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Electrochromic glazing: Visual and non-visual effects in highly glazed non-residential buildings in Brazil

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Vidro eletrocrômico: efeitos visuais e não visuais em edifícios envidraçados não-residenciais no Brasil

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Abstract

Windows, whose main component is glass, are responsible for important attributes related to the user's well-being, such as the presence of daylight. Since the 1980s, smart windows have been developed to maximize daylight and filter unwanted solar radiation. Among them, electrochromic glazing varies its visible transmittance from 60% to 1%, making it a prominent solution. Therefore, the aim of this research is to examine electrochromic glazing for daylighting conditions, including visual and non-visual effects in a representative model of a highly glazed non-residential room within the Brazilian climatic context. Computer simulations using Climate Studio and ALFA were conducted, combining 96 variations across six Brazilian cities/latitudes (Manaus - 3° south, Recife - 8° south, Bom Jesus da Lapa - 13° south, Brasilia - 15° south, Rio de Janeiro - 22° south, and Santa Maria - 29° south), considering four window orientations (north, east, south, and west) and four glazing materials, including electrochromic glazing, clear, neutral green, and reflective silver glass. Statistical analysis consisted of the categorization of 864 cases for visual effects and 34,560 cases for non-visual effects. The lowering of electrochromic glazing's states was scheduled to limit direct sunlight exposure, when more than 2% of the grid area received at least 1,000 lux directly. Results demonstrated that electrochromic glazing showed good compliance with the criteria for daylight autonomy, particularly at the back of the room, enhancing access to daylight compared to reflective silver glass. On the other hand, electrochromic glazing did not prevent problems of glare near the window, related to excessive illuminance levels in a clear state. Additionally, when in a medium and dark tint state, a lack of circadian lighting was detected in the positions in the middle and at the back of the room, especially for the north orientation in five of the six cities, except for Recife, and for the south in the cities with lower latitudes. Lack of circadian lighting for the east and the west were less frequent and detected in particular cases. Regarding the spectrum, distortions related to the higher transmission of blue light through electrochromic glazing in a dark tint state can be a source of criticisms from future users, as a more neutral and uniform spectral distribution is preferred. The main contribution of this study was the prediction of the performance of electrochromic glazing, indicating potentialities and limitations from a critical viewpoint if similar technologies are imported into Brazil.

Keywords: Electrochromic glazing. Non-residential buildings. Computer Simulations. Visual and non-visual effects. Brazilian luminous context.

Resumo

As janelas, cujo componente principal é o vidro, são responsáveis por atributos importantes relacionados ao bem-estar do usuário, como a presença da luz diurna. Desde 1980, tecnologias de janelas inteligentes foram desenvolvidas para maximizar a luz diurna e controlar a radiação solar indesejada. Entre elas, o vidro eletrocrômico varia sua transmitância visível de 60% a 1%. Portanto, o objetivo desta pesquisa é examinar o vidro eletrocrômico para as condições de iluminação, incluindo efeitos visuais e não visuais em modelo representativo de sala não residencial dentro do contexto climático brasileiro. Simulações computacionais usando Climate Studio e ALFA foram realizadas combinando 96 variações da sala não residencial em seis cidades/latitudes brasileiras (Manaus - 3° sul, Recife - 8° sul, Bom Jesus da Lapa - 13° sul, Brasília - 15° sul, Rio de Janeiro - 22° sul, e Santa Maria - 29° sul), considerando quatro orientações de janelas, e, quatro materiais de janela, incluindo os vidros eletrocrômico, claro, verde neutro e refletivo prata. A análise estatística consistiu na categorização de 864 casos para efeitos visuais e 34.560 casos para efeitos não visuais. O vidro eletrocrômico foi programado para limitar a incidência sol direto, quando mais que 2% da área de sensores recebeu pelo menos 1.000 lux de luz solar direta. Resultados demonstraram que o vidro eletrocrômico mostrou boa conformidade com os critérios de autonomia de luz natural, particularmente na parte de trás da sala em relação ao vidro refletivo prata. No entanto, o vidro eletrocrômico no estado claro não evitou problemas de ofuscamento perto da janela, relacionados a níveis excessivos de iluminância. Além disso, falta de luz circadiana foi detectada nas posições do meio e da parte de trás da sala para o vidro eletrocrômico nos estados intermediário 2 e escuro, especialmente para a orientação norte em cinco das seis cidades, exceto Recife, e para o sul nas cidades de menores latitudes. Nas orientações leste e oeste, problemas de falta de luz circadiana foram menos frequentes. Em relação ao espectro, distorções relacionadas à maior transmissão de luz azulada para o vidro eletrocrômico no estado escuro podem ser fonte de críticas de futuros usuários se tecnologias similares forem implementadas no Brasil. Em geral, o espectro neutro e uniforme é preferido. A principal contribuição deste estudo foi a previsão do desempenho do vidro eletrocrômico, indicando potencialidades e limitações a partir de uma visão crítica caso tecnologias semelhantes forem importadas para o Brasil.

Palavras-chave: Vidro eletrocrômico. Edifícios não-residenciais. Efeitos visuais e não visuais. Contexto luminoso – Brasil.

List of acronyms and abbreviations

IEA – International Energy Agency

CIE – Commission Internationale De L´Eclairage/ International Commission on Illumination

EC – Electrochromic

DA – Daylight Autonomy

sDA – Spatial Daylight Autonomy

UDI – Useful Daylight Illuminance

DGP – Daylight Glare Probability

EML – Equivalent Melanopic Lux

M/P ratio – Melanopic to Photopic ratio

ALFA – Adaptive Lighting for Alertness (software)

Mel-EDI/mel-EDI – Melanopic equivalent daylight illuminance

Mel-DER/mel-DER - Melanopic daylight efficacy ratio

A-opic/α-opic – Related to the specified human photoreceptor response due to its opsin-based photopigment in context of iPRGC-influenced responses to light

S cone – Short-wavelength cone/ Cyanopic photoreceptor

M cone – Medium-wavelength cone/ Chloropic photoreceptor

L cone – Long wavelength-cone/ Erythropic photoreceptor

LT – Light transmission

VT – Visible transmittance

Tmel/τmel – Melanopic transmittance

SHGC – Solar heating gain coefficient

ANOVA – Analysis of Variance

CV – Coefficient of variation

List of figures

List of tables

List of equations

Contents

Chapter 1. Introduction

Windows, whose main component is glass, are responsible for important attributes related to the user's well-being, such as the presence of natural light and a view of the outside, with visual and non-visual effects related to the circadian cycle (Lee et al., 2022). In this regard, the employment of innovative transparent and translucent materials on facades allows the maximization of daylight and the supply of circadian lighting (Gentile *et al.*, 2022).

In this context, innovative materials, such as smart windows, can control unwanted solar radiation (International Energy Agency, 2000; Knoop *et al.*, 2016). Smart windows present phase change properties – which, considering the luminous comfort, are characteristic of controlling the light transmittance (Attia *et al*., 2018).

One well-known technology of smart windows is electrochromic glazing, which is composed of a transparent electrolyte layer, e.g., a conducting polymer or an inorganic ionic conductor, and two other layers of transparent polyester. This conducting element is in the center and joins two nanoporous oxide films, typically tungsten oxide (WO_2) and nickel oxide (NiO). This pile of three layers functions as electric transparent batteries with different optical absorption depending on electrical charges. The application of a small voltage between the two transparent conductors, typically a few volts, charges the load between the tungsten oxide (WO_2) and the nickel oxide (NiO). The optical properties can be altered – dark, bleached, or intermediary- allowing highly energy-efficient operations. The optical changes are gradual and take place at a rate that depends on the device's size. An area of a few square centimeters may darken and bleach in seconds, whereas the response time can be tens of minutes for large glazing (Granqvist, 2016). This technology offers the advantage of controlling the properties of the visible transmittance. Therefore, visible radiation can be controlled (Casini, 2018; DeForest, 2017).

Since its development, many questions have arisen concerning the luminous performance and user acceptability of electrochromic glazing in built environments, particularly in non-residential buildings. A major drawback of using electrochromic glazing is the reduced visible transmittance in its "dark" state, and this aspect has been discussed in two studies. Day *et al*. (2019) identified through the evaluation of 1,068 questionnaires in three big commercial buildings criticisms coming from the users in the rooms with the electrochromic glazing because they were under constant darkness, and the light transmission was reduced to approximately 1%. In this regard, the electrochromic glazing was installed for energy efficiency, ignoring the users' subjective needs and acceptability of this technology. This statement also applies to technologies of solar control glasses with static properties, with fixed visible transmittance, like reflective glasses (Queiroz; Westphal; Pereira, 2019).

Additionally, Lee *et al*. (2022) reinforced that the current generation of electrochromic windows sacrifices some aspects of view and daylight quality to manage energy and glare by reducing visible transmittance from 60% to 1%. Here, spectral transmission is also of concern, but since the tint varies, the hours of operation of these windows in each optical state will need to be considered. So, in effect, it will be possible to determine if, for example, the technologies of electrochromic glazing and other smart windows can provide adequate access to daylight, view to the outside, and adequate circadian lighting.

The quantification of daylight is a challenge because it presents constant variations in intensity, color temperature, and sky conditions. At the same time, daylight has a positive influence when compared to artificial lighting because it positively influences non-visual effects, such as circadian lighting (Knoop *et al.*, 2020). More recently, many studies have identified two pathways of light from the stimulus to the physiological responses in the human body, which are received from our eyes and processed in the human body. They include visual and non-visual effects of light, which must be considered (Kort; Veitch, 2014). Visual effects include the luminous characterization of the space and can be evaluated through luminance values in the vertical field of view, illuminance distribution, evaluation of glare, etc. Non-visual effects include the circadian stimulus, which is evaluated based on the spectral power distribution in the eye. These are important elements to understanding the physiological responses of light in humans, specifically when the luminous performance of the electrochromic glazing is assessed (Kruisselbrink; Dangol, 2018; Vetter *et al.*, 2021). The following section is dedicated to describing the context of glazed facades applied on non-residential buildings in Brazil and the potentialities of electrochromic glazing.

1.1. Glazed facades and potentiality of the electrochromic glazing

Lighting accounts for approximately 15% of the global electric energy consumption (International Energy Agency, 2022) and air-conditioning for 20% (International Energy Agency, 2018c).[1] Non-residential buildings, in this context, carry much weight in the consumption of electric energy. In Brazil, around 21% of the electric energy is consumed by non-residential (commercial) buildings (Brasil, 2023). Moreover, according to the National Electric Energy Conservation Program (PROCEL), between 22% and 30% of the total electric energy consumption of buildings is intended for the end use of lighting and 40% to 46% for air-conditioning (Brasil, 2023, Empresa…, 2024).

Gonçalves *et al*. (2021) state that non-residential buildings present a tendency to increase the energetic demand by 20% by 2050 in a future of climatic changes and consequent heating of the urban climate. Nevertheless, these buildings have an enormous potential for energy savings of up to 50% when bioclimatic strategies are taken into account – considering building shape, envelope (façade composition), opening orientation, ventilation, external shading, etc. The employment of these strategies provides indoor environments access to daylight, natural ventilation, and external view and increases users' comfort and well-being (Alves *et al*., 2017; Amorim *et al.*, 2021a; Costa; Amorim; Silva, 2020; Gonçalves, 2020).

In this context, the intense use of glazed façades influences the increase in energy consumption for lighting and air-conditioning (Alves *et al*., 2017; Costa; Amorim; Silva, 2020; Gonçalves, 2020). Fabbrini (2020) made an important connection between Modern and Contemporary Architecture regarding the use of glass. Even though there are differences in its types and technologies, the use of glazed facades has been frequently offered as an architectural solution in non-residential buildings. Glass was widely used in Modern Architecture – mainly during the 1950s and 1960s, with the intention of preserving the principle of transparency between indoor and outdoor spaces. From the 1980s to 2000, there was an intense use of mirrored, milky,[2] and reflective glasses, thus becoming a symbol of corporate architecture (Broto, 2011). The use of glazed facades in

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[1] NA: More details at https://www.iea.org/reports/the-future-of-cooling. Last access: 15 Jul. 2022.

[2] According to Fabbrini (2020, p. 9) the milky glasses in the corporative architecture were employed with the aim to deny and criticize the principle of transparency of the Modern Architecture, "veiling or distorting what is seen". However, the milky glass does not have properties as the reflective or mirrored, which reflect part of the solar radiation, diminishing the negative thermal effects in warm climates, having, therefore, lower efficacy in this sense.

non-residential buildings in warm and arid climates causes problems related to glare and overheating of the indoor environment, causing an increase in consumption of air-conditioning due to a higher incidence of direct solar radiation absorbed by the windows (BAHAJ; JAMES; JENTSCH, 2008; TOUMA; OUAHRANI, 2017).

Gonçalves (2019, p. 5) affirms that "[…] the glass box building introduced the scenario of controlled environmental conditions, restricted by a narrow range of internal temperatures, justified by the thermal comfort theory developed by Fanger (1972), with the PMV index (Predicted Mean Vote)." Mechanical air conditioning systems were needed to achieve this range – around 22 °C. It was also at this time when this model of glass box office building was popularized worldwide.

According to Gonçalves *et al*. (2021), the office building market commercializes glasses claimed to be efficient in controlling the unwanted solar radiation, encompassing different types of colored, reflective, double, triple, and quadruple glasses.[3] However, using these technologies is recommended with caution when applied in tropical climates, as problems related to glare and overheating can occur, decreasing user's satisfaction.

Studies in Brazil have identified excessive use of glass on facades. In a survey of 298 office buildings in Belo Horizonte, Alves *et al*. (2017) identified that since the 2000s, the predominant type had a Window-Wall-Ratio (WWR) of 50% on the four facades. According to the authors, this factor contributed to the increasing of energy consumption for air-conditioning and lighting due to problems related to overheating of the indoor spaces and the occurrence of glare.

Studies highlight the increase in the typology of glazed facades in Brasilia. In a survey of 267 office buildings, it was verified that in almost 67% of the analyzed buildings, there were no shading devices, and in nearly half of them, the WWR was 75% or higher (Costa; Amorim; Silva, 2020). Consequently, the predominant typology is the glass box with the occurrence of similar problems to those related to Belo Horizonte. It has been verified that there is a tendency to use glazed facades, including in the retrofits of those buildings, from which external solar protections are removed and replaced for glazed facades (AMORIM *et al.*, 2021a).

Gonçalves (2019, p. 9) emphasizes that the use of glazed facades and deep-plan rooms follows the solution which "governs the production of a conventional office building

[3]Cebrace: glass for commercial buildings, available at: https://www.cebrace.com.br/#!/produtos/obras-comerciais. (CEBRACE, [2022?]); Sage Glass, available at: https://www.sageglass.com/en/products. (SAGE…, [2021?])

characterized by the following factors: the largest possible internal usable area about the total built-up area and the smallest façade area for the largest office plan area and the use of the fully glazed façade”. In this context, the use of reflective glasses reduces the thermal load for cooling per unity of internal volume, reducing the energy consumption for air-conditioning. At the same time, even employing reflective glasses on highly glazed facades, problems related to glare occur due to excessive illuminance levels.[4]

In addition, windows, whose main component is the glass, are also responsible for important attributes related to the user’s well-being, such as the presence of daylight and view to the outside, with visual and non-visual effects, including effects in the circadian cycle (International Energy Agency, 2021). Consequently, it is crucial to consider the economic logic and the benefits the windows, especially the glass, bring to formulate directives for improving users’ comfort and energy efficiency.

As a result, new glass technologies have been proposed since the 1980s as a solution to the problems caused by glazed surfaces. The so-called smart windows gained strong prominence from experimentation with new glass technologies and translucent surfaces (GRANQVIST, 2016). Innovative transparent and translucent materials[5] allows the control of unwanted solar radiation and is the future of increasing energy efficiency in buildings (Jelle *et al*., 2012). According to Dussault and Gosselin (2017), the goal of employing innovative materials in predominantly warm climates is to improve buildings' thermal, luminous comfort, and energetic performance. Questions arise in regard to their application in non-residential buildings in the Brazilian climatic context. The main question is whether the distribution of daylight and the simultaneous control of the incidence of direct solar radiation in the indoor environments of non-residential buildings can be improved when these materials are applied.

Innovative transparent and translucent material in non-residential buildings, which are inserted into the concept of advanced facade or building skin, is still not in agreement. According to Attia *et al*. (2018, p. 1), “adaptive [or advanced] facades (AF) are building envelopes that can adapt to changing boundary conditions in the form of short-term weather fluctuations, diurnal cycles or seasonal patterns. Such facades have the ability to

[4] Idem, 2019.

[5] According to the definition of the International Commission on Illumination, the term “translucency medium” is defined as the “medium that transmits visible radiation largely by diffuse transmission, so objects are seen indistinctly through it”. The term “transparent medium” is defined as the “medium in which the transmission is mainly regular and which usually has a high regular transmittance in the spectral range of interest” and “objects can be seen distinctly through a medium which is transparent in the visible region, if the geometric form of the medium is suitable” (COMMISSION…, 2020).

respond to or benefit from, changes in outside climatic conditions and dynamic occupant requirements”. In this context, the utilization of innovative material on facades is essential when a more efficient building envelope is to be considered. It is important to highlight that the term “advanced façade” encompasses the opaque materials – used for sealing, solar protection etc. and the transparent and translucent, which are the focus of this study.

The report of the International Energy Agency (2016a) included many innovative window technologies, among them smart windows. From these technologies of smart windows, electrochromic glazing presents a higher control of the properties of light transmission and solar factor or solar heating gain coefficient in relation to other similar technologies (Attia *et al.*, 2018; Casini, 2018; Granqvist, 2016; Painter *et al*., 2016).

Nevertheless, the majority of glass technologies are limited when the directionality of the transmitted energy is considered. Through comparative analysis of natural lighting systems, it was observed that shading devices, such as brise-soleil, have reached a better luminous performance than solar control glazing, including reflective glasses. Consequently, shading devices have an important feature which allows the redirection of admitted light energy improving the internal lighting conditions while ensuring reduction of solar heat gain (Felippe, 2016). Consequently, redirection of admitted light energy is not possible for the technologies of electrochromic glazing as well.

Additionally, Porto *et al.* (2020) evaluated electrochromic glazing in comparison with two clear glasses (Tvis 88%) in ZB 2 – Camaquã-RS, cooler climate, and ZB 8- Manaus-AM, warm and humid climate, regarding illuminance levels on the horizontal grid. It was identified that in none of the four orientations evaluated, north, south, east, and west, the illuminance levels overtook 500 lux for the results of electrochromic glazing. In this regard, for higher illuminance levels, clear glasses presented better results than electrochromic glazing. However, only two climates in Brazil were evaluated without further details regarding other aspects of visual comfort. The focus of this study was more on the performance considering aspects related to thermal comfort than visual comfort.

When well-designed, electrochromic glazing control can improve buildings' energy performance and the occupants' visual comfort in highly glazed buildings related to the visual effects of light (Wu *et al.*, 2019). However, electrochromic glazing produces a significant shift from neutral clear to deep blue when tinted, compromising some aspects related to the view to the outside and the supply of circadian lighting (Gentile *et al.*, 2022; Nazari; Matusiak; Stefani, 2023).

A balance and categorization were made, considering research that had been developed about daylight in buildings in Brazil. This categorization included the most important conferences and journals in the country. Among the issues discussed, it was pointed out that topics related to the non-visual effects of light and the possibility of using innovative transparent and translucent materials, which included electrochromic glazing, must be further researched in hot climates and lower latitudes (Alves; Schmid, 2023; Costa; Amorim, 2022). It is still unclear, therefore, how the employment of these materials affects circadian lighting within the Brazilian climatic context and if a balance can be achieved in a different context outside higher latitude places, mainly below 30º and in different luminous and climatic contexts.

In this respect, the question of this research is: how is the performance of electrochromic glazing regarding visual and non-visual effects of light in non-residential buildings in different latitudes of Brazil?

Therefore, similarly to the issues mentioned in the existing literature, this research hypothesizes that the use of electrochromic glazing in Brazilian climates shows limitations to balance user daylight conditions, including visual and non-visual effects, compared with conventional glasses. The contribution of the work is to determine these conditions in non-residential environments and compare the luminous performance of the electrochromic glazing with two conventional glasses and one reflective glass used in non-residential buildings in Brazil.

The originality of this research is to consider the influence of daylight, analyzing the impacts of innovative materials, particularly electrochromic glazing, on visual and non-visual effects. Both aspects of daylight are not discussed, considering different seasons in lower latitudes. Consequently, analyzing the electrochromic glazing in the Brazilian climatic context regarding daylight is also an original aspect.

1.2. Aim of the study

The aim of this research is to determine the performance of the electrochromic glazing for the daylighting conditions, including visual and non-visual effects in a representative model of non-residential room within the Brazilian climatic context.

1.3. Specific aims

1.3.1. Select criteria for visual and non-visual effects of light.

1.3.2. Analyze the performance of the electrochromic glazing regarding daylight autonomy, useful daylight autonomy and daylight glare probability in comparison with city/latitude, window orientation and position in a representative model of non-residential room.

1.3.3. Establish conditions and limitations for using electrochromic glazing considering the Brazilian climatic context regarding non-visual effects considering city/latitude, window orientation, position in the room, date and hour.

1.3.4. Compare the electrochromic glazing with two conventional glasses and one reflective glass found on façades in non-residential buildings in Brazil regarding visual and non-visual effects of light considering city/latitude, window orientation and position in representative model of non-residential room.

1.4. Structure of the thesis

This thesis is structured in 7 chapters. Chapter 1 is dedicated to introducing and identifying knowledge gaps regarding electrochromic glazing and describing the hypothesis and research aims. In Chapter 2, the many technologies of innovative transparent and translucent materials are described together with the choice of electrochromic glazing among the many smart windows technologies. Important studies on indoor spaces' luminous characterization regarding visual and non-visual effects are presented.

Chapter 3 describes important elements of visual comfort and non-visual effects for assessing electrochromic glazing. Daylight was chosen as the focus of the study because it presents constant variations in intensity, color temperature, and sky conditions, and it is the preferable source to provide circadian lighting and non-visual effects of light.

Chapter 4 describes metrics and tools to quantify and assess the visual and non-visual effects of light. This chapter describes metrics and tools to evaluate the performance of electrochromic glazing in the evaluated Brazilian climates. Additionally, one section is dedicated to describing the different proposals of Brazilian luminous zoning.

Chapter 5 presents the study method, divided into four sections to assess the performance of electrochromic glazing in terms of visual and non-visual effects of light. In section 5.1, the choice of six cities is described according to the proposals for luminous zoning in Brazil as a function of latitude to represent all three zones according to the three different latitude ranges. In the simulation studies, a representative non-residential model of a highly glazed facade was chosen from the literature review. The variables included six cities/latitudes, from Manaus (3° south) to Santa Maria (29° south), four window orientations, north, east, south, and west, four glasses, including electrochromic glazing, clear, neutral green, and reflective silver glass, nine positions in the room, date and hour. The simulation studies and definition of cases for spectral analysis are described in sections 5.2 to 5.2.4. To investigate the electrochromic glazing in the representative model of non-residential room within the Brazilian luminous context including visual and non-visual effects of light, eight questions were made to guide the analysis of the results. This is presented in section 5.3. In section 5.4, the methods for statistical analysis were presented.

Results are presented in the Chapter 6. Section 6.1 describes the generated shading schedules for electrochromic glazing according to Brazil's six cities/latitudes and window orientations: north, east, south, and west. Section 6.2 is dedicated to the description of results including the performance of electrochromic glazing regarding visual effects. Section 6.3 is dedicated to describing results including the performance of electrochromic glazing regarding non-visual effects. Section 6.4 describes the spectral analysis results of electrochromic glazing and the other simulated three glasses. In section 6.5, the overall performance of electrochromic glazing is described and recommendations are given in order to improve the performance of electrochromic glazing regarding visual and non-visual effects of light.

In Chapter 7 the conclusions were described together with key contributions to this study. Limitations and suggestions for future studies are discussed at the end. Supplementary information on the simulations and detailed results can be found in Appendix A to Appendix K. Appendix L describes the contributions of the publications from this research.

Chapter 2. Innovative transparent and translucent materials

Smart windows are classified among the main innovative transparent and translucent materials in the context of advanced facades. The term “advanced facades” is characterized by the utilization of innovative materials, and the description of them will be discussed in the following sections.[6] The focus of this study is on smart windows, particularly electrochromic glazing.

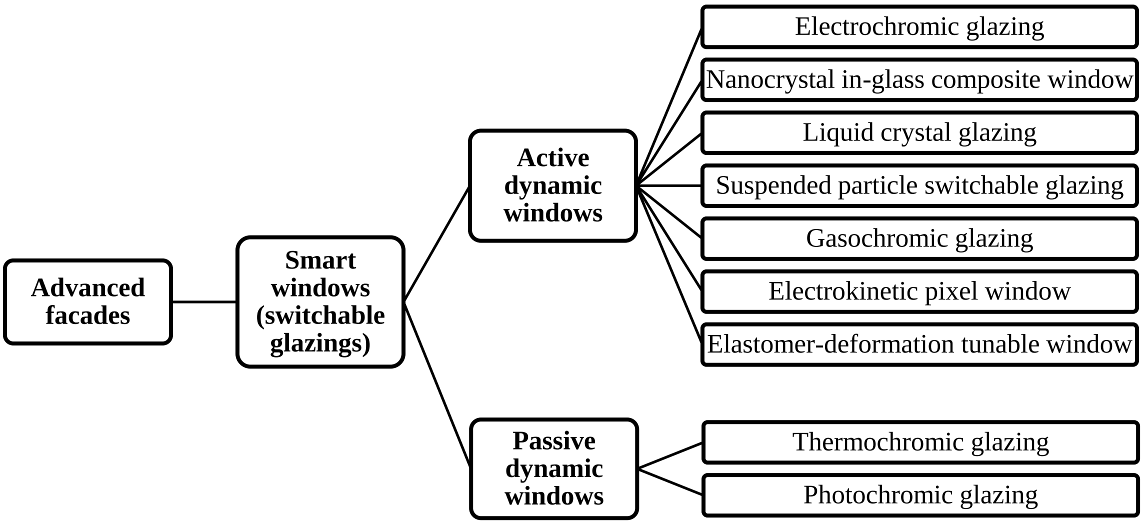
Jelle *et al.* (2012) and Attia *et al.* (2018) defined smart windows as those that present a phase change being altered as a consequence of the light transmission (LT) and the Solar Heat Gain Coefficient (SHGC) or solar factor (SF). The authors included the thermo-/photo-/electrochromic glazing in the category of smart windows. We considered this to be the inclusion criteria for the group of “smart windows” in our classification.

The classification proposal includes the advanced facades in one major category of smart windows (INTERNATIONAL…, 2016a). In this category, two groups of smart windows are distinguished. Active dynamic windows respond to electrical stimuli, changing their thermal and optical characteristics from external and internal environmental variations, which can be adjusted by the user, hence requiring the input of electric energy for their operation. Passive dynamic windows respond in an autonomous way to natural stimuli, such as solar radiation (photochromic glazing) or heat (thermochromic glazing), without the adjustment nor the control of the users, not requiring electric energy for their operation (CASINI, 2018).

The definition of smart windows include a larger group of window technologies, which includes all window technologies, such as opaque materials, solar shading devices and switchable glazings. The focus of the literature review was on the switchable glazings, characterized by the variations of the properties of solar heating gain coefficient and visible transmittance (Casini, 2018). Figure 1 shows the classification of smart windows with focus on the switchable glazings in the context of advanced facades. In this work, the term “smart windows” are used to refer to switchable glazings as well.

[6] The detailed description of the method of systematic review is found in Costa and Amorim (2022).

Figure 1 - Classification of smart windows (switchable glazings) in the context of advanced facades.



Source: Based on Costa; Amorim, 2022.

Even though it was possible, through the literature review, to classify the various types of systems and existing materials, the perspective of this study will be on the electrochromic glazing in the category of smart windows (switchable glazings). In the following sections, this choice is justified.

In section 2.1 the use of glazed facades in non-residential buildings briefly presents the international and the Brazilian context. In section 2.2 the many definitions of the advanced facade are discussed. In section 2.3 the various technologies of smart windows are described. Section 2.4 describes the studies focused on the luminous characterization of electrochromic glazing in non-residential spaces. Section 2.5 was dedicated to the conclusions from the literature review.

2.1. Glazed facades: International and Brazilian context

The use of glass caused a rupture in the field of environmental comfort and caused an evolution in the quality of life inside indoor environments in Europe, which were dark and cold. According to Butera (2009), glass took a long time to be largely used in buildings. The development of float glass in 1952 offered a smooth and parallel surface for the first time, advantages that offered superior quality to other previous glass technologies, which were more expensive and had optical deformations in the surface. The revolutionary innovation of float glass also allowed the development of new glazing typologies, like reflective, absorbing, tempered, and low-emissivity glasses. In this case, the low-emissivity glass is treated as a transparent material film against solar radiation, which reduces the losses of infrared radiation. These are positive characteristics but with disastrous effects on energy consumption and environmental comfort in buildings. The easy access to glasses of various types and colors at accessible prices triggered the “all glass” architectural trend, with devastating consequences from the energetic point of view. From this point on, the all-transparent glass box building was a common solution for many buildings with mechanical ventilation systems and artificial lighting, contributing to the buildings' reshaping (Butera, 2009, p. 175).

According to Mardaljevic (2021, p. 492), “the highly glazed office tower became the most conspicuous symbol of industrial progress, and hence an inspiration for architects and designers worldwide – regardless of their climatic conditions”. The confluence of economic, technical, and aesthetical factors working together served to establish the highly glazed office tower as a preeminent urban building form. Key factors included the development of curtain wall technology and the invention of float glass technology, which allowed the manufacture of large sections of glazing at relatively low prices. The development of air-conditioning systems and the refinement of artificial lighting, i.e., the introduction of fluorescent lamps as a replacement for incandescent lamps, also contributed to the spread of the highly glazed office buildings. This trend began during the 1950s in modernist architecture, when architects vaguely defined notions of “light” and “transparency” in the built form.

The employment of glazed facades was also identified by two architecture historians, starting with the analysis of Modern Architecture in the works of Giedion (1968) and Bruand (1981) in Brazil. Non-residential Modern Architecture is characterized by a set of features that define the buildings, such as transparency, mainly preserving the view to the exterior and interior, the necessity of experimenting with new materials, the free plan, and the aesthetics defined by the new materials, which were concrete, steel and glass. The architectural culture of the 1950s and 1960s was marked by industrial thinking, in which machines were present, including the systems of air-conditioning and artificial lighting (Giedion, 1968).

Even though there are differences in their types and technologies, the use of glazed facades has been frequently offered as a solution in non-residential buildings. In the imagination of the pioneers of Modern Architecture, it is worth mentioning that glass symbolized technological progress, democratic equality, and utopian transcendence. Its transparency allowed the integration between the indoor and outdoor space, which broke with the falsification of the ornamented facades that covered the life of its interior. That is the reason why glass was so largely used in the facades during the 1950s and 1960s, and it continued further on in Contemporary Architecture (Fabbrini, 2020). Besides that, Broto (2011, p. 9) also identified the use of glass in many Contemporary Buildings for aesthetic reasons, overcoming the “antithesis between exterior and interior”.

In the Brazilian context, the use of glass is not that different. The most important aspect to be considered is the dominant formula, which “governs the production of a conventional office building characterized by the following factors: the largest possible internal usable area concerning the total built-up area and the smallest façade area for the largest office plan area and the use of the fully glazed façade” (Gonçalves, 2019, p. 9).

It is a fact that the aesthetics of these luxurious highly glazed buildings tend to be skyline marks. Large companies intend to transmit the image of respect, impressiveness, and authority through these buildings. In their spaces, large companies want to show the image that their buildings are technologically advanced, and at the same time, they want to demonstrate a posture of ecologically correct. Therefore, the architecture of these buildings is intended to satisfy their business and to highlight the city skyline, ignoring the subjective needs of the users inside the buildings (Passos, 2019). Figure 2 illustrates corporate buildings along Brigadeiro Faria Lima Avenue in Sao Paulo (23° south/46° west).

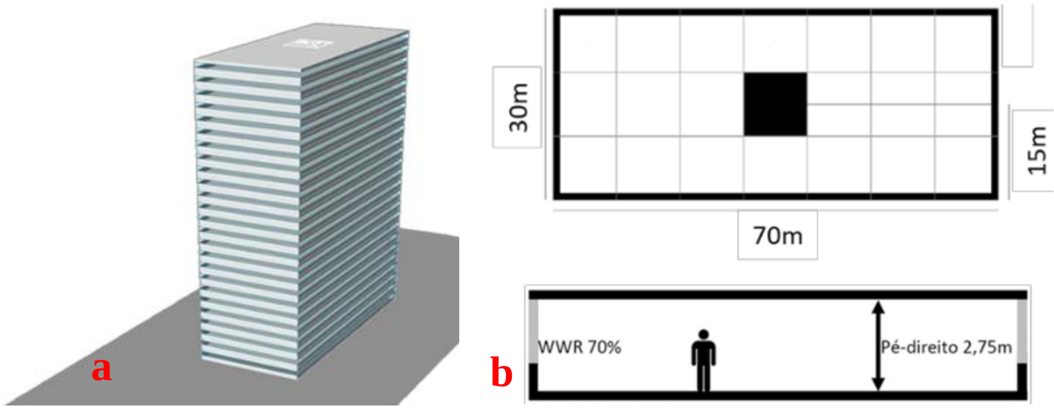
Figure 2 – Corporate buildings along Brigadeiro Faria Lima Avenue in Sao Paulo (23° south/46° west).

Source: Passos, 2019.

This solution of highly glazed facades has been replicated in large cities such as Sao Paulo, Belo Horizonte, and Brasilia. Studies reported problems related to glare, excess light on working surfaces, and an increase in energy consumption for lighting due to the incidence of direct sunlight inside the working environment (Alves, *et al*., 2017; Lima *et al*., 2022; Cavaleri; Cunha; Gonçalves, 2018; Costa; Amorim; Silva, 2020; Sarra; Mülfarth, 2020). Moreover, the use of clear glass was also identified on facades in Brasilia and Sao Paulo in modernist buildings, mostly built between the 1960s and 1970s (Costa; Amorim; Oliveira, 2017; Gonçalves, 2019; Sarra; Mülfarth, 2020). To mitigate problems related to glare and overheating, reflective glasses have been employed since the 2000s, but this was not sufficient to entirely solve these issues (Gonçalves *et al*., 2021).

In Sao Paulo, entirely glazed office buildings are frequent typologies. From 2005 to 2015, 28 cases of buildings were built with WWR equal to or greater than 70% with deep-depth floors containing open office plans. Additionally, the office plan presented a marked modulation, and the depth of 15 m was highlighted, as shown in Figure 3. The problems behind these typologies were related to excessive illuminance in the regions next to the window and the darkness in the periphery, in the middle of the plan, next to the elevators, shaft, and stairs.

Figure 3 – (a) Visualization of a representative of 28 cases of highly glazed office buildings built in Sao Paulo (23° south/46° west) between 2005 and 2015. (b) Open office plan with marked modulation and highlighted depth of 15m.



Source: Cavaleri; Cunha; Gonçalves (2018).

In the northeast region of Brazil, the intense use of glass was identified in Joao Pessoa (7° south/34° west), and two representative office buildings were chosen. In the first building, the east facade had 66% open area and used solar control glass. This glass consisted of an external layer of 4 mm solar control glass (Light Blue 52 on clear) and an internal layer of 4 mm clear glass, bonded by a layer of polyvinyl butyral (PVB) resin. This setup reduced light transmittance by 22%, external reflection by 3%, and heat absorption by 16%. In the second building, the north and south facades have 60% of open area and use 6 mm clear glass in all the frames, even after the retrofit. This glass did not have the same solar control properties as in Building 1, resulting in higher light transmittance and less heat control. Both buildings used internal solar protection systems, such as curtains and blinds, but did not have external protection devices. Through subjective assessment and the application of questionnaires, it was found that a wide range of illuminance indices (from 6 to 2,620 lux) demonstrated the difficulty of achieving uniform conditions, with recurrent indices around 750 lux leading to 30,15% of occupants' dissatisfaction. The results suggested that windows might be related to high dissatisfaction with daylight when they allow excessive incidence of sunlight, especially when associated with east-facing facades with no external solar protection. Additionally, when glare was perceived, there was the incidence of direct sunlight, curtains, and other internal shading devices were closed, and only 22% of the users actively controlled these devices, decreasing the incidence of daylight inside the offices. Figure 4 illustrates the two analyzed buildings in Joao Pessoa (7° south/34° west).

Figure 4 – Two representative analyzed cases of office buildings in Joao Pessoa (7° south/34° west) with highly glazed facades.

Source: Lima *et al.* (2022).

Lima and Caram (2015) evaluated the performance of three glasses with different visible transmissions, reflective (14%), grey (51%), and colorless (81%) regarding useful daylight illuminance in the city of Maceio, Alagoas (9° South/35° West). Additionally, the authors considered using solar shading and three different window-to-wall ratios (WWR) values: 25%, 50%, and 75%. It was concluded that the reflective glass combined with WWR of 50% and 75% is only superior to the other studied glasses if there is solar shading and only when evaluated about the criteria of light uniformity. The use of glazed facades in non-residential buildings in Maceio, Alagoas was intense and motivated this study. It was demonstrated that using reflective glass alone was insufficient to provide better access to daylight and reduce heat gains due to the incidence of direct sun.

Regarding the use of glasses, Queiroz, Westphal, and Pereira (2019) analyzed 14 types of glasses with different SHGCs, from 88% to 22%, and light transmissions, from 88% to 14% in a commercial room with dimensions of 7 x 4.50 and 3 m (31.5m^2) with WWR of 60% in Florianopolis. It was found that glasses with higher SHGCs can have similar performance to solar control glasses when combined with sun shading. Glasses with lower SHGCs and lower light transmissions, such as the Silver 20 Clear - LT 20%, Cool Lite 114 PN – LT 13%, and Neutral 14 Clear – LT 14%, provided low luminosity inside the room and demanded higher consumption for artificial lighting. In this context, regarding the window orientations, north, east, south, and west, the clear glasses NP 50 Clear - LT 47%, AG 43 Clear – LT 39%, and SNL 37 Clear – LT 33% performed well balancing thermal and luminous comfort, demanding less energy consumption for lighting and cooling. Consequently, caution is recommended regarding using reflective and less transparent glasses, as they decrease the luminosity of inside environments.

Sacht *et al.* (2016) made spectrophotometric characterization of glazings for the study of components to design a modular façade system based on the climates of Portugal, including warm and cold seasons. The studied glasses were solar control, green solar control, self-cleaning, and low emissivity glass. According to the results, solar control and green solar control glasses provided good illumination and weakened the infrared radiation, which reduced the heating. Therefore, such glazing was more efficient in decreasing the nominal need for cooling. The solar control glasses have shown little transparency to the ultraviolet. Therefore, they were more adequate for shopping malls, commercial centers, museums, and residences. The green solar control glass tended to decrease transmission in longer wavelengths, thus reducing heat. The self-cleaning glass presented a similar transmission to that of low emissivity glass regarding visible light, indicating stronger transmittances in the infrared intervals and stronger heating in an indoor habitable space with such glazing. Therefore, similarly to the climates of Portugal, solar control glasses are more recommended when cooling is needed. Inferring from this research, solar control glasses are more recommended for warmer climates, such as the ones found in Brazil.

Studies in Brazil have identified excessive use of glass on facades. In a survey of 298 office buildings in Belo Horizonte, Alves et al. (2017) identified that since the 2000s, the predominant type had a Window-Wall-Ratio (WWR) of 50% on the four facades. According to the authors, this factor contributed to the increasing energy consumption for air-conditioning and lighting due to problems related to overheating of the indoor spaces and the occurrence of glare. It was concluded that the variation between the 1970s and 2000s office building typologies increased up to 50% of the total electric energy consumption. Since the 2000s, there has been a significant increase in the typology of glazed facades with reflective glasses with SHGC of 56%, contributing to problems related to the higher consumption of air-conditioning and overheating. Figure 5 illustrates the different typologies of non-residential buildings in Belo Horizonte, with more predominance of entirely glazed facades in the buildings built after 2000, with frequent use of reflective glasses.

Figure 5 – Images of non-residential buildings in Belo Horizonte (19° south/43° west): (a) older typology of non-residential buildings built before 1990; (b) typology of entirely glazed facades built mainly after 2000.

Source: Alves *et al.* (2016; 2017).

In a survey of 267 office buildings in Brasília, envelope characteristics were identified, such as the WWR-values, the presence, and identification of the type of solar protection (brise-soleil, porches, balconies, etc.), facade orientation and projection format - square, rectangular, circular, etc. It was found that there was no sun protection in almost 67% of the buildings analyzed, and almost half had WWR values greater than 75% (Costa, Amorim; Silva, 2020). Consequently, the predominant typology is the glass box, which has problems similar to those related to Belo Horizonte. According to Amorim et al. (2021a), these buildings analyzed, with an average consumption of 132 kWh/m²year, could reduce up to 37% of the total electric energy consumption if strategies such as the reduction of the WWR from 75% to 50%, the addition of solar shading and the use of natural ventilation were used. In this regard, the predominant type of office buildings in the central zone of Brasilia is with glazed facades (glass boxes). Figure 6 shows a composition of the facades of office buildings in Quadra 6, Setor Comercial Sul, in the central zone of Brasilia.

Figure 6 – Composition of the facades of office buildings in Quadra 6, Setor Comercial Sul in the central zone of Brasilia (15° south/47° west).

Source: Amorim *et al.* (2020).

In Figure 7 some common characteristics of the facades can be seen, such as the intense use of glass in office buildings in Brasilia. The glass tower typology has been replicated, particularly for new buildings built after 2010.

Figure 7 – Building at Setor Comercial Norte, Brasilia.

Source: The Author.

Additionally, it was verified in commercial and office buildings in Brasilia that many principles of the Modernism were applied, including the employment of glass and brise-soleil, independently of the orientation of the facades. In this respect, the brise-soleil in wrong orientations caused excessive obstruction of daylight in some cases. For this reason, it was verified that glazed facades tended to be used, including in the retrofits of older buildings built before 1990, from which external solar protections were removed and replaced for glazed facades. (AMORIM *et al.*, 2021a). Figure 8 shows the chronology of the facade intervention of a building in Brasilia (15° south/47° west), with the brise-soleil been replaced by reflective glasses.

Figure 8 – Chronology of the facade intervention of a building in Brasilia – Setor Comercial Sul: replacement of the *brise-soleil* to reflective glasses.

