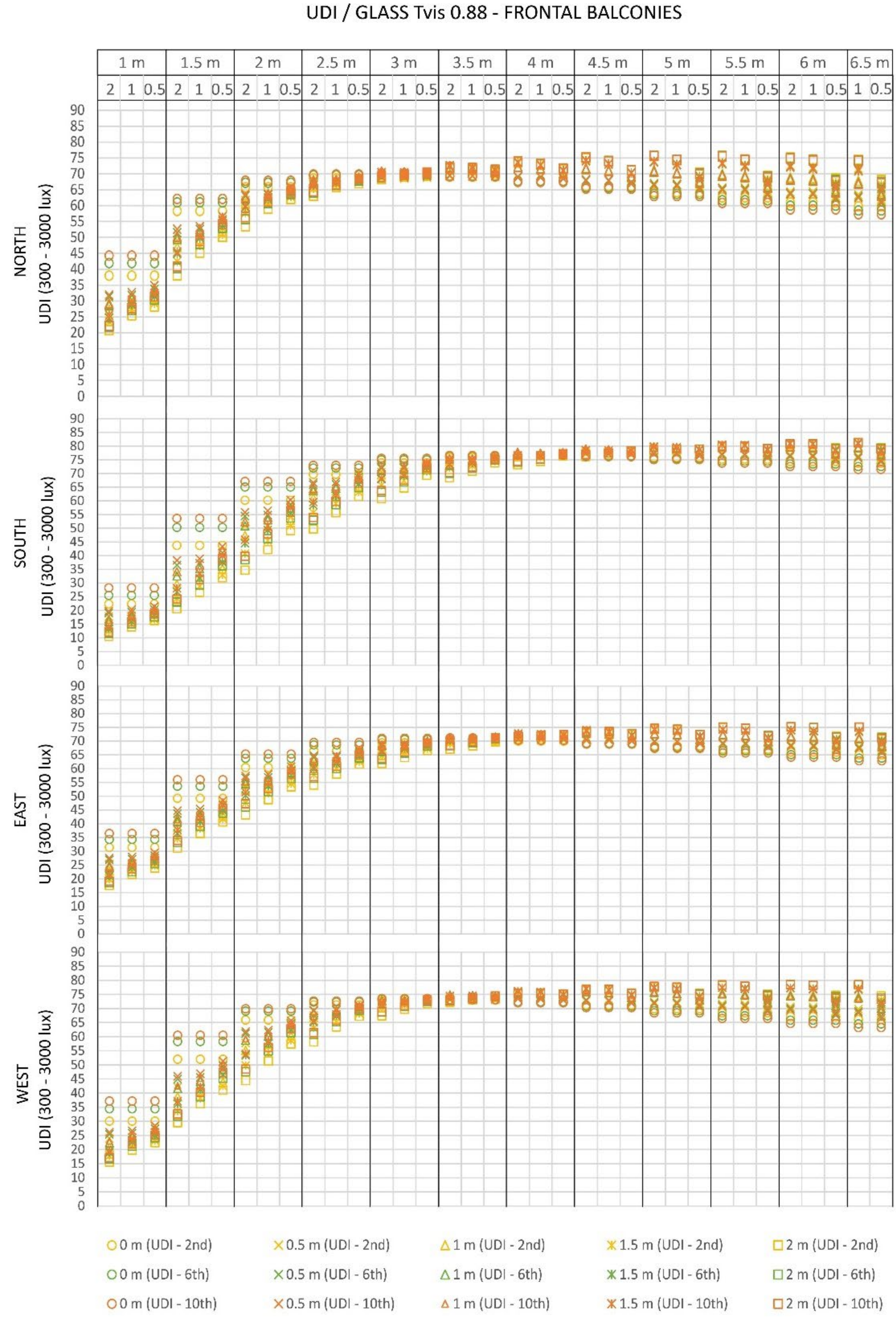


**Figure A.3:** Results for UDI - Scenarios with front balconies and clear glass (GTvis 0.88)

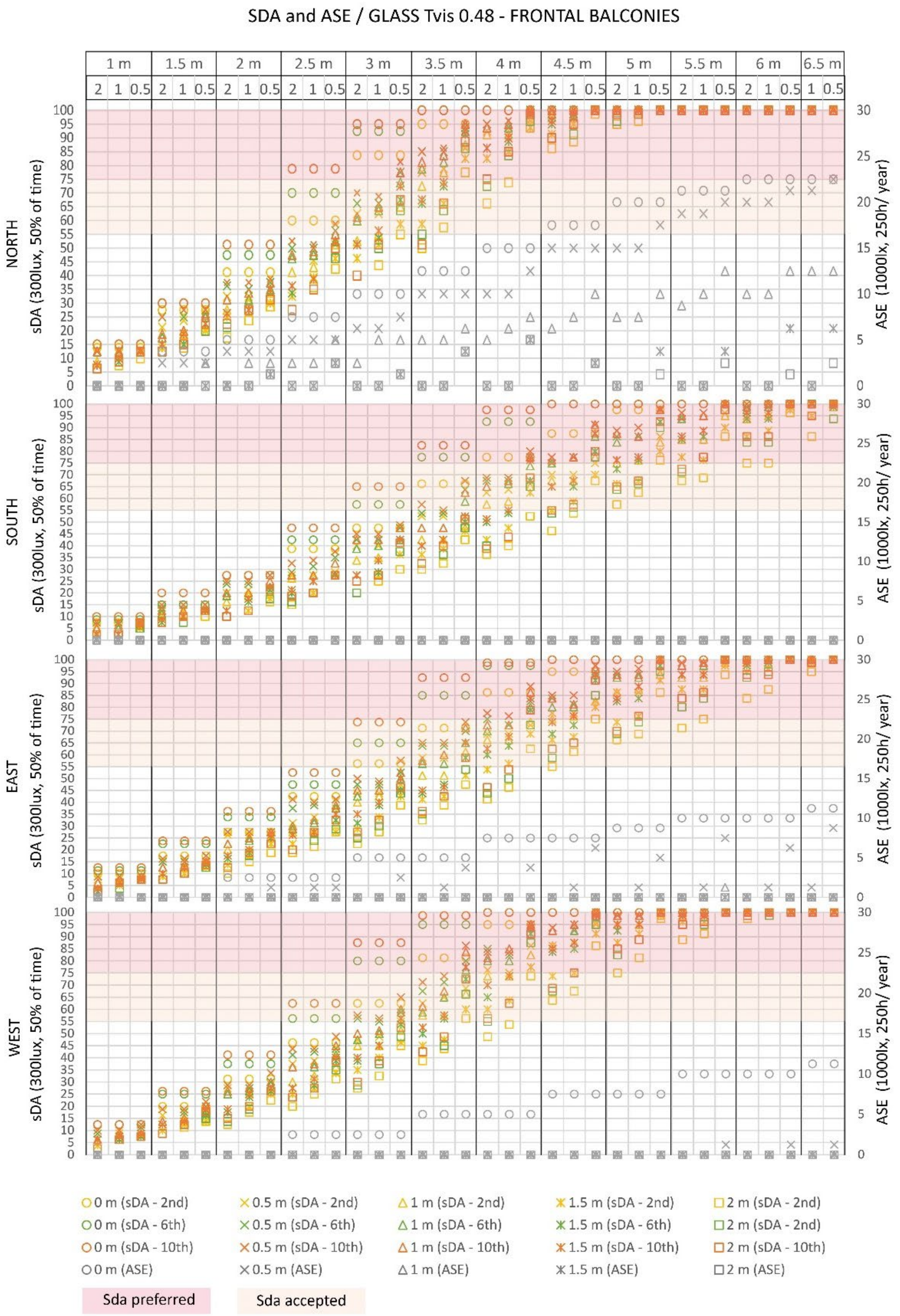


**Figure A.4:** Results for sDA and ASE - Scenarios with front balconies and laminated glass (GTvis 0.48)

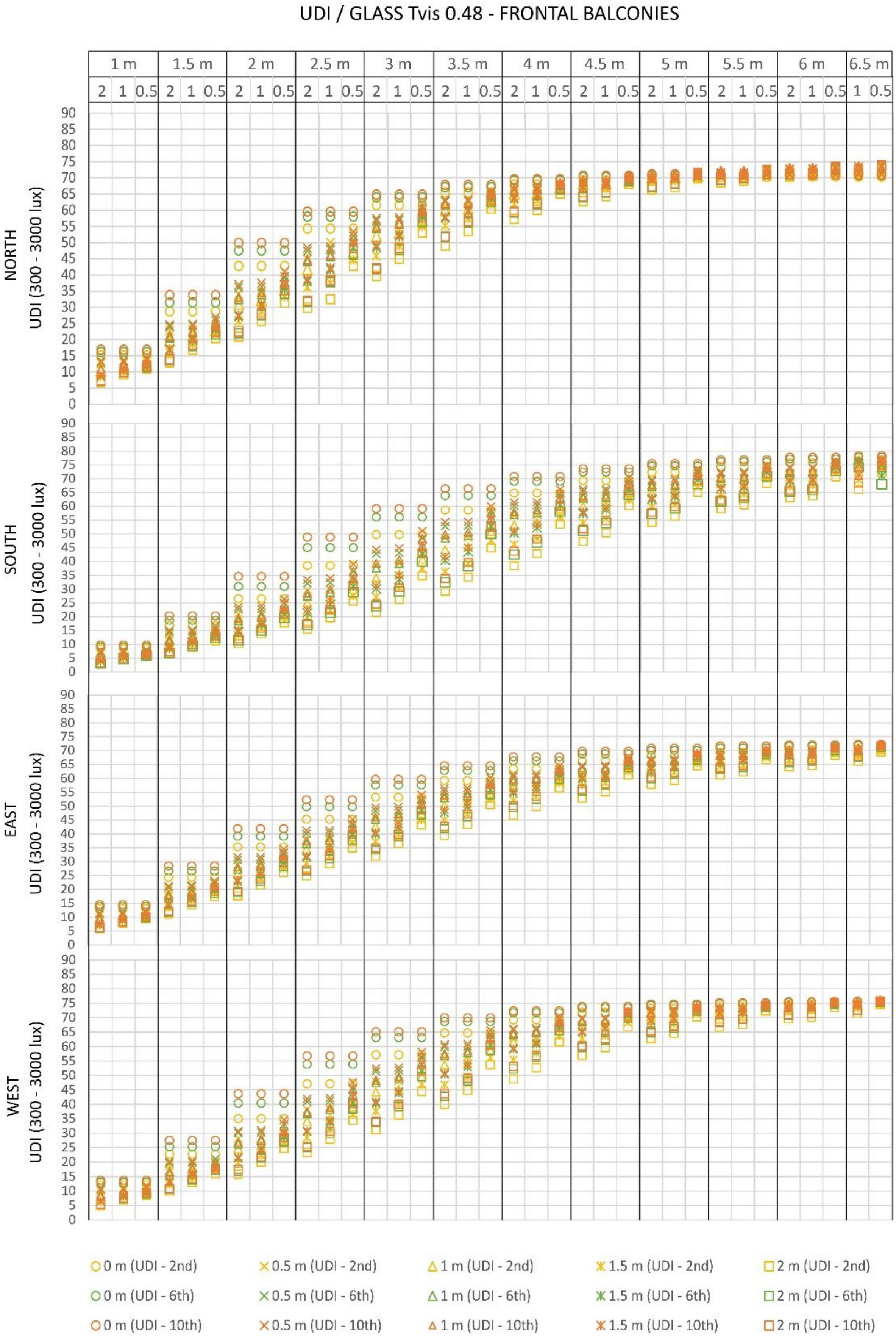


**Figure A.5:** Results for UDI - Scenarios with front balconies and laminated glass (GTvis 0.48)

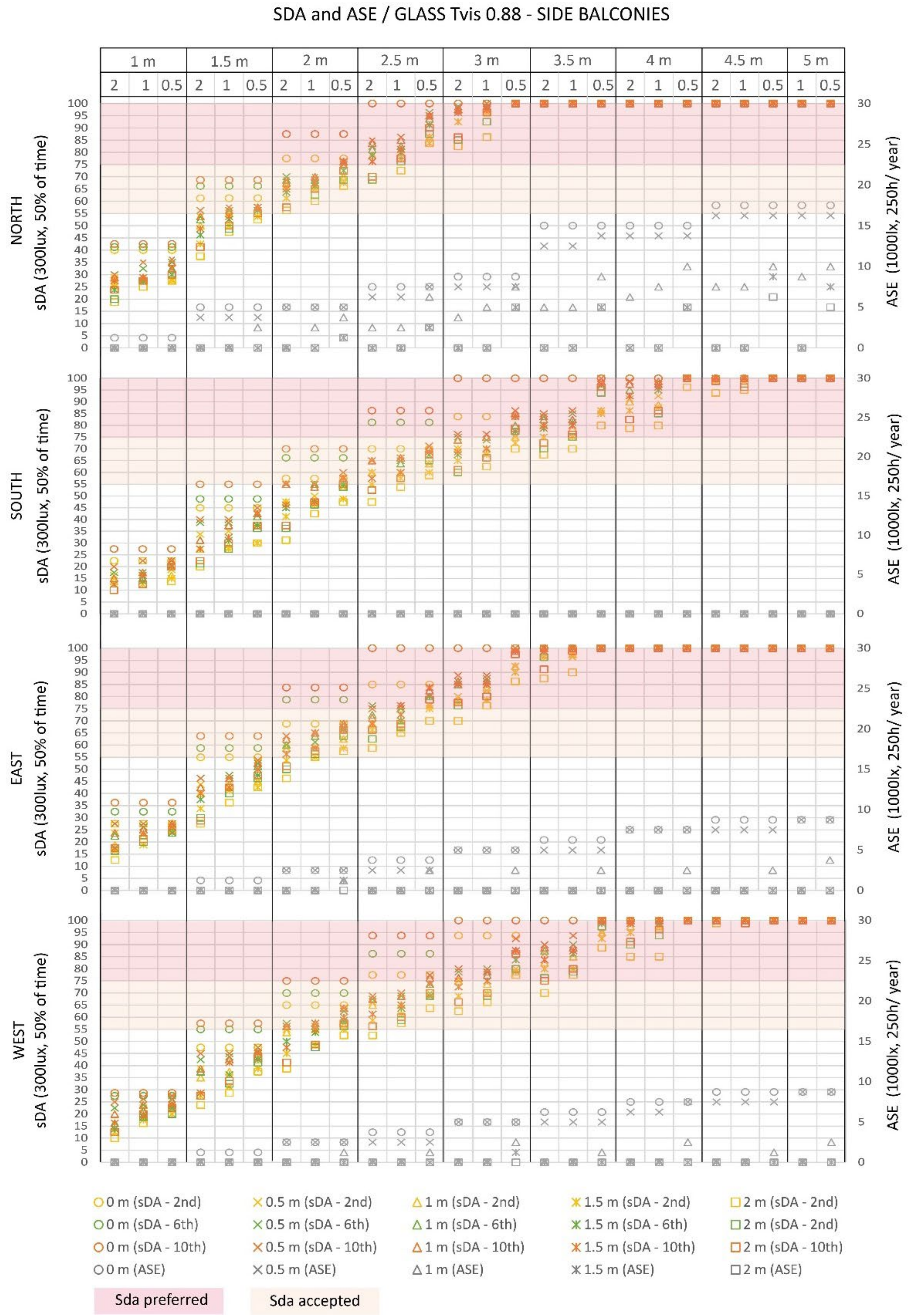


**Figure A.6:** Results for sDA and ASE - Scenarios with side balconies and clear glass (GTvis 0.88)

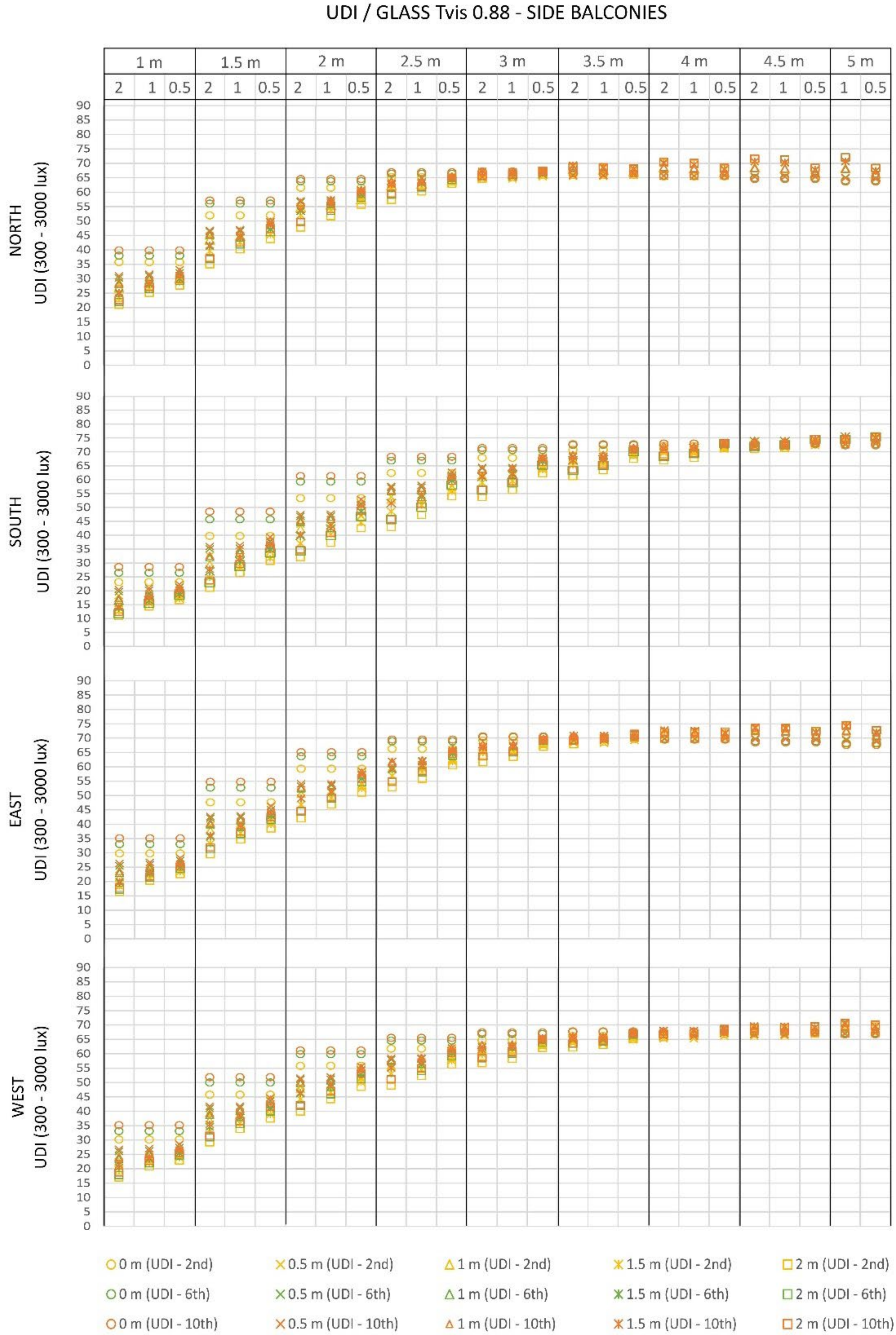


**Figure A.7:** Results for UDI - Scenarios with side balconies and clear glass (GTvis 0.88)

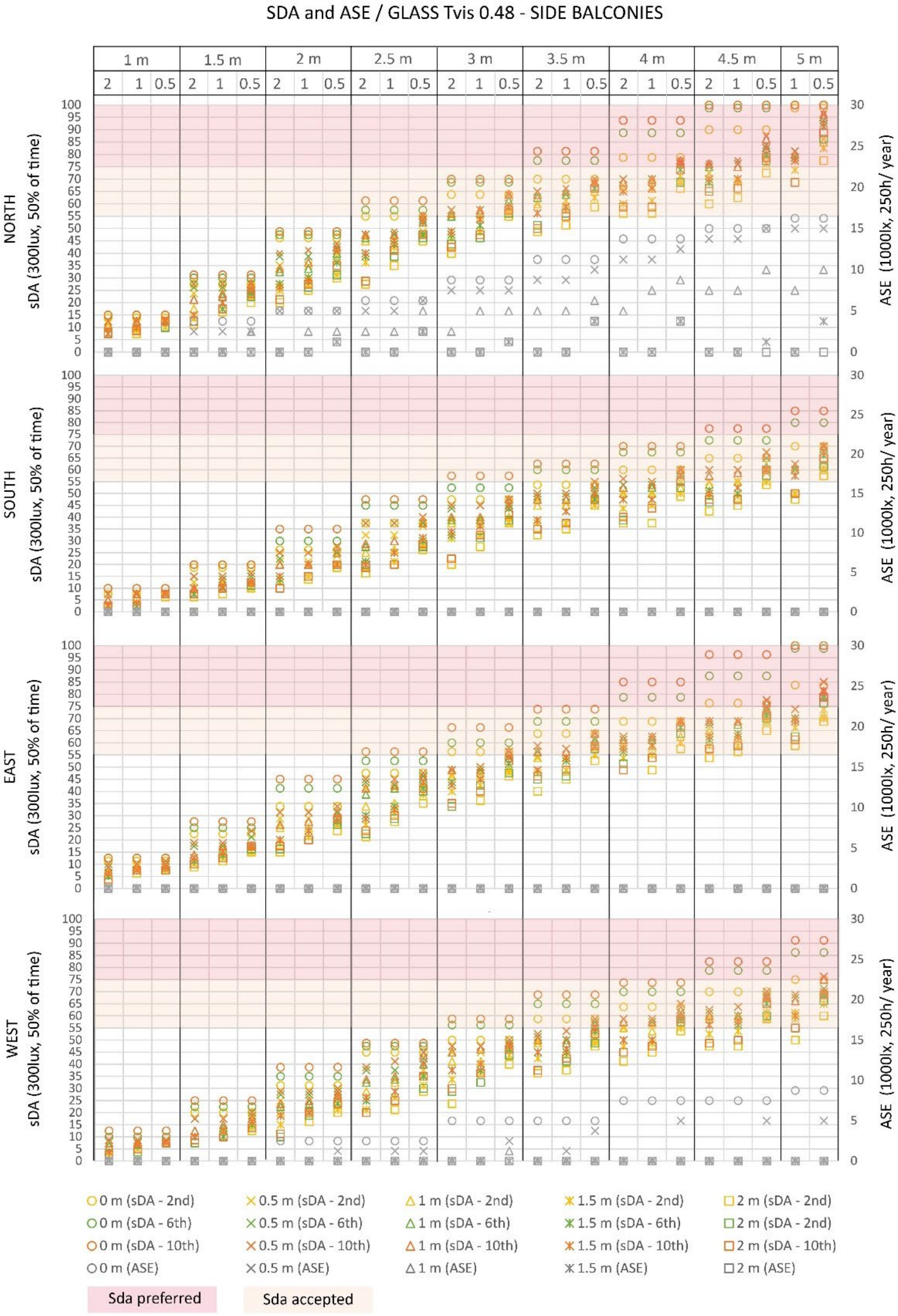


**Figure A.8:** Results for sDA and ASE - Scenarios with side balconies and laminated glass (GTvis 0.48)

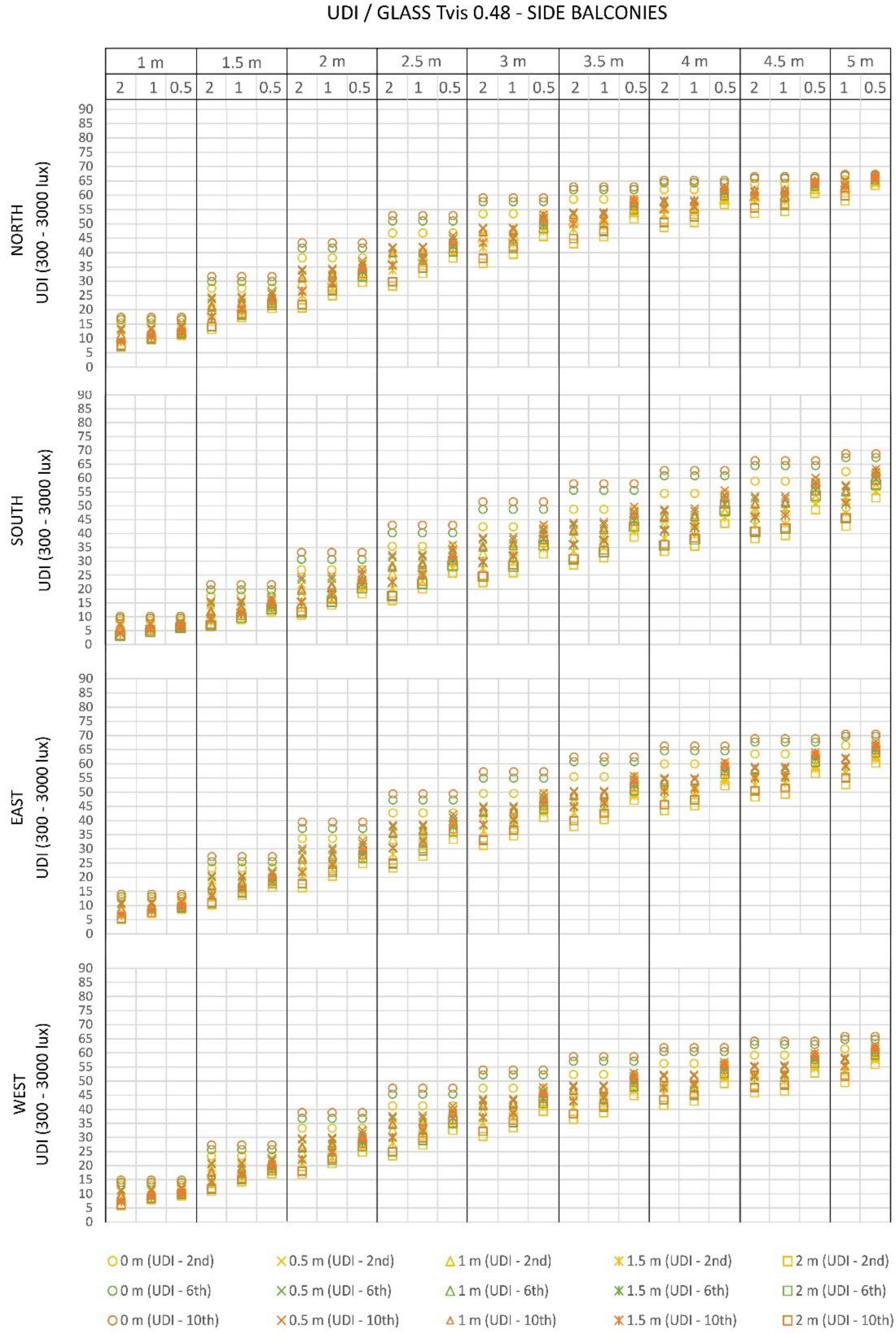


**Figure A.9:** Results for UDI - Scenarios with side balconies and laminated glass (GTvis 0.48)

## Appendix B. Wind tunnel experiments (Appendix of Chapter 3)

This appendix is the transcription of the following paper:

**Effects of Balconies on the Wind Pressure Coefficients of Naturally Ventilated High-Rise Office Buildings**

Authored by: Íris Loche[1], Kauan Polli de Oliveira[1], Matheus Durante[1], Bruna Fracalanza[1] and Letícia de Oliveira Neves[1]

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## Abstract

Natural ventilation and shading are effective bioclimatic strategies for buildings located in tropical regions. However, shading elements such as balconies also impact natural ventilation by influencing wind pressure coefficient (Cp) on building façades. This paper presents an investigation of the effects of balconies on the Cp values of high-rise office buildings, providing a detailed database of wind pressure coefficients. Wind tunnel tests were carried out for fifteen scenarios, considering an isolated building and surrounded by other buildings and combining balconies' location (side façades or frontal and back façades), its dimensions (width from 1 to 5 meters and depth from 0.5 to 2 meters) and 24 wind directions. Results showed that the provision of balconies impact on the Cp values and on the wind pressure difference between inlet and outlet openings (ΔCp) for both windward and leeward façades. For the first and middle floors, ΔCp values decreased when the balconies' depth increased, and balconies 1-meter and 5-meter wide showed higher ΔCp values than balconies 2.5-meter wide. The upper floor showed lower Cp values when balconies' depth and width increased. Also, surrounding buildings highly impacted Cp values, leading to negative values for all façades, including the windward façade.