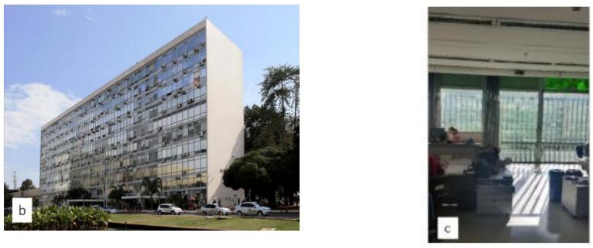
Source: Amorim *et al.* (2021a).

Brasilia was used as an illustration because previous research was conducted by our group, witnessing the tendency to employ glazed facades in non-residential buildings. This corroborated the description found in the studies of Alves et al. (2017), Gonçalves (2019), and Lima and Caram (2015) about the Brazilian context. Figure 9 illustrates the context of non-residential buildings in Brazil and the intense use of glazed facades, in which the incidence of direct sun and the occurrence of glare are among the reported issues. In the case study of Brasilia (15° south), the use of brise soleil was identified as a barrier against the incidence of direct sunlight for the west orientation (Amorim; Souto; Medeiros, 2021).

Figure 9 – Non-residential buildings in Brazil and the intense use of glazed facades.

a – Belo Horizonte (19° S/43° W)

b – Brasilia (15° S/47° W)



c - João Pessoa (7 S°/34° W)

d - Londrina (23°/51° W)

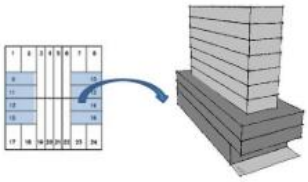
e - São Paulo (23° S/46° W)

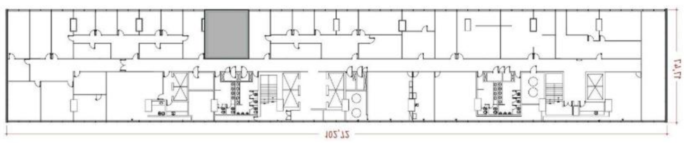
Source: (a) Alves (2016); (b) Amorim; Souto; Medeiros (2021); (c) Lima *et al.* (2022); (d) Ciappina; Urbano; Giglio (2022); (e) Passos (2019).

The studies in Brazil showed a timeframe of seven years from 2015 to 2021, and little has changed in these years regarding the use of glass. It is evident that the solution of the glazed facade for aesthetical reasons is common in non-residential buildings in Brazil, creating similar skylines of corporate buildings. Consequently, buildings became more compact, with limited access to daylight and problems related to glare and overheating with the intense use of glass on the facades, with daylight coming through side openings. Figure 10 illustrates the floor plans of non-residential buildings in Brazil of the mentioned studies, with daylight coming through side openings.

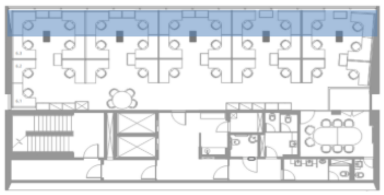
Figure 10 – Floor plans of high-rise non-residential buildings in Brazil with daylight coming through side openings.

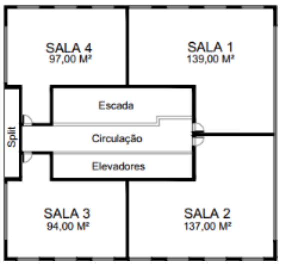
a - Belo Horizonte (19° S/43° W) b - Brasilia (15° S/47° W)





c - João Pessoa (7 S°/34° W) d - Londrina (23°/51° W) e - São Paulo (23° S/46° W)





Source: (a) Alves (2016); (b) Amorim; Souto; Medeiros (2021); (c) Lima *et al.* (2022); (d) Ciappina; Urbano; Giglio (2022); (e) Passos (2019).

In this regard, innovative transparent and translucent materials have been developed to filter unwanted solar radiation and increase energy efficiency in buildings. On the other hand, it is important to mention that the majority of glass technologies are limited when the directionality of the transmitted energy is considered. Through comparative analysis of natural lighting systems, it was observed that shading devices, such as brise-soleil, have reached a better luminous performance than solar control glazing, including reflective glasses. Consequently, shading devices have an important feature which allows the redirection of admitted light energy, improving the internal lighting conditions while ensuring reduction of solar heat gain (Felippe, 2016).

It is possible that the same limitations occur with other innovative transparent and translucent materials in Brazil regarding redirection of the admitted of light. In this context, the discussion of innovative transparent and translucent materials must be deepened. The following sections were dedicated to this matter.

2.2. Advanced facades and definitions

Initially, the intention was to systematize the knowledge based on the literature review. With this in mind, a classification of the translucent and transparent materials was proposed within the general context of Advanced Facades. According to Attia *et al*. (2018) the concept of “advanced façade” is characterized by the utilization of innovative materials on the building façade – opaque, transparent, and translucent. There has been a considerable advance in developing façade materials and systems. The authors used this term to designate façades to improve energy performance and users’ comfort (Casini, 2018). It is important to emphasize that the term “advanced façade” encompasses the opaque materials – used for sealing, insulation, solar protection, etc., and the transparent and translucent ones, which are the focus of this research, with particular attention to non-residential buildings.

According to recent research, the word ‘adaptive’ in the context of building facades is often associated with a long list of similar words in the literature. They can be described as ‘interactive,’ ‘adaptive,’ or ‘responsive,’ and have been used loosely and interchangeably, creating confusion regarding their specific meaning and their conceptual relationship to building performance and design (Gallo; Romano, 2017). Romano *et al*. (2018) analyzed 10 definitions to explain their differences in meaning, and they were summarized.

Active facades are defined by technological systems with integrated elements through which envelopes self-adjust to changes initiated by the internal or external building environments (Ochoa; Capeluto, 2008).

An advanced facade is the outer, weather-protecting layer that can contribute to heating, cooling, ventilation, and lighting requirements and promote interior comfort through efficient, energy-saving measures (Romano *et al.*, 2018).

Biomimetic facades are defined as those which try to mimic nature. For example, the skins of plants and humans tend to be seen as the most straightforward emulation model and inspiration source for multifunctional and truly sustainable enclosure systems. For example, there are examples of phototropism (i.e., changing in response to light) and heliotropism (i.e., changing in response to the sun), applied, for example, in the climate adaptive building shells concepts that enable the active collection or rejection of solar energy (Aa; Heidelberg; Perino, 2011).

Kinetic architecture can be defined as an architectural form that can be inherently displaceable, deformable, expandable, or capable of movement. To elaborate, a kinetic façade is a technological system with a certain kind of motion that can guarantee variable locations or mobility and/or variable geometry to all or one of its parts (Loonen, 2010; Romano *et al*., 2018).

Intelligent facades combine active and passive intelligence - active features and passive design strategies - to provide maximum occupant comfort using minimum energy. Therefore, intelligent skin is a composition of elements that act as a barrier to the outside environment and can respond to climatic changes through the automatic reconfiguration of its systems (Romano *et al*., 2018).

Interactive facades require human input to initiate a response, and it may also be equipped with sensors and an automated building management system programmed to optimize energy conservation while simultaneously ensuring the comfort of its inhabitants.[7]

Movable facades can be defined as technological systems that can rapidly adapt to environmental conditions and locations and are defined by the opening elements themselves.[8]

Responsive facades can be defined as technological systems in which external environmental conditions (e.g., ventilation, humidity, light volume, radiation, and temperature) influence the interior parameters of the building (i.e., thermal and luminous comfort). The most common solutions are based on several specialized subsystems (such as structural elements, sensors, mechanical actuators, membranes, control devices, etc.) that are responsible for changing the envelope’s geometry according to stimulus and programmed performance (Kolodziej; Rak, 2013; Romano *et al.*, 2018).

Smart facades are described as those containing smart surfaces (e.g., smart windows), and materials show properties that are changeable and thus responsive to transient needs. Switchable facades have a similar meaning, but they refer to the facades with “smart glasses” or, more generally, smart adaptive materials (Romano *et al.*, 2018).

Transformable facades must be efficiently tuned to adjust to boundary conditions such as climatic conditions, different locations, varying functional requirements, or emergencies. The transformation process goes from a compact to an expanded

[7] *Ibidem*, 2018.

[8] *Ibidem*, 2018.

configuration or vice versa. The transformation phase must consist of controlled, stable movements, resulting in a rigid and secure structure once it is locked in place (Chloë, 2016).

As described here, there are some common concepts among the ten definitions presented of “advanced facades”, which were included in the classification presented in Figure 1. One of them is the idea of the change according to boundary conditions. The smart windows can do that. Another idea behind these definitions is the improvement of the environmental conditions for the users of the buildings and the search for more energy-efficient building envelopes. The idea is to provide maximum occupant comfort using minimum energy.

Consequently, the concept used in this study of the term “advanced façade” is the idea of a weather-protecting layer of a building that can improve thermal and luminous comfort through efficient energy-saving measures. That was the baseline for the classification described in Figure 1. In section 2.3 the technologies of smart windows are described.

2.3. Smart windows: Technology, application, and applicability

Windows are the object of continuous improvement, with the objective of offering building users an increase in the use of daylight, thermal comfort, and control of solar radiation. In this context, smart windows, particularly switchable glazings, can change the properties of light transmission and solar heating gain coefficient and adjust according to external and internal environmental variables. Besides that, they can be controlled by users (Jelle *et al*., 2012). Inside the category of smart windows (switchable glazings), there are nine technologies mentioned in Figure 1. Among them, electrochromic glazing offers a wider control of the properties of light transmission and solar heating gain coefficient in relation to other technologies of switchable glazings (Casini, 2018; Jelle *et al*., 2012). Furthermore, this technology allows users to control and override, increasing its acceptability, and it is commercially available in diverse catalogs in the world market. This does not occur to the other eight technologies (Boubekri *et al.*, 2020; Casini, 2018; Jelle *et al.*, 2012; Painter *et al*., 2016).

The first part of this section describes the functioning of the nine smart window technologies. Due to the consolidation of the market and the highlight in relation to the other windows described, the electrochromic glazing will be described in more detail.

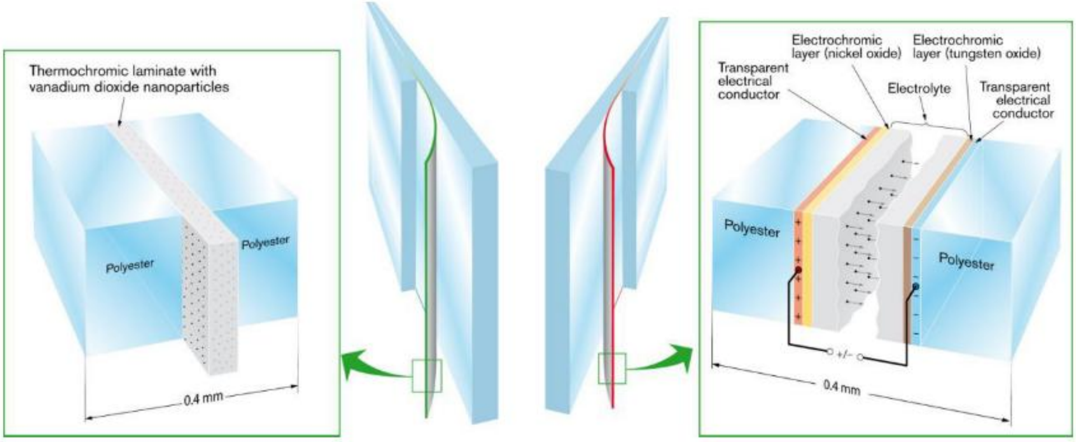
Since the 1980s, three technologies have been developed: thermochromic, photochromic, and electrochromic glazing. The thermochromic glazing interacts naturally according to the sun, altering its color when submitted to heat in such a way that the higher the incidence of the sun, the darker the coating becomes. The darken layers comprise Vanadium Dioxide – VO_2 (Salamati *et al*., 2019; Tällberg *et al*., 2019).

The photochromic glazing modifies its properties of light transmission and solar heating gain coefficient through the response to the incidence of global solar irradiation – sum of the diffuse and direct irradiation (W/m²) incident on the window plane. The higher the radiation, the darker the coating becomes. The glazing continues in the "clear" state when the values of solar global irradiation are below 100 W/m² and in the "dark" state with values above 450 W/m². The solar heating gain coefficient values range from 48% to 31%, and the light transmission from 73% to 13%, from the "clear" state to the "dark" state. The changing time can take between 15 mins. and 20 mins. (Tällberg *et al.*, 2019).

The change from the "clear" to the "dark" state of the thermochromic and photochromic glazing occurs because of the incidence of the sun. Users do not have control over this change, so this configuration is the main disadvantage of passive dynamic windows (Casini, 2018). From this moment on, the active dynamic windows are presented.

The electrochromic glazing comprises a transparent electrolyte layer, e.g., a conducting polymer or an inorganic ionic conductor, and two other layers of transparent polyester. This conducting element is in the center and joins two nanoporous oxide films, typically of Tungsten oxide (WO2) and Nickel (NiO) oxide. This pile of three layers functions as electric transparent batteries with different optical absorption depending on electrical charges. Applying a small voltage between the two transparent conductors, typically a few volts, charges the load between the Tungsten Oxide (WO2) and the Nickel Oxide (NiO). The optical properties can be altered – dark, bleached, or intermediary- allowing highly energy-efficient operations. The optical changes are gradual and occur at a rate that depends on the device's size. An area of a few square centimeters may darken and bleach in seconds, whereas the response time can be tens of minutes for large glazing (Granqvist, 2016, p. 7). Figure 11 shows the composition of the electrochromic and thermochromic glazings. Notably, the layers where the electrochromism occurs are not necessarily made of glass. However, the external sealing is usually composed of glass layers, also used for protection.

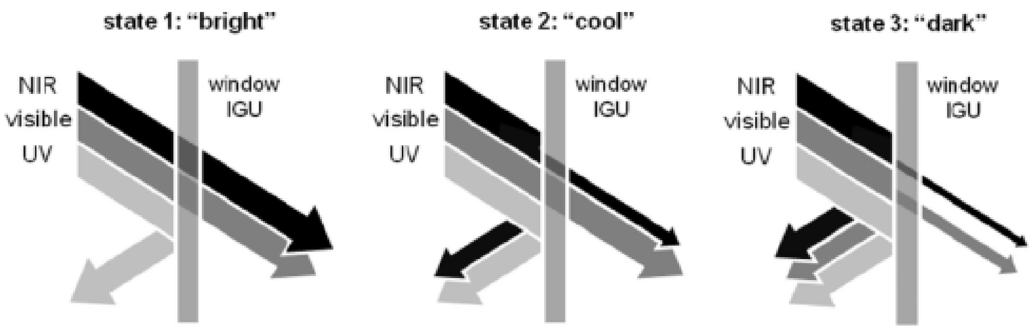
Figure 11 - Thermochromic glazing (a); Electrochromic glazing (b).



Source: Granqvist (2016).

As shown in Figure 12, the thermochromic glazing is composed of three states: bright or clear, cool and dark. In the "clear" state, the glazing functions as the common glasses through which the infrared and visible radiation can pass. In the "cool" state, part of the infrared radiation passes through and is reflected, but the significant difference is found in the reduction of heat gains through infrared radiation. Finally, in the "dark state," the three types of radiation are mostly reflected (infrared, ultraviolet, and visible spectrum), thus being partly absorbed. The ultraviolet radiation is reflected in the three states.

Figure 12 - Illustration of radiation transmittance of dynamic window insulated glass unit (IGU) in each operational state.



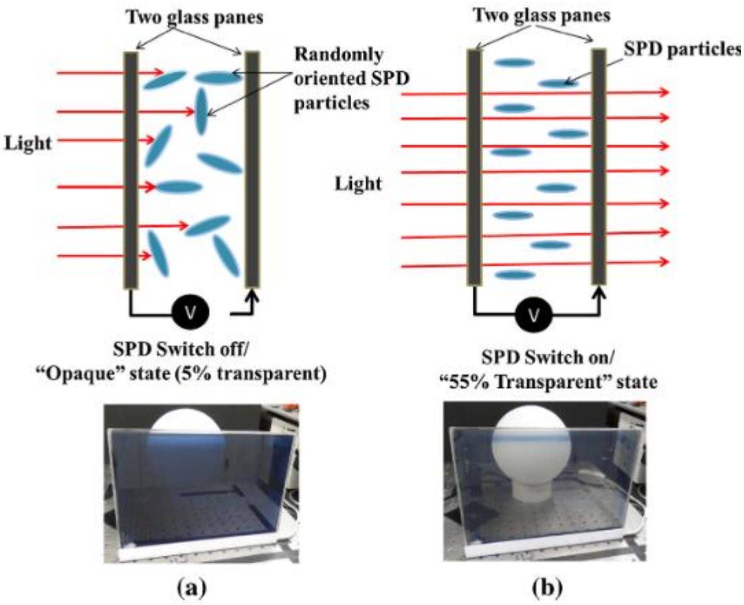
Source: Deforest *et al*. (2017)

Nanocrystal in-glass composite windows comprise Indium-Oxide nanocrystals embedded in a glassy matrix (ITO) of niobium oxide (NbOx). The functioning is similar to the electrochromic glazing, presented in the states "clear" (LT = 93%/SHGC = 91%), "cool" (LT = 54%/SHGC = 16%), and "dark" (LT = 22%/ SHGC = 7%) according to the voltage and the passage of electric current. Case studies in real actual buildings have not yet been carried out (Casini, 2018). The high values of solar heating gain coefficient

(SHGC) and light transmission (LT) are the main disadvantages of this technology in the "clear" state, above 90%.

Since 2006, the smart windows have included suspended particle switchable glazing and liquid crystal glazing. In the international context, the suspended particle switchable glazing is relatively new and is being tested in the laboratory in Dublin, Ireland (53° N). Switchable glazing has the same purpose of changing from the "dark" to the "clear" state as electrochromic glazing but functions differently. The suspended particles inside a liquid or an organic gel are rearranged in a way of letting or not letting the light pass through according to the passage of electric current, as shown in Figure 13. The liquid crystal glazing is a derivation of the technology of the suspended particles, and has a similar functioning of the suspended particle switchable glazing (Ghosh; Norton; Duffy, 2016; Ghosh; Mallick, 2018).

Figure 13 – Suspended particle switchable glazing (SPD) showing the "opaque" (a) and the transparent (b) states.



Source: Ghosh; Norton; Duffy (2016, p. 116).

The gasochromic glass is composed of five layers. The two more external layers are simple floating glasses. In between, there are three more, those being one layer of tungsten trioxide (WO3) and Palladium (Pd), one with transparent polymer, and the innermost layer with a mixture of gases. Only this last mentioned is necessary for the state change from "clear" to "dark". The addition of the mixture of Argon with Hydrogen gas alters this layer to the "dark" state (H_2/Ar) – LT = 15% and SHGC = 28%. To revert this layer to the “clear” state – LT = 54% and SHGC = 65%-, the utilized mixture is Argon with Oxygen (O_2/Ar). The disadvantages of this technology are the high costs of installation and maintenance. The gas layer must always be hermetically close, making it even harder for maintenance (Casini, 2018).

The electrokinetic pixel window is a technology that introduces the possibility of modulating the color tones and the received visible light temperature. This technology of polarized particles follows an approach closer to displaying liquid crystals, i.e., controlling the movement of colored particles through electrophoresis to modulate both the reception and transmission or hue of light. The system employs two planar electrodes, not so different from those found in LCD screens or even the electrochromic glazing, controlling an electrophoretic dispersion of two primary colors, complementary (blue/yellow, red/cyan or green/magenta are also viable for applications outside the window) and are characterized for opposite electric charges. The system is composed of a mesh of 500 mm honeycomb-shaped cells, composed of charged electrodes and capable of expressing thousands of color combinations. The controlled property of this technology is the light transmission – “clear” state with LT = 75% and the “dark” with LT = 22%. Solar heating gain coefficient values were not disclosed and are under study (CASINI, 2018).

The elastomer-deformation tunable window uses mechanical instead of electrochemical reactions, as described in the other smart windows. The technology explores the geometrical deformation of the glassy surface to control the dispersion of light, transforming the “clear”, transparent window to translucent or in any intermediate state. This effect is obtained through a sandwich of glass or polymer panels between two transparent dielectric elastomer layers, which are pulverized in a net of electric conductor silver nanowires. Because of their small size (some millimeters in length and 90 mm in diameter), the nanowires are invisible to the naked eye and do not significantly alter light transmission but are extremely reactive to electromagnetic stimuli. When tension is applied to the window, the nanowires are energized. They are transformed into electrodes, which tend to move from one direction to the other by Coulombic forces, squeezing and deforming the two elastomers of the layers below. As the nanowires are unevenly distributed, the glass surface becomes irregular and refracts the visible waves, reducing its transparency to 20% and being with a perfectly neutral color. When the circuit is shut off, the nanowires stay at regular position and the glass achieves a transparency of 80%. This technology is still being developed in the laboratory (Casini, 2018).

Based on the discussion of the changes between states, it is possible to summarize the properties of the smart windows, as shown in Table 1. It is important to emphasize that the electrochromic glazing, the nanocrystal, and the suspended particle switchable glazing operate in three states – “clear” (or “bright”), “cool,” and “dark”-while the others operate in the states “clear” or “dark” (Casini, 2018).[9]

[9] NA: It is important to mention that the focus of the study is the evaluation of these materials considering the visual and the non-visual effects of light. The thermal properties, such as the thermal transmittance (U) and the solar heating gain coefficient/solar factor (SHGC/SF) were described due to the influence on the consumption for air-conditioning and on thermal comfort, but they will not be considered in the studies of visual comfort.

Table 1 – Summary of the properties of the smart windows (switchable glazing).

Properties	Smart window – switchable glazing technology				
	Thermochromic	**Gasochromic**	**Electrochromic**	**Electrokinetic pixel**	**Liquid crystal**
Number of states	2	2	3	2	3
Operational states	Clear and dark	Clear and dark	Clear, cool and dark	Clear and dark	Clear, cool and dark
Visibility	Variable*	Variable*	Variable*	Variable*	Variable*
Light transmission (LT)	80% – 15%	54% – 15%	60% – 1%	75% – 22%	69% – 55%
Solar heating gain coefficient (SHGC)	60% – 20%	65% – 28%	46% – 6%	Not defined	75% – 50%
Power required for state transition	Not required	Not required	2.5 W/m²	Not defined	5 – 10 W/m²
Power required for state maintenance	Not required	Not required	0.4 W/m²	Not defined	5 – 10 W/m²
Operating voltage	Not required	Not required	12 V AC**	65-110 V AC**	65-110 V AC**
Time to change between states	Minutes	< 1 min	5 min a 12 min	10 s	Instantaneous –40 ms
Material colour	Variable	Blue	Blue or green	Big variation	Clear, bronze, grey or green
Durability	Non-defined	Non-defined	More than 30 years	Unknown	More than 10 years
Thermal transmittance (U)	Vary between 0.5 W/m²K and 1.6 W/m²K, according to the window composition				
Control	Temperature variation (68 °C)	Addition/ removal of H_2 or O_2	Wall switch, remote control, sensors (of light, temperature, *timer*)		

*Variable – transparent in the “clear” state and translucent in the “cool” or “dark” states/ **AC – Alternating current/ DC – Direct Current.

Source: Adapted from Granqvist (2016) and Casini (2018).

Electrochromic glazing was chosen as focus of this study, compared to other technologies of smart windows – switchable glazings, due to the higher capacity of controlling the light transmission and solar heating gain coefficient. According to DeForest *et al.* (2017), another advantageous characteristic of electrochromic glazing is the three operational states, including the “cool,” in which the solar factor is around 40%, while the light transmission is around 60%. The liquid crystal glazing also offers a “cool” state but with values above 50% in the solar heating gain coefficient and light transmission (GHOSH; NORTON; DUFFY, 2016). Instead of “cool” state, some authors use “medium tint” and “dark tint” or “fully tint” to refer to the electrochromic states (Jain; Karmann; Wienold, 2022; Neil *et al.*, 2012; Wu *et al.*, 2012).

Besides that, the visibility of the materials change. In the clear state, the windows function as transparent elements, and as they darken, they become translucent, making good visibility difficult. This happens to the electrochromic glazing as well. So, in effect, studies about the perception of the users were carried out highlighting users’ dissatisfaction, particularly for electrochromic glazing in a dark tint state (PAINTER *et al*., 2016; DAY *et al*., 2019). Studies regarding the application and acceptability of electrochromic glazing are discussed next.

DeForest *et al.* (2017) aimed to analyze the dual-band electrochromic glazing in residential and two commercial buildings in 16 climate zones within the USA, including warm, temperate, and cold climates. Simulations were carried out using the EnergyPlus software based on building reference models developed by the United States Department of Energy. The reduction in the energy consumption for lighting and air-conditioning can reach 36% in warm climates and 10% in cold climates. The authors' main conclusion is that the real economy potential can be increased for certain configurations, such as the customary use of glazed facades, which is very common in the design of urban office buildings. Regarding warm climates, in climate zones 1A (Miami – warm and humid) and 2A (Houston – predominantly warm and dry), the tested electrochromic glazing technologies were shown to be promising (Deforest *et al*., 2017, p. 108).

Chambers *et al.* (2019) evaluated the economic potential of representative model office buildings in different climates in Switzerland. The characteristics of electrochromic glazing were incorporated. The results showed that the electrochromic glazing was particularly effective in buildings that have a high demand for cooling, which was responsible for 20 kWh/m²year, with a potential reduction of 5.5 kWh/m²year or 5.2%

from the typical energy demand of these office buildings, of 105 kWh/m²year, including all end uses.

In Brazil, Porto (2019) compared two simple glasses (3 mm and 6 mm) and electrochromic glazing (SageGlass of 9 mm) to analyze the energy consumption and the thermal comfort provided by artificial climatization and natural ventilation. The simulations were carried out in the software EnergyPlus in two Brazilian bioclimatic zones: ZB 2 – Camaquã-RS and ZB 8- Manaus-AM. The environment was occupied from Monday to Friday between 8 h and 12 h and 14 h and 18 h with 100% occupancy and between 12 h and 14 h with 10%. The natural ventilation was configured through the AirflowNetwork, which allowed the opening of doors and windows, as defined by the temperature limits so that the natural ventilation was active when the indoor temperature was superior to 25 °C. The sensors applied in these simulations were the outdoor temperature, and the chosen setpoint was 23 °C to ZBR 2 and 26 °C to ZB 8; therefore, the glass is dark and coated when the external temperature is equal to 23 °C or 26 °C to ZB 2 and ZB 8, respectively. The thermal comfort analysis used the ASHRAE Standard 55 (American…, 2010) adaptive model. In reference to the “clear” and “dark” states established, in bioclimatic zone 2, the electrochromic glazing was always in the “clear” state during the winter months because the setpoint temperature for the state change was always higher than the outdoor temperature, thus needing contribution of solar radiation. The results showed in ZB 2 that the electrochromic glazing increased the discomfort due to cold during the winter months due to not allowing the entry of solar radiation into the indoor environment. It was possible to observe that the electrochromic glazing had a better performance when compared to the other glasses in bioclimatic zone 8, a very warm region where solar radiation control is essential, being accordingly a good option. The electrochromic glazing in ZB 8 reduced energy consumption by reducing light transmission from 67.6% to 19.3% and the solar heating gain coefficient from 63.1% to 26.3%. However, access to daylight was decreased and illuminance levels did not overtake 500 lux in the two cities/latitudes evaluated. Users’ subjective assessment was not evaluated in this study. In regard to the potential use of this type of glass in warm climates, it is concluded that further research is needed for the wide range of climates in the Brazilian context. Notably, the electrochromic glazing was only tested in two bioclimatic zones in this study, without covering other latitudes.

The studies described until here had a focus on the performance analysis of the electrochromic glazing under the optics of the reduction in the energetic consumption and thermal comfort. In office buildings, there are various studies about users' perception of electrochromic glazing. This is an important aspect in applying these technologies since the users' acceptance is a relevant section towards the good functioning of the innovative systems. User interaction in the work environment, satisfaction, and visual comfort are complex elements that need to be evaluated, especially in the case of electrochromic glazing.

Painter *et al.* (2016) aimed to describe and explain the process of users' interaction with the electrochromic glazing in office environment. Two installations of electrochromic glazing were used in two office environments in Montfort University, Leicester, in the United Kingdom (52° north/1° east), as illustrated in Figure 14. The method of the authors combined interviews, questionnaires, on-site measurements with HDR photos and measurements of illuminance values. The questionnaires and the interviews allowed the exploration of the underlying reasons for a user's preference for blinds or electrochromic glazing. In room A – where the control was manual, controlled by users -, the users had a positive opinion in relation to the application of the technology of the electrochromic glazing, whereas in room B – where the control was automated, without user override – the users were more skeptical and preferred to have the control of the window systems. It was concluded that the possibility of control by users is a satisfaction factor regarding the use of electrochromic glazing, as they preferred portions of the window in a clear state, keeping the office environment in neutral spectrum and with higher illuminance levels.[10]

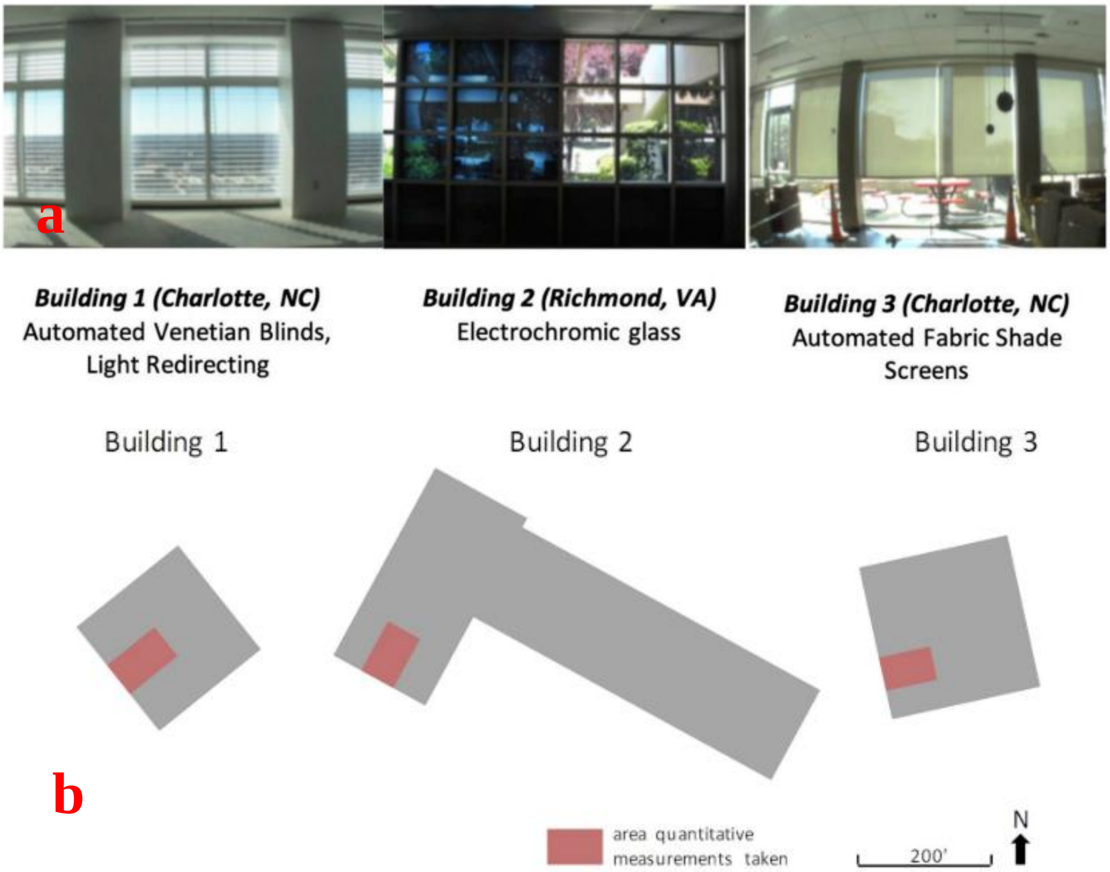
[10] Mardaljevic; Waskett; Painter (2016).

Figure 14 – Office environments in Monfort University, Leicester in United Kingdom (52° north/1° east) and configurations of the electrochromic windows showing the control zones.

Note: Electrochromic glazing was in a dark tint state in the upper portion of the window, while the lower portion remained in a clear state. Source: Painter *et al.* (2016).

Day *et al.* (2019) conducted on-site measurements and applied 1,068 questionnaires in three big commercial buildings that had different types of shading devices in the United States of America, automated blinds, electrochromic glazing, and roller shades, as shown in Figure 15. Among the findings, the direct relationship between the occupants' satisfaction with access to daylight and higher productivity and satisfaction with the work environment is crucial. Criticisms came from the users in the rooms with the electrochromic glazing because they were under constant darkness. In these rooms, the change between states was automated with sensors, dependent on the time, on the incidence of direct sun, and the depth of the direct penetration of the sun inside the building. When the glazing was found in the dark state, the light transmission was reduced to approximately 1%. It was concluded in the study about the importance of the project considering the user's perception in relation to the thermal and visual comfort. The employment of electrochromic glazing must not be designed for a higher energy efficiency only. The electrochromic glazing in the study was implemented for the purposes of economy and energy efficiency, ignoring the needs of visual comfort and user opinion.

Figure 15 – (a) Survey building sites and associated shading strategies in three commercial buildings in the United States of America; (b) Location of the studied environments and building footprints.



Source: Day *et al.* (2019).

Lee *et al.* (2022) reinforced that the current generation of electrochromic windows sacrifices some aspects of view and daylight quality to manage energy and glare by reducing visible transmittance from 60% to 1%. Here, spectral transmission is also of concern, but since the tint varies, the hours of operation of these windows in each optical state will need to be considered. So, in effect, it will be possible to determine if, for example, the technologies of electrochromic glazing and other smart windows can provide adequate access to daylight, view to the outside, and adequate circadian lighting.

In this regard, it is important to characterize the indoor spaces regarding their luminous distribution and not only the energy performance. This is discussed in the following section.

2.4. Electrochromic glazing, luminous characterization of indoor spaces and non-visual effects

At first, studies were directed at understanding the luminous distribution provided by employing electrochromic glazing on the facade. The efforts of researchers and manufacturers have resulted in a continuous improvement of electrochromic devices' performance. Wu *et al*. (2019) conducted experiments in a south-oriented full-scale testbed, with dimensions of 2 m x 4.5 m x 3.3 m and a WWR of 64%, to demonstrate the daylighting performance under various sky conditions. The electrochromic glazing used in the study had four states of luminous transmittance: 60% (clear), 18% (tint light), 6% (medium tint), and 1% (full tint). The control of the tint states was based on monitoring the luminance distribution of the sky and real-time lighting computation for a building interior using an embedded photometric device. Additionally, the window was divided into six parts, with division in the upper and lower parts to control the incidence of daylight. This optimized the tint states of electrochromic glazing to offer sufficient daylight provision and temper discomfort glare for occupants, potentially mitigating the excessive solar heat gain. The testbed was built in Berkeley, CA – United States (37° N/122° W). Experimental results showed that in 83% of the working time, the illuminance values for the work plane were constrained in comfort range, between 500 lux and 2,000 lux, and daylight glare probability was lower than 35% under clear skies. Figure 16 illustrates the testbed of a split-pane electrochromic window in Berkeley, California – United States (37° N/122° W).

Figure 16 – Testbed of a split-pane electrochromic window in Berkeley, California – United States (37° N/122° W).

Source: (a) Wu *et al.* (2019) and (b) Amorim (2024).

Jain, Karmann, and Wienold (2022) evaluated the performance of the electrochromic glazing in minimizing discomfort glare in a controlled user assessment setup and the performance of glare in the user's field of view, including the daylight glare probability (DGP). The experiments were conducted in a test room on the EPFL campus in Lausanne, Switzerland (46° N/6°E) in a room 6.55m deep, 3.05m wide, and 2.65m high. The test room was oriented to the south with a window-wall-ratio of 62%, and the window was divided into six parts, with the lower portion divided into three equal parts and the upper portion divided into three parts, as illustrated in Figure 17. This enabled a more accurate control of the electrochromic glazing. Results from the subjective evaluation indicated that a sun disk luminance of around 5 million cd/m² (visible transmittance of 0.6%) was sufficient to control glare when the sun was in the peripheral field of view of the participant. In contrast, the same was not applicable in critical viewing direction (e.g., sun position within a 30° cone around the fovea). Based on the subjective assessment of glare according to the sun disk illuminances, thresholds of discomfort due to glare were determined when the electrochromic glazing was found in the dark state. A threshold of 1,180 lux of vertical illuminance corresponded to a DGP of 40%, and 1,213 lux of vertical illuminance corresponded to a DGP of 43%.

Figure 17 – Test room of electrochromic glazing in Lausanne, Switzerland (46° N/6°E).

Source: Jain; Karmann; Wienold, 2022.

Regarding the non-visual effects of light, Boubekri *et al*. (2020) explored the impact of optimized daylight and views on the sleep and cognitive performance of thirty office workers in the Durham ID Building in Durham, North Carolina, U.S. (35° North/78° West). They spent one week working, from Monday to Friday, from 8 a.m. to 6 p.m. in each office environment oriented to the south with identical layouts, furnishings, and orientations in November. However, one was outfitted with electrochromic glazing and the other with dark fabric roller shade – traditional blind - 75% closed during all evaluation time, producing lighting conditions of 40.6 and 316 equivalent melanopic lux for the west, respectively. The visible transmittance of electrochromic glazing varied from 58% to 0.5% and the dark fabric roller shade had the visible transmittance of 1.5%. Additionally, regarding the spectrum, the room with electrochromic glazing presented CCT of 7,485 K and the room with traditional blinds, CCT of 4,122 K. Results demonstrated that participants slept 37 minutes longer and performed better in cognitive performance tests when exposed to optimized daylight and views during the day, with higher circadian lighting, which the electrochromic glazing could provide and not provided by the traditional blinds. It is important to emphasize that, in both rooms, illuminance levels were extremely reduced with 234 lux or less. In average, circadian lighting was less than 100 EML for the room with blinds and less than 150 EML for the room with electrochromic glazing. Consequently, all conditions regarding the supply of circadian lighting were favorable in the room with electrochromic glazing, but with limited access to daylight.

Saiedlue *et al*. (2019) conducted computer simulations in the software ALFA, Adaptive Lighting for Alertness, in a south-oriented side-lit open plan office space in Minneapolis, United States (44° North/93° West). Equivalent melanopic lux over 12 hours on March 21 with three zones, near (A), in the middle (B), and distant from the window (C). Three glazing systems were also evaluated: double glazing, with visible transmittance of 63%, and electrochromic glazing, with two and three zones. The software ALFA was used to measure the glazing performance at eye level in office spaces. In zone A, all glazing systems provided melanopic lux levels above 200 EML in all periods and all view directions. Electrochromic glazing with three zones provided 200 EML or higher photopic illuminances range between 7 a.m. and 5 p.m. in view direction facing the window (45°- 135°) in zone B. Zone C provided 200 EML or higher between 7 h and 17 h and between 3 p.m. h and 5 p.m. in view direction facing the window (22.5°- 157°). Findings showed that the electrochromic glazing with three zones provided the best performance in creating the balance among the new metrics (i.e., Equivalent Melanopic Lux – EML and Photopic Illuminance on a vertical plane at eye level). However, electrochromic glazing in a dark tint state still provided reduced illuminance levels and circadian lighting.

Nazari, Matusiak, and Stefani (2023) investigated visual and non-visual effects and color appearance of transmitted daylight through clear glass and electrochromic glazing. The method consisted of measurements and computer simulations of spectral data on irradiance, radiance, and surface reflectance in a controlled environment, a test cell laboratory facing south in Trondheim, Norway (63° North/10° East). Measurements were made using a spectroradiometer and lux meter for validation purposes. Additionally, simulations were carried out in Rhino 7, Grasshopper, and Lark. Spectral analysis was conducted using CIE Toolbox. Spectral irradiance was studied every 21st day of each month throughout the year, between 6 a.m. and 6 p.m. As expected, due to the higher visible transmission of clear glass, it was observed that the values of vertical illuminance and melanopic equivalent daylight illuminance (Mel-EDI) for electrochromic glazing in clear and dark states were reduced compared to clear glass. There were variations in vertical illuminance and Mel-EDI according to the sun altitude, sky condition (clear, overcast), and month of the year. Results demonstrated that the average melanotic daylight efficacy ratio (Mel-DER) for the dark state was 0.98 and 0.77 for the clear state, while the average for the clear glass was 0.88. Additionally, reduced illuminance levels were observed for all states of the electrochromic glazing, particularly in the maximum tint state compared to clear glass. In conclusion, it was found that in comparison with clear glazing, the hue and chroma values of smart glazing are acceptable for normal-function spaces. However, precaution must be considered for certain tasks that demand accurate color perception, such as in art studios, hospitals, etc., as the hue and chroma of purple and blue alter significantly. The positive effect of electrochromic glazing is the color shift towards yellow in the minimum coloration (overcast), which may contribute to a more joyful atmosphere in the room. The negative effect is that in maximum coloration (dark tint state), the vividness of all colors is strongly reduced, and vertical illuminance and Mel-EDI are also diminished. Figure 18 illustrates the Test Cell Laboratory facing south in Trondheim, Norway (63° North/10° East).

Figure 18 – Test Cell Laboratory facing south in Trondheim, Norway (63° North/10° East).

Source: Nazari; Matusiak; Stefani (2023).

Mardaljevic, Waskett and Painter (2016) highlighted that electrochromic glazing generally exhibits a shift in spectral transmission as the glass darkens, causing it to appear blue as it tints. Occupants, however, prefer a neutral spectrum of daylight illumination without any pronounced hue. It was predicted through theoretical model that it was possible to maintain a neutral spectrum of illumination with electrochromic glazing under normal operation provided that just a small proportion of the glazing is kept in a clear state. Predictions from the model were compared with measurements of the daylight spectra in an office with electrochromic glazing under various states of tint in two offices in Montford University in Leicester, United Kingdom (52° north/1.1° east), as illustrated in Figure 19. Results demonstrated that users were not satisfied with a large reduction in illuminance levels when electrochromic glazing was in dark tint state, but that was not the case for users exposed to direct sunlight. The users perceived daylight through electrochromic glazing as blue. However, as portions of the window were in a clear state or with clear glass, the environment's perception did not remain blue. The main conclusion was that the illuminance levels must be controlled, and at the same time, some part of electrochromic glazing should always remain in clear state, assuring a neutral spectrum, which was preferred by the users. In the mentioned study, about one eighth of the electrochromic window remained in a clear state or with clear glass. This increased users' satisfaction was well in the evaluated latitude.

Figure 19 - Photograph of the room equipped with electrochromic glazing at Montford University in Leicester, United Kingdom (52° north/1.1° east).

Source: Mardaljevic; Waskett; Painter (2016).

In Brazil, Porto *et al.* (2020) evaluated electrochromic glazing in comparison with two clear glasses (Tvis 88%) in ZB 2 – Camaquã-RS, cooler climate, and ZB 8- Manaus-AM regarding illuminance levels on the horizontal grid in one office room with dimensions of 4m x 4m (width and length) and 3m high. The simulations of daylight were carried out using Sketchup 2015, plug-in Legacy Open Studio 1.0.13 and Energy Plus v. 8.4. It was identified that in none of the four orientations evaluated, north, south, east, and west, the illuminance levels overtook 500 lux for the results of electrochromic glazing. In this regard, to achieve higher illuminance levels, clear glasses presented better results than electrochromic glazing. However, only two climates in Brazil were evaluated without further details regarding visual comfort. This article was more focused on the thermal performance of electrochromic glazing than on aspects related to visual comfort. Nevertheless, it was possible to observe, that in latitudes with higher daylight availability, such as in Brazil, electrochromic glazing tended to be in dark tint state for extended periods of time. This may jeopardize the well-being and the health of users in a long period of time, due to the decrease in the visible transmittance, with less daylight entering the room, and the supply of circadian lighting.

Electrochromic glazing is rarely discussed in warm climates, particularly in low latitudes. Studies in this regard must be conducted. In Brazil, electrochromic glazing was installed for exhibition purposes in Saint-Gobain Research in Capivari – Sao Paulo but is not commercialized (ABRAVIDRO, 2017). Figure 20 illustrates the electrochromic glazing inside its headquarters.

Figure 20 – Electrochromic glazing installed at Saint-Gobain Research Brazil.

Source: ABRAVIDRO, 2016.

From these studies mentioned, electrochromic glazing adjust the visible transmittance and daylight entering the room is controlled. In this regard, the transmittance should be diminished to prevent glare when direct solar radiation occurs and increase when there is diffuse light. Nevertheless, the use of electrochromic glazing in a dark tint state provides reduced circadian lighting and can alter the color appearance inside the room.

2.5. Conclusions from the literature review

Glazed facades on non-residential buildings in Brazil are still predominant, and little has changed in recent years regarding the use of glass. Consequently, buildings became more compact, with limited access to daylight and problems related to glare and overheating.

The reintroduction of daylight and natural ventilation in office buildings involves a redefinition of the architectural form, distribution of internal layouts, and the introduction of adequate treatment of the facades. Such redefinition is coupled with questions on the dominant economic formula behind the construction of office buildings, particularly regarding the use of glass. The redefinition of standards and urban codes can improve or mitigate issues related to the excessive use of glass on facades, such as overheating, the incidence of direct sunlight, and occurrence of glare (Matusiak, 2020).

Moreover, many technologies of smart windows – switchable glazings have been developed and they can control daylight entering the room. Among them, the technology of electrochromic glazing was selected for this study because it presents a higher capacity to control the properties of light transmission and solar heating gain coefficient in relation to other technologies of switchable glazings. However, the users' opinions and acceptability of this technology must be tested.

Four topics of investigation could be observed in relation to electrochromic glazing: a) examination of its thermal and luminous properties, b) studies about energy efficiency, c) thermal performance in two different climatic zones in Brazil and in the world context, d) luminous characterization of non-residential environments regarding visual effects and e) studies about circadian lighting considering the user's point of view.

From the user's point of view, the acceptability of the electrochromic glazing was higher, especially when it provided adequate lighting, without problems related to glare in the indoor environment, and with access to the outside view. In the case of the type of controls, the manual ones proved to be more adequate, with greater acceptance by the users. It is important to consider that electrochromic glazing and the majority of solar control glasses do not interfere with the spatial distribution of the transmitted energy (Felippe, 2016). Light distribution is an important aspect to be considered in deep environments with side openings, which is a common solution applied in commercial and office buildings in Brazil.

Additionally, it is not clear how the performance of electrochromic glazing is regarding visual and non-visual effects of light and whether the same problems related to the lack of daylight and reduced circadian lighting occur in different latitudes in Brazil. It is concluded, therefore, that there are few and still incomplete studies regarding the use of electrochromic glazing in Brazil. In this context, reinforcing this discussion is essential to point out more conclusive guidelines about the potential use of this glazing technology within the Brazilian context and its possible applications. To do so, it is essential to develop criteria to assess their performance regarding the adequate use of daylight inside a non-residential environment, including visual and non-visual effects. Consequently, the next sections were dedicated to the description of these effects of light on users and how to evaluate them.

Chapter 3. Lighting quality: Visual and non-visual effects of light

Lighting quality is a concept that allows excellent vision while providing high comfort. It cannot be measured directly, although it can be indicated by measuring different aspects of lighting quality individually (Kruisselbrink; Dangol; Rosemann, 2018). Matusiak (2020) considered the visual and non-visual effects and aimed to create a new Monitoring Protocol for Lighting considering four aspects: 1. Energy: energy end use for lighting and controls; 2. Photometry (or objective luminous environment) and its visual effects: characterization of space provided through luminance maps, daylight factor, etc., or Climate-Based Daylight Modelling (CBDM); 3. Circadian Potential (non-visual effects): Melanopic Lux, or circadian stimulus, based on the spectral distribution in the eye or vertical illuminance; 4. User (or subjective luminous environment): user's opinion about the environment. In this study, the electrochromic glazing will be evaluated considering daylight's visual and non-visual effects.

Daylight is dynamic, with constant variations in intensity and color temperature. This is a major challenge for scientific studies, making controlling it in buildings difficult. At the same time, daylight provides a great advantage compared to artificial lighting because it positively influences the human organism's non-visual effects, including the circadian cycle (Boyce; Hunter; Howlett, 2003).

Evidence shows that information about the external world is important to people in buildings. It is not just the total quantity of luminous energy that is important. Daylight entering a window carries information: falling directly on the eye, it is perceived as a view; falling onto the surfaces of the room, it is a changing pattern of room brightness, which also tells about the world outside (Tregenza; Mardaljevic, 2018).

The human metabolism and daily rhythms are regulated by variations in sunlight throughout the day and the year. This is an evident fact, for example, in the suitability of the organism to wake up in the light and fall asleep in the darkness. This human adaptability to the sunlight condition is spontaneous, as it is the original form of illumination, thus being the preferred light source (FIGUEIRO *et al*., 2002).

In task 61 of the International Energy Agency (2018a), it was recognized that light directly impacts the physiology of the human body. Adequate lighting levels can regulate hormone levels and the pace of daily activities such as sleeping and waking up. Light influences blood pressure and body temperature, regulates cardiovascular activity, and regulates human comfort (MATUSIAK, 2020). Comfort is a state of physical ease and freedom from pain or constraint, a pleasant feeling of being relaxed and free from pain. Discomfort is a feeling of being uncomfortable, physically or mentally (University of Cambridge, 2024; Fotios; Kent, 2021).

Assessing luminous comfort is essential for increasing user satisfaction and decreasing energy consumption. To assess lighting conditions in buildings, the International Energy Agency (International…, 2016b; Amorim *et al.*, 2021b) created monitoring protocols addressing photometric, energy, cost, and user satisfaction aspects. The purpose of these documents is to evaluate the performance of lighting conditions, considering artificial light and/or daylight in buildings.

In 2018, the International Energy Agency created Task 61, which focused on integrating solutions for natural and electric light, focusing on the user's point of view and the efficiency of artificial lighting systems (International..., 2018b).

According to Houser *et al*. (2021), human-centric lighting is the solution for integrated thinking about light and lighting as mediators of humans' visual, biological, and behavioral responses. Some are immediate, such as pupil dilation and glare perception, while others, such as mood, psychological, and physiological, can be delayed for hours or may not be evident for years. The circadian rhythm can be defined as our biological clock, which can be stimulated with light intensity and less intensely with the spectrum. Design professionals are attempting to integrate this knowledge in a manner that affects people most directly, and building owners look primarily to design professionals for guidance about light and health.

Vetter *et al*. (2021) summarized the physiological effects of light on human health and well-being, including a description of the processes underlying the photic regulation of the circadian rhythm. They concluded that integrative solutions that have biologically high potency light during the day and low potency during the night are perhaps the most immediate improvement to be made in order to support applications for humans better. It is also important to emphasize that daylight exposure is crucial for resetting the circadian clock.. To better understand the light and its effects, in section 3.1 the visual effects, and in 3.2, the non-visual effects are described.

3.1. Visual effects of light

Analyzing previous research and standards cited by Dubois *et al*. (2016), seven elements were proposed to objectively describe the quality of the natural and artificial light of the space: luminance, illuminance, glare, directionality, color, flicker, and exterior view. These constitute the qualification of visual comfort, and they are part of the visible spectrum of light (Veitch, 2014).

The illuminance, the areal density of the luminous flux, is measured by calibrated illuminance meters, which include a cosine correction. The directional response index describes the influence of the angle of a light incident within the measuring field of a luminance meter (Aarts *et al.*, 2017).

The most used metric in regulations and codes of practice for good lighting is illuminance on a given interior surface, such as a horizontal working plane. The measure of illuminance required is of the building in use, after completion of construction, after furnishing and decoration, and when the building is used for its intended activities. This implies that approval or rejection of a building proposal can be given only retrospectively. Windows affect more than just the daylight in a room: optimizing lighting in isolation can cause thermal, acoustic, ventilation, and sightline failures. Conversely, if daylight is considered solely a modifier of a building's energy use, the outcome can be visually unsatisfactory. The analysis and design of lighting as the distribution of information is an area of research with considerable potential (Tregenza; Mardaljevic, 2018). This means the evaluation of illuminance values alone is insufficient to predict visual comfort.

The luminance is the only photometric measure directly related to the incidence of reflected light on the retina and, consequently, most closely related to the human visual perception of brightness. The luminance is increasingly recognized as an important factor for visual comfort. Previously, the luminance was measured by a spot luminance meter. However, it is possible to determine luminance values based on pixels using current High Dynamic Range (HDR) technology. Luminance distribution measurement devices are highly suitable for measuring light quality for both ad hoc and continuous measurements and provide relevant input for lighting quality control algorithms (Kruisselbrink; Dangol; Rosemann, 2018; Tregenza; Mardaljevic, 2018). Images analyzing the luminance values on the vertical field of view are extremely important in evaluating light quality, in contrast to only measuring the illuminance values on the horizontal field. The latter is mostly used in building codes and standards to evaluate lighting in indoor environments.

Glare is defined by the condition of vision in which there is discomfort or a reduction in the ability to see details or objects caused by an unsuitable distribution or range of luminance or by extreme luminance contrasts. It can be divided into disability glare, which impairs the vision of objects, and discomfort glare, which causes discomfort without necessarily impairing the vision of objects (CIE, 2020). Discomfort glare can be caused by excessive brightness (i.e., saturation) or by extreme differences in bright and dark areas (i.e., contrast) (Commission…, 2020; Jain, Karmann; Wienold, 2022).

In a more detailed explanation, disability glare, although rarely occurring in buildings, is stray light in the eye that disrupts vision due to intraocular light scatter. It immediately reduces the visual performance and the ability to see. Discomfort glare occurs when there are high luminance contrasts or unsuitable luminance distributions within the visual field and it reduces users' visual performance or visibility. It is not necessarily the decrease in the visual comfort that the discomfort is caused, but it is caused by the stress of the entire visual system seeking to adapt to face extreme conditions. Over time, negative effects can occur, such as headaches, fatigue, and decreased concentration (Kruisselbrink; Dangol; Rosemann, 2018).

The flow of light can describe the directionality of a light scene. The concept of the flow of light consists of two aspects: the direction and the strength of the light flow. Another definition of the strength of the light flow, also called modeling, is the balance between diffuse and directional components of the lit environment. Adequate directionality helps distinguish a task's details, surface textures, and three-dimensional objects, including faces. As a result, it influences communication and the appearance and appreciation of an environment. Moreover, the directionality of light can influence health and well-being because of a non-homogeneous distribution of the non-image-forming cells in the eye. The directionality of light can cause three distinct patterns on objects: the illumination pattern, the shadow pattern, and the highlight pattern. Theoretically, the directionality of a point within a room is determined based on an infinitesimal sphere that is met by an infinite number of luminance rays from all directions. Consequently, these rays can be described as three-dimensional bound vectors. The vector-to-scalar ratio is commonly used, representing the relation between the approximated illumination vector and the approximated scalar illumination. Indicators for the direction of light are limited to the direction of the illumination vector. Most methods use only ad hoc measurements at specific times of day, room conditions, etc. (Dubois *et al.*, 2016; Kruisselbrink; Dangol; Rosemann, 2018). Directionality is difficult to evaluate, particularly because this requires evaluation at different times of the year, including different seasons, sky conditions, etc. For this reason, this element will not be evaluated in the study method.

Another quality element to be considered is the spectral power distribution (SPD), which represents the radiant power emitted by a light source at each wavelength or band of wavelengths in the visible region of the electromagnetic spectrum. The light source can be daylight, a luminaire, a reflecting surface, or a combination. The SPD indicates which colors are represented within the emitted light. It influences the color appearance and the color quality of the light. The SPD is a complex metric whose effects are not completely understood or easily communicable. Therefore, the effects of the SPD are separated into two concepts: color appearance and color quality. It also affects light's non-image-forming (non-visual) effects (Kruisselbrink; Dangol; Rosemann, 2018).

The color appearance relates to the apparent color of the emitted light independent of the context caused by available wavelengths within the visible spectrum and has the attributes of brightness, hue, and colorfulness. The color appearance of the light source is generally indicated by the correlated color temperature (CCT), which is the temperature of a black body radiator having a chromaticity associated with the chromaticity of the SPD of the light source. Preferably, the CCT is based on spectral measurements. It is best measured using a spectroradiometer focused at a white Lambertian reflector such as Spectralon or BaSO4. The Lambertian reflector is placed horizontally, perpendicular to the electric light source, at the measurement location and is measured from a 45° angle (Islam *et al.*, 2015; Kruisselbrink; Dangol; Rosemann, 2018). The preferred color appearance completely depends on the activity and influences the perceived brightness (Wei *et al.*, 2014).

The concept of light color quality consists of different dimensions that influence the observer's color perception in an environment. Six dimensions are identified: color fidelity, color discrimination, visual clarity (brightness), color preference, color harmony, and color acceptability. The color fidelity, or rendering, is the effect of the light (source) on the color appearance of objects by conscious or subconscious comparison with their color appearance under a reference illuminant. Color discrimination is the ability to distinguish between colors. Visual clarity relates to the feeling of contrast. Color preference and color harmony are aesthetic judgments for the individual objects and the relationship between objects, respectively. Finally, color acceptability relates to making a judgment about the whole environment. Good light color quality helps to improve visual performance, comfort, and well-being (Bodrogi *et al.*, 2013; Kruisselbrink; Dangol; Rosemann, 2018).

Flicker is the perception of visual unsteadiness induced by a light stimulus of luminance or spectral distribution, which fluctuates with time for a static observer in a static environment. The fluctuations of the light stimulus with time include periodic and non-periodic fluctuations and can be induced by the light source itself, the power source, or other influencing factors (COMMISSION…, 2020).

One source of environmental stress is flicker from fluorescent tubes, especially in rooms lacking daylight. The light from conventional light bulbs and other incandescent lamps is produced by heating a metal wire or other element using an electric current. This illumination is fairly stable even with alternating current. On the other hand, the light emitted from fluorescent lamps is based on electric discharges and is therefore modulated by the power supply. An alternating current of 50 Hz will cause a flicker of mostly 100 periods per second, which will not be seen by the naked eye but still may reach the brain. Young persons are most vulnerable to flicker from fluorescent tubes. Amongst the effects reported are eyestrain, headaches, disturbed performance, and increased secretion of cortisol. The flicker sensitivity is also higher in the peripheral than in the central field of view (Amorim *et al.*, 2021b; Dubois *et al.*, 2016; Houser; Esposito, 2021). Since flicker is mostly related to electric lighting, this element of lighting quality is not considered in the study, which focuses on daylight.

A crucial element of the lighting quality aspect is daylight. Often, daylight penetration is a given, depending on the fixed window openings, weather, and time. However, there are possibilities to optimize daylight penetration on the run. An increasing number of buildings are applied with dynamic sun shading (sunscreens), brightness control (blinds), and/or smart glazing integrated into the facade. Sun shading and smart glazing can block direct solar radiation and prevent glare or overheating. These systems are often fixed, but dynamic systems that follow the sun's trajectory are also available. Additionally, brightness control generally has a dynamic character as blinds are easily adjusted, manually or automatically, permitting optimizations. Hence, daylight penetration can be optimized by a control algorithm (Houser *et al.*, 2021; International…, 2016; Kruisselbrink; Dangol; Rosemann, 2018).

Light designers often adjust the users' view angle in order to avoid looking directly at the light source. This prevents problems related to glare and visual discomfort. In the case of daylight, the adequate internal distribution of the light energy greatly reduces the effects of this condition. Elements such as sun shading devices are better to redirect the admitted energy entering the room than the majority of glazings found in the market (Felippe, 2016).

Besides daylight, the outdoor view through windows is an indoor environmental factor that significantly affects mental health and is related to the perception of glare, among other factors. A good view depends on four parameters: width and distance of view, number of layers, and environmental information. A good view should have a width larger than 28° and a distance larger than 20 meters. It should include at least two layers and secure access to the following information: time, weather, location, and nature or people (Amorim *et al.,* 2021b; Fernandes, 2016; Yeom *et al.,* 2020).

In studies regarding visual comfort in non-residential buildings in Brasilia, Fernandes (2016) aimed to identify the influence of satisfaction with external view quality, proportioned by the window in offices, over a perception of glare on the user's visual field. The multimethod systematization was based on investigating the real environments of three public buildings: TJDF, the Ministry of Environment (MMA), and the Ministry of Mines and Energy (MME). The evaluation of the environments consisted of an evaluation with quantitative data (dynamic computational simulations of daylighting on the software DIVA-for-Rhino and classification of view quality), with the evaluation made by the user, with qualitative data (questionnaires about the satisfaction glare perception of the external view). Results of daylight autonomy, useful daylight autonomy, and annual glare were evaluated during the simulations. The results indicated no significant problem with the luminosity performance, and the simulations were sensitive to detect punctual problems in specific hours and months. It was detected that the biggest problem related to glare in real environments was not due to saturation but due to inadequate contrasts in the visual field of view. It was also identified that the probability of the user realizing glare reduces by 32.84% annually when there is a satisfying view. When realizing glare at the moment, the probability reduces by 60% when the user is satisfied with the view. Besides, that the possibility of the users changing their view directions to avoid a least glary source was considered. It was concluded that the results were important for future directions on studies in the lighting field because the quality of view must be regarded as an important project variable.

Since the evaluation of the view quality is subjective and depends on the size, location, and landscape, among other factors, this element will not be evaluated in this research method. The following elements will be considered to evaluate the daylight performance of innovative transparent and translucent materials: illuminance distribution in the horizontal field, luminance in the vertical field of view, and glare. These elements can be objectively analyzed and provide a good reference for visual comfort, especially with computer simulations. In the next section, 3.2, the non-visual effects are discussed.

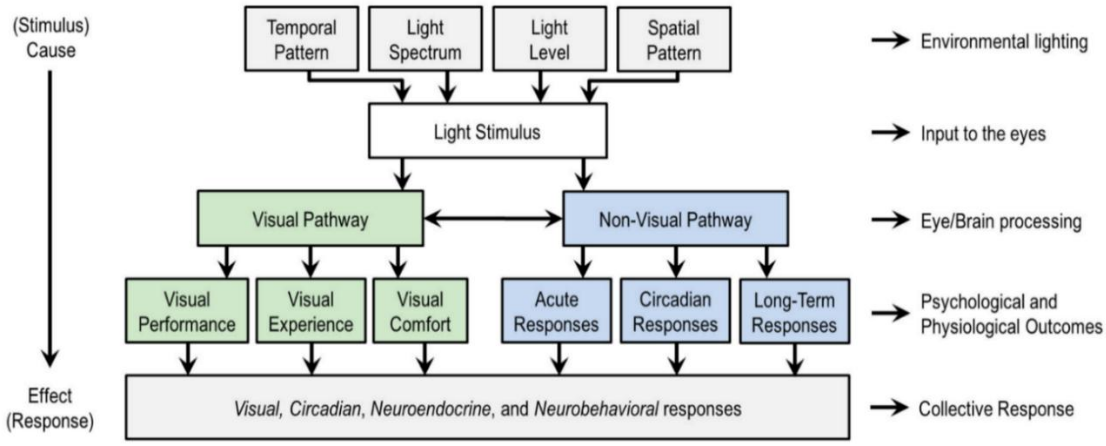
3.2. Non-visual effects of light

The physiological effects of light are mediated by the eye in humans. For many years, it was thought that there were only two classes of photoreceptors in the human eye: cones and rods. Nevertheless, another third photoreceptor type was discovered in the mammalian eye about two decades ago, from the present date. These photoreceptors are called ganglion cells, contain a photopigment called melanopsin, and are intrinsically photosensitive to light (Hattar *et al.*, 2002). From this moment on, many studies were directed to understand better how humans physiologically responded to light.

According to Houser and Esposito (2021), the stimulus-response relationship between light and humans depends on four aspects: time, spectrum, intensity, and spatial pattern. They can be manipulated to influence two categories of human responses to light, which are visual and non-visual. A visual response is located in the eye and brain and enables sight, contributing to the visual experience, including emotional responses and visual comfort or discomfort, such as glare. Non-visual responses might also be called non-image forming (NIF) effects of light, biological, or physiological responses. The International Commission on Illumination (*Commission Internationale de l'Eclairage*) adopted the phrase ipRGC-influenced light responses (Commission…., 2018). The Illuminating Engineering Society – IES (Illuminating…, 2012) uses the phrase visual, circadian, neuroendocrine and neurobehavioral responses. Circadian responses are internal biological processes that occur over a roughly 24-hour period, such as the sleep-wake cycle. Neuroendocrine responses refer to how the brain regulates hormones, such as the expression of melatonin. Neurobehavioral responses refer to the relationship between the action of the nervous system and human behavior.

Figure 21 illustrates the pathways of light from the stimulus to the effects in the human body. At the top level, the temporal pattern relates the timing and duration of exposure to a light stimulus, and the spatial pattern refers to the spatial distribution of light in the three-dimensional light field; light spectrum refers to the spectral power distribution (SPD) that governs color qualities, and light level refers to the quantity of light in radiometric or photometric units. These four factors contribute to the biological potency of the light stimulus. The exact pathway from the light stimulus and circadian responses in humans is still unclear and under scientific investigation (Houser; Esposito, 2021).

Figure 21 - Pathways of light and physiological responses in humans.



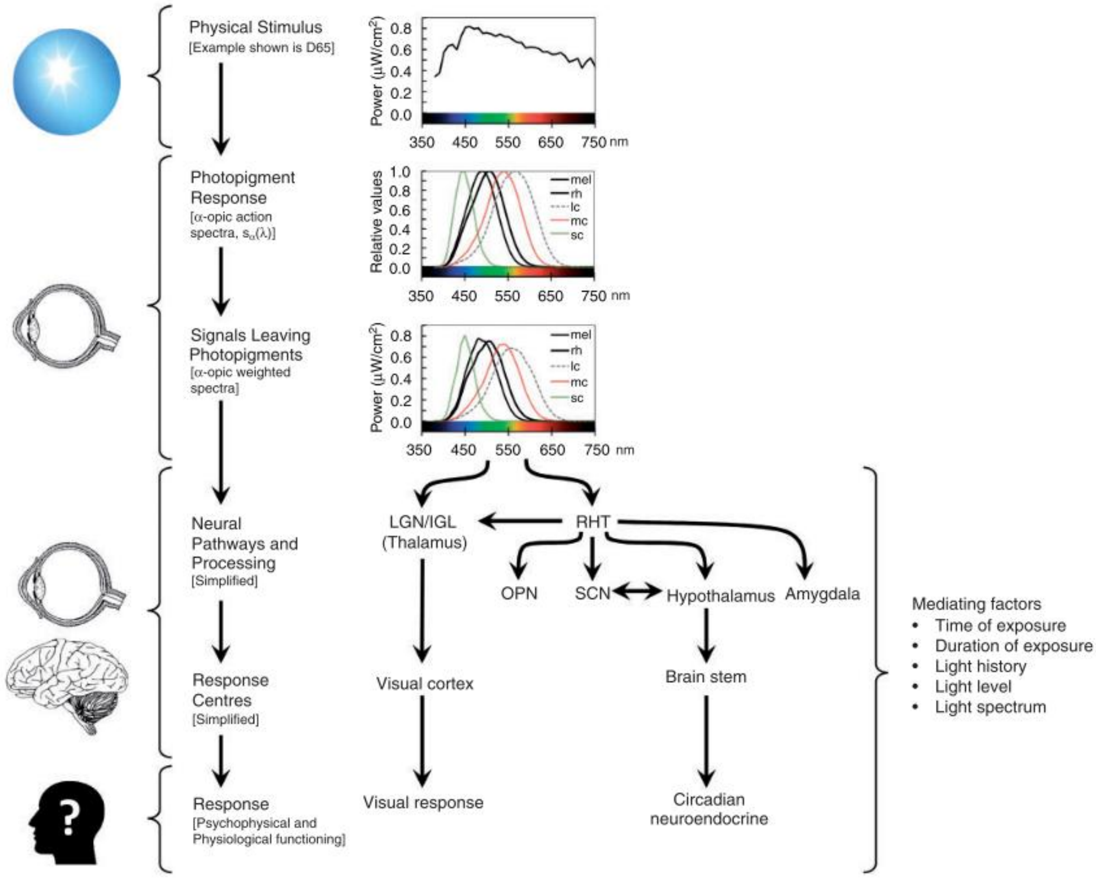
Source: Adapted from Houser; Esposito (2021) and Kort; Veitch (2014).

Recent advances in photobiology have set off revolutions among lighting researchers and the lighting industry. The physiological effects of light are mediated by the eye in humans. Light entering the eye stimulates retinal photoreceptors that convert photic information into neuronal signals, which get transmitted via ganglion cells to various regions in the brain, including the thalamus and hypothalamus, which regulate our biological clock. In a more detailed explanation, the intrinsically photosensitive retinal ganglion cells (ipRGCs) transmit environmental light information via the retinohypothalamic tract (RHT) to the central clock in the brain (SCN, suprachiasmatic nuclei). Other direct projections of ipRGCs include thalamic and other brain regions. The ipRGCs contain a photopigment called melanopsin, which is intrinsically photosensitive to light. The human circadian clock's physical stimulus depends on the timing, intensity, and duration of the light exposure. Moreover, melanopsin is most sensitive to short-wavelength light, with a peak response around 480 nm. The short-wavelength sensitivity of the ipRGCs is, at least in part, reflected in the circadian, neuroendocrine, and neurobehavioral responses to light described in humans (Houser *et al*., 2021; Kort; Veitch, 2014; Vetter *et al*., 2021; Xiao; Cai; Li, 2021).

Cones and rods also provide non-visual effects of light. S-, M-, and L-cone-topic action spectra take a maximum value of 1 at 447.9 nm, 541.3 nm, and 568.6 nm, respectively (Commission…, 2018). The photosensitivity of rods shows peak sensitivity at approximately 500 nm (Lucas *et al*., 2014).

The pathway from the physical stimulus of light to the physiological and psychophysical responses is complex and under study. According to Houser *et al*. (2021, p. 105), the physiological stimulus of light begins with light as a physical stimulus, which is transduced through the neuroanatomical underpinnings of eye-brain physiology, culminating with visual and non-visual responses. Cones and rods transmit light information via the lateral geniculate nucleus (LGN) and intergeniculate leaflet (IGL), continuing to the visual cortex. The melanopsin-containing ipRGCs generate an intrinsic melanopsin-driven response and receive extrinsic input from rods and cones. The signal leaving the ipRGCs is a function of both their intrinsic response and extrinsic input. The ipRGCs transmit light information via the retinohypothalamic tract (RHT) to the suprachiasmatic nuclei (SCN), the brain's central clock. Other direct projections of the ipRGCs include the olivary pretectal nucleus (OPN, pupil constriction), hypothalamic nuclei (including the ventrolateral preoptic nucleus, involved in sleep regulation), and amygdala (involved in emotion regulation). The specific ipRGC-influenced light response depends on the mediating factors shown, including time and duration, light history, level, and spectrum. Complexity and uncertainty increase from top to bottom, from the physical stimulus in the eye to the physiological response in humans. Figure 22 illustrates the schematic pathway of the non-visual effects of light from the stimulus until the physiological and psychophysical responses in humans.

Figure 22 – Schematic illustrating the pathway of the non-visual effects of light since the stimulus until the physiological and psychophysical responses.



Source: Houser *et al.*, 2021.

Xiao, Cai, and Li (2021) reviewed 27 publications relevant to the theme, in which factors affecting circadian rhythm, alertness, and mood were investigated. It was concluded in the review that the increase in illuminance and correlated color temperature (CCT) at night were both positively associated with melatonin suppression, thus affecting the circadian rhythm. Meanwhile, a high CCT is conducive to stimulating a positive mood. Blue light and high CCT light at night induced delayed phase shift and reduced objective alertness due to the lack of blue components. Additionally, high illuminance was positively correlated with alertness during the daytime, increasing positive mood in the morning and decreasing it in the afternoon. It was recommended that architects and designers consider daylight first and that artificial lighting be used to complement its deficiency, forming a mixed light environment that can improve users' satisfaction and simultaneously reduce energy consumption.

Alkhatatbeh and Asadi (2021) carried out a bibliographic review of 128 academic papers focused on the role of architecture in creating circadian-effective spaces. It was verified that new buildings are better adapted to do so. However, retrofit projects can adapt architectural and interior design features to provide circadian benefits. Easy adjustments to spaces can increase the indirect component of light and boost the circadian system, such as painting surfaces with neutral colors, adding highly reflectance finishes, and adjusting the luminaires' position/direction to face highly reflectance surfaces, especially the ceiling. Daylight is the best light source to provide circadian stimulation and energy efficiency. In this context, glazing technologies, including electrochromic glazing, can also balance visual comfort, mitigate discomfort such as glare, and provide circadian lighting. They concluded that future research should investigate the role of architecture in creating circadian-efficient spaces.

In this context, innovative technologies, such as smart glazing technologies, should investigate how efficiently they can proportionate the non-visual effects of light-circadian lighting.

3.3. Conclusions concerning visual and non-visual effects of light

In regard to the visual and non-visual effects of light, some conclusions were made in order to guide the evaluation of the performance of the electrochromic glazing. Daylight was chosen as the focus of the study because it presents constant variations in intensity, color temperature, and sky conditions. Unfortunately, these variations in daylight are aspects that softwares, such as ALFA and LARK, offer limitations to deal with (Moroder *et al*., 2021).

This is a major challenge, especially when different climates are analyzed. At the same time, daylight has a positive influence when compared to artificial lighting because it positively influences non-visual effects, including in the circadian cycle in the human organism.

Inside the concept of lighting quality, two aspects were chosen to evaluate the performance of the two innovative materials: visual and non-visual effects of light. Visual effects include the luminous characterization of the space, which can be evaluated through luminance values in the vertical field of view, illuminance distribution, evaluation of glare, etc. Non-visual effects include the circadian stimulus and are evaluated based on the spectral power distribution in the eye. It is important to understand light's physiological responses in humans.

From the seven elements of lighting quality mentioned inside the visible spectrum, four will be deepened in the discussion of the study and evaluated in the method, which will be luminance in the vertical field of view, glare, illuminance, and access to daylight. Since the exterior view is subjective and requires the understanding of the users, this will not be considered in the method. Color will be an element evaluated as a non-visual effect of light, specifically regarding the spectral power distribution of the light stimulus.

Visual and non-visual effects of light are complementary aspects of lighting quality. Therefore, one of the aspects of this work's originality is to consider daylight's influence on the user in-depth, analyzing the impacts of innovative materials, particularly the electrochromic glazing, on visual comfort and aspects related to the non-visual effects. The next section is dedicated to the theoretical review of methods and tools for evaluating their performance regarding daylight.

Chapter 4. Quantification of visual and non-visual effects of daylight

The introduction of daylight into buildings has great potential to positively impact building occupants and reduce energy consumption if linked with the electrical system. However, if the windows are poorly designed, the luminous environment may lead to glare, headaches, and eye strain (Day *et al.*, 2019; Jain; Karmann; Wienold, 2022). As discussed in Chapter 2, the focus of the study is on electrochromic glazing in the category of smart windows – switchable glazings. It is important, nevertheless, to identify the methods and tools used to evaluate its performance in terms of daylight.

Practitioners use a wide variety of different workflows, methods, and tools in the planning of integrated solutions for daylighting, electric lighting, and controls. Lighting design projects cover a huge variety of applications with different requirements, project types, and sizes (Moroder *et al*., 2021).

In this context, computer simulations provide unlimited simulation iterations. However, the metrics are simplified and still evolving. Moreover, inaccuracies in the building model can lead to misleading results, and to date, software tools cannot fully integrate advanced daylighting and electric lighting simulations. Circadian lighting can also be evaluated through computer simulations.[11] Computer simulations are an adequate method to investigate electrochromic glazing and test their performance in the Brazilian climatic contexts. This is a resourceful tool to predict hypothetical scenarios or when the execution of experiments is not possible.

Questions arise regarding the evaluation of the electrochromic glazing regarding visual and non-visual effects of light. Section 4.1 describes the quantification of the visual effects of light. In section 4.2 the quantification of the non-visual effects is described. Section 4.3 is dedicated to the description of the different proposals of Brazilian luminous zoning. In section 4.4 directions are given in order to subsidize the statistical analysis. Section 4.5 presents the conclusions regarding the quantification of visual and non-visual effects of light.

[11] Ibidem, 2021b.

4.1. Quantification of visual effects of (day)light

In the late 1990s, climate-based daylight modeling was developed. Climate-based daylight modeling (CBDM) predicts various radiant or luminous quantities (e.g., irradiance, illuminance, radiance, and luminance) using sun and sky conditions derived from standard meteorological datasets. Whilst it hardly needs remarking that daylight is inherently climate-dependent and time-varying, the accepted evaluation method, called the daylight factor, makes no account of this everyday reality (Mardaljevic, 2006).

After the development of the CBDM, many metrics were proposed to evaluate the illuminance distribution within a space. Two were used to describe daylight autonomy (DA) and useful daylight autonomy (UDI). The daylight autonomy at a point in a building is defined as the percentage of occupied hours per year when the minimum illuminance level can be maintained by daylight alone. In contrast to the more commonly used daylight factor, daylight autonomy considers all sky conditions throughout the year. The minimum illuminance level corresponds to the minimum physical lighting requirement, which must be maintained at all times so that a certain task can be carried out safely and without tiring the working occupant (Reinhart; Walkenhorst, 2001).

According to Mardaljevic (2006), useful daylight illuminance (UDI) is defined as the annual occurrence of illuminance across a work plane that is within a range considered useful by occupants. The range considered “useful” is based on a survey of reports of occupant preferences and behavior in daylit offices with user-operated shading devices. Daylight illuminances in the 100 to 500 lux range are considered effective as the sole illumination source or in conjunction with artificial lighting. Daylight illuminances in the range of 500 to 2000 lux are often perceived as desirable or tolerable. Consequently, illuminance levels between 100 and 2,000 lux are within the useful range, less than 100 lux fall short of the useful range, and greater than 2,000 lux exceed the useful range. These metrics, however, have limitations when they are used for predicting glare in the occupant's vertical field of view. Later, this threshold was extended to 100 lux and 3000 lux (Mardaljevic *et al.*, 2012).

According to Reinhart and Wienold (2011), daylight glare probability (DGP) quantifies the likelihood of experiencing glare based on light sources, size, position of the eye, and brightness in relation to the average background illuminance. According to human subject studies in Germany and Denmark, values greater than 45% correspond to intolerable glare, while those under 35% predict imperceptible glare. The software Rhinoceros and Daysim were used to calculate DGP through Evaglare. DGP can be calculated for a specific time, day, and sky condition; during the entire year, it is called annual glare. Annual daylight glare probability profiles are combined with an occupant behavior model in order to determine annual shading profiles and visual comfort conditions throughout a space. The shading profiles are then used to calculate daylight autonomy plots, energy loads, operational energy costs, greenhouse gas emissions, etc.

Mardaljevic *et al.* (2012) examined possible relationships between annual occurrence of glare (DGP) and useful daylight illuminance (between 100 and 3000 lux). The purpose was to determine if one or more of the UDI metrics (predicted for the horizontal work plane) could serve as a proxy for the daylight glare probability. For glare, the simplified daylight glare probability model was used. The setting was a residential building in two design configurations, each evaluated under all 32 combinations of 8 European climates and 4 building orientations. It was demonstrated that there was the potential to compute measures of daylight glare probability using indirect means, i.e., using the simplified DGP and without recourse to generating – computationally expensive – luminance renderings on a per-time-step basis.

Moroder *et al.* (2021) described workflows and software used to design integrated lighting solutions. This report contains three example projects located in Austria, Germany, and China and represents modern office spaces recently built or renovated. All described workflows utilize software tools to a greater or lesser extent to support the planning process or to evaluate design options. To provide an overview of the possibilities, strengths, weaknesses, and barriers of state-of-the-art lighting simulation, relevant and widely used software tools have been analyzed and documented. This report offers a useful tool in the choice of simulation software, and twelve were compared, including DIVA-for-Rhino, Radiance, DIAL+, and DIALux, already mentioned in the literature review. The general criteria for comparison were algorithms, engines, electric lighting, daylighting, glare assessment, and control systems.

The software DIVA-for-Rhino and Ladybug/ Honeybee, DIAL+, can execute climate-based annual simulations to calculate daylight autonomy and is sensible to solar orientation. DIAL+ offers limitations on calculating DGP. DIVA-for-Rhino and Ladybug/Honeybee calculate DPG. SOLEMMA developed Climate Studio, which provides environmental performance analysis of individual buildings and urban landscapes and calculates CBDM, such as daylight autonomy, useful daylight autonomy, and DGP. Climate Studio has many materials, constructions, and templates from real-world measurements and validated sources.[12] After describing the possibilities and limitations of each software, it was concluded that the investigated design software tools provide the possibility for every checked feature. However, no single software can cover all aspects related to visual comfort and quality of light. Each software has a specific workflow and is designed for a specific application. Some are mainly developed for daylighting analyses, while others strongly focus on electric lighting design or Building Information Modelling (BIM) functionality. As a general result, all tools and software cover basic functionality, such as illuminance calculation. Even more, the software systems hardly cover the relatively new field of non-visual effects of lighting. For these evaluations, special tools such as ALFA or LARK are available (Moroder *et al.*, 2021).

There are standards to evaluate daylight availability inside a space, its properties, and its surroundings. The European Standard EU 17037 (European…, 2018) proposes methods to assess daylight in the interior. One of the calculation methods determines daylight provision directly from simulated illuminance values on the reference plane. If the actual space is expected to contain any moveable shading device (e.g., blinds), then the simulation should include dynamic modeling. For a space with vertical and/or inclined opening with a given target illuminance, e.g., 300 lux, and appropriate reference plane fraction, i.e., 50 %, the criterion is that the target illuminance is achieved across the reference plane fraction for 2,190 h (i.e., half of the daylight hours of the year). For the minimum target illuminance, e.g., 100 lux, the criterion is that the minimum target illuminance is achieved across the entire reference plane (i.e., 95 %) for 2,190 h. Similarly, this detailed calculation method should be applied to spaces with horizontal daylight openings. To evaluate glare, the Daylight Glare Probability is used to assess protection for spaces where activities are comparable to reading, writing, or using display devices, and the occupants are not able to choose a position or view direction. The DGP assessment can be applied to a space with vertical or inclined daylight openings but does not apply to a space with horizontal daylight openings (CEN, 2018).

Similarly to the European Standard 17037 (European…, 2018), the National Institute of Metrology, Standardization and Industrial Quality (INMETRO) published the normative instruction n. 42 of February 2021 for classifying the energy efficiency of Brazil's commercial, public, and service buildings. There is a method to determine the potential for integration of natural and artificial light using computer simulations.

[12] SOLEMMA. Climate Studio. Available at: https://www.solemma.com/climatestudio. Accessed on 1 March 2024.

Through this method, the potential integration between the artificial lighting system and available daylight must be determined based on spatial daylight autonomy. “Areas with daylight autonomy” present at least 300 lux in at least 50% of the daylight hours (DA 300 lux, 50%), considering the hypothetical use of blinds to avoid discomfort due to glare. The proceedings for the use of computer simulations are described in Annex C. II. Regarding glare, it is suggested that all exterior windows in environments with visual activity must be modeled with blinds or curtains operated to avoid glare. Windows must be grouped and operated on an hourly basis so that they meet the criteria for Annual Sunlight Exposure - IES LM-83 (Illuminating…, 2023), which is the maximum of 1,000 lux in 250 hours per year in 7% of the area (BRASIL, 2021).

The following parameters were used to evaluate the performance of the innovative materials regarding visual effects of light: illuminance in the horizontal field evaluated with spatial daylight autonomy, useful daylight autonomy, and annual daylight glare probability. Computer simulations using the software Climate Studio and ALFA were carried out. The quantification of non-visual effects of light is described in the next section.

4.2. Quantification of non-visual effects of light

There are two methods to quantify light as a non-visual stimulus, and these are based on (Amorim *et al.*, 2021b):

1) Spectral response of the photopigments in the rods, cones, and ipRGCs.
2) The nocturnal suppression of the hormone melatonin.

There are two metrics for the first method, the Equivalent Melanopic Lux (EML) introduced by Lucas *et al.* (2013) and the Melanopic Equivalent Daylight Illuminance (M-EDI) proposed by CIE (2018), and one tool for the second method, the circadian stimulus (CS) (Rea; Figueiro, 2018).

Lucas et al. (2013) created the Irradiance Toolbox to assess user-related visual comfort in response to this need to assess user-related visual comfort. In it, the primary function is the application for calculating the effective illuminance for each of the five photopigments in the human eye based on measurements precisely distributed in the visible spectrum. Based on this tool, it is possible to study the impact of light reception on users' perception and their regulation of the circadian cycle.

The circadian potential of a space can be estimated by quantifying the Equivalent Melanopic Lux (EML). The MS Excel workbook “Irradiance Toolbox” can calculate the EML values. The toolbox provides both the photopic lux (they should be the same as measured by the illuminance meter) and the cyanopic, chloropic, erythropic, melanopic, and rhodopic lux, the first three corresponding to the three classes of cones present in the human retina, the following to the iPRGCs, and the final one to the rod photoreceptors. The information necessary to apply the conversion is either the measured irradiance or the measured illuminance and the spectral power distribution of the light source. Lucas' toolbox shows that the measured irradiance with a spectrometer is copy-pasted, and the illuminances are calculated. For the approximate measurement with an illuminance meter, the user should type the measured photopic illuminance and select the spectral power distribution from a pre-set list of light sources, e.g., incandescent, daylight, narrowband, white LED, etc. (Lucas *et al*., 2013).