**Keywords:** Natural ventilation; wind tunnel; balcony; office building

## B.1. Introduction

Natural ventilation and shading are effective bioclimatic strategies for buildings located in tropical regions. Balconies are horizontal overhanging structures used as fixed solar shading devices that behave as an eave to the lower floor, reducing the incidence of direct solar radiation and improving indoor comfort. Natural ventilation consists of a process that promotes air exchange between external and internal environment through building openings, assisting to provide health and comfortable room for occupants without energy consumption. When natural ventilation is wind-driven, the existence of façade elements modifies the wind pressure distribution on the building envelope, changing incident wind flow's characteristics (Castaño, 2017). This emphasizes the importance of knowledge about the pressure distribution on the building envelope to assess natural ventilation. The wind pressure on building surfaces can be evaluated through wind pressure coefficients (Cp), which characterizes air flow behaviour in buildings independently from the model scale (Neves, 2012). Cp values can be obtained through existing databases or through primary sources. The latter considers building particularities and parameters that influence Cp values.

Wind pressure coefficients' databases for simplified building geometries are available on the literature, e.g. the AIVC database (Knoll; Phaff; Gids, 1995), the ASHRAE Fundamentals Handbook (ASHRAE, 2017), TPU Aerodynamic database (Engineering, 2016). Analytical methods also estimate mean Cp values on a building surface, such as the model from Swami and Chandra (Swami; Chandra, 1988) and software tools such as Cp Generator (Knoll; Phaff; Gids, 1995) and CpCalc+ (Grosso, M.; Marino, 1996). All these sources include Cp values for low and high-rise buildings and most of them provide values for several wind directions, with exception of the AIVC database that presents 45$^{o}$ intervals for low-rise buildings and 90$^{o}$ intervals for high-rise buildings (Cóstola; Blocken; Hensen, 2009). However, these databases and analytical methods are limited. Among the sources mentioned, only the software tools Cpcalc+ and Cp Generator consider the surrounding terrain type. When it comes to façade detailing and specific geometries (such as balconies), exposure conditions (such as wind direction, existence of surrounding buildings and adjacent obstacles) the use of simplified Cp values may induce to significant mistakes on the results from natural ventilation analysis (Leite, 2015).

Data from primary sources is considered more accurate than existing databases and analytical models since wind pressure coefficients are influenced by a wide range of factors including air flow conditions, urban surroundings and building geometry. One of the most reliable ways to provide primary data is through wind tunnel experiments under controlled turbulence conditions (Neves, 2012). The wind tunnel experiments are performed using small-scale models and adjusting wind direction and speed (Neves *et al.*, 2017). The results obtained through the experiments may also help to evaluate building thermal energy performance, by using Cp values as input data on building energy simulation (BES) programs such as EnergyPlus.

The EnergyPlus Airflow Network component allows the user to specify whether the wind pressure coefficients are input manually or automatically calculated by the program. To input Cp values manually, the user must determine the external nodes' height and input the Cp values for different wind directions. The airflow is calculated through the interpolation of the specified Cp values for each timestep and wind direction (EnergyPlus, 2021). The Cp values automatically calculated by the software are valid only for rectangular buildings. For low-rise buildings, calculations are performed based on the model from Swami and Chandra (1988) and for high-rise buildings, wind pressure coefficients are generated based on the ASHRAE Fundamentals Handbook (ASHRAE, 2017).

Previous studies found that the provision of balconies significantly alters the wind pressure distribution on the building façade. Montazeri and Blocken (2013) performed CFD simulations validated with wind tunnel for predicting mean wind pressure distributions on windward and leeward façades of an undefined typology five-storey building with and without balconies. The authors concluded that balconies could lead to strong changes in wind pressure distribution, since they introduce multiple areas of flow separation and recirculation across the façade. Chand *et al*. (1998) analysed Cp values for a five storey-hostel building provided with balconies, varying wind direction from 0º to 45º. Results showed that the provision of balconies alters the wind pressure distribution on windward façades, subjected by wind direction and floor height, but does not introduce significant changes on the leeward side. Kotani and Yamanaka (2007) carried out wind tunnel tests to evaluate wind pressure coefficients, also for a five-storey apartment building with and without balconies, varying the balcony type (banister and fence shape) and the wind direction. Results showed that the distribution of the wind pressure coefficients on the building façade depended mainly on the wind direction and not so much on the types of balconies. Castaño (2017) performed wind tunnels experiments and concluded that the addition of a balcony on a single floor residence diminished the air flow up to 25%, leading to a small increase on indoor temperature of 0.1ºC.