The Circadian Stimulus (CS) can be extracted from a calculator that provides a coefficient for expressing the extent to which a given light source of specific intensity and spectrum elicits circadian responses, namely the suppression of melatonin secretion. The coefficient ranges from 0 to 0.7, from no melatonin suppression (0) to maximal observed melatonin suppression (0.7), respectively. Although the output is different, the CS Calculator is similar to the Lucas toolbox in the way in which the relative spectral power values imported from a .csv file, describing the spectral distribution of the light source, need to be introduced, or in the selection of a light source from a list with pre-set characteristics (Amorim *et al.*, 2021b; Rea; Figueiro, 2018).

Equivalent Melanopic Lux is expressed in units of melanopic lux (EML), which the International Energy Units (SI) does not recognize. As a result, the CIE proposed a new metric, the melanopic equivalent daylight illuminance (M-EDI), a new quantity that is SI compliant. The Mel-EDI combines the sensitivity of five photoreceptors (S cone, M cone, L cone, rhodopsin, and melanopsin) with standard daylight (D65) with its units in “lux”. To calculate Mel-EDI, the CIE has developed the “CIE S 026 α-topic toolbox”, a spreadsheet in the Microsoft Excel calculator, and a user guide on how to use the toolbox, both available on the CIE website (Commission, 2018). The CIE S 026 α-Opic Toolbox can also be used for detailed spectral analysis of non-visual effects of light.[13]

[13] Idem, 2018.

The spectrum M/P ratio represents the ratio between the melanopic and photopic illuminance produced by light sources of a given spectral power distribution (Alight; Jakubiec, 2021; Carmon, Altomonte, 2021). Melanopic daylight efficacy ratio (Mel-DER) is the ratio of a test source's melanopic efficacy of luminous radiation to the melanopic efficacy of luminous radiation of CIE Standard Daylight D65 as described in Equation 1.

Equation 1 – Calculation of melanopic daylight efficacy ratio as defined in CIE S026 (2018).

$$\mathrm{Mel - DER} = \frac{\text{Melanopic luminous efficacy of the light source}}{\text{Melanopic luminous efficacy of D65}}$$

Source: CIE (2018); Englezou; Michael, 2023; Esposito; Houser, 2022.

Melanopic DER is unitless, with the value 1 corresponding to the light source of D65. Alternatively, the melanopic equivalent daylight illuminance (mel-EDI) is the ratio of the photopic illuminance (Ev) produced by optical radiation of Mel-DER as shown in Equation 2.[14]

Equation 2 – Alternative calculation method for melanopic equivalent daylight illuminance as function of melanopic daylight efficacy ratio.

$$\mathrm{Mel - EDI = Ev\ x\ Mel(DER)}$$

Note: Mel-EDI is associated to lux. Source: CIE (2018); Esposito; Houser, 2022.

As described in Equation 3, Mel-EDI is a scalar multiplier of melanopic lux (EML), and Mel-EDI can be easily obtained by multiplying by 0.9058 the value of the melanopic illuminance calculated according to the method proposed by Lucas *et al.* (Bellia *et al*., 2023; Lucas *et al*., 2013).

Equation 3 – Conversion unit from units of equivalent melanopic lux to melanopic equivalent daylight illuminance.

$$\mathrm{Mel - EDI = EML\ x\ 0.9058}$$

Source: Bellia *et al.* (2023); Lucas *et al.* (2013).

[14] Both metrics, EML and Mel-EDI (with units in lux) are obtained by the same calculation method, obtained by the multiplication of the vertical illuminance with M/P ratio or Mel-DER. See the details in the study of Esposito and Houser (2022).

It is important to emphasize that the prefix melanopic, in the formula “mel,” refers to the photopigment melanopsin. The prefix “α” in the term “α-topic” indicates one of five different photoreceptor responses, and the symbol is also used to denote an index for quantity symbols. To evaluate the α-opic action spectrum for the five human photoreceptors, S cone, M cone, L cone, rhodopsin and melanopsin CIE S 026 α-opic Toolbox is used. According to the definition, α-opic equivalent daylight illuminance in a given direction and at a specific point is illuminance produced by radiation conforming to standard daylight D65 that provides an equal α-opic irradiance and is usually measured at the outer surface of the eye. Similarly to Mel-DER, α-opic-DER is the ratio of luminous radiation of a source to the α-opic efficacy of luminous radiation for daylight (D65). The definition is represented in Equation 4.

Equation 4 - Calculation of α-opic equivalent daylight illuminance as defined in CIE S026 (2018).

$$\alpha\text{-opic-EDI} = \mathrm{Ev} \times \alpha - \mathrm{opic\ DER}$$

Source: Commission…, 2018.

In summary, α-opic EDI is a more general term that can refer to any of the five photoreceptors, while Mel-EDI is specific to melanopsin. The difference between α-opic EDI and Mel-EDI lies in the types of photoreceptors each measures (Commission…, 2018):

- α-opic EDI: refers to the equivalent daylight illuminance for each of the five human photoreceptors (S-cones, M-cones, L-cones, rhodopsin, and melanopsin - iPRGCs).
- Mel-EDI: specifically measures the equivalent daylight illuminance for melanopsin, which is a photopigment sensitive to blue light and involved in regulating circadian rhythms.

To compare the luminous efficacy of the light sources with standard daylights, theoretical light sources were defined for specific SPDs – spectral power distributions. Illuminant refers to theoretical data on relative energy at each visible wavelength and near-UV-ultraviolet range. The SPD of a physical or real light source depends on several factors and varies widely. Sunlight or daylight varies according to geographical location, weather, time, etc. In 1963, CIE recommended a new standard illuminant D65 (color temperature 6500 K) to represent average daylight throughout the visible spectrum and

UV region up to 300 nm. Besides that, CIE defined many daylight illuminants – D50, D55, D75, etc. On the basis of actual daylight data, three daylight illuminants have been standardized: D55 for noon sky daylight, D65 for average daylight, and D75 for north sky daylight[15] having color temperatures of 5500 K, 6500 K, and 7500 K, respectively (Choudhury; 2014; Commission…, 2018).

Englezou and Michael (2023) examined the variability of the daylight spectrum, focusing on light intensity, the spectrum itself, and variations across seasons and hours. Strong correlations were found between variables Mel-DER and correlated color temperature (CCT) through on-site experiments in a south-oriented room in Cyprus (35° north/33° east), using a spectrometer. Strong correlations between Mel-DER and correlated color temperature were found, with an r-value of 0.98 (strongly positive) with 95% of confidence. No strong correlations among variables Mel-EDI and Mel-DER were found. In this context, CCT of 6500 K corresponded to the value of 1 and 5500 K with the value of 0.9. In this context, higher values of CCT correspond with higher values of Mel-DER. Consequently, higher values of Mel-DER were associated with more presence of blue light. Overall, due to the low sun angle and direct sunlight exposure in winter, Mel-EDI was much higher compared to the other three seasons, autumn, spring, and summer, whereas Mel-DER had the lowest values. For all seasons and times, most cases achieved the minimum recommendation for daytime light exposure of melanopic EDI of more than 250 lux.

The WELL building standard and Underwriters Laboratory (UL) recommend design targets for circadian lighting design. These standards are based on EML and Circadian Stimulus (CS) units. The criteria are based on the temporal pattern of light exposure (time of day and duration of exposure), light level, spectrum, and the location where the light is delivered (Amorim *et al.*, 2021b). Table 2 describes the thresholds for circadian lighting design. All metrics are evaluated in the vertical plane at eye level at approximately 1.20 m height, considering a period of 24 hours.

[15] In the Northern hemisphere characterized by incidence of more diffuse daylight, with more presence of blue light in comparison with CIE illuminants D55 and D65 (Choudhury; 2014).

Table 2 - Thresholds for circadian lighting design.

Standard	**Temporal pattern**		**Lighting Quality**			
	Timing of exposure	**Duration of exposure**	**Circadian Stimulus**	**Equivalent Melanopic Lux (EML)**	**Melanopic equivalent daylight illuminance (Melanopic EDI)**	**Photopic Illuminance (Lux)**
Well v 2.0 Requirement for 1 point	At least between 9 a.m. and 1 p.m. Light levels must be lowered after 8 p.m.	Minimum of 4 hours	≥ 0.30 with electric light only	≥150 (if electric light only) ≥120 from electric lighting (if certain daylight criteria are met)	≥136 with electric light only ≥109 from electric lighting (if certain daylight criteria are met)	N/A
Well v. 2.0 Requirement for 3 points			N/A	≥240 (if electric light only) ≥ 180 from electric lighting (if certain daylight criteria are met)	≥218 with electric light only ≥163 from electric lighting (if certain daylight criteria are met)	N/A
UL 24480	Through the day 7 am – 4pm	Minimum of 2 hours, morning if not full period	≥ 0.30	Comply with WELL criteria listed above to achieve 1 point or 3 points	N/A	≥ 500
	3 hours before bed 5pm –7 pm	During full period	≥ 0.20		N/A	N/A
	Nighttime - sleep environment After 8pm		≥ 0.10		N/A	N/A
Brown *et al.* (2022)	Through the day 6 am to 7 pm	During the full period	N/A	≥ 275	≥ 250	
	3 hours before bed 7 pm to 10 pm	During the full period	N/A	≤ 11	≤ 10	
	Nighttime During sleep After 10 pm	During the full period	N/A	≤ 1	≤ 1	

Source: Adapted from Houser; Esposito (2021).

When these metrics were proposed alongside the Lucas Toolbox (Lucas et al., 2013), a software was created to simulate and quantify the non-visual effects of light. The software Alfa – Adaptive Lighting for Alertness[16] is a plug-in used in Rhinoceros, which measures the non-visual effects of light, calculating the quantity of light absorbed by the users' photoreceptor using the photopigment melanopsin. The software considers the environmental characteristics, such as the type of sky (i.e., clear, hazy, and overcast), time of day, solar orientation, and the directions of the user's field of view. The output to measure the non-visual effects is called Equivalent Melanopic Lux (EML). As a result of the spectral calculations, ALFA offers the 360° interactive rendering tool, in which the user can click over the image and turn the camera. This allows the identification of different light spectra, values in units of EML (Equivalent Melanopic Lux), or the spectral power distribution of any part of the simulated environment. The software "comes with a library of high-resolution source spectra taken from measurements of real luminaires" and it has a radiative transfer library, libRadtran, in which various types of sky can be defined in any part of the planet – clear, hazy and overcast. The materials' surface reflectance and light transmission data are in a catalog with more than 500 measured spectral materials based on spectrophotometric measurements of real architectural objects. Additionally, Alfa is compatible with the International Glazing Database (IGDB)[17], making it easy to import tens of thousands of spectrally measured glazing products, which include glasses, window systems, etc. All this information is used by the software in the calculations of units of EML.

Alfa provides data for comparing many glazing types, opaque materials (walls, ceiling, and floor), shading systems, and their capability of reflecting or transmitting circadian light. It also offers a luminaire database for the definition of which are the most effective in providing non-visual effects. Based on the obtained results, it is possible to study how daylighting and/or artificial can affect the biological functions, visual comfort, and the users' well-being of the projected space (Saiedlue *et al*., 2019).

Bellia *et al*. (2023) studied the accuracy and applicability of the software ALFA. For the purpose of evaluating non-visual effects, two different approaches, based on the use

[16] SOLEMMA. ALFA - Adaptive Lighting for Alertness. Available at: https://www.solemma.com/alfa Accessed on 24 May 2022.

[17] The IGDB is a collection of optical data for glazing products. Spectral transmittance and reflectance are measured in a spectrophotometer and contributed to the IGDB by the manufacturer of the glazing product, and it subjected to a careful review. Available at: https://windows.lbl.gov/software-tools#igdb-heading. Accessed on 1 March 2024.

of ALFA and DIALux, were described, validated against on-field measurements, and compared. Spectral irradiance was measured at the work plane and the eye in a test room where the walls' finishes and the luminaires' spectrum were changed, obtaining 21 scenarios. When the test room was simulated using the two methods, acceptable results were obtained for horizontal illuminance, with percentage errors within the range of approximately 10%. In contrast, for the vertical plane, errors depend on the software and the lighting scenario. Overall, the simulations in ALFA performed better than in DIALux. However, it gave percentage errors trespassing more or less 10% in 38.10% and 52.38% of the scenes in estimating circadian stimulus and melanopic illuminance, respectively.

Additionally, Inanici, Abboushi, and Safranek (2022) evaluated the existing spectral sky models in lighting simulation software. They highlighted the advantage that ALFA can be calculated for different locations and times but reported similar problems related to the trespassing of melanopic and photopic illuminances of the sky in 17%. ALFA determines the spectra based on atmospheric models. This method calculates the spectral irradiance at the ground level as a function of irradiance at the top of the atmosphere. Atmospheric conditions, including trace gas and temperature profiles, aerosol particles and surface albedo, entered into radiative transfer programs – in this case, libRadtran. This explained the differences between simulated and measured data. On the other hand, variations in calculating correlated color temperature and light spectrum were minimal. In conclusion, both studies pointed out variations of the software ALFA to predict melanopic illuminances in 10% and 17% but also emphasized accuracy in calculating the light spectrum. One major advantage of using ALFA is that the software can calculate spectral irradiance for different locations and times, relying on historical atmospheric data and atmospheric radiative transfer library (libRadtran). The authors highlighted that recently developed sky models presented progress compared to colorless sky models, but further research was needed to simulate daylight spectra accurately.

The software Lark Spectral Lighting[18], a product of a collaboration between the University of Washington and ZGF Architects LLP, is a plug-in for Grasshopper used in Rhinoceros. This plug-in calculates the incident circadian lighting within a space based on daylighting. The plug-in offers output metrics measuring the non-visual effects of light. These effects are caused by the absorbed light by the melanopsin present in the human retina, which is capable of sending stimuli that adjust humans for a period of light.

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[18] INANICI, M. LARK- Spectral Light. University of Washington. https://faculty.washington.edu/inanici/Lark/Lark_home_page.html. Accessed on 24 May 2022.

In this context, the plug-in produces illuminance renderings and generates irradiance data, which allows the measurements of the non-visual effects, including impacts on the circadian system based on units of equivalent melanopic lux – EML (Brennan; Collins, 2018).

Lark calculates the luminance and illuminance levels based on the information of the opaque materials, the glasses, and the light spectrum of the sky, making it possible to interpolate data and define the spectral distribution of the scene–simulated environment. All this information is processed in Radiance. Besides that, the colors are configured in the RGB system, and each color spectrum (red, green, and blue) is divided into three, totaling nine results, three for each color. This increases the fidelity and accuracy of the analysis (Konis, 2017, 2019). Lark uses global horizontal correlated color temperatures, and these data can be captured using a spectrophotometer or colorimeter. However, this method does not describe color variations across the sky dome and requires on-site measurements from an unobstructed location.

Maskarenj, Deroisy, and Altomonte (2022) presented a new open-source workflow and simulation tool, OWL – *Occupant Well-Being through Lighting*, along with the originally scripted Rhino Grasshopper components. The OWL tool has been developed to estimate the spectral power distribution of the sky from an observer's point of view inside a space at any location and point in time, taking available weather data as input. To quantify the potential non-image forming effects available within an internal visual scene, alongside the stimulation obtainable under an unobstructed sky, this tool uses the melanopic metrics (melanopic irradiance, melanopic-ELR, melanopic-DER, and melanopic-EDI) that are subsets of the CIE a-opic units of measure (Commission…, 2018), as well as the circadian metrics (Circadian Stimulus). A detailed framework for the simulation process is presented. Based on the input data, such as the materials' location, internal reflections, spectral transmissivity, etc., this tool converts luminance data to correlated color temperature to spectral power distribution. The tool, alongside its workflow, responds to an existing gap in the literature, significantly extending the computational capabilities of available simulation platforms. Among other features, the tool addresses the challenge of calculating spectral data for dynamically changing sky conditions, generating relative-combined SPD from weather data by integrating existing models and protocols. Further to this, since the SPD at a view from an internal space is affected mainly by the exposed positions of the sky, the tool proposes a method for evaluating discretized luminance at the scene through image-based simulations, evaluating the SPD and the non-image forming (NIF) or non-visual effects potentials of space. A limitation is that the current version of the tool is limited to using only the direct sky component of luminance and does not consider inter-reflection.

Tools such as SKYSPECTRA, an open-source data package comprising spectral daylight measurements, are being developed. The dataset encompasses measurements from long-term measurement sites and specific periods or experiments. Data from 16 sites will be available within CIE Technical Committee 3-60, including Sao Paulo in Brazil (23° south/46° west). The aim of TC 3-60 is to review geographical, seasonal, and time-of-day variations in the spectral power distribution of daylight for the range between 380 nm and 780 nm when represented by D (daylight) illuminants. The second aim is to propose updating the CIE 015:2018 - reconstitution procedure to calculate D illuminants at a nominal correlated color temperature and provide spectral information for CIE standard general sky types (Balakrishnan *et al.*, 2023). In this context, data regarding spectral daylight measurements will be standardized and represent geographical locations, seasons, atmospheric conditions, and times of day at different sites worldwide. However, SKYSPECTRA is currently being proposed and developed.

New metrics were proposed to evaluate the non-visual effects of light in indoor environments. Software such as Alfa and Lark have the potential to assess different glazing and opaque materials in different locations, as well as sky conditions, dates, and times of the day. This is essential since daylight is dynamic, with constant variations during the day and time of the year, with variations in the spectrum according to geographical locations, seasons, atmospheric conditions, and times of day. Therefore, the next section discusses the different proposals of the Brazilian luminous zoning.

4.3. Brazilian luminous zoning: diffuse daylight illuminance, availability of daylight, and latitude

Brazil is an enormous territory, with latitudes ranging from 3.8° north and 33.7° south. The existing Brazilian Bioclimatic Zoning proposed a division of the territory into eight zones, and similarities in the climate grouped them. This was done to optimize the thermal performance of the buildings in each region according to NBR 15.220 – 3 (ASSOCIAÇÃO..., 2005). This zoning, however, did not consider the climatic characteristics that are important for the luminous performance of the buildings. As the focus of the performance of electrochromic glazing was on the visual and non-visual effects of light, questions related to the thermal performance of electrochromic glazing were not addressed in this work. The idea in this section was to choose the Brazilian cities representing the different zones according to the proposals for bioclimatic zoning based on daylight availability and latitude.

Aiming to fill this gap in regard to daylight performance, Pereira, Schmitt, and Moraes (2015) proposed a climatic zoning based on diffuse daylight illuminance. The proposal consisted of two zones based on the similarity of the profiles of histograms for the cumulative frequency of occurrence of external diffuse horizontal illuminance. The average profile of the cumulative frequency of occurrence histograms representative of zone 1 adopted overcoming the external illuminance of 30,000 lux as a reference in 50% of the working hours throughout the year. Moreover, the average profile representative of zone 2 exceeded the same illuminance in 30% of the period. The database originated from weather files EPW-INMET 2012 related to 181 sites. The major limitation was that the direct sunlight component was not considered. Figure 23 illustrates the bioclimatic zoning of Brazil based on diffuse daylight illuminance.

Figure 23 – Map showing bioclimatic zoning of Brazil based on diffuse daylight illuminance.

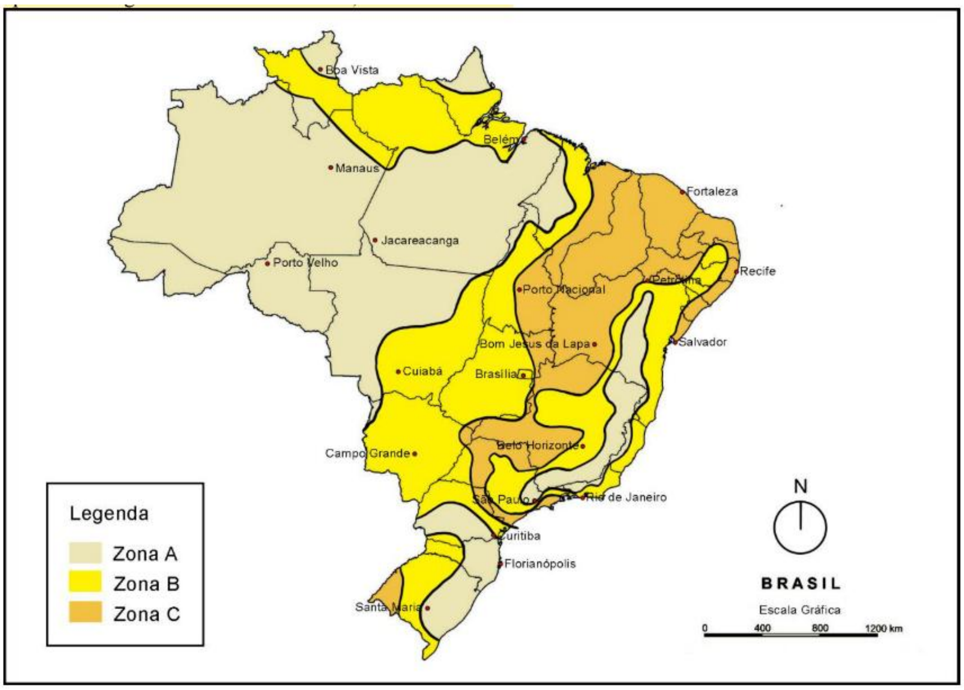
Source: Pereira, Schmitt, Moraes (2015); Fonseca *et al.* (2023).

Fonseca, Fernandes, and Pereira (2017) proposed zoning according to daylight availability in Brazilian territory. To do this, isoline charts from Solarimetric Atlas and 20 climate files of 20 cities in the SWERA format were analyzed, particularly in the capitals. Data regarding the cloudiness of the 20 locations were also analyzed to understand the predominant sky condition: cloudy, partly cloudy, or clear sky. The analyzed data were the average daily insolation hours and the outdoor horizontal illuminance levels. The authors determined three intervals of illuminance levels of global horizontal illumination to analyze the results better. Lower illuminance levels were considered below 48,000 lux, on average, between 48,000 lux and 84,000 lux and above 84,000 lux. This analysis proposed three zones for the zoning classification: A, B, and C. According to the authors:

> Zone A encompasses cities within an average of less than five insolation hours per day if the frequency of occurrence of the global horizontal illumination is higher for lower illuminance levels (i.e., approximately between 1,500 hours and 2,500 hours) and lower for higher illuminances (approximately between 350 and 750 hours) […]. Zone B encompasses cities within an average of six insolation hours per day if the frequency of occurrence of the global horizontal illuminance is higher for lower illuminance levels (approximately between 1,500 hours and 2,000 hours) and lower for higher illuminances (approximately between 500 and 1,000 hours) […]. Zone C encompasses the cities within an average of seven insolation hours per day if the frequency of occurrence of the global horizontal illumination is lower for lower illuminances (approximately between 1,500 and 1,800 hours) and lower for higher illuminances (approximately between 750 hours and 1,000 hours) […] (Adapted from Fonseca; Fernandes; Pereira, 2017, p. 1896-1897).

In this classification, the authors made a chart of the Brazilian bioclimatic zoning regarding the availability of daylight, as shown in Figure 24. The major advantage was that the direct component was considered in this proposal.

Figure 24 – Chart of the Brazilian bioclimatic zoning regarding the availability of daylight.



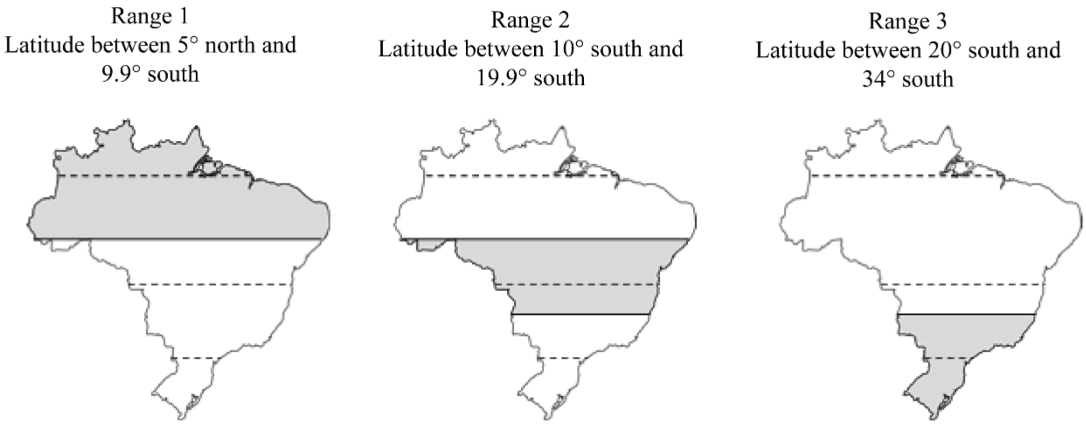
Source: Fonseca; Fernandes; Pereira (2017).

Fonseca *et al.* (2019) identified limitations regarding the Brazilian bioclimatic zoning based on the availability of daylight and energy consumption as a function of latitude. In some cases, estimations for the same building in locations with a wide variation of latitude resulted in higher energy consumption when it was a city with greater daylight availability than others with less availability. This trend was observed for determined orientations and between cities with a wide variation of latitude: for example, facing north, comparing the city of Curitiba (25.4809° S), located in Zone A, with lower daylight availability, with the city of Salvador (12.9777° S), located in Zone C, with higher daylight availability. Based on the annual cumulative global radiation incident in a hemisphere of unitary radius and point-in-time analysis of illuminance distributed in the work plane of a hypothetical indoor space confirmed higher daylight penetration in the southernmost city, Curitiba, considering specific orientations and dates, even if that city has lower daylight availability, according to the zoning.

Additionally, the study of Fonseca *et al.* (2019) showed that the greatest impact of latitude on the incident radiation was observed on south-facing surfaces. As the latitudes advanced further from the Equator, the radiation on south-facing surfaces decreased more than on other orientations. After the south orientation, the north was more impacted by latitude in relation to the global radiation, followed by the west and the east, with variations of 57%, 41%, 18%, and 7% between Boa Vista and Santa Maria, respectively. Unlike other orientations, north-facing surfaces received less radiation near the Equator than at more southern latitudes, resulting in a 41% increase in radiation between Boa Vista and Santa Maria. For the south orientation, incident radiation significantly decreased with increasing latitude: Boa Vista (2° North; 663 kWh/m²), Porto Velho (8° South; 473 kWh/m²), Belo Horizonte (19° South; 325 kWh/m²), and Santa Maria (29° South; 282 kWh/m²), with reductions of 29%, 31%, and 13% for every 10° of latitude. Consequently, these variations indicated that latitude possibly affected the luminous performance of buildings in different cities, depending on the evaluated orientation. For example, Boa Vista has higher radiation incidence on the east, south, and west facades compared to Santa Maria but lower incidence on the north facade. Consequently, the results of global consumption led to the conclusion that zoning based on latitude makes more sense for latitudes closer to the Equator. Global lighting consumption proved less sensitive to latitude variation for cities further south.

In this context, a third proposal of luminous zoning was considered according to three ranges of latitudes. Based on the proposal of the Brazilian Standard ABNT NBR 15575, the luminous zoning comprised three bands of latitudes. The first band comprises the parallels with a latitude between 5°N and 9.9°S; the second, with a latitude between 10°S and 19.9°S; and the third, with a latitude between 20°S and 34°S. The latitude bands were proposed during the revision of the National Standard ABNT NBR 15575, “lighting performance of indoor environments”. Figure 25 illustrates the third proposal of the Brazilian luminous zoning per latitude range.

Figure 25 - Brazilian luminous zoning per latitude range.



Source: Adapted from the revision of the National Standard ABNT NBR 15575.

Studying the influence of latitude and sky conditions on daylight harvesting in buildings, Fonseca *et al.* (2023) concluded that for locations with similar annual sky characteristics, particularly brightness, the influence of latitude on lighting energy consumption could be perceived. However, when the difference in the sky brightness conditions was significant, it was impossible to establish a relationship between the variable's latitude and energy consumption. Consequently, the climatic zoning based on daylight should first characterize the sky dome's light and brightness distribution and later combine this information with the latitude.

4.4. Fields of statistics and simulation studies

As a method, the two main fields of statistics are sample statistics and experimental statistics. In the first case, data is obtained from random samples using specific methods so that the part (sample) represents the whole (universe) with a high probability.

Descriptive, probabilistic, and inferential statistics are analytical methods in this field (Stevenson, 2001). Descriptive statistics includes organizing general data into summary measures, such as rates, indices, percentages, measures of central tendency, dispersion, frequency tables, cross-tabulations, and graphical representations. Probabilities are used to study situations involving chances. Inferential statistics refers to the interpretation of sample data and its representativeness of the data universe.

On the other hand, data in experimental statistics are collected through work carried out on purpose and under previously specified conditions. The effects on the response variables of the experiments are controlled and are therefore called control variables. In this case, the possibility that there are factors that have not been controlled and could alter the experiment's outcome, called random variations, is considered (Pimentel, 2009). Among the "work done on purpose" is data collection under controlled conditions using simulation models.

Simulation, as the name implies, is a type of imitation of the functioning of a system, a test, or an experiment, including from a statistical point of view. It is a tool for analyzing scenarios, as it makes it possible to handle the control variables that make up the system to check what happens to the response variables. Simulation can result from using mathematical models that approximate the true behavior of the system, with input parameters and result variables or response variables (Shwif; Medina, 2010). Systems analysis is used to study hypotheses about the relationship between the components of the representative model or to predict performance under certain conditions.

Simulations are powerful analysis tools aiming to determine the best system to implement or improve, making it possible to quantify the effects of various changes to the system. Using simulation models is a solution for situations in which a real experiment is impossible due to costs or operational difficulties (Camelo *et al.*, 2010). The simulation model must meet three requirements: i) being the lowest cost means of solving the problem, ii) being a satisfactory solution, and iii) allowing an interpretation that is accessible to the user. One of the purposes of simulations is to verify or demonstrate a new idea, system, or way of solving a problem, identifying the condition whose results are most favorable (Gavira, 2003).

Therefore, the model type is deterministic, defined by those whose control variables generate single results. In a deterministic model, the variables are called "independent" or "explanatory variables", and they generate single results known as "dependent" or "response variables" (Pimentel, 2009). In this case, electrochromic glazing is a factor that can modify visual comfort, including visual and non-visual effects of light in (non-residential) environments, which are often characterized by buildings with fully glazed facades. Under controlled characteristics, it is possible to understand better how these modifications happen.

4.5. Conclusions regarding quantification of visual and non-visual effects of light

Considering the approaches/methods to evaluate non-visual effects of light, computer simulations offer a good advantage to testing indoor environments in distinct locations and different contexts/scenarios. This is particularly important for this study since the application of electrochromic glazing in Brazil in non-residential buildings was not fully discussed in academic documents/papers. In this context, computer simulations provide a quicker approach and a more comprehensive analysis to test them in different locations and climates. New metrics, such as units of equivalent melanopic lux (EML) and melanopic equivalent daylight illuminance (Melanopic EDI), have excellent potential to assess the non-visual effects of light.

Metrics are available to assess the performance of daylight in indoor environments. As discussed in sections 4.1 and 4.2 regarding the assessment of visual and non-visual effects of light, the following metrics will be used in the method:

1) Daylight autonomy (DA) and useful daylight illuminance (UDI).
2) Daylight glare probability (DGP): annual glare.
3) Melanopic-EDI to assess the non-visual effects of light.

It is summarized in Table 3 the metrics and thresholds for adequate conditions of visual comfort and circadian lighting. Only a cycle of 24 hours is considered to evaluate the circadian lighting or non-visual effects. Consequently, evaluating different dates covering all four seasons is highly recommended. The results obtained in ALFA are expressed in units of “EML” and they were later converted into Mel-EDI with units directly associated in lux using Equation 3.

Table 3 – Metrics and thresholds for adequate conditions of visual comfort and circadian lighting.

Visual effects of light – visual comfort			
	Available metric	Criteria	Reference
Illuminance in the horizontal grid	DA - Daylight autonomy	300 lux in at least 50% of the hours	IES LM-83 (2012) EN 17037 (CEN, 2018) INI – C Brasil (2021)
	UDI – Useful Daylight Illuminance	Between 100 and 3,000 lux in 50% of the time	Mardaljevic (2006) ABNT 15215 - 4 (2023)
Point-in-time glare/ Annual Glare	Daylight Glare Probability (DGP)	Imperceptible DGP ≤ 35% Noticeable 35% < DGP < 40% Disturbing 40% ≤ DGP < 45% Intolerable DGP ≥ 45%	Reinhart and Wienold (2011) EN 17037 (CEN, 2018)
Non-visual effects of light			
	Available metric	Criteria	Reference
Melanopic illuminance during a cycle of 24 hours	Equivalent Melanopic Lux (EML)/ Melanopic equivalent melanopic illuminance (Melanopic EDI)	275 EML/250 lux (Mel-EDI) on the user's vertical field of view at a height of 1.20 m during daylight hours.	Brown *et al.* (2022) CIE (COMMISSION…, 2018)

Source: The author.

From what was discussed in these studies and from the discussion presented in section 2.3, there are common approaches and methods for assessing electrochromic glazing and other glazing technologies. Computer simulations offer the advantage of predicting its visual comfort and performance in hypothetical indoor environments, climates, and scenarios. Simulations are useful to evaluate the performance of electrochromic glazing and conventional glazing systems, such as clear and reflective glasses, regarding visual and non-visual effects in different climatic contexts, and latitudes, among other variables.

Climate Studio was chosen among other software because it provides environmental performance analysis of individual buildings and calculates CBDM, such as daylight autonomy and useful daylight autonomy, and daylight glare probability can also be calculated. Moreover, the software is compatible with the International Glazing Database (IGDB), making it easy to import tens of thousands of spectrally measured glazing products, which include glasses, window systems, etc. This software is used to evaluate the visual effects of light.

Regarding the simulation tools of non-visual effects, the tool OWL is limited to using only the direct sky component of luminance and does not consider inter-reflection. Lark, in particular, does not describe color variations across the sky dome and requires spectral data measured directly by global horizontal correlated color temperatures. That makes evaluating a model in different locations, seasons, dates, and hours demanding. Consequently, ALFA was chosen because the software can calculate spectral irradiance for different locations and times, as it relies on historical atmospheric data and the atmospheric radiative transfer library (librarian), and that is the main advantage.

Despite the commented limitations on the two proposals for Brazilian luminous zoning, distinct latitudes must be considered as variables to represent the different luminous contexts in Brazil. In this regard, climatic zoning based on daylight should first characterize the sky dome's light and brightness distribution and later combine this information with the latitude. Consequently, characteristics such as sky brightness, cloudiness, and daylight availability were also considered when choosing cities. The choice of the different cities as a function of latitude to represent the Brazilian climatic context and the method of the simulation studies are described in the next chapter.

Chapter 5. Method

The first stage encompassed the literature review. An overview of the main innovative transparent and translucent materials applied on glazed facades was described in the Chapter 2. Electrochromic glazing was selected among the many technologies of smart windows – switchable glazings due to the dynamism provided by controlling the property of the light transmission from 60% to 1%. As most of the studies were located in higher latitudes, in Europe and the United States, there are few and incomplete studies regarding the use of electrochromic glazing in Brazil. Consequently, it is unclear how the performance of this technology of smart windows is considering visual and non-visual effects within the Brazilian luminous context.[19]

Therefore, the second stage of the method consisted of the execution of computer simulations to assess the performance of electrochromic glazing regarding visual and non-visual effects of light in comparison with two conventional and one reflective glass: clear, green and reflective silver glass. As discussed in Chapter 2 conventional and reflective glasses are commercialized in the Brazilian context (CEBRACE, 2022?; Lima; Caram, 2015; Queiroz; Westphal; Pereira, 2019). Besides that, six cities with distinct latitudes were chosen to illustrate the Brazilian luminous context. Then, the test room was modeled representing a generic highly glazed non-residential room based on studies discussed in section 2.1 – literature review. Four window orientations were considered: north, east, south, and west. Nine positions were considered according to the distance from the window. For the assessment of visual effects, the software Climate Studio was used. A total number of 864 cases[20] were analyzed considering the climate-based yearly metrics Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), and annual glare (DGP). For non-visual effects, the software ALFA was used. A total of 34,560 cases were analyzed considering the metrics melanopic daylight illuminance (Mel-EDI) to assess the intensity of circadian lighting and melanopic daylight efficacy ratio (Mel-DER) to evaluate light spectrum. As these metrics are static, i.e., considering the conditions per hour, four dates were chosen close to solstices and equinoxes, and ten hours per day, from 8 a.m. to 6 p.m.

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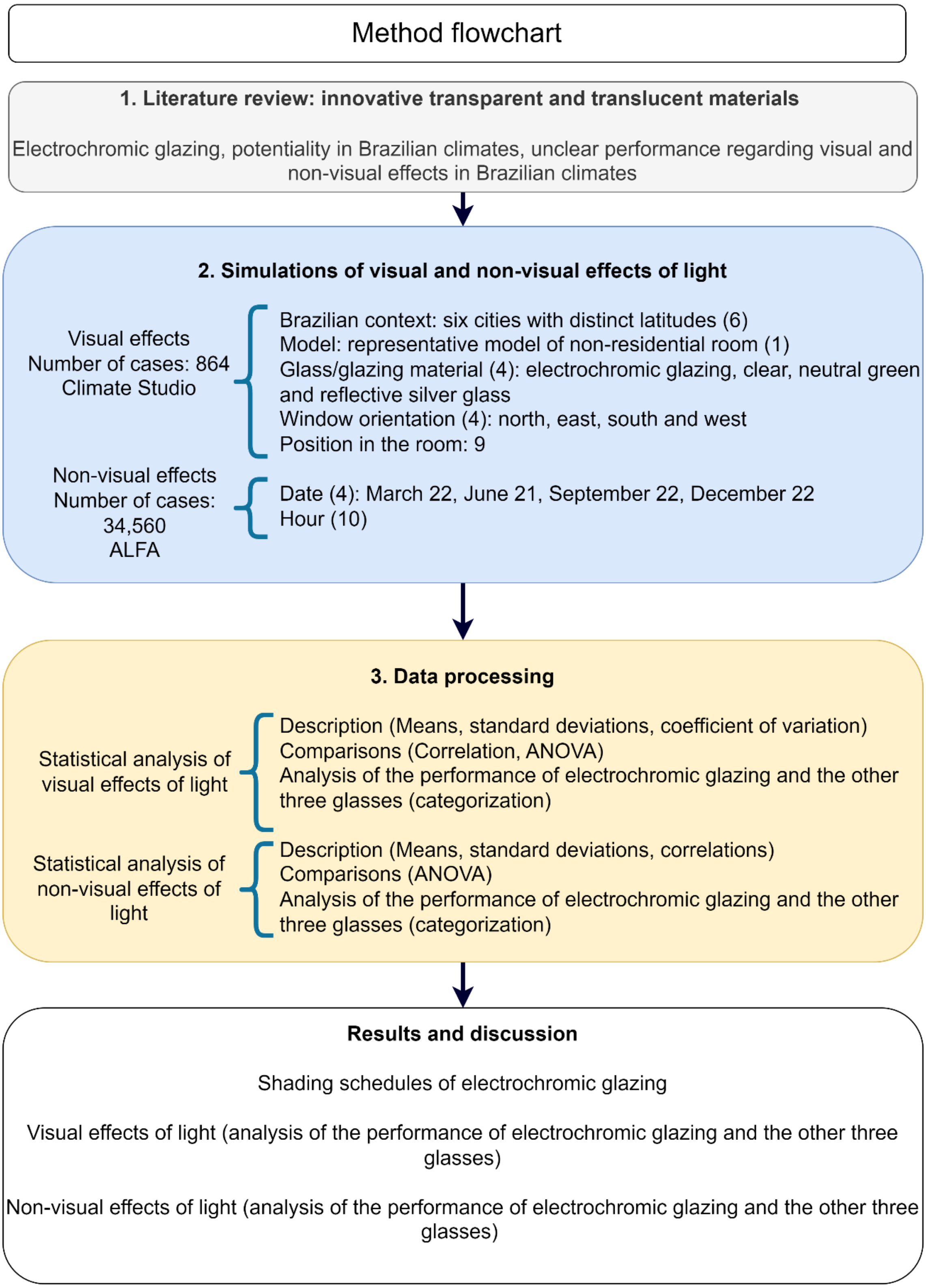
[19] NA: The focus of this research was on visual and non-visual effects of light. Aspects related to thermal performance of electrochromic glazing were not assessed in this study.

[20] NA: A case is defined by a unique situation resulting from the combination of the category of variables defined in a study (Barbetta, 2008).

Statistical analyses were conducted in three steps. In the first step, the results were described, calculating means, medians, standard deviations, and coefficients of variation. In the second step, comparisons were made using analysis of variance (ANOVA). In these two steps, the relationships among the explanatory and response variables, as defined in the method, were described. The third step was the analysis of the performance of electrochromic glazing and the other three glasses, categorizing the results according to the stablished assessment criteria for visual and non-visual effects. The same steps were conducted for visual and non-visual effects of light.

After the statistical analysis, results were described and discussed in Chapter 6. Firstly, the generated shading schedules of electrochromic glazing according to city/latitude and window orientation were described and discussed. Then, the performance of electrochromic glazing and the other three glasses were analyzed and described regarding visual and non-visual effects of light. Figure 26 illustrates the phases and the general structure of the method.

Figure 26 – Method flowchart.



Source: The Author.

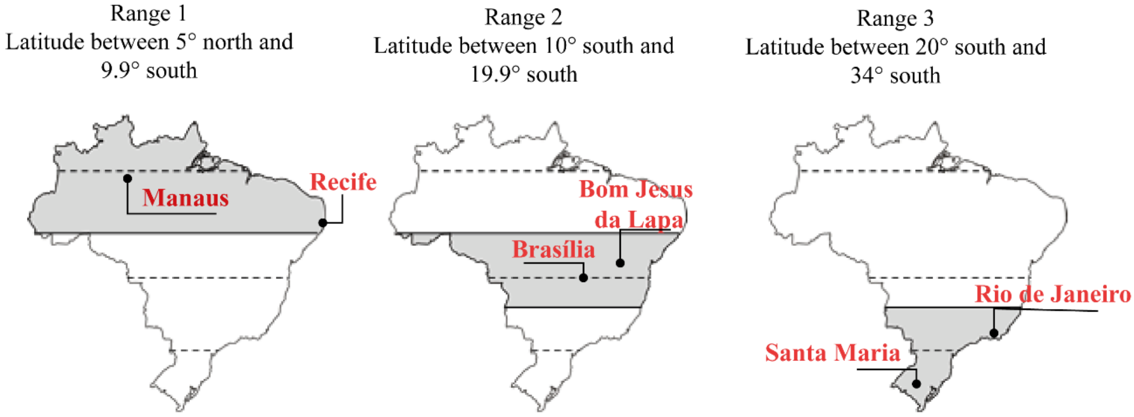
The details are explained in the next sections. In section 5.1 the Brazilian climatic context is described according to daylight availability and the choices of simulated cities. In sections 5.2 and 5.2.1 the details of simulation studies are presented together with parameters and simulated variables of the test room representing a generic office environment. In section 5.2.2 the assessment criteria for visual and non-visual effects are presented. The simulation workflow for Climate Studio and ALFA is detailed in the section 5.2.3. The section 5.2.4 details the definition of cases for spectral analysis regarding non-visual effects of light. The detailing of the initial question in the introduction regarding the performance of electrochromic is presented in the section 5.3. Statistical analysis and generated results are described in the section 5.4.

5.1. Brazilian luminous zoning: choice of the simulated cities/latitudes

As discussed in section 4.3, despite the commented limitations on the proposals for Brazilian luminous zoning based on diffuse illuminance and availability of daylight, distinct latitudes must be considered as variables to represent the different climates in Brazil. In this regard, different sites, represented by cities, were chosen according to the three different latitude ranges and availability of daylight, with different sky conditions, cloudiness, and different illuminance levels.

Based on the last proposal of the Brazilian luminous zoning, six cities were chosen to represent the different latitude ranges. This division into 3 latitude ranges were proposed to enable the development of the Abacus Method proposed on the revision of the Brazilian Standard 15.575. This was a simplified method to determine daylight conditions inside the room in different Brazilian latitudes based on the crossing of information of the room with external obstructions. Additionally, characteristics such as sky brightness, cloudiness and daylight availability were considered for the choice of the cities. Therefore, the six cities were selected according to different latitudes, covering from 3° south to 29º south, with different means of annual global illumination and cloudiness, different occurrences of sky type - i.e. clear sky, partly cloudy sky, and overcast sky. Within latitudes of 5° north and 9.9° south, Manaus and Recife were chosen. Within latitudes of 10° south and 19.9° south, Bom Jesus da Lapa and Brasilia were chosen. Moreover, Rio de Janeiro and Santa Maria were chosen within latitudes of 20° south and 34° south. Figure 27 illustrates the Brazilian luminous zoning per latitude range and the selected cities' locations for simulation studies.

Figure 27 - Brazilian luminous zoning per latitude range and location of the selected cities for simulation studies.



Source: Author based on the proposal for revising the National Standard ABNT NBR 15575.

Table 4 summarizes the annual daily averages of global illuminance, cloudiness, and direct and diffuse radiation for the six simulated cities. The daily averages of horizontal global illuminance of Bom Jesus da Lapa and Recife are higher than the illuminance of the other four cities, with 51 klux and 59 klux, respectively. However, Bom Jesus da Lapa presents daily average of cloudiness of 34% and Recife 66%. The averages of global illuminance in Brasilia and Manaus are 46 klux and 43 klux, respectively, and the cloudiness of the two cities are different. The daily average of cloudiness in Brasilia is 52% and in Manaus 75%. Rio de Janeiro and Santa Maria present the lowest averages of illuminance, with 40 klux and 38 klux, respectively. Both cities present similar averages of cloudiness, with 71% in Rio de Janeiro and 67% in Santa Maria. The data regarding monthly daily averages of horizontal global illuminance, cloudiness, and direct and diffuse radiation are presented in Appendix A.

Table 4 – Annual daily averages of horizontal global illuminance, cloudiness, direct and diffuse radiation for the six simulated cities.

City	Horizontal global illuminance	Cloudiness	Direct radiation	Diffuse radiation
	Lux	%	Wh/m²	Wh/m²
Manaus (3° S/60° W)	43,398	75%	160	195
Recife (8°S/ 34° W)	59,165	66%	273	197
Bom Jesus da Lapa (13° S/43° W)	51,584	34%	221	190
Brasília (15° S/47° W)	46,656	52%	179	189
Rio de Janeiro (22° S/43° W)	40,287	71%	145	166
Santa Maria (29° S/53° W)	38,747	67%	135	159

Source: National Institute of Meteorology - INMET (2018). [21]

Manaus is located in the time zone GMT -4:00, and the cities Recife, Bom Jesus da Lapa, Brasilia, Rio de Janeiro, and Santa Maria are located in the time zone GMT -3:00 (Brasil, 2013; Instituto Brasileiro de Geografia e Estatística, 2021). The simulations parameters and variables of the simulated room are described in the next section.

5.2. Simulation parameters and variables of the simulated room

The simulated model was a representative highly glazed non-residential room with dimensions of 3.48 m wide, 6.03 m long, and 3.00 m high, with WWR of 85%, as described in Figure 28. This model represents a non-residential room, and its dimensions were based on the studies of Alves *et al.* (2016), Amorim *et al*. (2021a), Cavaleri, Cunha, and Gonçalves 2018, Lima *et al.* (2022) and Sarra and Mülfarth (2020). Its dimensions were adapted from the surveys of office buildings of Belo Horizonte (19° south), Brasilia (15° south), Joao Pessoa (7° south), Londrina (23° south), and Sao Paulo (23° south). The room's dimensions represent a naturally daylit environment, with its length not overtaking two times the height of the window above the floor.[22] This model, however,

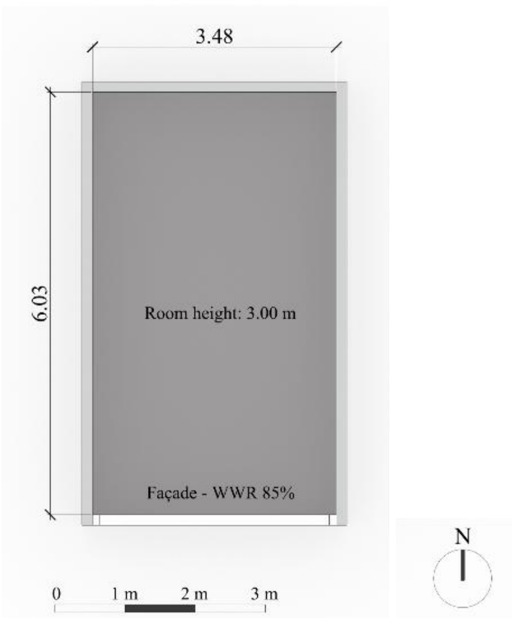
[21] The climate files can be downloaded at: https://climate.onebuilding.org/WMO_Region_3_South_America/BRA_Brazil/index.html. Last access: 2 jun. 2022.
[22] According to the reports of the International Energy Agency (2000, 2016), as a rule of thumb a daylight zone may be considered to be a depth of about two times the window head height.

does not represent deep-floor office environments, with areas that require artificial lighting, which was not the focus of this study.

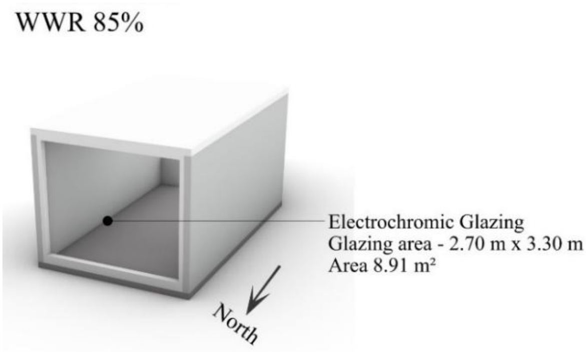
The walls, floor, and roof were modeled in the software Rhinoceros v. 7 using the command “box,” inserting the already described dimensions, with a width of 0.15 m. The surfaces corresponding to the floor, ceiling, and window were modeled using the command “_SrfPt.” It is important to mention that the surface corresponding to the window had to be modeled and directed to the outside. To verify if this condition was fulfilled, the command “dir” was used. These were the tools and commands used to model the simulated room.

Figure 28 – Dimensions of the window of the simulated model.

Floor plan



WWR – 85%



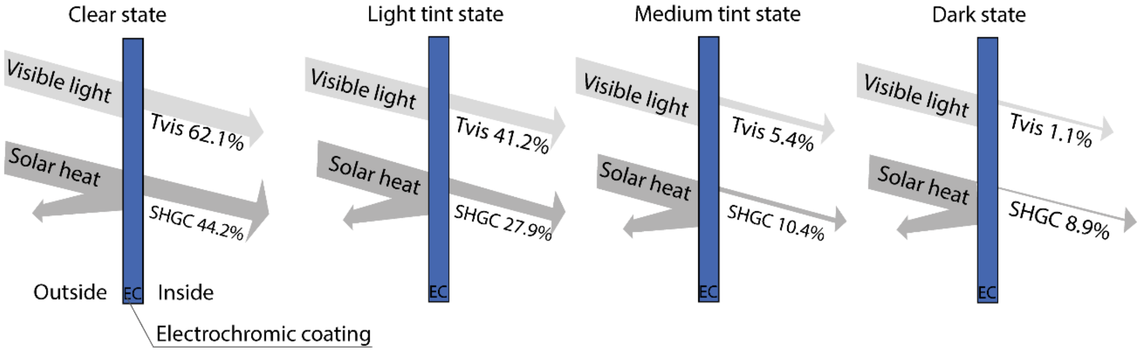
Source: The author.

The Smart Glass Insulated Unit has a visible light transmittance of 62.1% (clear state), 41% (light tint), 5.4% (medium tint), and 1.1% (fully tinted state) (Lawrence Berkeley National Laboratory, 2023). The clear glass has a visible transmittance of 88%.[23] The occupation was during working hours, between 8 a.m. and 6 p.m. (Geraldi *et al.*, 2022; Cavaleri; Cunha; Gonçalves, 2018). Figure 29 illustrates the properties related to visible light transmission and solar heating gain coefficient for each operational state of the electrochromic glazing.[24]

[23] Idem, 2023.

[24] As mentioned in the beginning of this chapter, aspects related to the thermal performance of electrochromic glazing was not evaluated as the focus was on the evaluation considering visual and non-

Figure 29 - Visible light transmission and solar heating gain coefficient for each operational state of the electrochromic glazing.



Source: The author with properties taken from the International Glazing Database – IGDB (Lawrence Berkeley National Laboratory, 2023; MITCHELL *et al*., 2019).

Reflectance values were chosen following the recommendations of the Brazilian National Standard NBR 8995 (2013), which were between 60% and 90% for the ceiling, 30% and 80% for the walls, 20% and 60% for the work environment, and 10% and 50% for the floor. Table 5 shows the optical properties of the simulated materials, with the photopic and melanopic reflectance values for the opaque materials and visible transmittances for each state of the electrochromic glazing. The third column presents each material's melanopic/photopic ratio (Berman; Clear, 2019).

visual effects of light. Therefore, the property of solar heat gain coefficient was not considered in the simulations.

Table 5 - Optical properties of the simulated materials.

Material	**Photopic Reflectance**	**Melanopic Reflectance**	**M/P**	**Reference**
White ceiling	84%	78.4%	0.93	(SOLEMMA, 2023a; 2023 b; Associação…, 2018)
Wall	63.4%	58.3%	0.92	
Floor	23%	21.9%	0.95	
Electrochromic glazing – Smart Glass Unit	**Photopic transmittance**	**Melanopic transmittance**	**M/P**	
Tvis 0 – Clear state	62.1%	55.7%	0.90	(SOLEMMA, 2023b; Lawrence…, 2023)
Tvis 1 – Light tint state	41%	37.4%	0.91	
Tvis 2 – Medium tint state	5.4%	7.0%	1.28	
Tvis 3 – Fully tint (dark) state	1.1%	1.8%	1.65	
	Photopic transmittance	**Melanopic transmittance**	**M/P**	
Clear glass 6 mm	88.3%	89.0%	1.01	(SOLEMMA, 2023b; Lawrence…, 2023)
Neutral green glass 6 mm	43.0%	47.3%	1.10	
Reflective Silver glass 6 mm	20.8%	23.4%	1.12	

Source: The Author.

Additionally, Table 6 describes the simulation parameters with recommendations from the existing literature. For the simulations in ALFA, the ground albedo was configured at 15%, simulating a generic urban environment as recommended by Martins (2014).

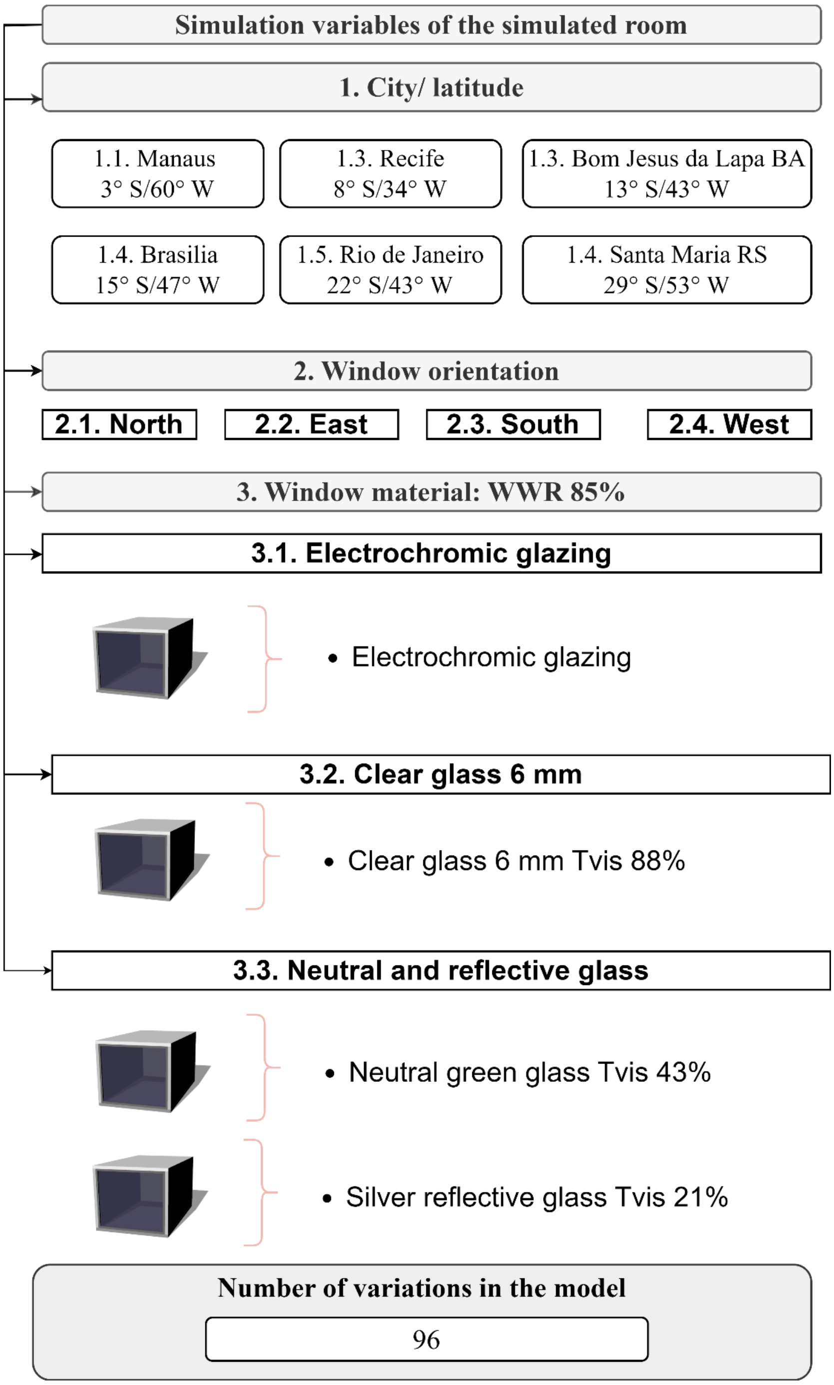
Table 6 - Simulation parameters in Climate Studio and ALFA.

Parameter	**Value**	**Reference**
Sample per pass	128	Jones; Reinhart (2017); Reinhart; Walkenhorst (2001)
Max number of passes	100	
Ambient bounces	15	
Weight limit	0.01	

Source: The Author.

The simulated variables of the representative highly glazed non-residential room were six cities/latitudes, four solar orientations north, south, east, and west, four glazing materials, electrochromic glazing, clear 6 mm, neutral green, and reflective silver glass. The idea behind the variables was to understand the impact of visual and non-visual effects of light. In total, 96 variations of the non-residential room were tested. Figure 30 illustrates the simulation variables of the simulated room.

Figure 30 – Simulation variables of the simulated room.

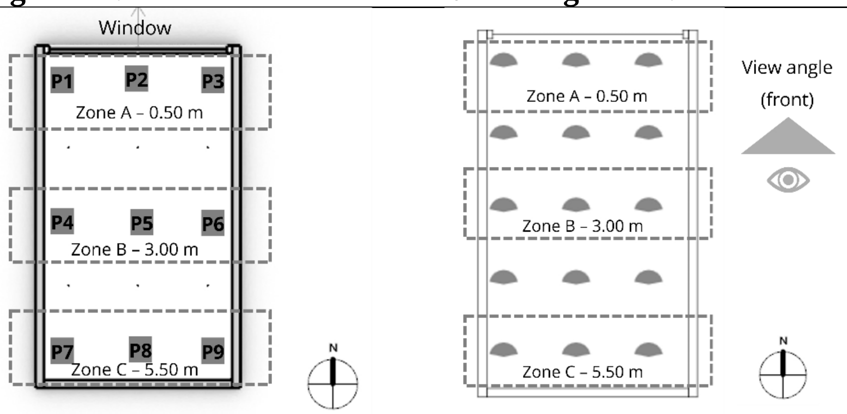


Source: The Author.

To measure visual and non-visual effects of light, nine positions in the room were chosen for analysis of daylight following the recommendations of the Brazilian Standard, ABNT NBR 15215 – 4 (2023) as illustrated in Figure 31. The sensor grid was positioned 0.75 m above the floor. To assess glare, vertical illuminance, and non-visual effects, the sensors were placed at eye level, 1.20 m above the floor, and all sensors were placed facing the window, with a view angle to the front. The positions in the room were named P1 to P9 and located in three zones, which were considered according to the room depth. P1, P2, and P3 were located in zone A, close to the window, at 0.50 m far from the window; P4, P5, and P6, in the middle (zone B), 3 m far from the window; and P7, P8, and P9, at the back of the room (zone C), at a distance of 5.5 m from the window. This zone reference was based on Saiedlue et al.'s study (2019). The sensors representing the nine positions were spaced 2.5 m from each other over the room's depth and 1.25 m over its width.

Figure 31 – Analysis points corresponding to positions/sensors P1 to P9.

Horizontal grid – 0.75 m above floor	**Vertical grid – 1.20 m above floor**



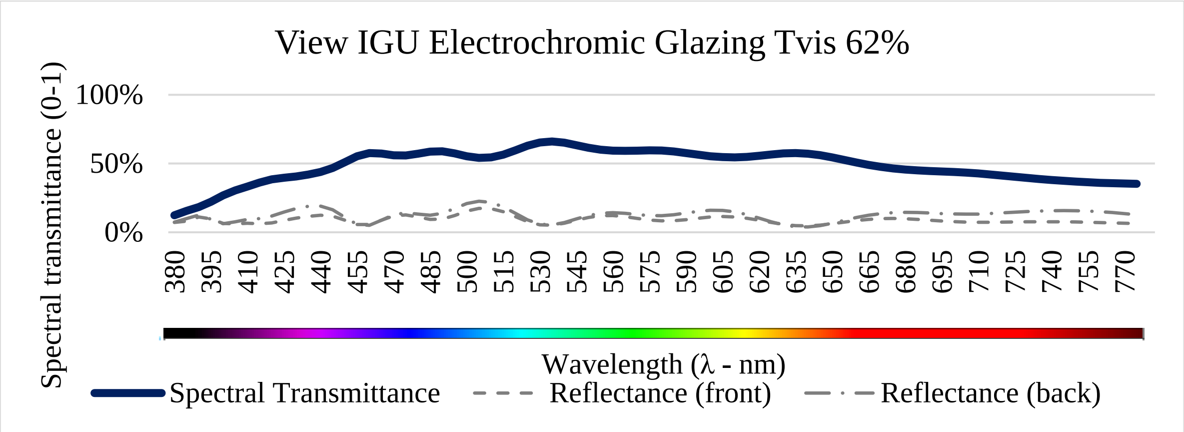
Source: The Author.

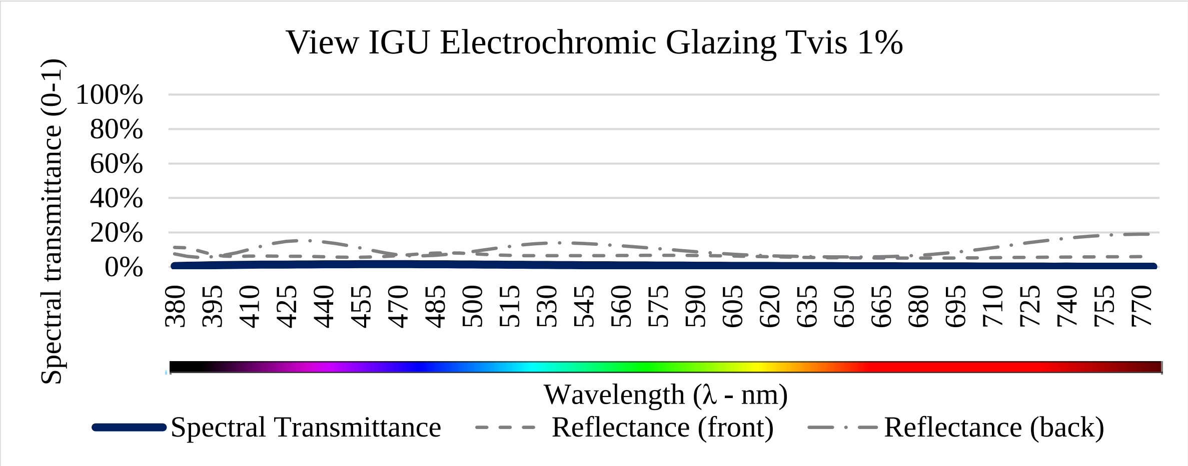
In the next section, the extraction and the spectral data of the glazing materials is described.

5.2.1. International Glazing Database and Spectral Data Extraction

Data on the four glazing materials were extracted from the International Glazing Database – IGDB (Lawrence…, 2023), including the spectral transmission and back and front transmittances. As this database is compatible with Climate Studio and ALFA software, the glazing products were visualized in Window v. 7.8 (Lawrence…, 2022) and Optics v. 6.0 (2013).[25] The reflective silver glass and the neutral green glass were chosen from the catalog of CEBRACE (2022) corresponding to the codes SGC Cool Lite ST 120 and SGC Cool Lite KNT 455, and they were also found in IGDB. Figure 32 illustrates two examples of the detailed data of the electrochromic glazing in the clear state and in the dark tint state.

Figure 32 - Spectral transmission of the View IGU Electrochromic Glazing in the clear state.





Source: The Author.

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[25] The details on how to use both softwares, Window and Optics are described in the manuals written by Mitchell *et al.* (2019) and Versluis, Powles and Rubin (2002). In these manuals, the process of exporting the glazing materials to Radiance .rad file is described.

Detailed data regarding the spectral transmission of the four simulated glazings, including the four states of electrochromic glazing are found in Appendix B and assessment criteria for visual and non-visual effects of light are described in the next section.

5.2.2. Assessment criteria for visual and non-visual effects of light

The criteria, metrics, and threshold for adequate conditions of visual comfort and circadian lighting were defined in the section 4.5. Two aspects of light were assessed. The first one was related to the visual effects of light in regard to illuminance levels and glare mitigation. The evaluation of daylight autonomy was based on the minimum illuminance target of 300 lux in at least 50% of daylight hours (Brasil, 2021; Illuminating…, 2023). Useful daylight autonomy (UDI) was also considered in the simulations with an interval between 100 and 3,000 lux in at least 50% of daylight hours (Associação…, 2023; Mardaljevic *et al.*, 2012). The third criterion was Daylight Glare Probability (annual glare), with a maximum threshold of 40% in at least 60% daylight hours (European…, 2018; Jain; Karmann; Wienold, 2022; Wu *et al.*, 2019). The daylight hours were considered during work hours, from 8 a.m. to 6 p.m., in the interval of one year. Table 7 describes the metrics and thresholds for adequate conditions of visual comfort.

Table 7 – Metrics and thresholds for adequate conditions of visual comfort.

Visual effects of light: assessment criteria			
Illuminance on the horizontal grid at the height of 0.75m	DA – Daylight Autonomy	300 lux in at least 50% of the time	IES LM-83 (2023) EN 17037 (CEN, 2018) INI – C (Brasil, 2021)
	UDI – Useful Daylight Illuminance	Between 100 and 3,000 lux in 50% of the time	Mardaljevic (2006) ABNT 15215 – 4 (2023)
Annual glare – vertical field of view at the height 1.20 m	Daylight Glare Probability	DGP lower than 40% in at least 60% of the time	Jain, Karmann, Wienold (2022) EN 17037 (CEN, 2018) Wu *et al.* (2019)

Source: The Author.

The second aspect was related to the non-visual effects of light, and three metrics were considered. The first metric of non-visual effects was related to the potency of light based on non-visual effects on humans. It was defined by the metric melanopic equivalent daylight illuminance (Mel-EDI), defined as the illuminance produced by radiation of the standard illuminant D65 that provides an equal α-opic irradiance as test sources with respect to melanopsin activation (COMMISSION…, 2018). To assess the circadian lighting during a cycle of working hours, from 8 a.m. to 6 p.m., a minimum of 250 lux of Mel-EDI (melanopic equivalent daylight illuminance) was considered, with a recommendation of the full daylight period on the user's vertical field of view at the height of 1.20 m (International Well Building Institute, 2022; Underwriters Laboratory, 2019; Brown *et al.,* 2020).

The second metric was related to the ratio of the test source's melanopic efficacy of luminous radiation to the melanopic efficacy of luminous radiation of CIE Standard Daylight D65, as described in Equation 1, represented by the metric melanopic daylight efficacy ratio (Mel-DER). Mel-DER is multiplied by the illuminance level to obtain the metric Mel-EDI, as described in Equation 2. Melanopic DER is unitless, with the value 1 corresponding to the melanopic luminous efficacy ratio light source of D65. In summary, Mel-DER is directly related to the light spectrum, and it measures the effectiveness of the light source in activating melanopsin receptors in the human eye, comparing it to CIE Illuminant D65 (Daylight 6500 K). As daylight is evaluated in this study, the minimum of 0.904 of Mel-DER was considered[26], with the same melanopic efficacy of CIE Illuminant D55 (Daylight 5500 K). Below the threshold of 0.904, the melanopic efficacy ratio is lower than these two illuminants representing CIE standard daylights D55 and D65 (Commission…, 2018). Mel-DER below 0.404 corresponds to CCT of 3000 K (Englezou; Michael, 2023) with lower melanopic efficacy.

In the simulated room, both metrics, Mel-EDI and Mel-DER were calculated considering the two solstices and the two equinoxes from 8:00 a.m. to 6 p.m., totalizing 40 hours for each solar orientation, north, east, south, and west for each position inside the room, P1 to P9. The intention was to verify the potency of the received circadian lighting and its melanopic daylight efficacy ratio.

[26] NA: To fulfill this condition, Mel-EDI expressed in lux must be 90.4% the value vertical illuminance (Ev). This corresponds to the same melanopic efficacy of standard CIE Standard Daylight D55 (Commission…, 2018). In results of EML, for example, a vertical illuminance of 100 lux corresponds to 100 EML, same value. A vertical illuminance of 100 lux, if Mel-DER is 0.904, corresponds to 90.4 lux of Mel-EDI.

To evaluate the light spectrum, the third metric, α-opic-EDI (equivalent daylight illuminance) was used. According to the definition, α-opic equivalent daylight illuminance in a given direction and at a specific point is illuminance produced by radiation conforming to standard daylight D65 that provides an equal α-opic irradiance and is usually measured at the outer surface of the eye. Similarly to Mel-DER, α-opic-DER is the ratio of the luminous radiation of a source to the α-opic efficacy of luminous radiation for daylight (D65). The term α-opic-EDI refers to the equivalent daylight illuminance for each of the five human photoreceptors (S-cones, M-cones, L-cones, rhodopsin, and melanopsin - iPRGCs) (Commission…, 2018). As no minimum criterion is recommended for α-opic-EDI for the five photoreceptors, the results were solely described and compared to the existing literature. Table 8 summarizes the metrics and thresholds for adequate conditions of circadian lighting. It is important to emphasize that the results in ALFA are calculated in units of EML and M/P ratio. Both results were converted into units of Mel-EDI and M/P ratio, following the methods described in the section 4.2.

Table 8 – Metrics and thresholds for adequate conditions of circadian lighting.

Non-visual effects of light: Assessment criteria			
Vertical field of view at the height 1.20 m	Melanopic daylight illuminance (Mel-EDI)	Minimum of 250 lux	Brown *et al.* (2022)
	Melanopic daylight efficacy ratio (Mel-DER)*	Minimum of 0.904	CIE S026 (Commission…, 2018)
	α-opic EDI (equivalent daylight illuminance)	No recommended minimum criterion: assessment based on direct comparisons of the results	Nazari; Matusiak; Stefani (2023)

Note: Mel-DER is an equivalent of M/P ratio as described by Esposito; Houser (2022).
Source: The Author.

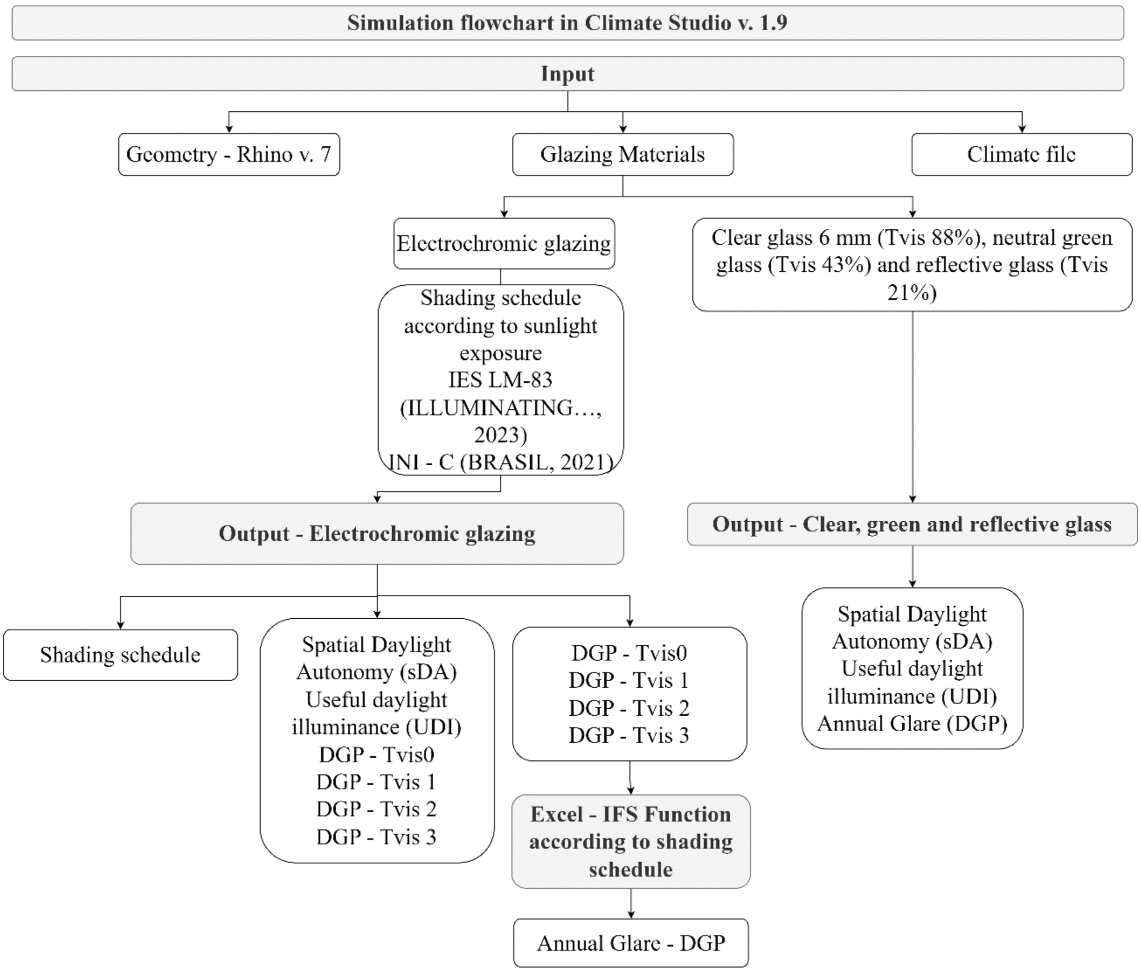
Adapted from the study of Nazari, Matusiak, and Stefani (2023), the analysis of α-topic-EDI was based on the description of illuminances calculated for each one of the five photoreceptors of the light source using tables and radar charts.[27] The α-opic action spectrum was considered uniform when there were no visible deformations in the lines connecting the spokes. If the resulting polygon was regular, in this case, five spokes representing each of the five photoreceptors, no significative differences were found. Otherwise, if the polygon, in this case, a pentagon, was irregular, the α-opic action spectrum was considered not uniform, and significative different stimuli of non-visual effects for the five photoreceptors were found. To analyze α-opic-EDI, 16 cases were selected to assess the different stimuli of the five photoreceptors of the light transmitted by the electrochromic glazing compared to the other three glasses. The selection of cases for the analysis of the α-opic action spectrum is explained in the section 5.2.4. After the discussion of the assessment criteria of visual and non-visual effects of light, it is presented in next section the simulation workflow in Climate Studio and Alfa.

[27] Radar charts compare multiple quantitative variables and are useful for visualizing which variables have similar values, or if outliers exist among the variables. Radar charts consist of a sequence of spokes, with each spoke representing a single variable (International Business Machines Corporation, 2024). The radar chart or star plot consists of a sequence of equiangular spokes, called radii, with each spoke representing one of the variables. The data length of a spoke is proportional to the magnitude of the variable for the data point relative to the maximum magnitude of the variable across all data points. A line is drawn connecting the data values for each spoke. This gives the radar chart a star-like appearance and the origin of the name of this plot (National Institute of Standards and Technology, 2003).

5.2.3. Simulation workflow in Climate Studio and ALFA

As discussed in Chapter 2 electrochromic glazing is dynamic and can be controlled according to the variations of daylight, such as seasonal variations, sky conditions, the incidence of solar radiation, etc (Attia *et al.*, 2018; Casini, 2018; Wu *et al.*, 2019). Therefore, it was necessary to create two workflows to assess the performance of the evaluated electrochromic glazing regarding visual and non-visual effects. One was created for Climate Studio, and the other for ALFA. In Climate Studio, the materials were configured as described in sections 5.2 and 5.2.1, and the climate files containing the climatic data for the six cities/latitudes were inserted to consider daily and seasonal variations in the sky (Solemma, 2023a). The simulation workflow is illustrated in Figure 33.

Figure 33 - Simulation flowchart in Climate Studio v 1.9.



Source: The Author.

The shading schedule of the electrochromic glazing was configured to limit direct sunlight on the horizontal plane. For each hour of the occupied period, between 8 a.m. and 6 p.m., if more than 2% of the horizontal grid area, analysis points receive direct sunlight, defined as more than 1,000 lux directly from solar disc, the transmitting window is instructed to lower the visible transmittance of the glass until either the sensors are brought below 1,000 lux or the glass unit is in its darkest state (Brasil, 2021; Illuminating…, 2023). The schedule of dynamic glazing in Climate Studio is generated considering all 8,760 hours of the year in a 24-hour period per day (Solemma, 2023a).

Results of Daylight Autonomy and Useful Daylight Illuminance were obtained as output and exported to .csv files. The hourly shading schedule was also exported to a .cvs file and used to generate input data for the simulations of non-visual effects in ALFA. The Annual Glare was calculated for the four states of electrochromic glazing, one for each visual transmittance. Tvis 0, or "0", corresponds to a visible transmittance of 62.1 % (clear state), Tvis1, or "1", to 41% (light tint), Tvis2, or "2", 5.4% (medium tint) and Tvis 3, or "3" to 1.1% (fully tinted) (Lawrence…, 2023). After that, the values of the daylight glare probability of the four tint states were exported to .csv files and were associated with each corresponding hourly tint state of the electrochromic glazing using the IFS function in Excel. Following these procedures, it was possible to calculate the Annual Glare for the simulated electrochromic glazing considering all four states. The results were analyzed for all nine positions, P1 to P9.

One major limitation of ALFA is that the simulations are static. This means that for each hour, one sky condition must be inputted, among clear, hazy, and overcast, and one tint state of the electrochromic glazing (Amorim *et al.*, 2021b). Therefore, the procedures the International Energy Agency recommended for evaluating daylight and electric light-integrated projects for point-in-time simulations were followed. Single measurements, in this case, simulations must ideally be as close as possible to a solstice or equinox.[28] The simulation input of the six climate files corresponded to the year 2018 (LABEEE; 2018). Consequently, four dates were defined, which were March 22, autumn equinox; June 21, winter solstice; September 22, spring equinox; and December 22, summer solstice.

For this reason, the data of the climate file was opened in Climate Consultant, v. 6.0, filtered, and exported to .csv (University of California, 2018). To determine the sky condition for each hour, data on the cloudiness was filtered for the four described dates

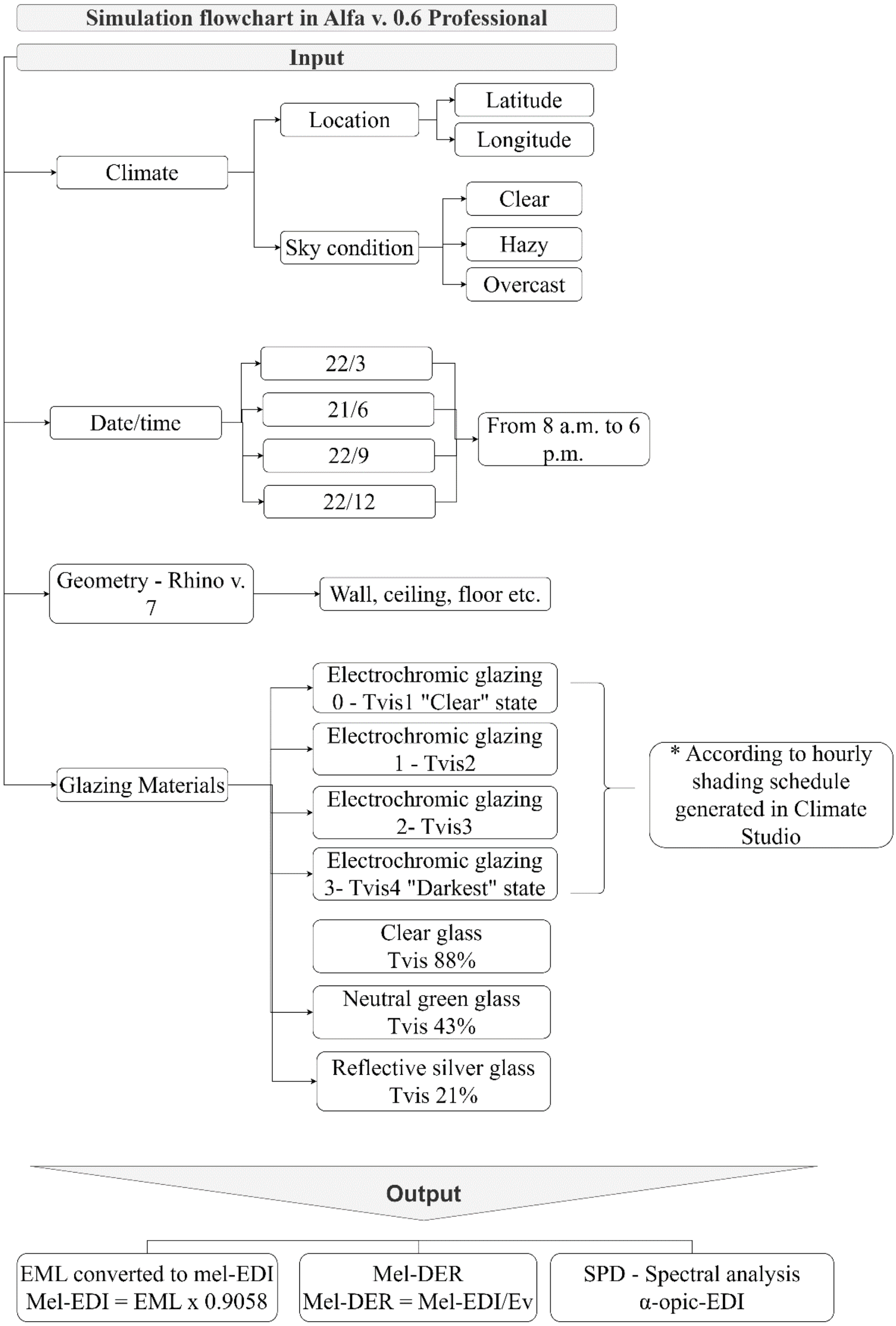
[28] Idem, 2021b.

between 8 a.m. and 6 p.m. Then, to determine the sky condition, from 0% (clear sky) to 100% (overcast), the Brazilian Standard ABNT NBR 15.215 – 2 recommendation was followed. Three sky conditions were considered: clear sky, for cloudiness between 0% and 25%; intermediate sky, for cloudiness of 25% and 75%; and overcast, for values between 75% and 100% (Associação…, 2022).

Following that, the climate file for each of the six cities/latitudes was inserted, and the same model described in the section 5.2 was considered. To consider the dynamism of the electrochromic glazing, each state from Tvis 0 (clear) to Tvis 3 (dark tint) was inputted for each hour considering the generated shading schedule in Climate Studio. The data regarding simulation inputs for Alfa is presented in Appendix C.

As output, values in units of equivalent melanopic lux (EML), M/P ratio, and spectral power distribution (SPD) were obtained for each hour. Figure 34 illustrates the simulation flowchart in ALFA v.0.6. Later, the results of EML were converted to Mel-EDI, and the results of Mel-DER were calculated. These calculations were described in the section 4.2. Moreover, results of spectral power distribution (SPD) were calculated by ALFA, and they were used to conduct spectral analysis of particular cases, including the four tint states of electrochromic glazing and the other three glasses.

Figure 34 - Simulation flowchart in ALFA v. 0.6 Professional.



Source: The Author.

Spectral analyses of the glazing materials using CIE α-opic Toolbox are described in the next section.