These findings provide evidence of the variation in the wind pressure distribution on building façades due to the addition of balconies. However, detailed information on how balconies' dimensions, location and different wind directions influence the wind pressure distribution is still lacking, in particular for high-rise office buildings. In Brazil, commercial buildings were responsible for 14.3% of total energy consumption in 2018 (EPE, 2019), mainly due to intensive use of air conditioning systems. The use of solar shading devices (such as balconies) and natural ventilation may improve building thermal performance, reducing energy consumption. Therefore, this paper aims to provide a database containing wind pressure coefficient values for a high-rise office building with balconies, in order to provide input values for thermal and energy simulations. The database presents Cp values for an isolated building and for a building surrounded by other buildings, considering different balconies' dimensions, location and wind direction.

## B.2 Methods

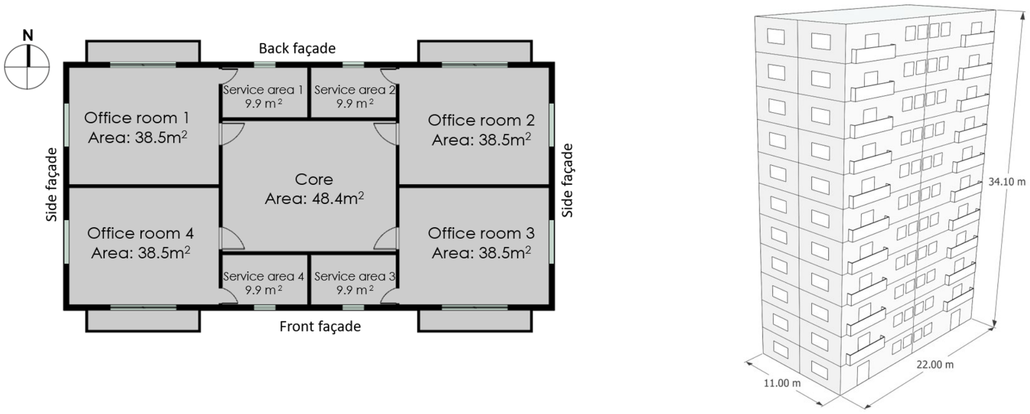
This is an experimental research based on wind tunnel experiments.

### B.2.1 Base case

A base case was determined based on a database containing design parameters of 153 mixed-mode office buildings located in the city of São Paulo, Brazil (Neves; Melo; Rodrigues, 2019). The building's fixed parameters are shown on Table B.1 and Figure B.1.

**Table B.1:** Base case - fixed parameters

| | |
|---|---|
| **Building** | |
| Width | 11 m |
| Length | 22 m |
| Height | 34.1 m |
| Number of floors | 11 |
| **Floor** | |
| Total area | 242 $m^2$ |
| Circulation area | 48.4 $m^2$ |
| Number of offices | 4 |
| **Offices** | |
| Office room shape | rectangular |
| Area | 38.5 $m^2$ (5.5 m x 7 m) |
| Floor height | 3.1 m |
| Ventilation type | cross ventilation in adjacent façades |




a) Base case model floor plan

b) Base case model elevation

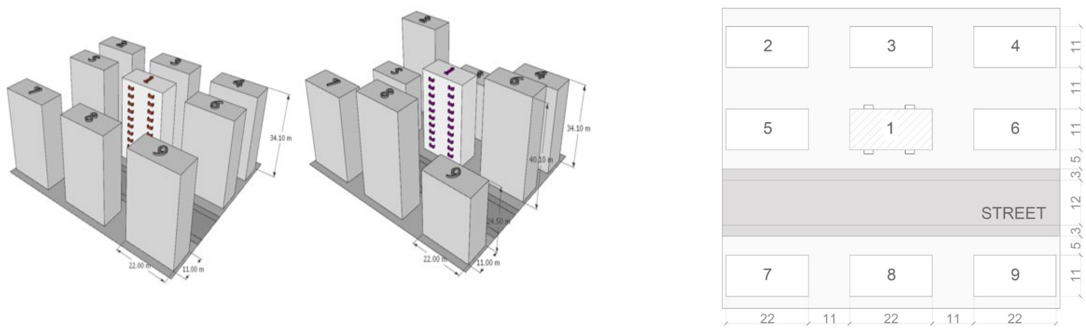
**Figure B.1:** Base case floor plan

## B.2.2 Scenarios

Fourteen scenarios were created combining the base case with variable parameters, such as balconies' location and dimensions and building's surroundings, based on balconies' configurations identified on the database. A scenario without balconies, named as reference, was created for results comparison. Twelve scenarios were created considering an isolated building, with no interference from surrounding buildings (Table B.2). Two scenarios were created considering the building surrounded by other constructions (Figure B.3 and Tables B.3 and B.4). The surrounding urban design was defined based on the evaluation of the density profile of the region where the buildings from the database developed by Neves, Melo and Rodrigues (2019) were located. Satellite images from Google Maps were used to define a density profile corresponding to 0.34 (ratio of constructed area to total area). The indentation between buildings and the urban design were defined based on the Building Work Code for the city of São Paulo (São Paulo, 2017) (Figure B.2). The impacts of the surroundings on the wind pressure coefficients were analysed considering two different contexts. For results comparison, the following assumptions were applied: the building in analysis would have the same variable parameters (Table B.4) and both tested surroundings the same density profile (0.34), altering only the surrounding buildings' height. Context 1 was formed by surrounding buildings with the same height as the building in analysis. Context 2 was formed by different surrounding buildings' heights, defined by the height' standard deviation from the database developed by Neves, Melo and Rodrigues (2019) (Table B.3).

**Table B.2** Scenarios - Isolated building

| Scenario | Balcony location | Balcony width (m) | Balcony depth (m) |
|---|---|---|---|
| **Reference** | Without balconies | | |
| **1** | Right and Left-side façades | 1.0 | 0.5 |
| **2** | | 1.0 | 1.0 |
| **3** | | 2.5 | 0.5 |
| **4** | | 2.5 | 1.0 |
| **5** | Frontal and back façades | 2.5 | 0.5 |
| **6** | | 2.5 | 1.0 |
| **7** | | 2.5 | 1.5 |
| **8** | | 2.5 | 2.0 |
| **9** | | 5 | 0.5 |
| **10** | | 5 | 1.0 |
| **11** | | 5 | 1.5 |
| **12** | | 5 | 2.0 |
| **13** | | 2.5 | 1.0 |
| **14** | | 2.5 | 1.0 |




a) Context 1 b) Context 2 c) Floor plan for Contexts 1 and 2

**Figure B.2** Surrounding buildings

**Table B.3:** Surrounding buildings height for context 1 and 2

| Buildings | Buildings height (Context 1) | Buildings height (Context 2) |
|---|---|---|
| 1, 4 and 7 | 34.1 m | 34.1 m |
| 2, 6 and 8 | | 40.1 m |
| 3, 5 and 9 | | 24.5 m |

**Table B.4:** Scenarios – Building with surrounding constructions

| Scenario | Context | Location | Width (m) | Depth (m) |
|---|---|---|---|---|
| 13 | 1 | Frontal and back façade | 2.5 | 1.0 |
| 14 | 2 | | | |

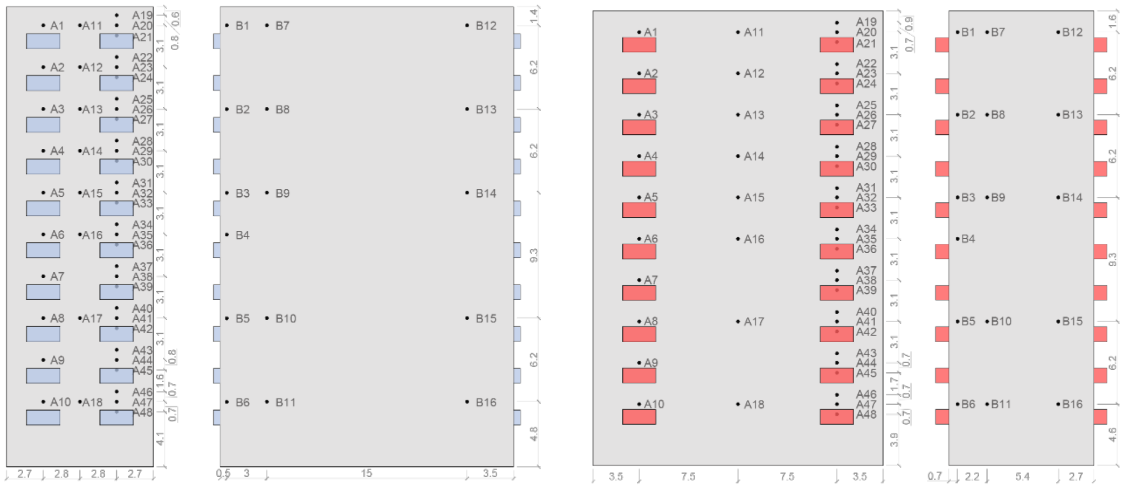
### B.2.3 Wind tunnel experiments

The wind tunnel experiments were carried out at the Institute of Technological Research (IPT), São Paulo, Brazil. The wind tunnel has a length of 40 meters and a test section of 6 $m^2$. According to Silva (1999), the maximum obstruction area at the test section should be 7%. Assuming that, the isolated building (used for the reference model and scenarios 1 to 12) was modelled in a scale of 1:50 and the building with surroundings (used for scenarios 13 and 14) was modelled in a scale of 1:100. Thus, the models obstructed approximately 5% of the test section area. The models were built using 3 mm and 6 mm MDF panels. Sixty-four pressure sensors with ±0.05% full scale accuracy after Rezero (DTC INITIUM, 2016) were positioned in two façades of the model – 48 sensors on the façade with balconies and 16 on the adjacent façade (Figure B.4). Since the model is symmetric, all the four façades could be evaluated by orbiting the model in 180°. Measurements were taken every 15°, corresponding to 24 wind directions for each building façade.

a) 1:50 scale model (isolated building)

b) 1:100 scale model (building with surroundings)

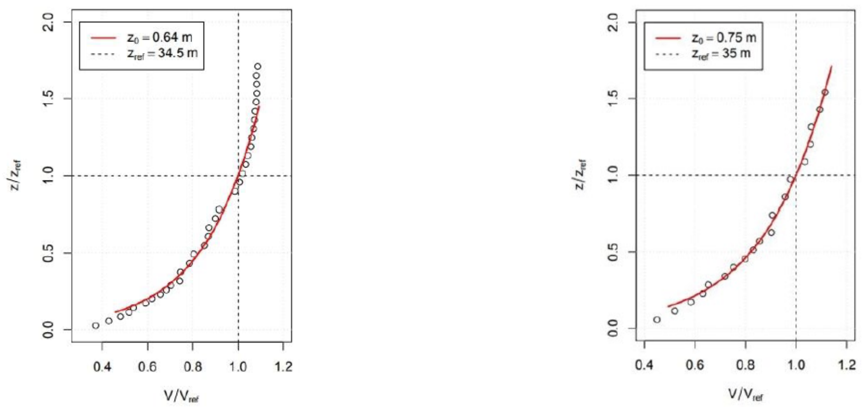
**Figure B.3:** Scale models used in the wind tunnel experiments



a) Scenario 3 (side balconies 2.5 m x 1m) b) Scenario 6 (front balconies 2.5 m x 1 m)

**Figure B.4:** Sensors position for scenarios with side and front balconies

The roughness category simulated in the experiments were verified by measuring the wind speed at different heights, by using a hot-wire anemometer sensor. Considering the building's height in analysis (34.1 m at full-scale), the roughness (z0) was 0.64 m for the scenarios 1 to 12 (considering an isolated building) and 0.75 m for the scenarios 13 and 14 (considering the surrounding buildings), representing the roughness category IV (ABNT, 1988) which consists of terrains covered by several obstacles with little space in-between them (Figure B.5).




a) Scenarios 1 to 12 (isolated building) b) Scenarios 13 and 14 (with surrounding buildings)

**Figure B.5:** Velocity profile obtained through wind tunnel tests

To create the atmospheric boundary layer, the wind tunnel was provided with roughness elements and spires (Figure B.6).