5.2.4. Definition of cases for spectral analysis: CIE α-opic Toolbox

CIE S026 α-opic Toolbox v1.049a – 2020/11 was used to conduct spectral analysis of electrochromic glazing compared to the other three simulated glasses (Commission…, 2018). Brasilia was chosen because it is located at the intermediate latitude compared to the other five cities/latitudes, 15° South, ranging from 3° south to 29° south, and on September 22 for the North. Besides that, the focus of the spectral analysis was to compare and understand the spectral distribution of light per glazing material. As electrochromic glazing is usually tested for orientations with a high incidence of direct sunlight, the north-facing window was chosen.[29]

It was necessary to analyze the light spectrum regarding all four states of electrochromic glazing in comparison with the other three simulated glasses, clear, neutral green, and reflective silver; the date was September 22 - and a sunny day was chosen. In total, 16 cases were analyzed, considering the city/latitude of Brasilia – 15° South (1), north orientation (1), four glazing materials (4), in the middle sensor/position (P5)[30] on September 22 (1 date) and 4 hours (from 9 a.m., 12 p.m., 2 p.m., and 5 p.m.). These hours were selected to encompass all four states of electrochromic glazing on the selected date for the north in Brasilia, as can be seen in Appendix C. Considering only the electrochromic glazing the number of analyzed cases was 4.

The input consisted of the insertion of results of the spectral power distribution (SDP) simulated in ALFA for 16 selected cases. Alternatively, the most adequate method is to measure SPD directly from a spectrophotometer (Amorim *et al.*, 2021b). Irradiance results were inputted in the spreadsheet CIE S026 α-opic Toolbox for each 5 nm of wavelength (λ), ranging from 380 nm to 780 nm, visible spectrum, and the option source of the spectral data by "user" was selected. Figure 35 illustrates the selected option and the entered spectral irradiance values in the spreadsheet CIE S026 α-opic Toolbox.

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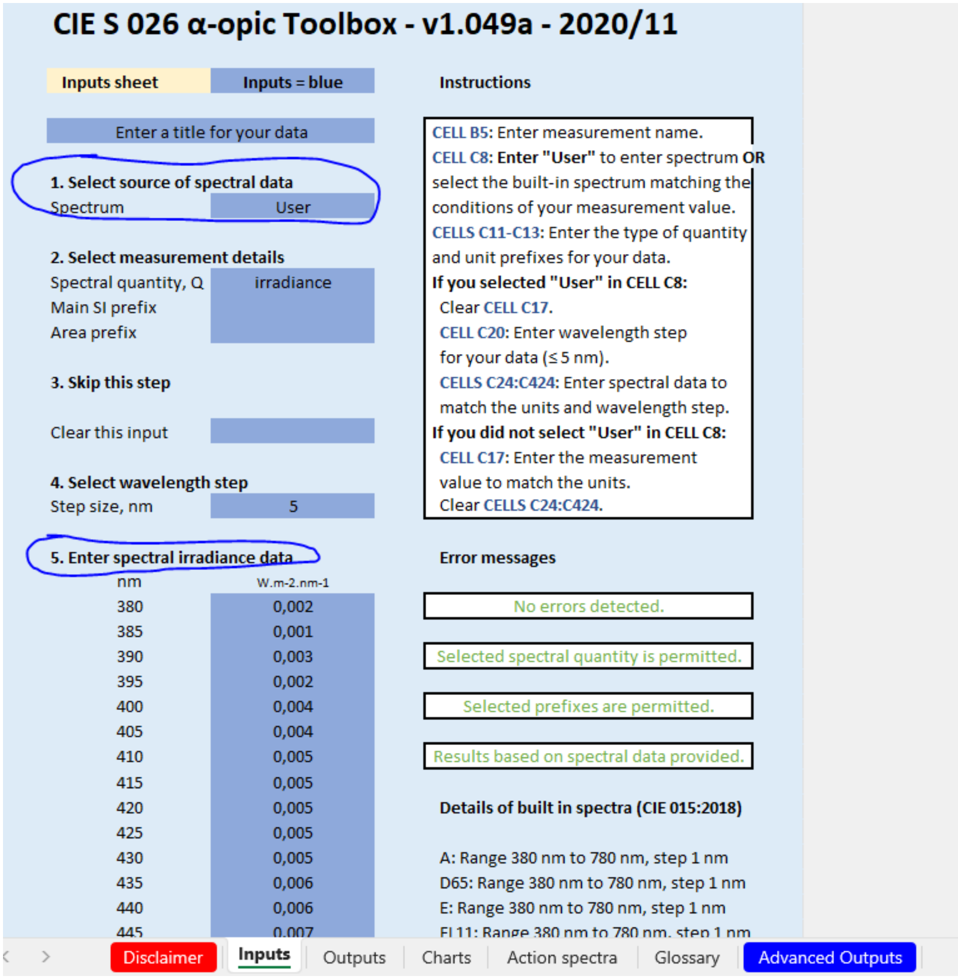
[29] As described in section 2.4, electrochromic glazing was tested in orientations with high incidence of direct sunlight (Jain, Karmann, Wienold, 2022; Nazari; Matusiak, Stefani, 2023). This meant the south orientation for described studies in high latitudes in the Northern hemisphere. In Brazilian latitudes, the equivalent orientation is the north.

[30] The middle of the room was also chosen for spectral analysis in the reference study of Nazari, Matusiak and Stefani (2023).

Figure 35 – CIE S026 α-opic Toolbox, selected option and entered SPD values by irradiance according to irradiance at each 5 nm of wavelength (λ – nm).



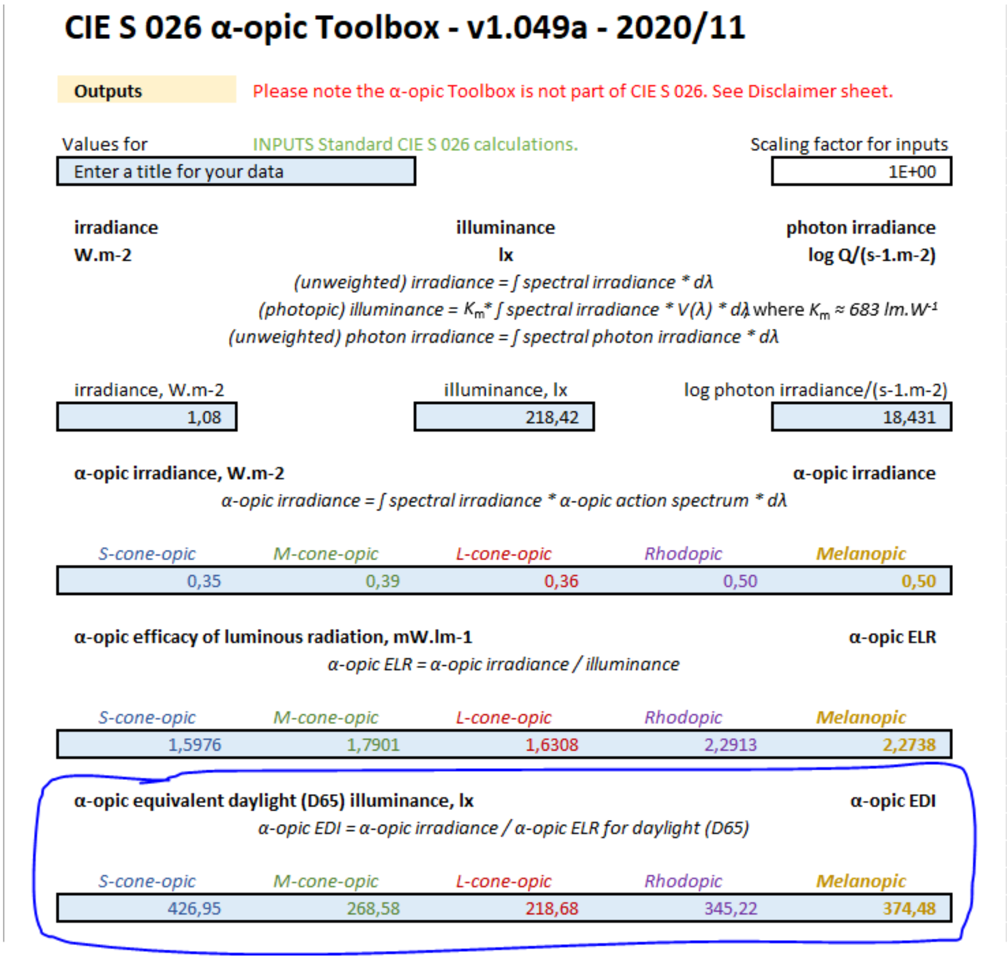
Source: The Author.

The output consisted of the distribution of light spectrum according to α-opic equivalent daylight (D65) illuminance - α-opic EDI for each of the five photoreceptors present in the human eye, S-cone-opic, M-cone-opic, L-cone-opic, rhodopic and melanopic. The main advantage of this toolbox is that the units are SI compliant (Commission…, 2018).[31] Figure 36 illustrates the outputs of the CIE S026 α-opic Toolbox. This process was done for the 16 selected cases for the spectral analysis. [32]

[31] It is important to mention that CIE S026 α-opic Toolbox is a more detailed calculation of light spectrum related to non-visual effects of light, encompassing results of all five photoreceptors in the human eye. Results of Mel-EDI, and vertical illuminance were already calculated in ALFA.

[32] According to Nazari, Matusiak and Stefani (2023, p. 18): "[…]-DER alone cannot assess the transmitted daylight through glazing regarding non-visual metrics, which supports the notion […] that Melanopic EDI can serve as a reliable predictor of non-visual responses, thereby validating its usefulness in assessing glazing performance". For this reason, α-opic EDI was chosen to quantify the stimulus according to the five photoreceptors in the eye.

Figure 36 – Output of CIE S026 α-opic Toolbox containing results of α-opic EDI for the five photoreceptors present in the human eye.



Source: The Author.

As described in the literature review regarding the spectral distribution of the light source transmitted through electrochromic glazing, a neutral or slightly warm spectrum is preferred by users. Therefore, for ideal conditions, the values of α-opic-EDI for the five photoreceptors must be as equal as possible (Nazari; Matusiak; Stefani, 2023; Mardaljevic; Waskett; Painter, 2016).

The detailing of the initial questions of this thesis is described next.

5.3. Detailing of the initial questions of this thesis

As described in the introduction, the main question of this thesis is: how is the performance of electrochromic glazing regarding visual and non-visual effects of light in non-residential buildings in different latitudes of Brazil?

In order to investigate the electrochromic glazing in a representative model of non-residential room within the Brazilian luminous context including visual and non-visual effects of light, the initial question was rewritten in eight to include the explanatory and response variables. Eight questions were rewritten concerning this research’s question:

5.3.1. How does the electrochromic glazing perform in relation to the established criteria of DA, UDI, and annual glare (DGP < 40%) in relation to city/latitude, orientation, and position in the room (sensor)?

- Solution: Description and count of results that achieved the criteria of DA, UDI, and annual glare (DGP < 40%) per city/latitude, orientation, and sensor/position in the room for electrochromic glazing.

5.3.2. Visual effects: How does the choice of the glazing material affect the light distribution inside the room, measured with the metrics DA and UDI, and annual glare (DGP < 40%) according to variables city/latitude, orientation, and sensor/position?

- Solution: Description and count by disaggregation per city/latitude, orientation, glazing material, and sensor/position as defined by the established criteria described in the section 5.2.2.

5.3.3. What is the performance of the electrochromic glazing in relation to measured circadian light supply using the metric Mel-EDI in relation to city/latitude, orientation, and sensor/position in the room?

- Solution: Description of results and frequency analysis of Mel-EDI equal or greater than 250 lux by disaggregation of city/latitude, orientation, and sensor/position in the room.

5.3.4. In which cases there is a lack of circadian lighting when there is not a minimum of 250 lux of Mel-EDI in at least 70% of hours per day in relation to city/latitude[33], orientation, the position of the room/depth, and date?

- Solution: Identification of the cases (per city/latitude, orientation, sensor/position, date, and hour) in which the minimum of 250 lux of Mel-EDI was not achieved in 70% of the hours per day. Then, these cases were extracted, counted, and described.

5.3.5. Non-visual effects: How does the choice of glazing material/glass affect the minimum supply of 250 lux (Mel-EDI) according to city/latitude, orientation, and sensor/position in the room?

- Solution: Description and count by disaggregation per city/latitude, orientation, glazing material, and sensor/position as defined by the established criteria for Mel-EDI.

5.3.6. Non-visual effects: What are the variations in the melanopic daylight efficacy ratio (Mel-DER) per city/latitude, orientation, glazing material, sensor/position, and date when the glazing material is modified?

- Solution: Description and count by disaggregation per city/latitude, orientation, glazing material, sensor/position, and date according to the established criteria for Mel-DER.

5.3.7. What is the spectral distribution/stimulus according to color in the four states of the electrochromic glazing (clear, light tint, medium tint, and dark tint) considering the position in the room/sensor?

- Solution: Selection of 4 cases in which electrochromic glazing is in distinct states (clear, light tint, medium tint, and dark) for the city of Brasilia (15° South), on September 22 to the north and respective hours (9 a.m., 12 p.m., 2 p.m., and 5 p.m.). The output of SPD given by ALFA was inputted in CIE S026 α-opic Toolbox and respective results of mel-, s-cone-, m-cone-, l-cone-, and rhodopic equivalent daylight illuminance (α-opic EDI) were described.

[33] As described in Table 2, the Well Building Standard v2 (International Well Building Institute, 2022) and the UL DG 24480 (Underwriters…, 2019) recommend a minimum of 4 hours of minimum of circadian lighting, between 9 a.m. and 1 p.m. As 10 hours per day were simulated, this meant that this requirement was only during 40% of the hours. Following the recommendation of Brown *et al.* (2022), the exposure of full work period is recommended. Therefore, 70% of the simulated hours per day was used as recommendation.

5.3.8. Are there significant changes in the spectral distribution of light/stimulus according to color related to the choice of glazing material/glass?

- Solution: Comparison and description of 16 selected cases using the respective results of spectral distribution in units mel, s-cone-, m-cone-, l-cone-, and rhodopic equivalent daylight illuminance (α-opic EDI) regarding the four glazing materials, including electrochromic glazing and hour (9 a.m., 12 p.m., 2 p.m., and 5 p.m.).

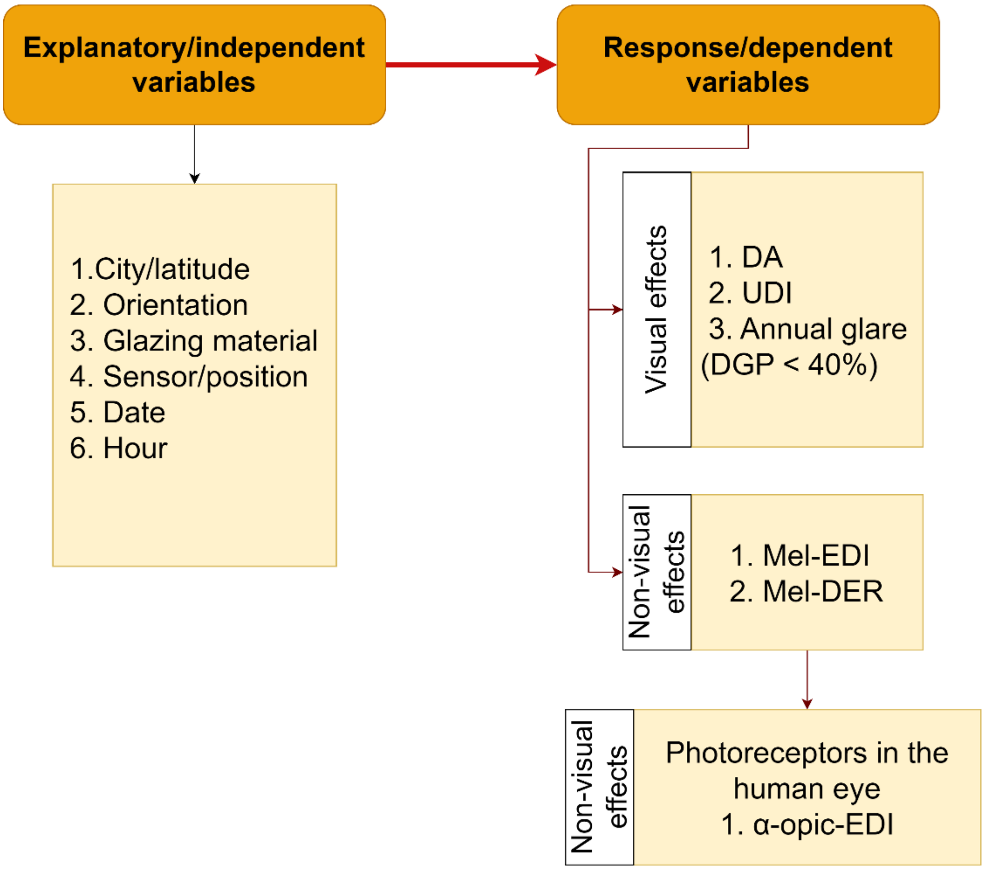
In light of these eight questions, the procedures for the statistical analysis are described in the next section.

5.4. Data processing: statistical analysis

As discussed in the introduction, it is expected that the use of electrochromic glazing can lead to improved visual comfort and, at the same time, provide circadian lighting for users under specific conditions compared to the other three conventional glasses, clear, green, and reflective silver. The execution of computer simulations in the simulated model and the substantial quantity of generated results can prove that this is possible using these materials in six different locations within the three zones of the Brazilian territory according to the three latitude ranges.

In total, 96 variations of the model were simulated according to the described variables in the section 5.2. The explanatory/independent variables are city/latitude, window orientation, north, south, east, and west, and glazing material, including the electrochromic glazing, date, and hour. For visual effects of light, the response or dependent variables are the results of daylight autonomy (DA), useful daylight autonomy (UDI 100 – 3000 lux), and annual glare (DGP < 40%). For non-visual effects of light, the response variables are melanopic equivalent daylight illuminance (Mel-EDI) and melanopic equivalent efficacy ratio (Mel-DER). For detailed spectral analysis, 16 selected cases of α-opic-EDI were analyzed to understand the received light spectrum, as described in the section 5.2.4. Figure 37 presents the analyzed explanatory and response variables of the study.

Figure 37 – Data processing with analyzed explanatory and response variables.



Source: The Author.

As mentioned at the beginning of this chapter, the statistical analysis consisted of three steps. The first step was the description of the results. The second step was the comparisons among explanatory and response variables. The third step was the analysis of the performance of electrochromic glazing and the other three glasses regarding visual and non-visual effects of light. The last step was the most important to answer the two questions presented in section 5.3 – method.

5.4.1. Description of the results

As described in section 4.4, descriptive statistics encompasses the organization of general data in summary measures. The first analysis was made using indices, percentages, frequency tables, crosstabulation, and graphical representations, such as boxplot, scatter, and bar charts. Additionally, averages, standard deviations and coefficients of variation (CV) were determined according to the defined explanatory and response variables (Barbetta, 2008).

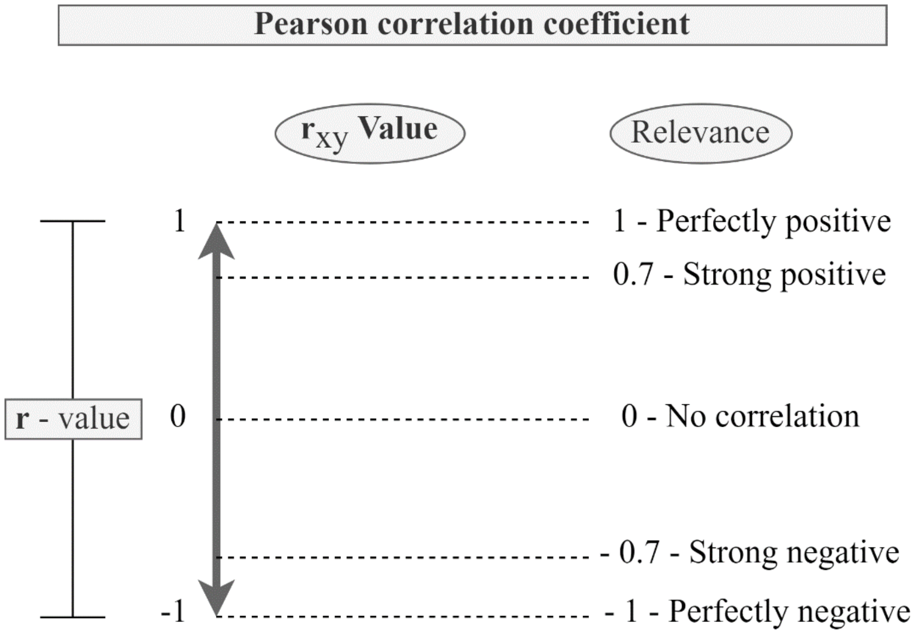
At this step, the general description was done to understand and summarize the results, combining each explanatory variable (city/latitude, window orientation, glazing material, the position in the room, date, and hour) with each response variable for visual effects of light (DA, UDI, and annual glare) and non-visual effects (Mel-EDI and Mel-DER). After this process, the second step of the statistical analysis was carried out, comparing the explanatory and response variables. This is described in the next section.

5.4.2. Statistical comparisons: associations among explanatory and response variables

The intention of the second step was to understand the associations among the defined explanatory and response variables in the method, identifying possible relationships. This was done to verify if the affirmations and assumptions about the response variables were true or not – e.g. is the performance of electrochromic glazing regarding visual and non-visual effects of light better than reflective silver glass? Are there relationships among the response variables UDI, annual glare and Mel-EDI?

For these reasons, two statistical methods were used to associate the explanatory and response variables described in the method: correlation and analysis of variance (ANOVA). The first association was the correlation for each of the two response variables for visual and non-visual effects. Two variables, X and Y, are positively correlated when they move in the same direction. On the other hand, they are negatively correlated when one variable, X, moves in the opposite direction of variable Y, i.e., one increases while one decreases. The Pearson linear correlation will be in the interval -1 to 1. The correlation will be stronger when it is closer to 1 than to 0, with no correlation. For negative correlations, the strongest ones will be closer to -1 than 0, with no correlation, when it is descending (Barbetta, 2008). The correlation is considered positively strong when the r-xy value is equal to or greater than 0.70 for positive r-values and -0.70 for negative r-values (Dancey; Reidy, 2019). Figure 38 illustrates the Pearson correlation coefficient (r) and relevance in function of r-value.

Figure 38 – Pearson correlation coefficient (r) and relevance in function of r-value.



Source: Adapted from Barbetta (2008) and Dancey; Reidy (2019).

For visual effects, a Pearson linear correlation matrix was created, associating the response variables DA, UDI, and annual glare (DGP > 40%). For non-visual effects, Mel-EDI and Mel-DER were associated, and these two response variables were correlated.

For the perfectly positive and perfectly negative correlations, linear regression models were created for the response variables of visual and non-visual effects of light. As in correlation studies, regression analyses are also based on paired observations (x, y) relating to the response variables. A given y is said to depend, in part, on the corresponding x value. The dependence is simplified by a linear relationship between x and y, such as defined in Equation 5.

Equation 5 – Formula of linear regression as *y* as dependent on *x*.

$$y = a + bx$$

Source: Barbetta, 2008.

At first, comparisons and contrasts were made separately for visual and non-visual effects as the number of cases was different, as described below:

- Non-visual effects contain 34,560 cases measured in:
    - 6 cities/latitudes.

  - 4 orientations (north/south/east/west).
  - 4 types of glass/windows.
  - 9 positions.
  - 4 dates (Mar/Jun/Sep/Dec).
  - 10 hours per day (8 a.m. to 6 p.m.).
- Visual effects contain 864 cases measured in:
  - 6 cities.
  - 4 orientations.
  - 4 types of glass/windows.
  - 9 positions.

At the end, joint analyses were carried out to analyze the response variables of visual and non-visual effects. In order to work together with visual and non-visual effects, the two files had to be compatible so that the merged file/spreadsheet contained 864 records.

Therefore, the Mel-EDI and Mel-DER data had to appear in the merged file disaggregated only by city, orientation, glass/window, and position. In this regard, the data had to be aggregated by date and time (40 records for 4 dates and 10 hours) and represented using a summary measure, such as arithmetic mean or median. To do this, it was necessary to check which descriptive measure was a good aggregate representative of date and hour for Mel-EDI and Mel-DER.

Due to the large coefficient of variation (CV) of the results of Mel-EDI, described in the next chapter, the median was considered a good representative value to merge both files. Automatically, the median was the best solution for this case of high data dispersion and variability. In this case, each record represented 40 values of Mel-EDI and Mel-DER in the merged file totalizing 864 records. With this process, it was possible to associate each response variable corresponding to visual and non-visual effect of light based on the Pearson linear correlation. It is important to emphasize that the correlations did not associate the explanatory and response variables. All correlations were performed using R.

Comparisons and associations combining explanatory and response variables were done using hypothesis tests. The intention was to verify if the affirmations and assumptions about the response variables were true or not. In this context, significance tests, including analysis of variance (ANOVA), were made to verify whether the affirmations regarding the response variables as a function of the explanatory variables were true.[34] Analysis of Variance (ANOVA) is a statistical technique used to determine if two averages from two or more populations are similar. The tested hypothesis is the equality between the averages. The adopted significance value – tolerated a margin of error of 1%, which supports rejecting the null hypothesis. The difference between two or more averages is significant if the calculated Sig or P-value is below 0.001. Otherwise, if the P-value is equal to or above 0.001, the averages are considered statistically equivalent, even though the numerical results are not identical. These hypothesis tests were calculated using R Script (Stevenson, 2001).

The comparisons and associations among the explanatory and response variables were important to understand the influence of each explanatory variable to assess the performance of electrochromic glazing regarding visual and non-visual effects of light. With these tests, it was possible to understand, for example, if the results of visual and non-visual effects of light vary as function of variables city/latitude, window orientation, glazing material or the position in the room. The next step was the analysis of the performance of electrochromic glazing and the other three glasses regarding visual and non-visual effects of light (data categorization), as described next.

5.4.3. Analysis of the performance of electrochromic glazing and the other three glasses regarding visual and non-visual effects of light (data categorization)

In the third step of the statistical analysis, the performance of electrochromic glazing and the other three glasses were evaluated according to the assessment criteria for visual and non-visual effects defined in section 5.2.2. Therefore, the data categorization was done using counts and classification/ranking of frequencies or recode.

Categorization is defined by the process of organizing populations or things into groups based on their type. A similar definition of this term is to put things into groups with the same features (Barbetta, 2008; Cambridge, 2024).

These groups or categories were defined according to the percentages/frequencies of achievement of minimum thresholds for the criteria regarding visual and non-visual effects of light. These frequencies were related to the achievement of minimum thresholds for daylight autonomy (DA), useful daylight autonomy (UDI), annual glare, melanopic

[34] For example, does electrochromic glazing provides more circadian lighting (Mel-EDI) than reflective silver glass?

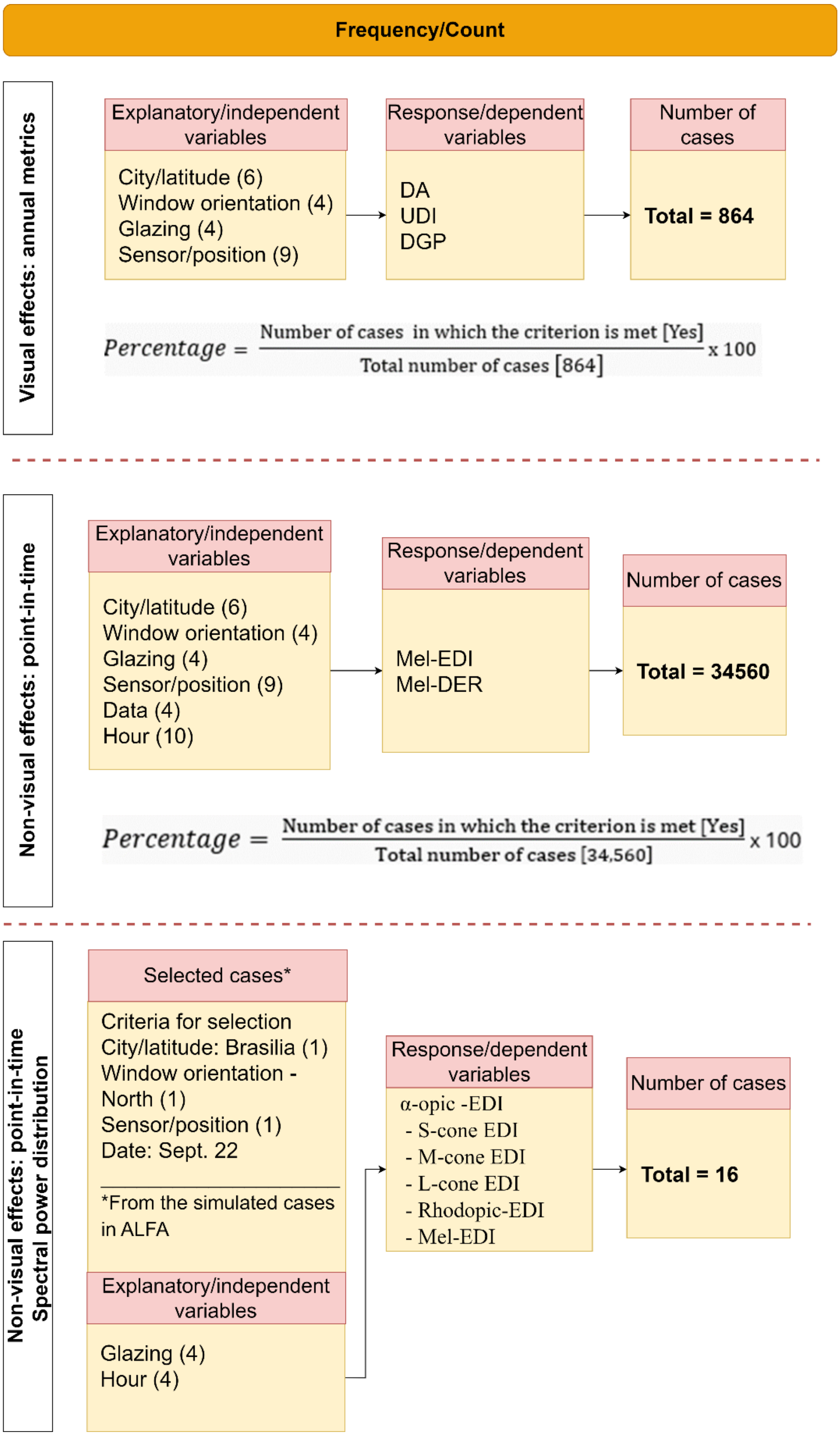
daylight equivalent illuminance (Mel-EDI), and melanopic daylight efficacy ratio (Mel-DER).

As the metrics in Climate Studio are climate-based, a single year is simulated for the metrics DA, UDI and DGP between 8:00 a.m. and 6:00 p.m. (Jones; Reinhart 2017; Reinhart, Wienold, 2011). Consequently, the analyses were carried out for 864 cases for visual effects.

The major difficulty was when non-visual effects of light were analyzed, which had to be in specific hours to comply with the adequate thresholds presented in Table 3. The analysis of the circadian lighting must be during daylight hours, between 8:00 a.m. and 6:00 p.m., in the morning and afternoon. In this regard, solstices and equinoxes were considered, which were March 22, June 21, September 22, and December 22. In this regard, 34,560 cases were generated in units of Mel-EDI, considering the 4 dates and 10 hours for each of the simulated variations of the test room. For spectral analysis, 16 cases were selected from the ones simulated in ALFA to understand the distribution of the light spectrum in each of the five photoreceptors in the human eye according to the glazing material, including the four states of electrochromic glazing and selected hours.

Figure 39 describes the count of explanatory and response variables and the total number of analyzed cases for visual and non-visual effects of light. The categorization was made as percentages between the number of cases each criterion was met and the total number of cases for visual and non-visual effects.

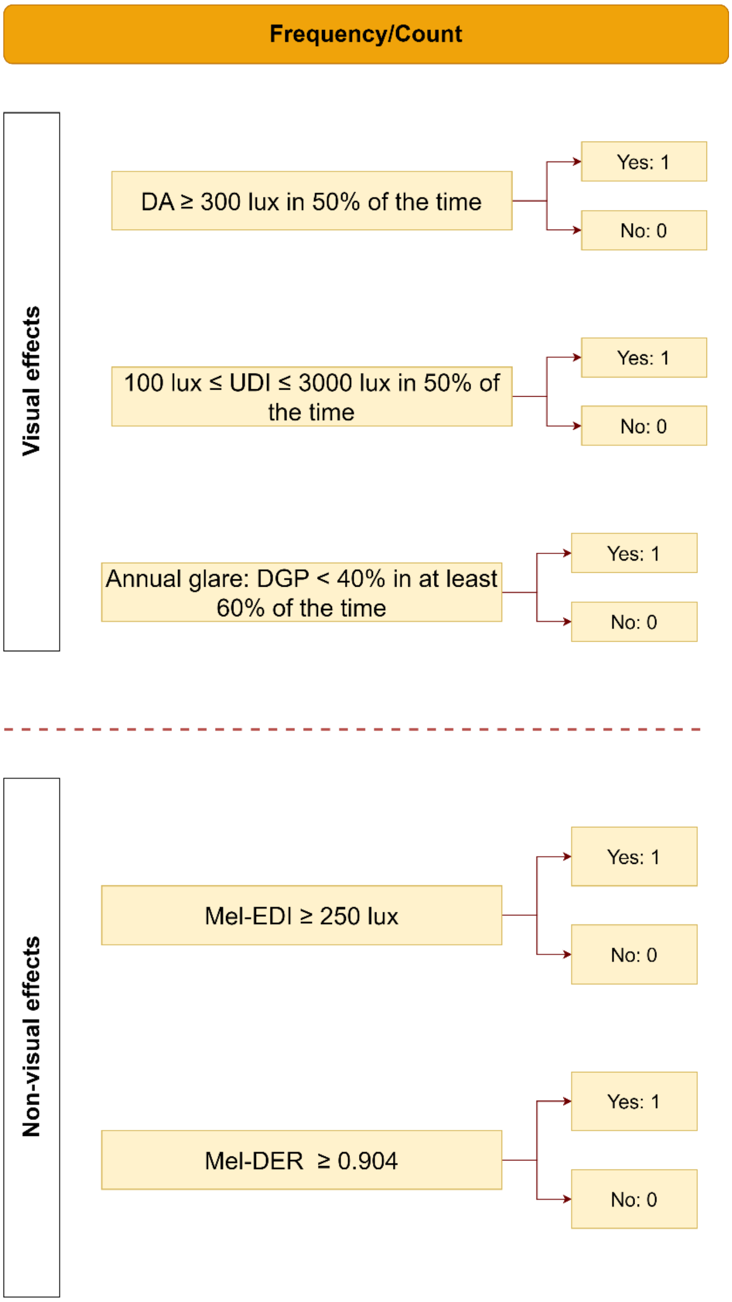
Figure 39 – Count of explanatory and response variables and total number of analyzed cases for visual and non-visual effects of light.



Source: The Author.

The counts were done for each response variable as there were different requirements as described in section 5.2.2. If the criterion was achieved, it was counted with number "1", otherwise, the case was not counted, and it was registered with zero "0". Figure 40 illustrates and describes how the frequencies for each criterion for visual and non-visual effects were calculated.

Figure 40 – Frequency/count of percentages for the stablished criteria of visual and non-visual effects of light.



Source: The Author.

Consequently, two groups in the categorization of the results were created according to the achievement of minimum criterion for DA, UDI, and annual glare (DGP < 40%) for visual effects of light, and Mel-EDI and Mel-DER for non-visual effects of light. The first group or category was “yes” with value “1” when the minimum criterion was achieved and the second group was “no” with value “0” when no minimum criterion was achieved.

The data categorization assessing the performance of electrochromic glazing and the other three glasses according to the criteria for visual and non-visual effects of light were made using the tool “Pivot Tables” in EXCEL. Firstly, the criteria for each variable of visual and non-visual effects were defined using the “IF Function” associating the value with 1 for achievement of minimum criterion and 0 when no minimum criterion was achieved. Then, the Pivot Tables were generated selecting the results filtered by variables city/latitude, window orientation, glazing material/glass, position in the room/sensor, date, and hour. Secondly, the pivot tables included all four glazing materials/glasses describing the results per variables city/latitude, window orientation, position in the room, date, and hour. At last, to assess the performance of electrochromic glazing, the pivot tables for the same explanatory variables were generated separately to answer the research questions.

After describing the results concerning all three steps of the statistical analysis, the results were summarized, and the conclusions were established. The results are described in the next chapter.

Chapter 6. Results and discussion

This chapter described the results focused on the performance of electrochromic glazing regarding the visual and non-visual effects of light. In section 6.1, the generated shading schedules for electrochromic glazing according to the six cities/latitudes in Brazil, as well as window orientations (north, east, south, and west) are described. Section 6.2 focuses on describing results, including the performance of electrochromic glazing regarding visual effects. Section 6.3 addresses the results in regard to the performance of electrochromic glazing regarding non-visual effects. Section 6.4 describes the results of spectral analyses of electrochromic glazing and the other simulated three glasses. In section 6.5, the overall performance of electrochromic glazing is described and recommendations are given in order to improve the performance of electrochromic glazing regarding visual and non-visual effects of light.

6.1. Shading schedules of the electrochromic glazing per city/latitude and window orientation

As discussed in section 2.4, the shading schedule of electrochromic glazing was generated using Climate Studio to limit direct exposure to sunlight, i.e., when more than 2% of the grid area receives at least 1,000 lux directly. The idea was to lower its visible transmittance to control the incidence of direct sun on the horizontal sensor grid. The schedules were generated automatically by the software considering all 8,760 hours if the year. State percentage or “state pct” is referred to the percentage of time in the year when the lowering of states is required. Results of the shading schedule were displayed by city/latitude and window orientation.

Implementing shading schedules for electrochromic glazing in real buildings involves integrating the glazing with smart building systems that include light sensors and automated controls. These sensors provide real-time data on illuminance and direct sunlight to a building management system, which uses control algorithms to adjust the glazing based on predefined criteria. A user interface allows for customization, and the system can also be integrated with energy management systems to optimize energy use, enhancing both comfort and efficiency.[35] In this regard, generating shading schedules in

[35] More details in the studies of Matusiak (2020) and Gentile *et al.* (2022).

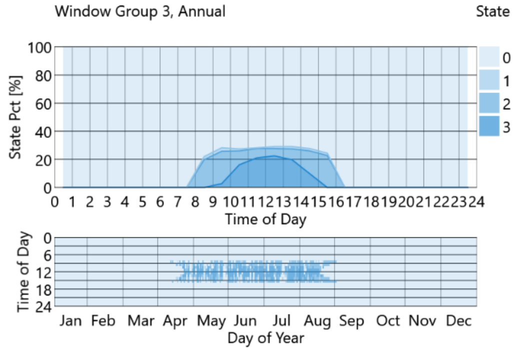
Brazilian cities/latitudes through computer simulations is the initial step to implement control systems in real buildings using technologies of electrochromic glazing.

Figure 41 illustrates the generated shading schedule for Manaus as an example The complete shading schedule per city/latitude and window orientation is presented in Appendix D. The shading schedules showed the frequencies of percentages of each state (from 0 – clear to dark – 4) of electrochromic glazing according to daily hours and months of the year.

Figure 41 - Shading schedule of electrochromic glazing for Manaus.

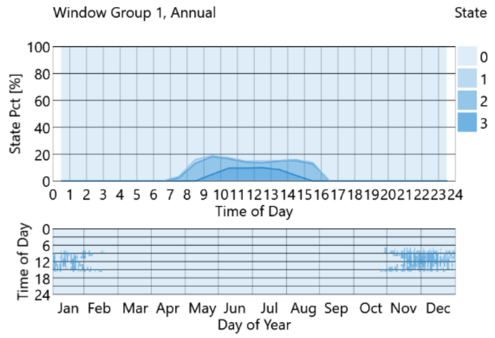
Manaus (3°6' S/60°1' W)

North



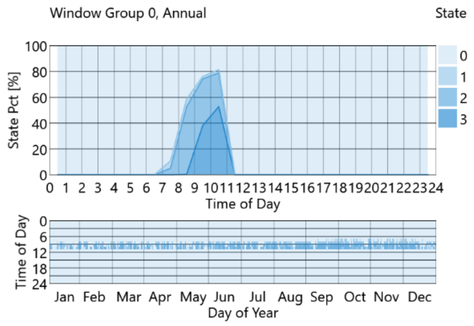
Clear state – 78% of the year

South



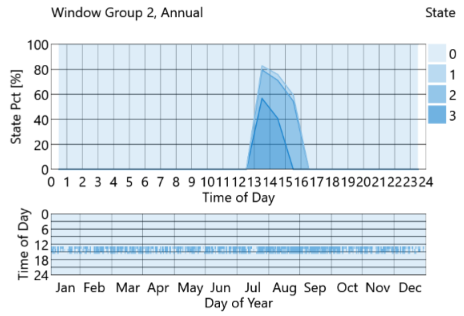
Clear state – 87% of the year

East



Clear state – 78% of the year

West



Clear state – 78% of the year

Note: *0 – Tint states: Tvis 0 62.1%/ 1- Tvis 1 41.4%/ 2- Tvis 2 5.4%/ 3- Tvis 3 1.1%.
Source: The Author.

Differences were found in the shading schedules according to city/latitude and window orientation. The schedules were analyzed per city/latitude and window orientation. As there were significant differences, comparisons were made per similar latitudes, i.e., between Manaus (3° south) and Recife (8° south), later Bom Jesus da Lapa (13° south) and Brasilia (15° south), and finally, Rio de Janeiro (22° south) and Santa Maria (29° south).

In Manaus (3º south) the electrochromic glazing was in state 2 (medium tint) to the north from 7:30 a.m. to 9 a.m. and from 3 p.m. to 4:30 p.m. From 9 a.m. to 3 p.m., the electrochromic glazing was in state 3 (dark tint). In comparison with Recife (8º south), state 2 (medium tint) begins at 6:30 a.m. to 8:30 p.m. and from 2:30 p.m. to 4:30 p.m., and state 3 (dark tint) begins at 8:30 a.m. until 2:30 p.m. According to the season, the electrochromic glazing oriented to the north darkened from the middle of April until the end of August in Manaus from 7 a.m. until 4 p.m. In Recife, the tint states lowered in the beginning of April until the beginning of September from 7:30 a.m. until 4 p.m. for the north orientation.

To the east, the lowering of states was present in the morning period during all seasons of the year, and differences in periods of time were found between Manaus and Recife. In Manaus, states 2 and 3 were present from 7 a.m. until 11:30 a.m., and in Recife, these darker states – 2 and 3 – were present from 6:30 a.m. until 11 a.m.

To the west, the lowering of states was detected in the afternoon during all seasons of the year, and differences in periods of time were found between Manaus and Recife. In Manaus, states 2 and 3 were present from 12:30 p.m. until 4:30 p.m., and in Recife, these darker states – 2 and 3 – were present from 11:30 p.m. until 4:30 p.m.

Regarding the south, only Manaus and Recife presented lower tint states in more than 10% of the year, as there was the incidence of direct sun in the summer months, November, December, and January. States 2 and 3 were detected from 7 a.m. to 8 a.m. and 3:30 p.m. to 4:30 p.m., and state 3 from 8 a.m. to 3:30 p.m. in Manaus. In Recife, states 2 and 3 were detected from 6:30 a.m. and 10 a.m. and later from 12 p.m. and 4:30 p.m.

In Bom Jesus da Lapa (13º south), the electrochromic glazing was in state 2 (medium tint) to the north from 7:30 a.m. to 9 a.m. and from 2:30 p.m. to 4:30 p.m. From 9 a.m. to 2:30 p.m., the electrochromic glazing was in state 3 (dark tint). In comparison with Brasilia (15º south), state 2 (medium tint) begins at 8 a.m. to 9:30 a.m. and from 3:30 p.m. to 4:30 p.m., and state 3 (dark tint) begins at 9:30 a.m. until 3:30 p.m. The electrochromic glazing oriented to the north darkened from 7:30 a.m. until 4:30 p.m. from the end of March until the middle of September in Bom Jesus da Lapa. In Brasilia, the tint states lowered in the middle of March until the end of September for the north orientation from 8 a.m. to 4:30 p.m.

To the east, the lowering of states was present in the morning period during all seasons of the year, and differences in periods were found between Bom Jesus da Lapa and

Brasilia. In Bom Jesus da Lapa, states 2 and 3 were present from 6:30 a.m. until 11:30 a.m., and in Brasilia, these darker states – 2 and 3 – were present from 8 a.m. until 10:30 a.m.

To the west, the lowering of states was detected in the afternoon during all seasons of the year, no differences in the two cities were observed. In Bom Jesus da Lapa and Brasilia, states 2 and 3 were present from 12:30 p.m. until 4:30 p.m.

To the south, the electrochromic glazing was configured to lower states in short periods of time from the middle of November until the end of January in Bom Jesus da Lapa and Brasilia. States 2 and 3 were present from 7 a.m. to 9 p.m. in both cities. In the afternoon, states 2 and 3 were present from 2:30 p.m. until 4:30 p.m. in Bom Jesus da Lapa and from 3 p.m. to 4 p.m. in Brasilia.

In Rio de Janeiro (22º south), the electrochromic glazing was in state 2 (medium tint) to the north from 7:30 a.m. to 9 a.m. and from 2 p.m. to 4 p.m. From 9 a.m. to 2 p.m., the electrochromic glazing was in state 3 (dark tint). In comparison with Santa Maria (29º south), state 2 (medium tint) was present from 8:30 a.m. until 10 a.m. and from 3 p.m. until 4:30 p.m. and state 3 (dark tint) from 10 a.m. until 3 p.m. The electrochromic glazing oriented to the north in Rio de Janeiro darkened from the beginning of March until the beginning of October from 7:30 a.m. to 4 p.m. In Santa Maria, the tint states lowered from the middle of February until the end of October from 8:30 a.m. to 4:30 p.m. for the north orientation. In comparison with the latitudes of Manaus and Recife, which are lower, the lowering of states of electrochromic glazing in Rio de Janeiro and Santa Maria is extended for almost two months for the north orientation.

To the east, the lowering of states was present in the morning period during all seasons of the year and differences in time periods were found between Rio de Janeiro and Santa Maria. In Rio de Janeiro, states 2 and 3 were present from 7 a.m. until 11:30 a.m. in Santa Maria, these darker states – 2 and 3 – were present from 8:30 a.m. until 12 p.m.

To the west, the lowering of states was present in the afternoon during all seasons of the year, and differences in time periods were found between Rio de Janeiro and Santa Maria. In Rio de Janeiro, states 2 and 3 were present from 12:30 p.m. until 4:30 p.m. In Santa Maria, states 2 and 3 were present from 1 p.m. and 5 p.m. Additionally, no lowering of states was required nor detected for the south of Rio de Janeiro and Santa Maria.

These results of the shading schedule per city/latitude and window orientation were generated according to limit direct exposure to sunlight, i.e., when more than 2% of the grid area receives at least 1,000 lux directly. When the shading schedules were compared, differences per city/latitude and window orientations were found, and they were similar to the findings of Fonseca *et al.* (2019) when analyzing the incidence of annual global radiation of the twenty sites in Brazil with different latitudes. For the east and the west, the lowering of states of the electrochromic glazing did not present significative differences due to the increasing latitude. The reported differences in these two orientations were according to the hour, start, and end of medium-tint and dark-tint states, and in all seasons, the lowering of states was required in the morning for the east and in the early afternoon for the west.

Most of the differences as the latitude increased could be perceived to the south. For Manaus (3° south) and Recife (8° south), the lowering of states was required during the summer months, from November to January. For Bom Jesus da Lapa (13° south) and Brasilia (15° south), the lowering of states was required in some periods from November to January but with less frequency than for Manaus and Recife. For the north orientation, the lowering of states was required as the latitude increased. In Manaus (3° south), the lowering of states occurred during the late morning and early afternoon from the middle of April until the end of August, and in Santa Maria (29° south), this occurred from the middle of February until the end of October in the same periods of the day as Manaus.

Comparing the shading schedules with higher latitudes, in Europe and the United States, differences were found for the north and the south orientation, orientations with high incidence of direct sunlight for the southern and northern hemisphere, respectively. To the south orientation in high latitudes in the northern hemisphere, electrochromic glazing had to lower its states during almost all seasons. In this context, the use of electrochromic glazing to prevent direct sunlight offers more advantages in higher latitudes than in lower latitudes. This was confirmed in the studies of Wu *et al.* (2019) and Jain, Karmann and Wienold, 2022 concerning the shading schedules to the south orientation in high latitudes in Europe and the United States.

In Brazil, even for the highest latitudes represented by Rio de Janeiro (22° south) and Santa Maria (29° south), the electrochromic glazing did not lower its states during summer months for the north, offering less benefits for this orientation with high incidence of direct sunlight. In Brazil concerning all latitudes, the east and west orientations required shading – lowering of states during all seasons of the year. For the south orientation, only few periods of shading – lowering of states were required during summer for the cities with latitude ranges from Manaus (3° south) to Brasilia (15° south).

In this regard, no benefits were seen in using electrochromic glazing to the south in the Brazilian luminous context.

After discussing the differences in the shading schedules of electrochromic glazing according to city/latitude and window orientation, the results concerning the performance of electrochromic glazing regarding visual effects of light are presented and discussed in the next section.

6.2. Visual effects of light: assessment of the performance of electrochromic glazing

The intention of counting, categorizing, and comparing the explanatory and response variables was to answer questions 5.3.1 and 5.3.2 related to the performance of electrochromic glazing and the other three glasses (silver, clear, and reflective silver glass) regarding visual effects of light.

After the comparisons of the means using ANOVA, the variables were categorized according to the assessment criteria for visual effects of light, presented in section 5.2.2. The details of the statistical comparisons using ANOVA can be found in Appendix F. The categorization was done to evaluate the performance of each variable regarding the visual effects of light.

The criterion for daylight autonomy (DA) was the minimum illuminance of 300 lux in 50% of the time. A total of 832 cases achieved the minimum required, representing 96% of the simulated cases. Only in 32 cases was the minimum of 50% of the time not achieved. The list of these cases was displayed in Appendix G. Regarding the electrochromic glazing, only three cases in Santa Maria to the north did not achieve the minimum requirements for DA in positions P7, P8, and P9 (back of the room).

The reflective silver glass was the worst glass regarding the criterion for DA 300 lux, with 29 cases not achieving the minimum required of 50% of the time, but only for positions at the back of the room, P7, P8, and P9. This represented only 3% of the cases.

Two means for the two categories of daylight autonomy were calculated: the first one in less than 50% of the time and the second one in 50% of the time or more. They were created according to the assessment criteria for DA, with ‘yes,’ 0, or ‘no,’ 1. The means of these comparisons between the two bands of DA-50%, ‘yes’ – 1 or ‘no’ – 0, are presented in Table 9.

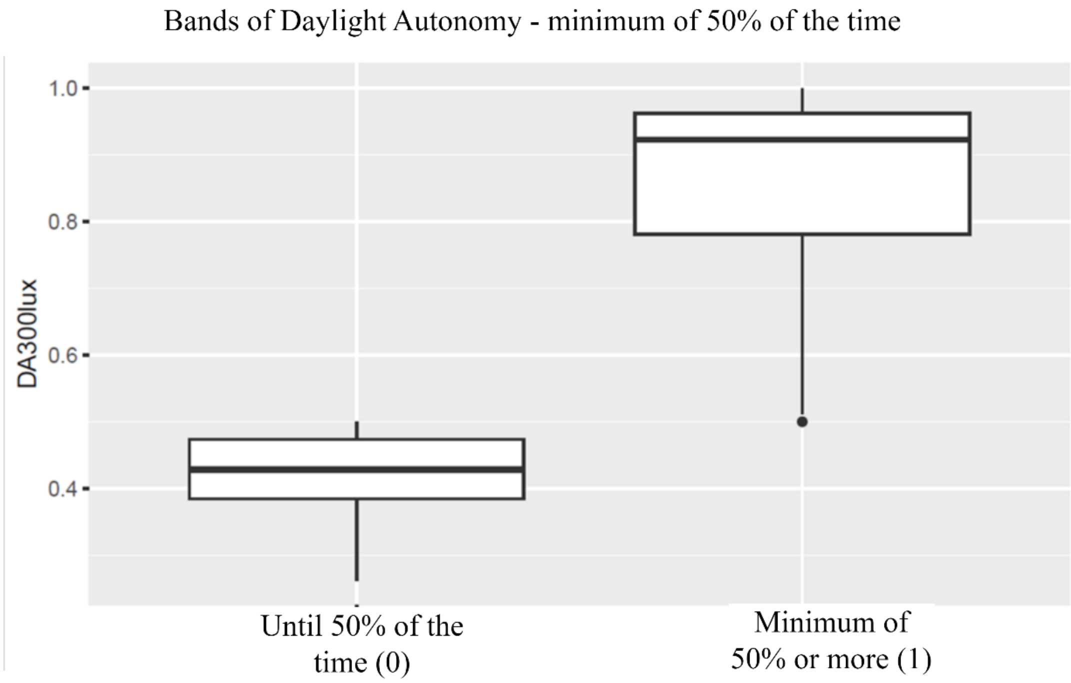
Table 9 – Comparison of means of the two categories according to the requirements of DA 300 lux in 50% of the time.

Categories of DA – 300 lux	**No (0)**	**Yes (1)**	**Total – 864 cases**
DA 300 Lux	0.415	0.860	0.844
UDI 100 to 3000 Lux	0.825	0.735	0.740
Annual glare (DGP > 40%)	0.0004	0.296	0.285

Source: The Author.

For the first category, 'no', no minimum requirement for DA was achieved; the mean was 41.5%. For the second category, 'yes,' the mean was 86% of the time. The results of the two categories can be visualized in Figure 42.

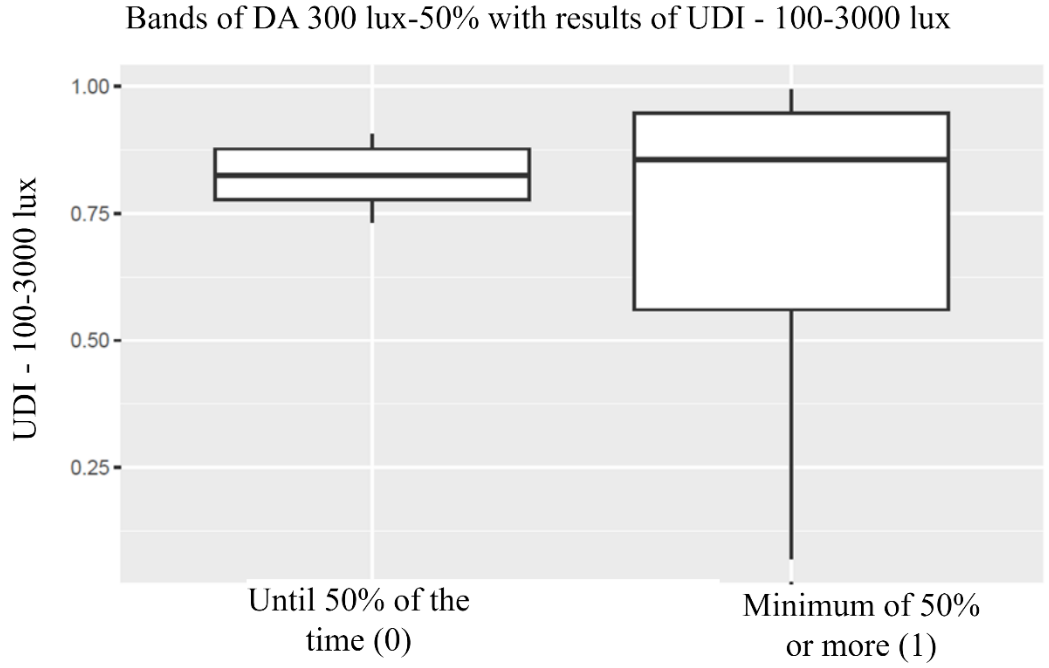
Figure 42 – Categorization of results in categories for DA according to the minimum of 50% of the time.



Source: The Author.

The second categorization was to compare the results of DA with useful daylight autonomy, between 100 lux and 3,000 lux. Differences in the means were also significant. When the minimum of DA of 50% was not achieved, 'no' – 0, the mean of UDI was 82.5%. For the category DA – 'yes,' the mean of UDI dropped to 73.5%, meaning that there was an excess light in the second category but also more variability in the results of UDI. This comparison of the two categories of DA with UDI can be visualized in Figure 43.

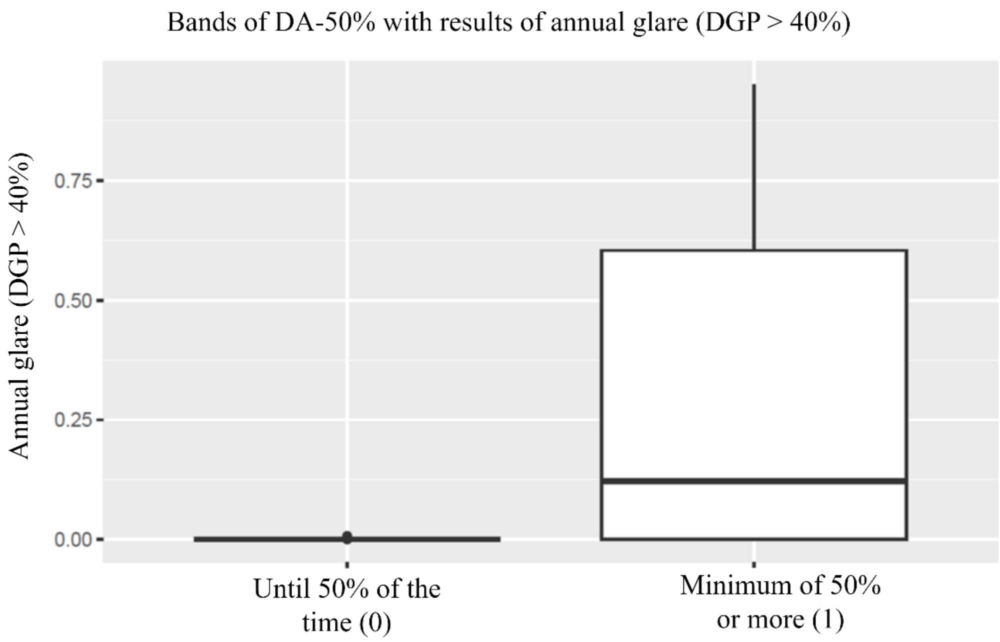
Figure 43 – Comparison between the two categories of DA 300 lux of the time with the results of UDI – 100-3000 lux.



Source: The Author.

The third categorization was to compare DA results with annual glare (DGP < 40%) results. Differences in the means were significant. When the minimum of DA of 50% was not achieved, ‘no’ – 0, the mean of annual glare was almost zero - 0% or no glare. For the category DA – ‘yes,’ the mean of annual glare increased to 29.6%, meaning that there was an excess light in the second category and more variability in the results of annual glare. This comparison of the two categories of DA with UDI can be visualized in Figure 44.

Figure 44 - Comparison between the two categories of DA with the results of annual glare (DGP).



Source: The Author.

The assessment of DA was analyzed separately per each response variable. The first analysis was performed per city/latitude, and they were described in the next section.

6.2.1. Daylight autonomy: data categorization

As detected through ANOVA, the only significant difference in the means was for the city's latitudes of Rio de Janeiro (22° south) and Santa Maria (29° south), which had the lowest. Comparing the cities/latitudes between 3° south, Manaus until the latitude of Brasilia, 15° South, only 1 to 4 cases of the category ‘no’ – 0 was counted. For Rio de Janeiro (22° south), the minimum criterion of DA – 50% was not achieved in 9 cases and for Santa Maria (29° south), in 13 cases. Results can be seen in Table 10.

Table 10 – Categorization of results for DA per city/latitude according to the achievement of the minimum of 50% of the time.

		DA 300 lux in 50% of the time			
City	**Latitude**	**No - 0**	**Yes - 1**	**Total**	**% Yes**
Manaus	3° south	3	141	144	98%
Recife	8° south	1	143	144	99%
Bom Jesus da Lapa	13° south	2	142	144	99%
Brasilia	15 south	4	140	144	97%
Rio de Janeiro	22° south	9	135	144	94%
Santa Maria	29° south	13	131	144	91%
Total number of cases		32	832	864	96%

Note: All four glasses included in the analysis. Source: The Author.

For the electrochromic glazing, the only 3 cases without the achievement of the criterion of DA 300 lux 50% of the time were detected in Santa Maria (29° south), as shown in Table 11. In all other cities, the count of yes was 100%.

Table 11 – Electrochromic glazing: categorizing results for DA per city/latitude according to the achievement of the minimum of 50% of the time.

		DA 300 lux in 50% of the time			
City/latitude	**Latitude**	**No - 0**	**Yes - 1**	**Total**	**% Yes**
Manaus	3° south	0	36	36	100%
Recife	8° south	0	36	36	100%
Bom Jesus da Lapa	13° south	0	36	36	100%
Brasilia	15 south	0	36	36	100%
Rio de Janeiro	22° south	0	36	36	100%
Santa Maria	29° south	3	33	36	92%
Total number of cases		3	213	216	99%

Source: The Author.

According to the window orientation, ANOVA did not detect any differences in the means. The results and the achievement of DA did not differ according to this variable. This result was expected as the facade was highly glazed. For the north, the east, and the west, the criterion for DA 300 lux was not achieved between 6 and 7 (in 2% and 3%) of cases and for the south in 14 cases, representing 6% of the cases. The simulated room had a WWR of 85% with depth of 6m, meaning that enough daylight - 300 lux - was received in at least 50% of the time in 96% of the cases. Table 12 describes the categorization of results for DA per window orientation according to the achievement of the minimum of 50% of the time.

Table 12 - Categorization of results for DA per window orientation according to the achievement of the minimum of 50% of the time.

	DA 300 lux in 50% of the time			
Orientation	**No - 0**	**Yes - 1**	**% Yes**	**Total**
East	6	210	97%	216
North	5	211	98%	216
West	7	209	97%	216
South	14	202	94%	216
Total	32	832	96%	864

Note: All four glasses included in the analysis. Source: The Author.

These three cases of "no" were detected in the north orientation for the electrochromic glazing, as described in Table 13. These results meant that no significative differences were found for the electrochromic glazing, and north was the worst orientation regarding criterion DA, which was achieved in 94% of the cases for this glazing material.

Table 13 – Electrochromic glazing: categorizing results for DA per window orientation according to the achievement of a minimum of 50% of the time.

	DA 300 lux in 50% of the time			
Orientation	**No - 0**	**Yes - 1**	**% Yes**	**Total**
East	0	54	100%	54
North	3	51	94%	54
West	0	54	100%	54
South	0	54	100%	54
Total	3	213	99%	216

Source: The Author.

According to the glazing material, ANOVA detected significant differences. **The only equivalence was between the electrochromic glazing and the silver reflective glass for response variable DA**. The visible transmittances of both glasses were similar for this variable. Results categorizing the glazing materials in the two categories of DA are displayed in Table 14. For electrochromic glazing, the category DA 'yes' was achieved in 99% of the cases, and for the reflective silver glass in 87% of the cases. All cases were counted in the category DA – 50% 'yes' for the other two glasses, neutral green and clear glass.

Table 14 - Categorization of results for DA per glazing material/glass according to the achievement of the minimum of 50% of the time.

	DA 300 lux in 50% of the time			
Glazing material/glass	**No - 0**	**Yes - 1**	**% Yes**	**Total**
Electrochromic glazing	3	213	99%	216
Reflective silver glass	29	187	87%	216
Clear glass	0	216	100%	216
Neutral green glass	0	216	100%	216
Total Geral	32	832	96%	864

Source: The Author.

The comparisons using ANOVA indicated that for the positions at the same distance from the window, the means were equivalent. In P1 to P6, all counted cases achieved the minimum criterion of DA, fitting in the category ‘yes’. In P7, 88% of the cases were counted in the category DA - ‘yes’, P8 in 92%, and P9 in 88% of the cases. Results are displayed in Table 15.

Table 15 - Categorization of results for DA per sensor/position in the room according to the achievement of the minimum of 50% of the time.

	DA 300 lux in 50% of the time			
Sensor/position	**No - 0**	**Yes - 1**	**% Yes**	**Total**
P1	0	96	100%	96
P2	0	96	100%	96
P3	0	96	100%	96
P4	0	96	100%	96
P5	0	96	100%	96
P6	0	96	100%	96
P7	12	84	88%	96
P8	8	88	92%	96
P9	12	84	88%	96
Total	32	832	96%	864

Note: All four glasses included in the analysis. Source: The Author.

As described in Table 16, these three cases without the achievement of the criterion of DA were detected in P7, P8, and P9, with one case each for the results of the electrochromic glazing.

Table 16 – Electrochromic glazing: categorizing results for DA per sensor/position in the room according to the achievement of the minimum of 50% of the time.

	DA 300 lux in 50% of the time			
Sensor/position	**No - 0**	**Yes - 1**	**% Yes**	**Total**
P1	0	24	100%	24
P2	0	24	100%	24
P3	0	24	100%	24
P4	0	24	100%	24
P5	0	24	100%	24
P6	0	24	100%	24
P7	1	23	96%	24
P8	1	23	96%	24
P9	1	23	96%	24
Total	3	213	99%	216

Source: The Author.

The results of useful daylight illuminance data categorization are described in the following section.

6.2.2. Useful daylight illuminance: data categorization

Two categories were created for variable UDI 100-3000 lux, as described in the method. The evaluated criterion was if UDI between 100 lux and 3,000 lux was achieved in at least 50% of the simulated hours. The two categories were ‘yes’ – 1 for the achievement of this criterion or ‘no’ – 0. The count of ‘yes’ was 690 cases, meaning that 80% of them achieved the established criterion, 16% lower than the ones counted for DA – 50% - ‘yes’.

When compared to each city/latitude, ANOVA did not detect significant differences in the means of UDI. The lowest percentage of UDI – ‘yes’ was for Manaus (3° south), counted in 74% of the cases, and Recife (8° south), in 78% of the cases. The highest percentage was for Santa Maria (29° south), representing 84% of the cases. The categorization, count, and percentages of the two categories of UDI are displayed in Table 17.

Table 17 – Categorization of results for UDI – 100-3000 lux per city/latitude according to the achievement of the minimum of 50% of the time.

		UDI – 100-3000 lux in 50% of the time			
City	**Latitude**	**No - 0**	**Yes - 1**	**% Yes**	**Total**
Manaus	3° south	37	107	74%	144
Recife	8° south	32	112	78%	144
Bom Jesus da Lapa	13° south	29	115	80%	144
Brasilia	15 south	29	115	80%	144
Rio de Janeiro	22° south	24	120	83%	144
Santa Maria	29° south	23	121	84%	144
Total number of cases		174	690	80%	864

Note: All four glasses included in the analysis. Source: The Author.

The same differences were observed for the categorization of results of UDI – 100-3000 lux for the electrochromic glazing, as described in Table 18. The lowest percentage of UDI – 'yes' was for Manaus (3° south), counted in 72% of the cases, and Recife (8° south), in 78% of the cases. The highest percentage was for Santa Maria (29° south), representing 86% of the cases. In the intermediate latitudes, Brasilia (15º south) and Bom Jesus da Lapa (13° south), the count of yes for the criterion of UDI was 81%.

Table 18 – Electrochromic glazing: categorizing results for UDI – 100-3000 lux per city/latitude according to the achievement of the minimum of 50% of the time.

		UDI – 100-3000 lux in 50% of the time			
City	**Latitude**	**No - 0**	**Yes - 1**	**% Yes**	**Total**
Manaus	3° south	10	26	72%	36
Recife	8° south	8	28	78%	36
Bom Jesus da Lapa	13° south	7	29	81%	36
Brasilia	15 south	7	29	81%	36
Rio de Janeiro	22° south	5	31	86%	36
Santa Maria	29° south	4	32	89%	36
Total number of cases		41	175	81%	216

Source: The Author.

The city/latitude with the lowest percentages of achievement for the minimum criterion of DA, Santa Maria – 29° south, presented the lowest percentages of UDI above 3000 lux: of 11%. In comparison, the cities/latitude of Manaus (3° south) and Brasilia (8° south) presented the highest percentages of UDI overtaking 3000 lux in more than 50% of the time, 28% and 22%, respectively. The details can be seen in Table 19.

Table 19 - Electrochromic glazing: categorizing results for UDI lower than 100 lux and UDI greater than 3000 lux per city/latitude according to the achievement of the minimum of 50% of the time.

		UDI < 100 lux in 50% of the time	**UDI > 3000 lux in 50% of the time**	
City	**Latitude**	**No - 0**	**Yes - 1**	**Total**
Manaus	3° south	0%	28%	100%
Recife	8° south	0%	19%	100%
Bom Jesus da Lapa	13° south	0%	19%	100%
Brasilia	15° south	0%	22%	100%
Rio de Janeiro	22° south	0%	14%	100%
Santa Maria	29° south	0%	11%	100%
Total Geral		0%	19%	100%

Source: The Author.

According to the window orientation, ANOVA did not detect any differences in the means. That meant the UDI – 100-3000 lux results did not differ according to this variable. For the East, 83% of the cases achieved the minimum criterion; for the West, the count was for 77% of the cases. For the north and the south, the category 'yes' was counted in 80% of the simulated cases. Results can be seen in Table 20.

Table 20 - Categorization of results for UDI – 100-3000 lux per window orientation according to the achievement of the minimum of 50% of the time.

	UDI – 100-3000 lux in 50% of the time			
Orientation	**No - 0**	**Yes - 1**	**% Yes**	**Total**
East	37	179	83%	216
North	43	173	80%	216
West	50	166	77%	216
South	44	172	80%	216
Total	174	690	80%	864

Note: All four glasses included in the analysis. Source: The Author.

For the electrochromic glazing, the best orientations were the east, with 94% of achievement for criterion UDI, and the north, with 87%. The worst orientations were the west and the south, with 76% and 67% achievement, respectively, for the evaluated variable, as can be seen in Table 21.

Table 21 – Electrochromic glazing: categorizing results for UDI – 100-3000 lux per window orientation according to the achievement of the minimum of 50% of the time.

	UDI – 100-3000 lux in 50% of the time			
Orientation	**No - 0**	**Yes - 1**	**% Yes**	**Total**
East	3	51	94%	54
North	7	47	87%	54
West	13	41	76%	54
South	18	36	67%	54
Total	41	175	81%	216

Source: The Author.

ANOVA detected significative differences in the means according to the glazing material/glass. **The only equivalence found was between electrochromic glazing and neutral green glass for response variable UDI**. This equivalence corresponded to the excessive illuminance levels, with values higher than 3000 lux, in the positions close to the window. All other glasses performed differently from each other regarding UDI. For electrochromic glazing and neutral green glass, the count of 'yes' regarding UDI – 100-3000 lux was 81% and 73%, respectively. Reflective silver glass performed the best regarding variable UDI, with 99% of the counted cases for 'yes,' while clear glass performed poorly in comparison with the other three glasses, with a count of 67% for the category 'yes.' For electrochromic glazing and neutral green glass, the count for UDI-100-3000 lux, 'yes' – 1 was 81% and 73%, respectively. These differences are explained by the different visible transmittances and in a highly glazed facade of the simulated room, reflective silver glass, with the lowest visible transmittance, presented the best performance regarding UDI. Results are displayed in Table 22.

Table 22 - Categorization of results for UDI – 100-3000 lux per glazing material according to the achievement of the minimum of 50% of the time.

	UDI – 100-3000 lux in 50% of the time			
Glazing material/glass	**No - 0**	**Yes - 1**	**% Yes**	**Total**
Electrochromic glazing	41	175	81%	216
Reflective silver glass	3	213	99%	216
Clear glass	72	144	67%	216
Neutral green glass	58	158	73%	216
Total Geral	174	690	80%	864

Note: All four glasses included in the analysis. Source: The Author.

The same observations were made regarding the sensor/position in the room for UDI in the two categories, 'yes' and 'no.' ANOVA indicated similar results for the positions located within the same distance from the window. The only exception is that positions P4 to P9 are presented with equivalent means. This did not happen to the analyzed positions for the DA – 300 lux variables. Results can be seen in Table 23.

Table 23 - Categorization of results for UDI – 100-3000 lux per sensor/position in the room according to the achievement of the minimum of 50% of the time.

	UDI – 100-3000 lux in 50% of the time			
Sensor/position	**No - 0**	**Yes - 1**	**% Yes**	**Total**
P1	55	41	43%	96
P2	65	31	32%	96
P3	54	42	44%	96
P4	0	96	100%	96
P5	0	96	100%	96
P6	0	96	100%	96
P7	0	96	100%	96
P8	0	96	100%	96
P9	0	96	100%	96
Total	174	690	80%	864

Note: All four glasses included in the analysis. Source: The Author.

The lowest count of the category 'yes' for UDI – 100-3000 lux 50% of the time was for positions P1 to P3, between 32% and 44% of the cases, at a distance of 0.50 m from the window. For positions P4 to P9, all evaluated cases were counted as 'yes' for UDI.

Equally, this behavior was similar to the counted cases for electrochromic glazing. The lowest count of the category 'yes' for UDI – 100-3000 lux in 50% of the time was for positions P1 to P3, between 25% and 50% of the cases, at a distance of 0.50 m from the window. For positions P4 to P9, all evaluated cases were counted as 'yes' for UDI. Results can be seen in Table 24.

Table 24 – Electrochromic glazing: categorizing results for UDI – 100-3000 lux per sensor/position in the room according to the achievement of the minimum of 50% of the time.

	UDI – 100-3000 lux in 50% of the time			
Sensor/position	**No - 0**	**Yes - 1**	**% Yes**	**Total**
P1	12	12	50%	24
P2	18	6	25%	24
P3	11	13	54%	24
P4	0	24	100%	24
P5	0	24	100%	24
P6	0	24	100%	24
P7	0	24	100%	24
P8	0	24	100%	24
P9	0	24	100%	24
Total	41	175	81%	216

Source: The Author.

As seen in the section 6.2.1, the highest percentages for the minimum criterion of DA – 300 lux/50% of the time were for positions P1 to P3, close to the window. For UDI levels below 100 lux, no counted cases were counted. This is explained by the elevated WWR of 85%, highly glazed facade. For the positions P1 to P3, 0.50 from the window, between 46% and 79% of the counted cases presented illuminance levels above 3,000 lux in at least 50% of the time.

Table 25 - Electrochromic glazing: categorizing results for UDI lower than 100 lux and UDI greater than 3000 lux per position according in at least 50% of the time.

Sensor/position	**UDI < 100 lux in 50% of the time**	**UDI > 3000 lux in 50% of the time**	**Total**
P1	0%	46%	100%
P2	0%	79%	100%
P3	0%	46%	100%
P4	0%	0%	100%
P5	0%	0%	100%
P6	0%	0%	100%
P7	0%	0%	100%
P8	0%	0%	100%
P9	0%	0%	100%
Total	0%	19%	100%

Source: The Author.

The results regarding annual glare (DGP) data categorization are described in the next section.

6.2.3. Annual glare (DGP < 40%): data categorization

Regarding the results of annual glare (DGP < 40%), two categories were created: no glare or perceived, and mostly not disturbing (DGP < 40%), at least 60% of the time, with the attributed value of 'yes' - 1 and with glare (DGP ≥ 40%), in more than 40% of the time, 'no' – 0, as this criterion was not achieved. In total, 559 cases achieved the criterion of no glare, representing 65% of the total cases.

When compared per city/latitude, ANOVA did not detect significative differences in the means of annual glare (DGP). The lowest percentage of annual glare – 'yes' was for Bom Jesus da Lapa (13° south), counted in 63% of the cases, and Recife (8° south), in 63%. The highest percentage was for Rio de Janeiro (22° south), representing 67% of the cases, 4% more than the lowest means. The categorization, count, and percentages of the two categories of annual glare are seen in Table 26.

Table 26 – Categorization of results for annual glare per city/latitude according to the achievement of the criterion DGP < 40% - no glare at least 60% of the time.

		Annual glare (DGP) < 40%			
City	**Latitude**	**No - 0**	**Yes - 1**	**% Yes**	**Total**
Manaus	3° south	51	93	65%	144
Recife	8° south	54	90	63%	144
Bom Jesus da Lapa	13° south	53	91	63%	144
Brasilia	15 south	51	93	65%	144
Rio de Janeiro	22° south	47	97	67%	144
Santa Maria	29° south	49	95	66%	144
Total number of cases		305	559	65%	864

Note: All four glasses included in the analysis. Source: The Author.

When the results of electrochromic glazing were analyzed separately, the percentages were 67% for all cities, without significant differences from the results considering the four glasses, as can be seen in Table 27.

Table 27 – Electrochromic glazing: categorizing results for annual glare per city/latitude according to the achievement of the criterion DGP < 40% - no glare in at least 60% of the time.

		Annual glare (DGP) < 40%			
City	**Latitude**	**No - 0**	**Yes - 1**	**% Yes**	**Total**
Manaus	3° south	12	24	67%	36
Recife	8° south	12	24	67%	36
Bom Jesus da Lapa	13° south	12	24	67%	36
Brasilia	15 south	12	24	67%	36
Rio de Janeiro	22° south	12	24	67%	36
Santa Maria	29° south	12	24	67%	36
Total number of cases		72	144	67%	216

Source: The Author.

According to the window orientation, ANOVA did not detect any differences in the means. That meant the annual glare (DGP < 40%) results did not differ according to this variable. For the north and west, the mean was 63%; for the east, 64%; and for the south, 69%. Results can be seen in Table 28.

Table 28 - Categorization of results for annual glare per window orientation according to the achievement of the criterion DGP < 40% - no glare at least 60% of the time.

	Annual glare (DGP) < 40%			
Orientation	**No - 0**	**Yes - 1**	**% Yes**	**Total**
East	77	139	64%	216
North	80	136	63%	216
West	80	136	63%	216
South	68	148	69%	216
Total	305	559	65%	864

Note: All four glasses included in the analysis. Source: The Author.

With similar equivalences, the percentages of the criterion for annual glare (DGP) per window orientation were equal to 67% for the four window orientations for the electrochromic glazing, as described in Table 29.

Table 29 – Electrochromic glazing: categorizing results for annual glare per window orientation according to the achievement of the criterion DGP < 40% - no glare in at least 60% of the time.

	Annual glare (DGP) < 40%			
Orientation	**No - 0**	**Yes - 1**	**% Yes**	**Total**
East	18	36	67%	54
North	18	36	67%	54
West	18	36	67%	54
South	18	36	67%	54
Total	72	144	67%	216

Source: The Author.

ANOVA detected significative differences in the means according to the glazing material/glass. The only equivalence found was between electrochromic glazing and neutral green glass. All other glasses performed differently from each other regarding annual glare. Results are displayed in

Table *30*. The worst performance regarding annual glare was for clear glass, and the category 'yes' – 1 was only counted for 35% of the cases. The count 'yes' – 1 regarding glare for the electrochromic glazing and neutral green glass was similar, 67% and 66%, respectively. **This meant that electrochromic glazing did not perform better than neutral green glass regarding glare. The best glass to prevent glare was the reflective silver glass**, with the count 'yes' – 1 in 91% of the cases.

Table 30 - Categorization of results for annual glare lux per glazing material according to the achievement of the criterion DGP < 40% - no glare in at least 60% of the time.

	Annual glare (DGP) < 40%			
Glazing material/glass	**No - 0**	**Yes - 1**	**% Yes**	**Total**
Electrochromic glazing	72	144	67%	216
Reflective silver glass	20	196	91%	216
Clear glass	140	76	35%	216
Neutral green glass	73	143	66%	216
Total Geral	305	559	65%	864

Note: All four glasses included in the analysis. Source: The Author.

The same observations were made regarding the sensor/position in the room for the annual glare in the two categories, 'yes' – 1, no glare, and 'no' – 0, with glare. ANOVA indicated similar results for the positions located within the same distance from the window. Results can be seen in Table 31.

As can be seen in Table 31 , the lowest count of the category ‘yes’ -1 was for positions P1 to P3, only counted in 10% to 22% of the time, at the distance 0.50 m from the window. For positions P4 to P6, between 74% and 77% of the cases were counted in the category ‘yes’ – 1 at distances of 3m and 5.5m from the window. In positions P7 and P9, glare was not a problem, and all cases were counted in the category ‘yes’ – 1, no glare.

Table 31 - Categorization of results for annual glare per sensor/position in the room according to the achievement of the criterion DGP < 40% - no glare in at least 60% of the time.

	Annual glare (DGP) < 40%			
Sensor/position	**No - 0**	**Yes - 1**	**% Yes**	**Total**
P1	75	21	22%	96
P2	86	10	10%	96
P3	75	21	22%	96
P4	22	74	77%	96
P5	25	71	74%	96
P6	22	74	77%	96
P7		96	100%	96
P8		96	100%	96
P9		96	100%	96
Total	305	559	65%	864

Source: The Author.

When electrochromic glazing was analyzed separately per position, results showed that in P1 to P3, 0.50 m from the window, the count of yes for no glare was counted in none of the simulated cases. This meant that the **use of electrochromic glazing with the generated shading schedule was insufficient to prevent disturbing and intolerable glare in the positions of the room close to the window**. For positions P4 to P9 all simulated cases were counted in the category ‘yes’ – 1, meaning glare was not an issue at the distances of 3m and 5.5m from the window. Table 32 describes the categorizing results of annual glare (DGP < 40%) for electrochromic glazing per sensor/position in the simulated room.

Table 32 – Electrochromic glazing: categorization of results for annual glare per sensor/position in the room according to the achievement of the criterion DGP < 40% - no glare in at least 60% of the time.

	Annual glare (DGP) < 40%			
Sensor/position	**No - 0**	**Yes - 1**	**% Yes**	**Total**
P1	24	0	0%	24
P2	24	0	0%	24
P3	24	0	0%	24
P4	0	24	100%	24
P5	0	24	100%	24
P6	0	24	100%	24
P7	0	24	100%	24
P8	0	24	100%	24
P9	0	24	100%	24
Total	72	144	67%	216

Source: The Author.

Concerning the employment of electrochromic glazing, problems related to glare were also identified by Jain, Karmann and Wienold (2022) also in a high latitude site, in Lausanne – Switzerland (46° north). The same issue was observed in the Brazilian cities/latitudes evaluated. Considerations regarding data categorization of assessment criteria of visual effects of light are described next.

6.2.4. Considerations regarding data categorization of assessment criteria of visual effects of light for electrochromic glazing

Question 5.3.1 was related to the specific aim 1.3.2 regarding the performance of electrochromic glazing related to the visual effects of light: How does the electrochromic glazing perform in relation to the established criteria of DA, UDI, and annual glare (DGP < 40%) in relation to city/latitude, orientation, and position in the room (sensor)?

As described in section 6.2, the data categorization of the criteria for visual effects of light was done to assess the performance of electrochromic glazing. The first categorization was made according to city/latitude. Regarding response variable daylight autonomy, criterion DA – 300 lux/50%, the worst performance was for Santa Maria (29° south), a city with the highest latitude, with a percentage of 92%. From Manaus (3° south) to Rio de Janeiro (22° south), all simulated cases (100%) achieved the minimum criterion for DA 300 lux, presenting similar performances.

For variable UDI – 100-3000 lux, the best performances of the electrochromic glazing were for the cities with the highest latitudes, Rio de Janeiro (22° south), with 86% of the cases achieving the minimum criterion and Santa Maria (29° south), with 89% of the cases. Bom Jesus da Lapa (13° south) and Brasilia (15° south) presented the percentages of achievement of 81% for variable UDI. In these cities/latitudes, the performance of the electrochromic glazing was intermediate. The cities with the lowest latitudes presented the worst performances, with a percentage of achievement for criterion UDI of 72% for Manaus (3° south) and 78% for Recife (8° south). **When compared to the luminous zoning per latitude range (Figure 27), electrochromic glazing was performed according to the three ranges of latitudes for variables DA and UDI. This was possibly explained because the cities of Rio de Janeiro (22° south) and Santa Maria (29° south) presented the lowest means of global horizontal illuminance and global radiation compared to the other four cities with lower latitudes, among other factors that reduced the excess of brightness in relation to the other four cities with lower latitudes.**

However, the performance of electrochromic glazing, considering the minimum criterion for annual glare (DGP lower than 40%) as a function of latitude, was not confirmed. In all six cities/latitudes, the performance of the dynamic glazing was equivalent. For all six cities/latitudes, the same percentage considering the achievement of the minimum criterion for annual glare was found: 67%. As discussed in section 4.3, the differences in brightness across the sky dome did not vary as a function of latitude as mentioned by Fonseca *et al.* (2023). This is the first possible reason for this result. Besides that, the second reason is that in highly glazed facades, excessive light entering the room increases the problems related to glare in different Brazilian latitudes/sites, as described by Gonçalves (2019). Therefore, glare was an issue for electrochromic glazing for all cities/latitudes in Brazil as well.

According to window orientation, the worst performance of the electrochromic glazing for DA 300 lux was for the north, with 94% achievement. For the other three orientations, the west, the east, and the south, the percentage of achievement of the minimum criterion for DA 300 lux was 100%. High percentages of the achievement of minimum criterion of DA 300 lux was expected since the simulated room was highly glazed. As indicated through ANOVA, there were no significant differences in variable DA's window orientation. Consequently, the performance of electrochromic glazing considering the minimum criterion of DA 300 lux was not affected by this variable.