**Figure B.6:** Wind tunnel interior: roughness blocks and spires.

To precisely determine wind pressure coefficients, the environment inside the wind tunnel must be controlled. Turbulence conditions must be assured within the tunnel to guarantee that the flow characteristics around the building are independent of the Reynolds number (Re>$10^5$) (Neves, 2012). Tests were performed rotating clockwise the model, from 0º to 45º, in order to ensure a turbulent flow inside the wind tunnel during the experiments. The wind velocity inside the tunnel was increased gradually until the independence of the Reynolds number was achieved, which occurred at 350 rpm (approximately 15 m/s). Also, a beehive-like structure located in the air entrance of the tunnel also contributed to provide a turbulent flow.

B.2.4 Wind pressure coefficients (Cp)

According to Blessmann (1983), the wind pressure coefficient (Cp) consists of the ratio between the dynamic pressure at a certain point of the building surface ($P_e$) and the undisturbed air flow dynamic pressure ($P_d$):

$$C_P = \frac{P_e}{P_d}$$

Then, to obtain $C_P$, $P_e$ and $P_d$, the following equation was used:

$$C_P = \frac{P_{T_{Mod}} - P_{E_{Mod}}}{f(P_{T_{Ref}} - P_{E_{Ref}})}$$

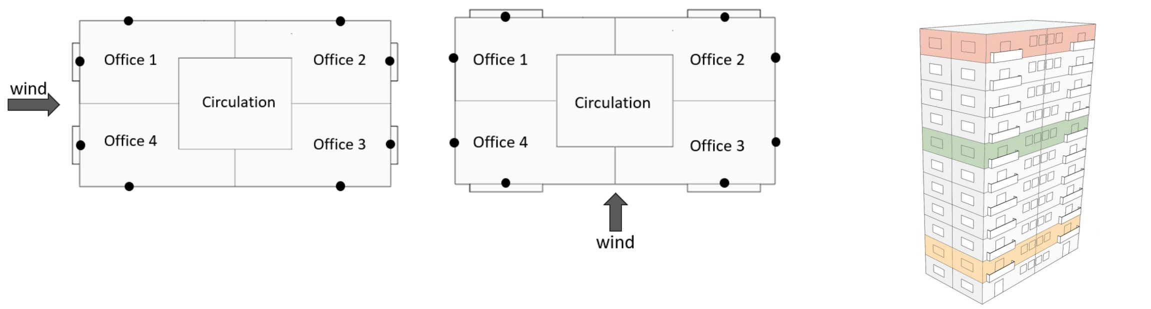
The model static pressure ($P_{E_{Mod}}$) was measured by a piezometric ring, which calculates the average static pressure around the test section. The reference total pressure $P_{T_{Ref}}$ and the reference static pressure $P_{E_{Ref}}$ were obtained using a Pitot Tube. The correction factor for the dynamic pressure ($f$), which consists of the ratio between the dynamic pressure at the height of the model and the reference dynamic pressure, was 0.79 for the isolated building and 0.52 for the building with surroundings.

Data analysis and graphic workspace software Origin 8 was used for displaying the Cp values obtained by the wind tunnel experiments.

## B.3 Results and discussion

A database, containing detailed wind pressure coefficient values for all 15 scenarios and 24 wind directions, was developed to provide full access to all the results, available at:http://www.fec.unicamp.br/~conforto/trabalhos/iris_loche/index.php. This database is a useful source to future research studies and to evaluate natural ventilation through the Airflow Network (AFN), usually coupled with Building Energy Simulation (BES) software, such as EnergyPlus.

To evaluate the impact of balconies on natural ventilation, the difference between inlet and outlet openings' wind pressure coefficient values (ΔCp) obtained in the experiments was calculated and compared. One wind direction was chosen for each scenario to evaluate the impact of balconies for the windward and leeward façades (90º for balconies at right and left-side façades and 0º for balconies at front and back façades). Also, the first, the middle and the upper floors were selected to perform the analysis (Figure B.7).

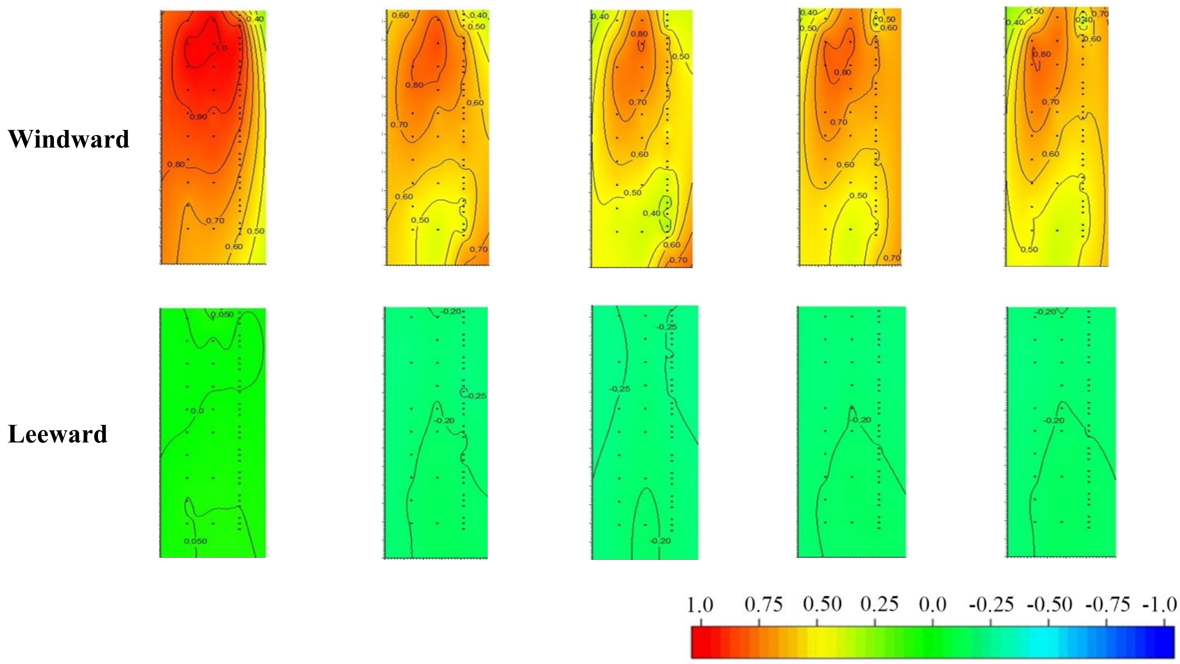



a) 1- Floor plan – scenarios 1 to 4 b) Floor plan – scenarios 5 to 14 c) Selected floors highlighted

**Figure B.7:** Floor plans, location of Cps in analysis and selected floors.

a) Balconies located at right and left-side façades

The models with balconies located at side façades are represented by the scenarios 1 to 4 (Table B.2 and Figure B.7). We chose the wind direction of 90º to observe the wind pressure coefficients' behaviour. Figure B.8 shows that Cp values are higher for the scenario without balconies, not only in the windward façade, but also in the sideward and leeward façades of the building. In all the scenarios, Cps have higher values on the upper floors. Figure B.9 shows that offices 1 and 4, located at the windward façade, presented higher ΔCp values than offices 2 and 3, whose openings are located at the leeward and sideward façades. The first floor showed lower values than the middle and upper floors. The first and middle floors showed a higher impact of the balconies' depth than of the balconies' width, since values decreased when the balconies' depth increased. However, on the upper floor, the balconies' width also impacted the ΔCp values, which decreased together with the increase of the balconies' width and depth for the scenario 4. Scenarios 1 and 3, both with balconies 0.5 m depth, showed higher ΔCp values for the first and middle floors for all scenarios, including the reference case, with no balconies. Conversely, in the upper floor, the reference case and the scenario 1 showed the highest values of ΔCp, which decreased when the balconies' depth and width increased.




a) Ref. b) Scenario 1 c) Scenario 2 d) Scenario 3 e) Scenario 4

**Figure B.8:** Wind direction 90º - Wind pressure coefficient values for windward and leeward façades

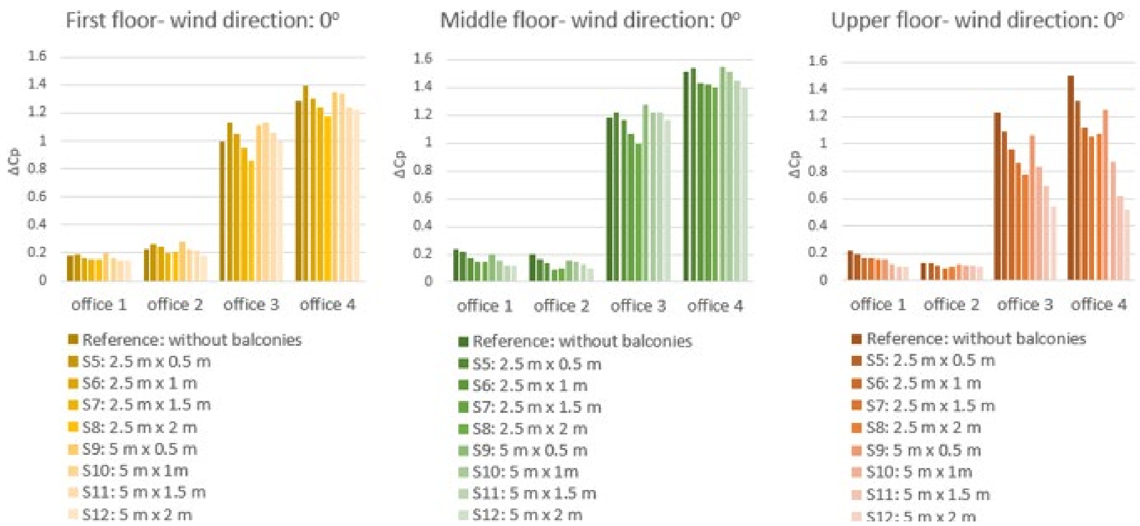



**Figure B.9:** ΔCp for scenarios with balconies located at side façades and wind direction of 90º

b) Balconies located at front and back façades

The models with balconies located at front and back façades are represented by scenarios 5 to 12 (Table B.2 and Figure B.6). We chose the wind direction of 0º to observe the wind pressure coefficients' behaviour. Alike scenarios 1 to 4 (Figure B.7), Figure B.9 shows that Cp values are higher in all façades for the scenario without balconies and on the upper floors for all other scenarios. Figure B.10 shows that offices 3 and 4, located at the windward façade, presented higher ΔCp values than offices 1 and 2, whose openings are located at the leeward and sideward façades. The middle floor showed higher values than the first and upper floors. The impact of varying the balconies' depth was higher than the balconies' width, since values decreased when the balconies' depth increased. However, on the upper floor, the balconies' width also impacted the ΔCp values, which decreased with the balconies' width increase. Scenarios 5 and 9 (balconies 0.5 m depth) showed the highest ΔCp values for the first and middle floors. Conversely, for the upper floor the scenario with no balconies showed the highest ΔCp values, which decreased when the balconies' depth and width increased. Higher ΔCp values were obtained for the first floor of offices 1 and 2, located at the leeward and sideward façades. Higher ΔCp values were achieved for the scenario with no balconies and for the scenarios with shallow balconies.

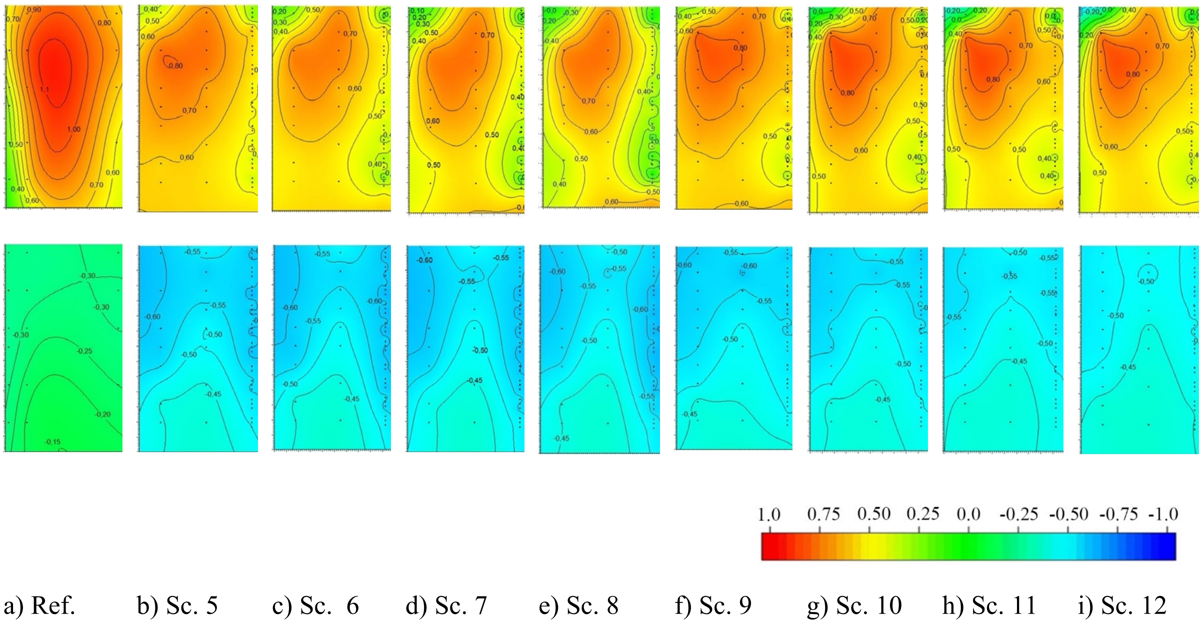



**Figure B.10:** Wind direction 0º - Wind pressure coefficient values for windward and leeward façades

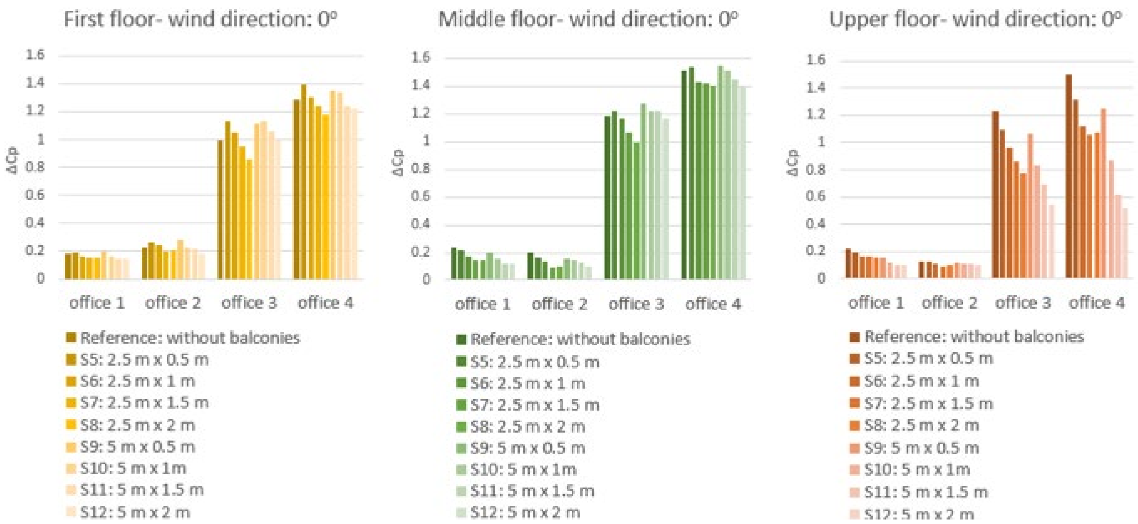



**Figure B.11:** ΔCp for scenarios with balconies located at frontal and back façades and wind direction of 0º

B.3.1 Building with surroundings

The models with surrounding buildings are formed by longitudinal balconies and represented by scenarios 13 and 14 (Tables B.3 and B.4). We chose the wind direction of 0º to perform the analysis. Figure B.12 shows that the surrounding buildings caused a decrease in the wind pressure coefficients, showing negative values even on the windward façades. Figure B.13 shows that the surrounding buildings' height influences directly on the ΔCp values on windward and leeward façades. Offices 1 and 3 showed higher ΔCp values for scenario 14, mainly on the first floor, due to the influence of buildings 3, 4 and 9, which are smaller in scenario 14 than in scenario 13. Offices 2 and 4 showed higher ΔCp values for scenario 13, since buildings 6 and 8 are smaller.

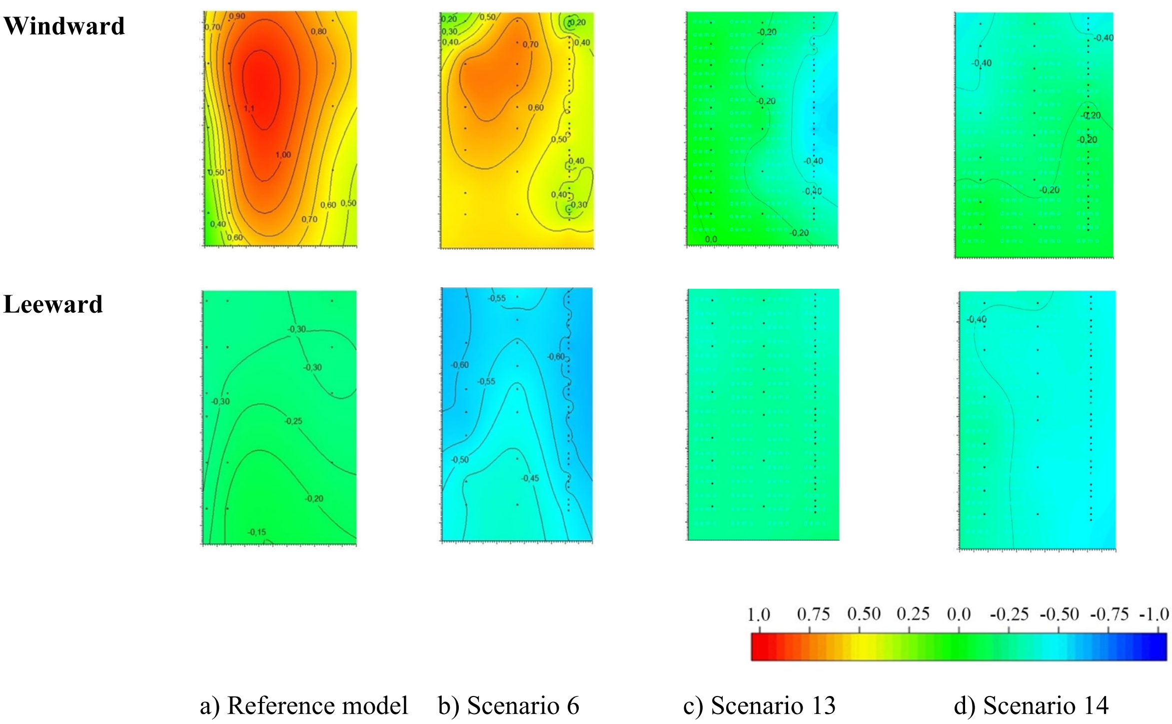


**Figure B.12:** Wind direction 0o - Wind pressure coefficient values for windward and leeward façades

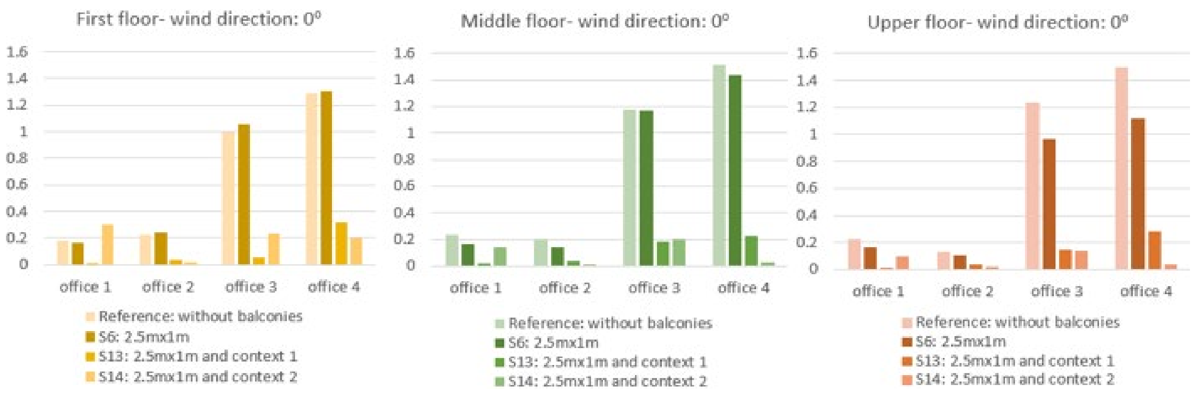



**Figure B.13:** ΔCp for scenarios with surrounding buildings and wind direction of 0º

## B.4. Conclusion

A series of wind tunnel tests have been conducted to investigate the effects of balconies on the wind pressure coefficient values of high-rise office buildings isolated and with surroundings, by combining balconies locations and dimensions for 24 wind directions. From this study, the following conclusions can be obtained:

The provision of balconies showed high impact on the wind pressure coefficient (Cp) values for both windward and leeward façades. The difference between inlet and outlet openings' wind pressure coefficient values (ΔCp) for all the scenarios showed higher values for the offices containing openings located at windward façades than the ones with openings located at the leeward façade.

The middle and upper floor showed higher Cp and ΔCp values than the first floor. The upper floor showed high impact when balconies' depth and width increased, resulting lower ΔCp values for deeper and larger balconies. For the first and middle floor, ΔCp values also decreased when the balconies' depth increased, and balconies 1-meter wide and 5-meter wide showed higher ΔCp values than 2.5-meter width balconies.

The distribution of wind pressure coefficient and ΔCp values is highly influenced by surrounding buildings. When surrounding buildings were included, results showed negative Cp values, even for the windward façade. The ΔCp values also decreased substantially when surrounding buildings were considered, mainly when influenced by the higher buildings surrounding the building in analysis. These results reinforce the importance of considering the context in which the building is located when analysing natural ventilation.

This paper provides a database containing all the results obtained by the wind tunnel experiments, elaborated with detailed wind pressure coefficient values for all the scenarios, according to 24 wind directions. The wind pressure coefficient values available on the database are useful to further the researchers access to natural ventilation, providing input data for simulations in Building Energy Software (such as Energy Plus) reducing results uncertainties and encouraging the use of natural ventilation in new constructions.

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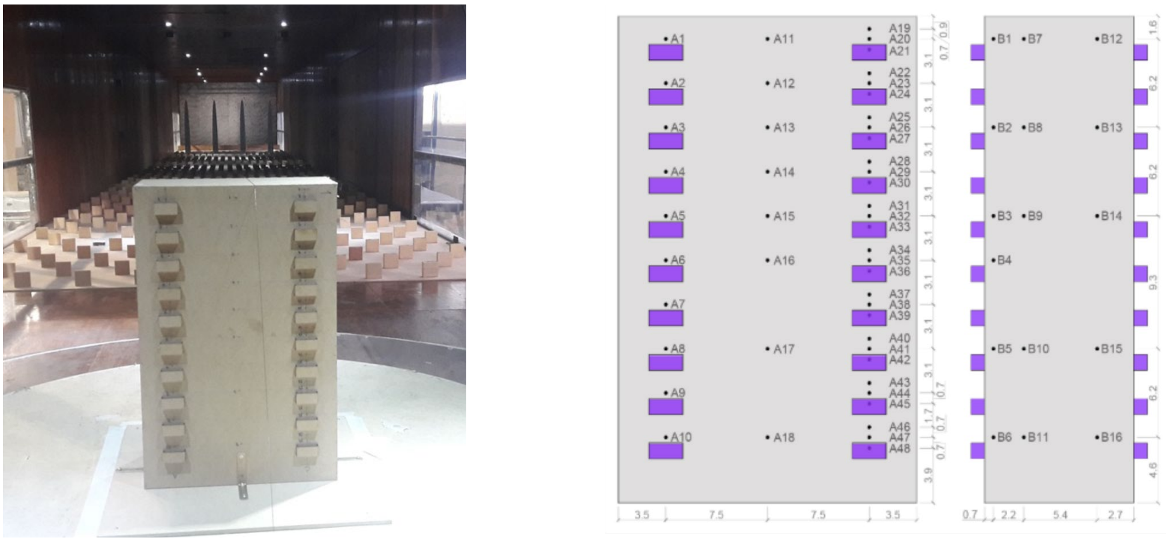
## Appendix C: Validation of CFD simulations (Appendix of Chapter 4)

This appendix presents a complementary validation of the CpSimulator platform. Three case studies are assessed to represent the buildings studied in this work, both with and without balconies. First, a study to determine the grid independence of the CFD results is conducted. Following this, the predictive capabilities of the platform are examined by comparing the results obtained by CpSimulator with the results obtained through wind tunnel experiments.

### A.1 - Case studies and wind tunnel experiments.

Three building designs were studied based on the representative mixed-mode office building depicted in the main body. These scenarios are i) a building without balconies (REF), ii) a building with balconies on the short-axis façade (SA), and iii) a building with balconies on the long-axis façade (LA). Balconies have dimensions of 2.5 m in width and 1 m in depth.

The validation dataset was taken from wind tunnel experiments performed at the Institute of Technological Research (IPT), São Paulo, Brazil (Loche *et al.*, 2020). The wind tunnel employed has a length of 40 m and a test section of 6 $m^2$. Buildings were built using 3 mm and 6 mm Medium-density fibreboard (MDF) panels and on a scale of 1:50, obstructing approximately 5% of the test section area. Figure C.1a shows one of the models. Sixty-four pressure sensors were positioned on two façades of the model: 48 sensors on the façade with balconies and 16 on the adjacent façade, as shown in Figure C.1b. Since the model is symmetric, all four façades could be evaluated by orbiting the model in 180º. The pressure measurements were performed for 24 wind incidences (every 15°) for each building façade. To represent the atmospheric boundary layer, the wind tunnel was provided with rough elements and spires. The wind profile was established by measuring the wind speed at different heights with a hot-wire anemometer sensor. Considering the log-law, the fitting corresponds to an aerodynamic roughness (z0) of 0.447 m for the full-scale model, which represents a suburban surrounding condition. In the experiment, the wind velocity inside the tunnel was set at 14.85 m/s, which guarantees the independence of the Reynolds number. Thus, a reference wind velocity of 44.54 m/s was employed for performing the CFD simulations in full scale. This velocity magnitude was obtained by scaling the experimental wind tunnel with a velocity scale of 1:3 (Quan *et al.*, 2007).




a) 1:50 scale model used in the experiment b) Sensor locations.

**Figure C.1:** Building with balconies on the long axis.

## A.2 - CFD results

The methodology outlined in Section 2.2 is adhered to by the CFD simulations executed in this appendix. The inlet wind profile matches the ABL recorded in the wind tunnel studies (Figure C.2). This profile was selected to employ a constant wind configuration in all scenarios evaluated throughout this work, in addition to being necessary for comparison with experimental data.

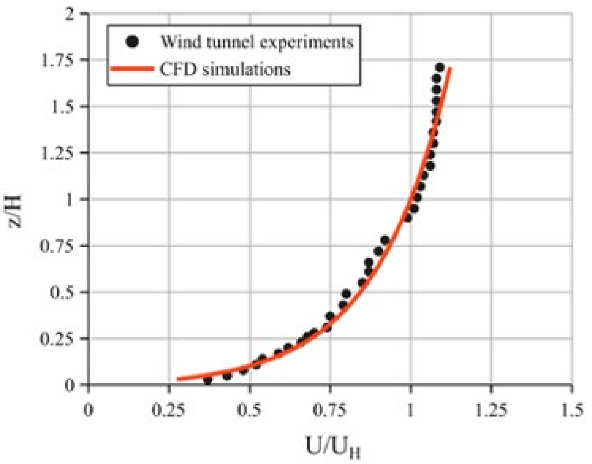
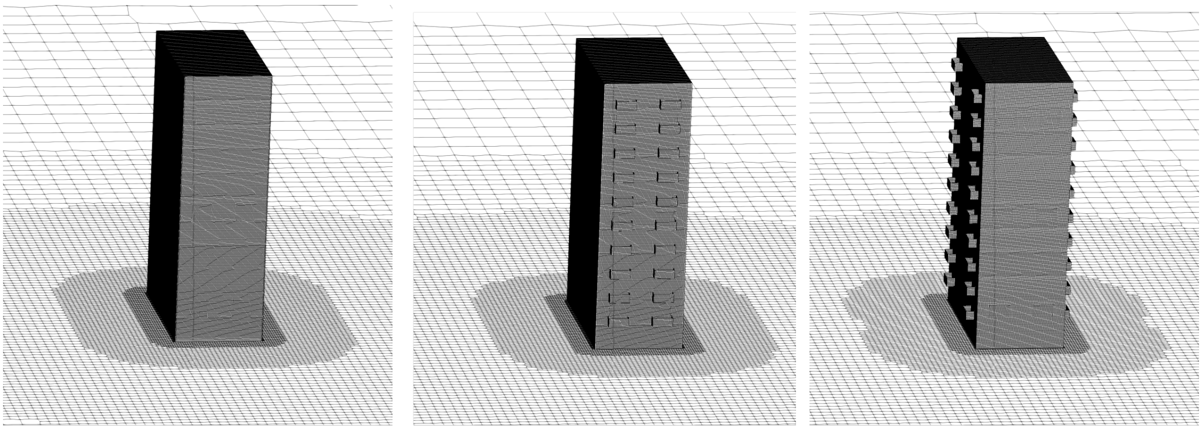



**Figure C.2:** Comparison of ABL inlet wind profiles used in experiments and CFD simulations.

### A.2.1 - Grid sensitivity analysis

A sensitivity analysis of the CFD simulation results to the computational grids generated by the automatic meshing procedure is evaluated. In the CpSimulator platform, the meshing procedure initiates from a background hexahedral mesh with homogeneous cell size DX. This base mesh is refined recursively to shape the input surfaces that define the buildings and the boundaries of the computational domain. Next, the mesh is fitted to the surfaces splitting the hex cells around the objects. Finally, the mesh is shrunken back, and prismatic cell layers are inserted over the building surfaces. To achieve successive mesh refinements, the reference size of the background grid, DX, is modified while keeping constant both the volumetric and surface recursive refinement levels. Four grid levels are selected for the sensitivity analysis: Coarse, Intermediate, Fine, and Finest, respectively. Figure C.3 presents the meshes obtained for the three scenarios using the Fine configuration.



a) without balconies b) with balconies (short-axis façade) c) with balconies (long-axis façade)

**Figure C.3:** Grid details on ground and building surfaces for the three scenarios analysed in the present appendix. These correspond to the Fine configuration selected for the automatic meshing with the CpSimulator platform.

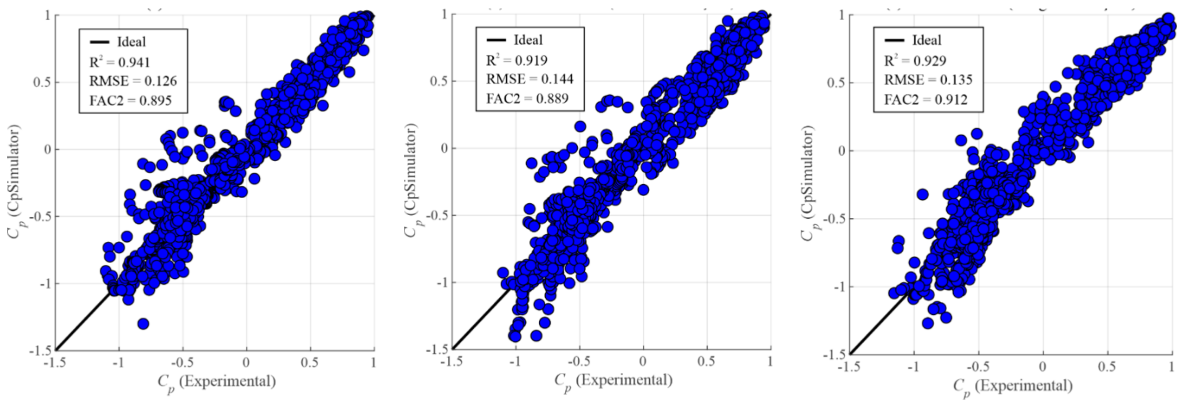
For each of the three case studies and four meshes, CFD simulations were performed to evaluate the 24 wind incidence angles, resulting in 288 simulations. The time-averaged wind pressure coefficients on sampling points obtained with the finest grid are considered the reference solution. The coefficient of determination, $R^2$, is employed to evaluate the performance of the successive coarsening quantitatively (Aguerre *et al*., 2024; Gimenez; Bre, 2023). The results shown in Table C.1 reflects the consistency of the CFD prediction by indicating that, in the worst case, 99% of the variations, i.e. the spread, of the Cp values are determined, i.e. explained, by the location of the measurement point. In other words, less than 1% of the variation could be attributed to the mesh refinement, even considering the coarsest mesh. We consider this uncertainty low enough in any case. Therefore, the Fine mesh configuration is chosen for this work, which is also the default configuration on the CpSimulator platform.

**Table C.1:** Summary of the mesh configurations evaluated for each case study and R2. A value of one in this indicator means a perfect agreement.

| **Mesh** | | **Without balconies** | | **With balconies (Short-Axis Façade)** | | **With balconies (Long-Axis Façade)** | |
|---|---|---|---|---|---|---|---|
| **Case** | **DX/H** | **#Cells** | **$R^2$** | **#Cells** | **$R^2$** | **#Cells** | **$R^2$** |
| **Coarse** | 0.7 | 433k | 0.994 | 655k | 0.991 | 605k | 0.996 |
| **Intermediate** | 0.47 | 885k | 0.993 | 1013k | 0.998 | 1003k | 0.997 |
| **Fine** | 0.35 | 1542k | 0.998 | 1695k | 0.999 | 1681k | 0.999 |
| **Finest** | 0.27 | 2630k | 1 | 2680k | 1 | 2182k | 1 |

### A.2.2 - Comparison with experimental data

This section evaluates the reliability of the CpSimulator by comparing the predicted wind pressure coefficients at each sampling point with the experimental data from the wind tunnel. A scatter plot is used in Figure C.4 to show the agreement of the results at each measurement point. Without a distinction between the wind incidence angles, each building scenario is shown independently. Some outliers and deviations can be observed between measured and simulated data, which can be explained by inaccuracies in experimental tests when adjusting wind incidence directions. However, the R2 metric, where the fit is 0.919 in the worst scenario, quantifies the high degree of agreement between experiments and simulations. These results validate the methodology employed for CFD simulations and provide complementary validations for confirming the CpSimulator platform as a reliable tool for the accurate prediction of wind pressure coefficients.




a) without balconies b) with balconies (short-axis façade) c) with balconies (long-axis façade)

**Figure C.4:** Comparison between measured and simulated Cp data.

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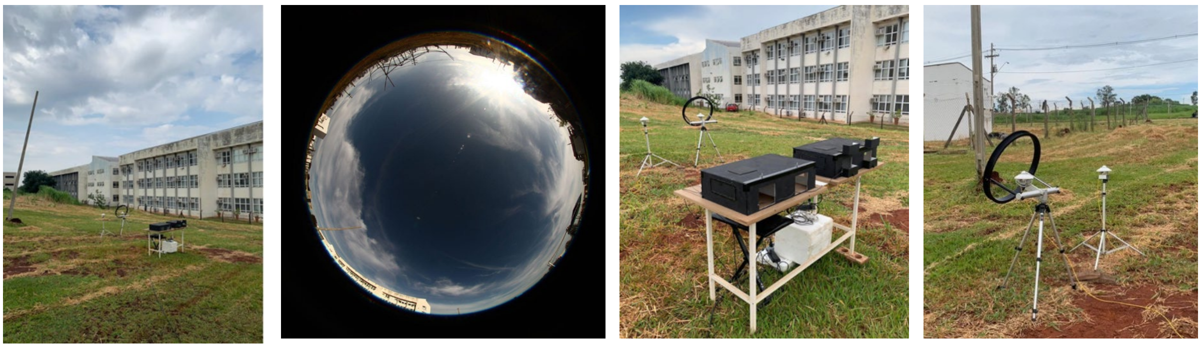
## Appendix D: Validation of daylight simulations (Appendix of Chapter 5)

This research used a scale model to perform daylight experiments under real sky. This method is commonly used as an effective approach for evaluating the daylight levels of interior spaces of buildings (Boccia; Zazzini, 2015; Zazzini *et al*., 2020). The measured data was used to validate the daylight simulations performed in this study. One reference case without balconies and one design case with balconies placed in the short-axis façade were assessed to represent the cases studied in this research.

### D.1 Daylight experiment in scale models

The experiment was conducted on November 22th, 2023, from 14h to 17h, in the site of University of Civil Engineering, Architecture and Urban Design (FECFAU-UNICAMP) located in Campinas, Brazil (Figure D.1a). The place was chosen to guarantee that less than 10 degrees of shading obstructions to perform the experiments (Figure D.1b). Two models were constructed in the scale 1:20. One model contained two office rooms with balconies, while another contained two office rooms without balconies. Both models were equipped with a 2.5-meter-wide glazed door, with windows positioned on the short-axis façade. The model featuring balconies had a balcony measuring 2.5 meters wide and 1 meter deep. Both models were positioned on the site with windows facing North (Figure D.1c). Solar radiation was measured next to the model by two pyranometers, recording data in in $W/m^2$. One pyranometer, shaded by a shadow ring, measured diffuse solar radiation, while the other unshaded pyranometer measured global radiation. One sensor Li-cor was positioned in the center of the office with balcony and without a balcony, positioned 0.8 meters from the floor to represent the workplane (scaled to 4 cm in a 1:20 scale).



a) Location where the experiment was conducted

b) Photo taken with fish-eye lens to verify obstructions

c) Scale models placed for the experiments with windows facing North

d) Pyranometers with and without shadow ring

**Figure D.1:** Location of the experiments and reduced-scale model
Source: the authors

D.2 Comparison of daylight simulations with experimental data

The reflectance values used for the scale model were also employed in the simulation, as indicated in Table D.1. In the simulation, the sky conditions during the experiments were replicated by using minute-by-minute radiation values obtained during the experiments, adjusted to the latitude of the location where the experiments were carried out. Direct radiation was calculated by subtracting the diffuse radiation from the measured global radiation (Figure D.2).

**Table D.1:** Reflectance values used for the building performance simulations

| Surfaces | Colour | Reflectance |
|---|---|---|
| External walls, external balcony parapet, roof | black | 0.1 |
| Internal walls, internal balcony parapet, balcony floor, ceiling | white | 0.9 |
| Office room floor | beige | 0.5 |
| Ground | Dark green | 0.3 |

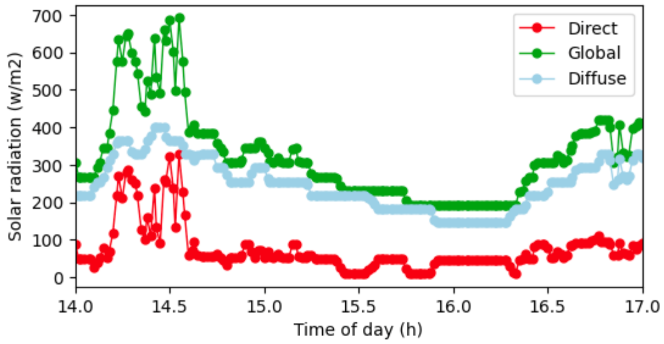
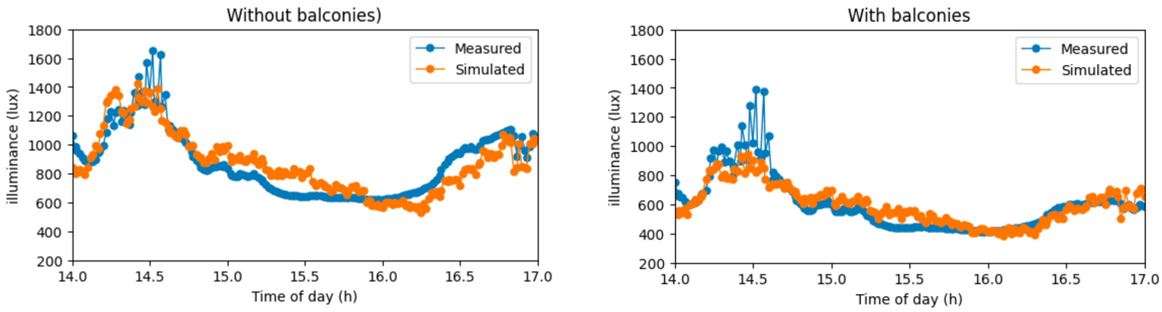



**Figure D.2:** Solar radiation measured during the experiments

The results measured per minute during the experiments were compared with simulated data for both offices with and without balconies (Figure D.3). From 14:00 to 14:40, there was a significant incidence of direct solar radiation (Figure D.2), resulting in high illuminance peaks in both models with and without. During the peaks of direct radiation, the disparity between measured and simulated data is more pronounced. This is attributed to the possibility of direct solar radiation reaching the sensors directly, causing illuminance peaks within the scale model.




a) Model without balconies b) Model with balconies

**Figure D.3:** Comparison between data measured in the experiments and simulated

To compare the results of the simulation model with experimental data, two statistical indices were used: the Normalized Mean Bias Error (NMBE), and the Coefficient of Variation of the Root Mean Square Error (CVRMSE). The NMBE represents the average of errors in a sample, indicating the overall performance of the estimated values relative to the regression line. The CVRMSE assesses the error variability between simulated and measured values, demonstrating the simulation model's ability to predict illuminance values within office rooms.

As a reference for NMBE and CV RMSE values, the studies by Reinhart and Pierre-Felix (2009), Reinhart and Walkenhorst (2001), and Mcneil and Lee (2013) were used, which indicated that for a daylight performance simulation to be considered satisfactory, the comparison between simulation and measurement should be less than 15% for NMBE and less than 32% for CV RMSE. The NMBE and CV RMSE values obtained in the comparison of results for models with and without a balcony were within the established limits for simulated data to be considered satisfactory, showing that the results from daylight simulations provided in this study are reliable (Table D.2).

**Table D.2:** Comparison of measured and simulated data for models with and without balconies

| | MAE (lux) | NMBE (%) | CV RMSE (%) |
|---|---|---|---|
| **Without balconies** | 99.4 | 0.12 | 13 |
| **With balconies** | 64.7 | 0.3 | 17 |

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