When variable UDI 100-3000 lux was evaluated for the results of electrochromic glazing per window orientation, the south presented the worst performance, with a percentage of achievement of 67%. This occurred because electrochromic glazing was not required to lower its states, Consequently, its visible transmittance remained at 62.1%, except for the cities with lower latitudes, Manaus (3° south) and Recife (8° south), during summer months. The lowering of states to the south occurred with less frequency in Bom Jesus da Lapa (13° south) and Brasilia (15° south) in summer, in less than 3% of the year. In the clear state, the visible transmittance of electrochromic glazing remained at 62.1% in more than 87% of all year (8,760 hours) in all six cities/latitudes, causing excess light entering the room. **To the east, the west, and the north, the performance of electrochromic glazing was better, with percentages of achievement for a minimum criterion of UDI of 87%, 76%, and 94%, respectively. This was explained because, in these three orientations, electrochromic glazing was required to lower its states to medium tint and dark tint states. Consequently, less light entered the room and the illuminance levels were reduced, avoiding excess of light.**

The decrease in illuminance levels and control of excess light at more comfortable levels due to the lowering of states of the electrochromic glazing was confirmed in the experiment conducted by Wu *et al*. (2019) in a south-facing testbed at Berkeley, United States (37° N/122° W). In this study, the same decrease in illuminance levels was observed. The same was observed in the six Brazilian cities/latitudes evaluated. Additionally, Porto *et al.* (2020) also identified the decrease in the illuminance levels of electrochromic glazing when it was found in medium tint and dark tint states in two Brazilian latitudes: Camaquã – RS (30° south) and in Manaus (3° south). The problem of the study of Porto *et al.* (2020), however, is that visual comfort was not evaluated concerning glare and other aspects of visual comfort.

The performance of electrochromic glazing regarding annual glare did not present significant differences per window orientation. The percentages of achievement of minimum criterion (DGP lower than 40%) were similar, with differences of 5%. To the south, the percentage was 69%; to the west and the north, 63% and to the east, 64%. This indicated that the performance of electrochromic glazing was not affected by variable window orientation for variable annual glare – minimum criterion of DGP lower than 40%.

As mentioned by Jain, Karmann and Wienold (2022), problems related to glare also occurred with the employment of electrochromic glazing on work environments. From the studies mentioned in the literature review, the south was the most studied orientation regarding the performance of electrochromic glazing, due to the high incidence of direct sunlight and they were concentrated in the northern hemisphere, in high-latitude sites. To prevent problems related to glare and excess of light, electrochromic glazing was required to lower its tint states, decreasing also, therefore, illuminance levels inside the room.

Observations were made regarding light distribution across the nine positions inside the simulated room. For variable DA, lack of light – detected by the minimum criterion of 300 lux in at least 50% of the time – only 3 cases without achieving the criterion of DA 300 lux in 50% of the time were detected in Santa Maria (29° south). Regarding electrochromic glazing, glare was significant in positions P1 to P3, at the distance of 0.50m from the window, identified as disturbing and intolerable in almost all of the simulated cases. At the distances of 3m and 5.50m from the window, glare was not detected in any of the simulated cases.

For variable UDI considering the performance of electrochromic glazing, the lowest percentages for the achievement of minimum criterion for UDI 100-3000 lux were for the positions close to the window (P1 to P3), varying from 25% to 54%. In positions P4 to P9, in the middle and at the back of the room, all counted cases achieved the minimum criterion for this variable. This indicated that excess light was detected in the positions close to the window. This was more evident when variable annual glare was categorized.

For positions P1 to P3, close to the window, no cases for electrochromic glazing achieved the minimum criterion of DGP lower than 40% at least 60% of daylight hours. For positions P4 to P9, in the middle and at the back of the room, all cases achieved the minimum criterion of no glare (DGP < 40%). This indicated that the employment of electrochromic glazing did not prevent problems related to glare in the positions close to the window at a distance of 0.50m. Additionally, light distribution inside the room was not uniform, and excess light was detected in the positions close to the window, confirming the discussion in Chapter 2, in the studies conducted by Gonçalves (2019).

Even employing advanced technologies, such as electrochromic glazing, glare, and excess light can be a potential problem for highly glazed facades. Through measurements and subjective evaluations, Jain, Karmann, and Wienold (2022) addressed this problem in a high-latitude site – Lausanne, Switzerland (46° N/6°E). The same observation about the occurrence of glare facing the electrochromic glazing can be made regarding the evaluated Brazilian climates/latitudes.

Except for variable annual glare (DGP < 40%), which presented equivalences per city/latitude, the overall performance of electrochromic glazing regarding variables DA and UDI can be reported according to latitude range. Regarding annual glare (DGP < 40%), equivalence was observed among the six cities/latitudes. Therefore, recommendations for the use of electrochromic glazing based on the performance regarding visual effects of light were made according to the three latitude ranges illustrated in Figure 27. These recommendations are presented at the end of the discussion.

6.2.5. Considerations regarding data categorization of assessment criteria of visual effects comparing all four glasses

Question 5.3.2 was related to the specific aim 1.3.4 regarding the performance of electrochromic glazing in comparison with two conventional and one reflective glass regarding visual and non-visual effects. Visual effects: How does the choice of the glazing material affect the light distribution inside the room, measured with the metrics DA and UDI, and annual glare (DGP < 40%) according to variables city/latitude, orientation, and sensor/position?

The choice of glazing material/glass significantly influenced variables DA, UDI, and annual glare (DGP) due to the differences in the visible transmittances: electrochromic glazing, variable from 62.1% to 1.1%, reflective silver glass, 20.8%, neutral green glass, 43% and clear glass, 88%. Results of daylight autonomy considering all glasses presented mean higher than 50%. This was expected as the simulated room was highly glazed – with a WWR of 85%.

Overall, the luminous zoning per latitude range (Figure 27) in relation to variable city/latitude regarding visual effects made sense when the performance of all glasses was evaluated, including electrochromic glazing. The lowest results of daylight autonomy were for the cities with the highest latitudes, which were Rio de Janeiro (22° south) and Santa Maria (29° south), with values of global horizontal illuminance across the sky dome of 40 klux and 38 klux, and global radiation of, 362 kWh/m² and 349 kWh/m², respectively. Among the possible reasons, the annual daily averages of the global horizontal illuminance and radiation of the six simulated cities/latitudes were lower for the two mentioned cities with higher latitudes, as can be seen in Table 4. Among the cities with lower latitudes, from Manaus (3° south) to Brasilia (15° south), no statistically significant differences in the results of daylight autonomy were found. As described in section 5.1, the values of global horizontal illuminance and global radiation of these other four cities are higher, indicating higher results for daylight autonomy. These differences among the six/cities' latitudes regarding variable DA applied to all glasses, including electrochromic glazing.

The best performance for variable DA was for clear glass and neutral green glass, with percentages of achievement for criterion DA of 100%. The use of electrochromic glazing also presented a good performance with a percentage of achievement of 99%. The worst performance was for silver glass, with a percentage of achievement of 87%, but it still complied with the DA requirement – 300 lux at least 50% of the time per sensor/position. Despite the commented differences in DA categorization, electrochromic glazing, and reflective silver glass presented statistically similar performances. This is explained by the reduction of electrochromic glazing of its visible transmittance according to the shading schedule, from 62.1% of visible transmittance for the clear state to 1.1% in the dark tint state.

In regard to variable DA according to window orientation, no significant differences were found. To the north, the percentage of achievement for minimum criterion DA 300lux/50% was achieved in 98% of the cases; to the east, 97%; to the west, 97% and to the south, 94%. This was expected because the simulated room was highly glazed, allowing an excess light, and this explained the high percentages for variable DA. When variables UDI 100-3000 lux and annual glare were analyzed, problems related to excess of light were more evident.

As discussed this section, **no significative differences were found between the results of UDI and annual glare (DGP) according to the variables city/latitude and window orientation. In highly glazed facades, problems related to glare and excess of light occurred in all simulated cities/latitudes and window orientations, north, east, west, and south.** That explained one of the possible reasons for this equivalence detected through ANOVA. This was corroborated with the studies related to highly glazed facades of non-residential buildings in Brazil described in Chapter 2. In the studies regarding highly glazed facades employed in non-residential buildings, glare and excess of light were a common issue.

In the simulated model of a highly glazed non-residential room, the same problems occurred. Considering variable UDI-100-3000 lux, clear glass presented the worst performance due to its elevated visible transmittance, with a percentage of achievement of 67%. Neutral green glass and electrochromic glazing presented similar performances, with a percentage of achievement of 73%, and electrochromic glazing, with 81%. The best performance for variable UDI was reflective silver glass, with a percentage of achievement of 99%. This is explained by the reduced visible transmittance compared to the other glasses, and consequently, glare was reduced. It is important to mention that electrochromic glazing with predominant conditions in clear and light tint states presented higher visible transmittances, of 62.1% and 41%, respectively. That explained its similar performance compared to neutral green glass (VT – 43%).

When annual glare was evaluated, the performance varied according to the choice of glazing material/glass. As expected, the best performance regarding glare was for reflective silver glass, with a percentage of achievement for minimum criterion (DGP < 40%) of 91% of the cases. **The intermediate performance was for electrochromic glazing and neutral green glass with similar performances, with percentages of achievement for minimum criterion (DGP < 40%) of 67% and 66%, respectively. The worst glass to prevent glare was clear glass, with a percentage of 35% for minimum criterion related to annual glare**. The same reasons explained the equivalences with electrochromic glazing and neutral green glass – similar visible transmittances: electrochromic glazing with predominant conditions in clear and light tint states presented higher visible transmittances of 62.1% and 41%, respectively, and neutral green glass with visible transmittance of 43%.

As discussed in Chapter 2, differences in light distribution across the room were detected. This was a common characteristic for highly glazed non-residential buildings with side openings. The same situation was found in this study. Considering the position in the room/sensor[36], the majority of glasses, including electrochromic glazing, offer limitations to distribute variations of the transmitted energy entering the room. This findings were similar to the study of Felippe (2016). In this regard, shading devices offer better advantages than electrochromic glazing because these elements can redirect daylight, increasing daylight penetration inside the room and blocking direct sunlight.

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[36] NA: As mentioned at the beginning of this section, results of sensor disaggregated per glazing material/glass for variables regarding variables and criteria for DA, UDI and annual glare (DGP) were detailed in Appendix G.

From discussion mentioned in the literature review and comparing the performance of the electrochromic glazing with two conventional and one reflective glass, similar problems were detected considering light distribution in the simulated room (Amorim *et al.*, 2021a; Cavaleri; Cunha; Gonçalves, 2018; Lima *et al.*, 2022; Sarra; Mühlfart, 2020). In the simulated representative non-residential room, problems related to excess of light were detected in the positions close to the window. In this regard, **the use of electrochromic glazing is recommended with caution, as the employment of this technology on highly glazed facades did not prevent problems related to glare, particularly in the positions close to the window.**

For variable DA, positions P1 to P3, at the distance of 0.50 m from the window, and P4 to P6, 3 m from the window, presented adequate lighting for all glasses, with all simulated cases achieving the minimum criterion. The choice of reflective silver glass jeopardized the minimum of 300 lux at least 50% of the time in 46% of the cases in positions P7 to P9, at a distance of 5.50 m from the window.

Additionally, the use of reflective silver glass presented the best performance for reducing glare. For the other three glasses/glazing materials, including electrochromic glazing, the minimum of 300 lux was guaranteed in at least 99% of the simulated cases for criterion DA300/50%. The minimum criterion of DA was detected in 100% of the cases for clear and neutral green glass and 99% for electrochromic glazing. Only three cases without the achievement of minimum criterion for DA were counted for electrochromic glazing, in sensors P7 to P9 – back of the room for the north orientation, in Santa Maria (29° south), representing 4% of the cases for this glazing material/glass. As explained at the beginning, Santa Maria (29° south) was a city with higher latitude and lower solar radiation values and daily averages of global illuminance compared to the other five.

Despite similar performances for the criterion for UDI 100-3000 lux, the categorization for electrochromic glazing and neutral green glass was different in positions P1 to P3 – close to the window. The achievement percentages were between 25% to 50% for electrochromic glazing and between 8% to 25% for neutral green glass. All cases considering electrochromic glazing and neutral green glass in relation to the criterion for UDI in positions P4 to P9 achieved minimum criterion – in the middle and at the back of the room.

The best glazing material in relation to glare prevention and useful daylight illuminance in positions P1 to P3, close to the window, was reflective silver glass, with only 4%, 3 cases not achieving the minimum criterion for UDI and with 12% of the cases, 20 cases with glare (DGP < 40% in at least 60% of the time) in positions P1 to P3.

Electrochromic glazing and neutral green glass presented similar performances related to glare, with no cases achieving the minimum criterion for "no glare" in positions P1 to P3 – close to the window. For positions P4 to P9 – in the middle and at the back of the room, 99% of the cases for electrochromic glazing and neutral green glass achieved the minimum criterion for "no glare." Clear glass presented the worst performance regarding glare, with no cases of achievement of the minimum criterion for "no glare" in positions P1 to P6, at distances of 0.50 m and 3 m from the window – close to the window and in the middle of the room. Additionally, all cases for clear glass in P7 to P9, at the back of the room, achieved the minimum criterion for "no glare."

For the simulated highly glazed non-residential room for all cities/latitudes and the four window orientations, reflective silver glass presented the best performance in relation to the requirements of visual effects of light. However, reflective silver glass jeopardized the achievement of the requirement for DA 300 lux in the back of the room 46% of the time, whereas the reduction for electrochromic glazing was only 4%.

Electrochromic glazing and neutral green glass presented similar performances regarding variables UDI and annual glare (DGP). The problem with both glasses was the presence of disturbing and intolerable glare at a distance of 0.50 m from the window. Moreover, glare was not an issue for the positions in the middle and in the back of the room, positions P4 to P9 for electrochromic glazing and neutral green glass. T**he worst performance was for clear glass due to the related problems of intolerable and disturbing glare close to the window and in the middle of the room.**

All in all, potentialities related to the use of electrochromic glazing for the simulated Brazilian cities in the three ranges of latitude, from Manaus (3° south) to Santa Maria (29° south). The reduction in the visible transmittance of electrochromic glazing prevented excess of light, and this capability is not present in conventional and reflective glasses, which are commonly used in Brazil. Additionally, as described by Wu *et al.* (2019) and Jain, Karmann, and Wienold (2022), more accurate glare controls based not only on controlling the incidence of direct sunlight but also monitoring the luminance distribution of the sky can improve the performance of electrochromic glazing. In this context, they can be adapted for Brazilian climates as well.

The results concerning the performance of electrochromic glazing regarding non-visual effects of light are described in the next section.

6.3. Non-visual effects of light: Data categorization regarding assessment criteria for the performance of electrochromic glazing

The intention of categorizing the explanatory and response variables was to answer questions 5.3.3. to 5.3.6, related to the performance of electrochromic glazing and the other three glasses (silver, clear, and reflective silver glass) regarding non-visual effects of light.

After the comparisons of the means using ANOVA[37], the variables were categorized according to the assessment criteria for non-visual effects of light, presented in section 5.2.2. The categorization was done to evaluate particularly the performance of the electrochromic glazing regarding non-visual effects light. Detailed categorization per variable was displayed in Appendix J. The results of Mel-EDI were analyzed per hour, and secondly, the lack of circadian lighting and the lack of a minimum criterion of 250 lux of Mel-EDI were analyzed.

6.3.1. Categorization of variable Mel-EDI: assessment of the performance of electrochromic glazing and the other three glasses

This section was dedicated to answering question 5.3.3 related to the specific aim 1.3.3 regarding the performance of electrochromic glazing regarding non-visual effects of light: What is the performance of the electrochromic glazing in relation to measured circadian light supply using the metric Mel-EDI in relation to city/latitude, orientation, and sensor/position in the room? Question 5.3.5 was related to the specific aim 1.3.4 regarding the performance of electrochromic glazing compared to two conventional and one reflective glass regarding visual and non-visual effects. Non-visual effects: How does the choice of glazing material/glass affect the minimum supply of 250 lux (Mel-EDI) according to city/latitude, orientation, and sensor/position in the room?

The general criterion, Mel-EDI equal or greater than 250 lux, was achieved in 95% of the cases, 32,733 cases from the total of 34,560 (100%). As described in Appendix F, all described means per explanatory variables, city, window orientation, glazing material, sensor/position, date, and hour, were above the minimum criterion for Mel-EDI.

[37] NA: The comparisons between explanatory and response variables concerning non-visual effects of light can be seen in Appendix I.

Among the cities/latitudes, two groups with equivalent means were detected through ANOVA: Brasilia (15° south), Manaus (3° south), and Rio de Janeiro (22° south), and the other, Recife (8° south), Rio de Janeiro (22° south) and Santa Maria (29° south). Bom Jesus da Lapa (13° south) did not present equivalences to five other cities/latitudes.

Differences were detected among the cities when the results were disaggregated per city/latitude. For the city/latitude of Recife (8° south), no minimum criterion ('no' – 0) was counted in 9% of the cases, followed by Santa Maria (29° south) and Rio de Janeiro (22° south) in 6%, and Brasilia (15° south) and Manaus (3° South) in 3% of the cases. In Bom Jesus da Lapa (13° south), with distinct means as the other five cities, no minimum criterion was detected in 3% of the cases. Results can be seen in Table 33.

Table 33 – Categorization of results for Mel-EDI per city/latitude according to the achievement of the minimum of 250 lux.

		Mel-EDI ≥ 250 lux				
City	**Latitude**	**No - 0**	**Yes - 1**	**Total**	**% Yes**	**% No**
Manaus	3° south	236	5524	5760	98%	4%
Recife	8° south	529	5231	5760	99%	9%
Bom Jesus da Lapa	13° south	148	5612	5760	99%	3%
Brasilia	15 south	237	5523	5760	97%	4%
Rio de Janeiro	22° south	347	5413	5760	94%	6%
Santa Maria	29° south	330	5430	5760	91%	6%
Total number of cases		1827	32733	34560	96%	5%

Note: All four glasses included in the analysis. Source: The Author.

Regarding results for the electrochromic glazing per city/latitude, the best performance for electrochromic glazing regarding variable Mel-EDI was for Bom Jesus da Lapa (13° south), with the percentage of achievement for the minimum criterion of 250 lux in 93% of the cases. The intermediate performance according to variable Mel-EDI was for Manaus (3° south), with the percentage of achievement for the minimum criterion of 90%, followed by Rio de Janeiro (22° south), 89%, and Brasilia (15° south), with 88%. The worst performances were for Recife (8° south), with a percentage of 85%, and Santa Maria (29° south), with a percentage of 89%. The city/latitude of Rio de Janeiro (22° south) presented similar performance regarding variable Mel-EDI to two groups: the first with Manaus (3° south) and Brasilia (15° south); and the second with Recife (8° south) and Santa Maria (29° south). Bom Jesus da Lapa (13° south) did not present equivalences regarding variable Mel-EDI to any of the other five cities/latitudes. Results can be seen in Table 34.

Table 34 – Electrochromic glazing: categorizing results for Mel-EDI per city/latitude according to the achievement of the minimum of 250 lux.

		Mel-EDI ≥ 250 lux				
City	**Latitude**	**No - 0**	**Yes - 1**	**Total**	**% Yes**	**% No**
Manaus	3° south	143	1297	1440	90%	10%
Recife	8° south	210	1230	1440	85%	15%
Bom Jesus da Lapa	13° south	104	1336	1440	93%	7%
Brasilia	15 south	171	1269	1440	88%	12%
Rio de Janeiro	22° south	161	1279	1440	89%	11%
Santa Maria	29° south	141	1299	1440	90%	10%
Total number of cases		930	7710	8640	89%	11%

Source: The Author.

No relationships were found between the existing proposals for Brazilian luminous zoning, per availability of daylight, and latitude. Consequently, the performance of the electrochromic glazing regarding Mel-EDI could not be compared to the luminous zoning per availability of daylight nor latitude range, presented in Chapter 4. It is important to emphasize that this zoning was proposed concerning visual effects of light, in particular, the photopic illuminance, and not circadian lighting.

As mentioned in section 4.2, **Inanici, Abboushi, and Safranek (2023) highlighted that recently developed sky models presented progress compared to colorless sky models, but further research is needed to simulate daylight spectra accurately. The same can me said within the context of the six Brazilian simulated cities/latitudes.** The similarities and differences among the different sites of the Brazilian luminous zoning must take into account the light spectrum, particularly data containing spectral irradiance at different seasons and hours. In this respect, it will be possible to identify relationships regarding the results of Mel-EDI per city/latitude. Fortunately, data packages such as SKYSPECTRA have been proposed to encompass measurements from both long-term measurement sites and specific periods or experiments of spectral sky data, including the city of Sao Paulo - 23° south (Balakrishnan *et al.*, 2023). However, these tools were not made available yet and comparisons to the six evaluated Brazilian cities/latitudes could not be made. For this reason, recommendations based on the performance of electrochromic glazing considering variable Mel-EDI per city/latitude were made individually for each city/latitude evaluated.

As described in Appendix I, **ANOVA identified two equivalent results according to window orientation, to the north and the east.** The other two presented statistically different results, to the south and the west. The percentages with the minimum criterion for Mel-EDI were counted in 94% of the cases for the north and the east, and for the west and the south, in 96%. The differences per orientation according to the achievement of the minimum criterion of Mel-EDI were less than 2%. Results can be visualized in Table 35.

Table 35 – Categorization of results for Mel-EDI per window orientation according to the achievement of the minimum of 250 lux.

	Mel-EDI ≥ 250 lux				
Orientation	**No - 0**	**Yes - 1**	**Total**	**% Yes**	**% No**
East	538	8102	8640	94%	6%
North	529	8111	8640	94%	6%
West	388	8252	8640	96%	4%
South	372	8268	8640	96%	4%
Total	1827	32733	34560	95%	5%

Note: All four glasses included in the analysis. Source: The Author.

For electrochromic glazing regarding criterion for Mel-EDI, the count for the north and the east were the lowest and were similar, with percentages for "yes" of 86% and 88%, respectively. For the west the percentage for "yes" was 89%. The highest percentage for criterion of Mel-EDI was the south, with 95% of the cases with achieved minimum criterion of 250 lux. Results can be seen in Table 36.

Table 36 – Electrochromic glazing: categorizing results for Mel-EDI per window orientation according to the achievement of the minimum of 250 lux.

	Mel-EDI ≥ 250 lux				
Orientation	**No - 0**	**Yes - 1**	**Total**	**% Yes**	**% No**
East	266	1894	2160	88%	12%
North	313	1847	2160	86%	14%
West	240	1920	2160	89%	11%
South	111	2049	2160	95%	5%
Total	930	7710	8640	89%	11%

Source: The Author.

The lower percentages of achievement for the minimum criterion of Mel-EDI according to the window orientation could be explained because of the lowering of states according to the shading schedules presented in section 6.1, and detailed in Appendix D. As explained in section 5.2.3, the lowering of states of the electrochromic glazing was configured according to the incidence of more than 1,000 lux on the horizontal grid of the simulated room. **In this context, from the clear state in relation to the dark tint state, the melanopic transmission decreased from 55.7% to 1.8%, allowing less circadian lighting to enter the room than the other three glasses. The melanopic transmissions of clear, neutral green and reflective silver glass were 89%, 47.3%, and 23.4%, all higher than 1.8% (i.e. electrochromic glazing in dark tint state).** For the south orientation, with less direct sunlight, the lowering of states was required in specific periods, especially for Manaus (3° south) and Recife (8° south); however, in no more than 13% of the year. This explained the higher percentages of achievement for this orientation (south) considering all six simulated cities/latitudes. **Consequently, analyzing the lowering of states of electrochromic glazing and the melanopic transmissions of the four states in an hourly schedule per city/latitude and window orientation is a good prediction of the behavior of the results of Mel-EDI.**

Saiedlue *et al.* (2019) and Nazari, Matusiak and Stefani (2023) evaluated the performance of electrochromic glazing oriented to the south, with high incidence of direct sun in the northern hemisphere. For this reason, it was possible to identify that to prevent problems related to glare due to the incidence of direct sunlight, the decrease in circadian lighting also occurred. As described in Appendix H, the variables annual glare (DGP) and median-Mel-EDI are directly correlated.

ANOVA detected that the four glazing materials/glasses presented statistically different means. The most significant difference in the categorization was for electrochromic glazing, with the lowest number of cases for 'yes', achieved in 89% of the cases. **Regarding response variable Mel-EDI, electrochromic glazing performed the worst compared to the other three**. The count of 'yes' – 1 (Mel-EDI ≥ 250 lux) for reflective silver glass was 93%, for neutral green glass 97%, and for clear glass 99**%. This meant that the best glass/glazing material to provide circadian lighting was clear glass, and the worst to perform was electrochromic glazing**. **The worst performance for the electrochromic glazing could be explained by the reduction in the melanopic transmittances, from 55.7% (clear state) to 1.8% (dark tint state)**

configured according to the incidence of direct sunlight. As described in sections 5.2 and in Appendix B, the differences in the percentages of achievement of the criterion for Mel-EDI were explained by the distinct melanopic transmittances of each glazing material/glass. For this reason, analyzing the melanopic transmissions of the simulated glasses are a good indicator of the behavior of the results of Mel-EDI – circadian lighting. Results can be seen in Table 37.

Table 37 – Categorization of results for Mel-EDI per glazing material/glass according to the achievement of the minimum of 250 lux.

	Mel-EDI ≥ 250 lux				
Glazing material/glass	**No - 0**	**Yes - 1**	**Total**	**% Yes**	**% No**
Electrochromic glazing	930	7710	8640	89%	11%
Reflective silver glass	567	8073	8640	93%	7%
Clear glass	107	8533	8640	99%	1%
Neutral green glass	223	8417	8640	97%	3%
Total	1827	32733	34560	95%	5%

Source: The Author.

As for the date, June 21 (winter solstice) presented the lowest percentage with the number of hours, which achieved the minimum criterion of Mel-EDI in 91% of the cases. The highest percentage was for December 22 (summer solstice), with 97%. Close to the equinoxes, on March 22, the percentage was 95%, and on September 22, 96%. Results of Mel-EDI per date can be seen in Table 38.

Table 38 – Categorization of results for Mel-EDI per date according to the achievement of the minimum of 250 lux.

	Mel-EDI ≥ 250 lux				
Date	**No - 0**	**Yes - 1**	**Total**	**% Yes**	**% No**
March 22: Autumn equinox	408	8232	8640	95%	5%
June 21: Winter solstice	761	7879	8640	91%	9%
September 22: Spring equinox	385	8255	8640	96%	4%
December 22: Summer solstice	273	8367	8640	97%	3%
Total	1827	32733	34560	95%	5%

Source: The Author.

Similar to the results for all four glasses, the worst performance for electrochromic glazing was in the autumn equinox and the winter solstice. As for the date, June 21 (winter solstice) presented the lowest percentages with the number of hours with the achievement of the minimum criterion of Mel-EDI in 88% of the cases.

The highest percentage was for December 22 (summer solstice), with 92%. Close to the equinoxes, on March 22, the percentage was 86%, and on September 22, 91%. As detailed in Appendix I, the results of Mel-EDI were impacted in light of the seasonal variations of daylight, with lower availability during the winter months. Results of the categorization of Mel-EDI for the electrochromic glazing per date can be seen in Table 39.

Table 39 – Electrochromic glazing: categorizing results for Mel-EDI per date according to the achievement of the minimum of 250 lux.

	Mel-EDI ≥ 250 lux				
Date	**No - 0**	**Yes - 1**	**Total**	**% Yes**	**% No**
March 22: Autumn equinox	259	1901	2160	88%	12%
June 21: Winter solstice	292	1868	2160	86%	14%
September 22: Spring equinox	204	1956	2160	91%	9%
December 22: Summer solstice	175	1985	2160	92%	8%
Total	930	7710	8640	89%	11%

Source: The Author.

As for the positions, all percentages in P1 to P9 were above 90%. The percentages not achieving the minimum criterion for Mel-EDI were in P7 to P9, at the distance of 5.50 m from the window, detected in 10% of the cases. Results of categorization for Mel-EDI per sensor/position for all four glasses can be seen in Table 40.

Table 40 - Categorization of results for Mel-EDI per sensor/position according to the achievement of the minimum of 250 lux.

	Mel-EDI ≥ 250 lux				
Sensor/position	**No - 0**	**Yes - 1**	**Total**	**% Yes**	**% No**
P1	39	3801	3840	99%	1%
P2	17	3823	3840	100%	0%
P3	21	3819	3840	99%	1%
P4	199	3641	3840	95%	5%
P5	181	3659	3840	95%	5%
P6	191	3649	3840	95%	5%
P7	401	3439	3840	90%	10%
P8	385	3455	3840	90%	10%
P9	393	3447	3840	90%	10%
Total	1827	32733	34560	95%	5%
P1	39	3801	3840	99%	1%

Note: All four glasses included in the analysis. Source: The Author.

When analyzing results for the electrochromic glazing, it was identified that in P1 to P3, at the distance of 0.50 m from the window, the minimum criterion for Mel-EDI was achieved in 98% of the cases. As the distance from the window increased to 3 m, the results for P4 to P6 showed that the minimum criterion for Mel-EDI was not achieved in 12% of the cases. At the distance of 5.50 m from the window, no minimum criterion for Mel-EDI was achieved in 19% to 20% of the cases. **As discussed in Chapter 2, the majority of solar control glasses and switchable glazings, such as electrochromic glazings, offer limitations to redirect the transmitted energy inside the room. Consequently, the result is a lack of uniformity of daylight entering the room and an uneven distribution of circadian lighting inside the room**. Results of categorization for Mel-EDI per sensor/position for the electrochromic glazing can be seen in Table 41.

Table 41 – Electrochromic glazing: categorizing results for Mel-EDI per sensor/position according to the achievement of the minimum of 250 lux.

		Mel-EDI ≥ 250 lux			
Sensor/position	**No - 0**	**Yes - 1**	**Total**	**% Yes**	**% No**
P1	17	943	960	98%	2%
P2	1	959	960	100%	0%
P3	5	955	960	99%	1%
P4	118	842	960	88%	12%
P5	114	846	960	88%	12%
P6	118	842	960	88%	12%
P7	190	770	960	80%	20%
P8	182	778	960	81%	19%
P9	185	775	960	81%	19%
Total	930	7710	8640	89%	11%
P1	17	943	960	98%	2%

Source: The Author.

When the hours were evaluated, equivalences were detected through ANOVA. The most significant group was formed between 10 a.m. (10:00) and 4 p.m. (16:00), with percentages of cases that achieved minimum criteria between 95% and 99%. The hour with the highest percentage of achieved minimum criterion was 3 p.m. (15:00), 99%, and the lowest percentage was for 5 p.m. (17:00), counted in 78% of the cases. Results of Mel-EDI per hour can be seen in Table 42.

Table 42 – Categorization of results for Mel-EDI per hour according to the achievement of the minimum of 250 lux.

Mel-EDI ≥ 250 lux					
Hour	**No - 0**	**Yes - 1**	**Total**	**% Yes**	**% No**
08	237	3219	3456	93%	7%
09	128	3328	3456	96%	4%
10	154	3302	3456	96%	4%
11	58	3398	3456	98%	2%
12	76	3380	3456	98%	2%
13	164	3292	3456	95%	5%
14	110	3346	3456	97%	3%
15	43	3413	3456	99%	1%
16	98	3358	3456	97%	3%
17	759	2697	3456	78%	22%
Total	1827	32733	34560	95%	5%

Note: All four glasses included in the analysis. Source: The Author.

When analyzing the results for the electrochromic glazing per hour (shown in Table 43), different results were observed from the ones in Table 42, which included all four glasses/glazing materials. The decrease in the number of cases with the achievement of a minimum criterion of Mel-EDI was due to reductions in melanopic transmission, as configured in the hourly shading schedule, mainly from 8 a.m. to 11 p.m. and from 1 p.m. to 2 p.m., described in section 6.1. Variations according to the achievement of the minimum criterion of Mel-EDI as a function of the reduction in the melanopic transmission of medium tint and dark tint states of the electrochromic glazing were also observed by Nazari, Matusiak, and Stefani (2023).

Table 43 – Electrochromic glazing: categorizing results for Mel-EDI per hour according to the achievement of a minimum of 250 lux.

Mel-EDI ≥ 250 lux					
Hour	**No - 0**	**Yes - 1**	**Total**	**% Yes**	**% No**
08	93	771	864	89%	11%
09	106	758	864	88%	12%
10	147	717	864	83%	17%
11	58	806	864	93%	7%
12	76	788	864	91%	9%
13	164	700	864	81%	19%
14	110	754	864	87%	13%
15	31	833	864	96%	4%
16	0	864	864	100%	0%
17	145	719	864	83%	17%
Total	930	7710	8640	89%	11%

Source: The Author.

Overall, the glazing material/glass choice directly affected the minimum supply of 250 lux of Mel-EDI. Most of the problems were detected for electrochromic glazing in the positions at the back of the room, distance of 5.50 m from the window due to its reduced melanopic transmittance: in clear state, 55.7%, in light tint, 37.4%, in medium tint, 7% and dark state, of 1.8%. Moreover, for reflective silver glass, Tmel 20.8%, problems occurred at the back of the room in the cities/latitudes of Rio de Janeiro (22° south) and Santa Maria (29° south). No cases of lack of circadian lighting, minimum criterion for Mel-EDI were detected for clear glass (Tmel 89%) and neutral green glass (Tmel 47.3%).

Regarding the other three glasses, no cases with a lack of circadian lighting were detected for clear glass and neutral green glass, both glasses with higher melanopic transmittances. Only a few exceptions related to lack of circadian lighting were detected for reflective silver glass in Rio de Janeiro (22° south) and Santa Maria (29° south), cities with the highest latitudes: for the south in both cities and for the west, in Santa Maria (29° south). **Therefore, it was possible to conclude that electrochromic glazing presented the worst performance in relation to the minimum criterion of Mel-EDI**. The percentage of achievement for electrochromic glazing for criterion Mel-EDI was 89%. Reflective silver glass also presented problems related to the lack of circadian lighting in the cities of higher latitudes, with a percentage of achievement for Mel-EDI of 93%. **The best performances related to the achievement of the criterion for Mel-EDI were for neutral green glass**, with percentages of achievement of 97%,

and clear glass, 99%, with no detected cases of lack of circadian lighting in more than 30% of the hours per day. Overall, the reduced melanopic transmissions in medium tint (T_{mel} 7%) and dark tint states (T_{mel} 1.8%) of electrochromic glazing in relation to conventional glasses, like clear glass (T_{mel} 88%) is the major disadvantage of using this technology. This was confirmed by the study of Nazari, Matusiak, and Stefani (2023). **Lack of circadian lighting will potentially be a major drawback if electrochromic glazing technologies are implemented in Brazilian climates.**

To better understand and identify the cases of lack of circadian lighting, no minimum criterion of Mel-EDI, combining more than one response variable at a time was necessary. This is discussed in the next section.

6.3.2. Cases of lack of circadian lighting: performance of electrochromic glazing and the other three simulated glasses

This section was dedicated to answering question 5.3.4 related to the specific aim 1.3.3 regarding the performance of electrochromic glazing regarding lack of circadian lighting: In which cases there is a lack of circadian lighting when there is not a minimum of 250 lux of Mel-EDI in at least 70% of hours per day in relation to city/latitude, orientation, the position of the room/depth, and date?

Until this point, the first analyses were carried out per each explanatory variable for the response variable of Mel-EDI. To identify the cases in which the minimum criterion for Mel-EDI was not achieved, it was necessary to disaggregate the data per explanatory variable, city/latitude, window orientation, glazing material, sensor/position, and date. In this analysis, the daily combinations were made to aggregate the variable hours. Therefore, the evaluated criterion here was the minimum of 250 lux of Mel-EDI achieved in at least 70% per day. A total number of 3,456 combinations were analyzed. The question 5.3.4 is: In which cases there is a lack of circadian lighting when there is not a minimum of 250 lux of Mel-EDI in at least 70% of hours per day in relation to city/latitude, orientation, the position of the room/depth, and date?

The next step was to combine each explanatory variable. Firstly, two by two, three by three, and four by four. Until three by three variables, 100% of the combinations achieved the minimum criterion for Mel-EDI. When the explanatory variables were combined four by four, the differences and specific cases with no minimum criterion were identified. The detailed analysis of these combinations was displayed in Appendix J.

In general, 98% of the analyzed four-by-four combinations achieved the minimum criterion, representing 3,371 combinations. Only in 85 cases, 2% of the combinations lack circadian lighting was detected. Here are the general observations regarding the four-by-four combinations:

- City/latitude (6), orientation (4), glazing material/glass (4), and sensor/position (9): 99% of the combinations achieved the minimum criterion. Total number of combinations: 864. Not achieved in:
    - Positions P4 to P9 for electrochromic glazing to the north in Brasilia – 15° south (6 cases[38]).
    - Positions P7 and P8 for electrochromic glazing to the west in Recife – 8° south (2 cases).
    - Positions P7 for electrochromic glass to the north in Rio de Janeiro – 22° south (1 case).
    - Positions P7 to P9 for electrochromic glazing to the north in Santa Maria – 29° south (3 cases).
- City/latitude (6), orientation (4), glazing material/glass (4), and date (4): 98% of the combinations achieved the minimum criterion. Total number of combinations: 384. Not achieved in:
    - June 21, to the north, electrochromic glazing for Bom Jesus da Lapa (13° south); Total: 1 case for electrochromic glazing.
    - March 22, June 21, and September 22 to the north, electrochromic glazing for Brasilia (15° south): 3 cases for electrochromic glazing.
    - June 21, to the north, electrochromic glazing Manaus – 3° south (1 case); December 22, to the south, electrochromic glazing (1 case), both cases for Manaus – 3° south. Total: 2 cases for electrochromic glazing.
    - December 22, to the south, electrochromic glazing for Recife – 8° south (1 case); March 22, September 22, to the west, electrochromic glazing for Recife – 8° south (2 cases). Total: 3 cases for electrochromic glazing.
    - June 21 to the east, electrochromic glazing for Rio de Janeiro – 22° south (1 case); June 21, March 22, to the north, electrochromic glazing

[38] Here in this section, each case represents 10 hours in one day, in which no minimum of 250 lux (Mel-EDI) was achieved in at least 7 hours, 70% of the hours.

for Rio de Janeiro (2 cases); June 21, to the south, reflective silver glass for Rio de Janeiro – 22° south (1 case). Total: 3 cases for electrochromic glazing and 1 case for silver glass.

- March 22 and June 21, to the east, electrochromic glazing, Santa Maria – 29° south (2 cases); March 22 and September 22, to the east, reflective silver glass, Santa Maria – 29° south (2 cases); March 22 and September 22, to the north, electrochromic glazing for Santa Maria – 29° south (2 cases); June 21, to the west and the south, silver glass, Santa Maria – 29° south (2 cases). Total: 4 cases for electrochromic glazing and 4 cases for silver glass.

- City/latitude (6), glazing material/glass (4), sensor/position (9), and date (4): 98% of the combinations achieved the minimum criterion. Total number of combinations: 864. Not achieved in:
    - Brasilia (15° south), electrochromic glazing, P7 to P9 on June 21 (3 cases).
    - Manaus (3° south), electrochromic glazing, P7 to P9 on June 21 (3 cases).
    - Recife (8° south), electrochromic glazing, P7 to P9 on June 21 (3 cases).
    - Rio de Janeiro (22° south), electrochromic glazing, P7 to P9 on June 21 (1 case).
    - Santa Maria (29° south), reflective silver glass, P7 to P9, June 21 (3 cases).
- Window orientation (4), glazing material/glass (4), sensor/position (9), and date (4): 98% of the combinations achieved the minimum criterion. Total number of combinations: 576. Not achieved in:
    - North, electrochromic glazing, P4 to P6, on March 22 and June 21.
    - To the four orientations, P9 on June 21 in 9 cases.
    - For the south, lack of circadian lighting for the silver glass, on June 21 (3 cases).

Considering achieving the positive criterion of 70% of the day with the minimum criterion, Mel-EDI was not considered a good discriminating performance variable, as all the explanatory variables, city, window orientation, sensor/position, date, and time, had above 90% of positive performance. The problems regarding this response variable were only detected by combining four-by-four explanatory variables.

Bom Jesus da Lapa (13° south) presented the best performance regarding electrochromic glazing, except for June 21 to the north and only for the north. The worst performance regarding orientation for electrochromic glazing was for the north, with the highest listed cases in the six cities/latitudes.

Regarding the north orientation, the electrochromic glazing had the worst performance for Brasilia (15° south), with three counted cases on March 22, June 21, and September 22 in positions P4 to P9. For Santa Maria (29° south), the electrochromic glazing also did not achieve the minimum criterion of Mel-EDI on these three dates as Brasilia (15° south), but for positions P7 to P9, and not in the ones in the middle of the room. In Rio de Janeiro (22° south) for the north, a lack of circadian lighting was detected on March 22 and June 21 in positions P7 to P9. Lack of circadian lighting in Manaus (3° south) for the north was detected on June 21 in P7 to P9.

In general, window orientation east did not present problems of performance in the six simulated cities regarding electrochromic glazing, with some exceptions, in Manaus (3° south), Rio de Janeiro (22° south), and Santa Maria (29° south) on June 21 and Santa Maria (29° south) on March 22. For the cities of lower latitudes, Manaus (3° south) and Recife (8° south) presented problems with electrochromic glazing for the south on December 22. Particularly to the west, Recife (8° south) presented problems with the performance of the electrochromic glazing on March 22, September 22, and December 22, predominantly in positions P7 to P9.

As expected, most of the problems were detected for the electrochromic glazing due to its reduced melanopic transmittance in medium tint, 7%, and dark state, 1.8%. Regarding the other glasses, no cases with a lack of circadian lighting were detected for clear and neutral green glass. Only a few exceptions of lack of circadian lighting were detected for reflective silver glass in Rio de Janeiro (22° south) and Santa Maria (29° south), cities with the highest latitudes, for the south (both cities) and the west, in Santa Maria (29° south). Therefore, it was possible to conclude that the electrochromic glazing presented the worst performance in relation to the minimum criterion of Mel-EDI.

Comparisons were made with the existing proposals of luminous zoning in Brazil as described by Fonseca *et al.* (2019, 2023). Except for the south, no relationship with the lack of circadian lighting could be identified as a function of latitude regarding the performance of electrochromic glazing considering the lack of daylight. As mentioned, the cities of lower latitudes, Manaus (3° south) and Recife (8° south), presented problems with electrochromic glazing for the south on December 22 – the summer solstice, related to the lack of circadian lighting. However, **for the north, the west, and the east orientations, the lack of circadian light did not increase as a function of latitude. Variations in the shading schedule – lowering of states per city/latitude and orientation took into account other factors than latitude, such as cloudiness, outdoor illuminance levels, and variations in the sky spectrum per date, and hour.** For example, in Brasilia (15° south), a city with a lower latitude, a lack of circadian lighting was detected in 3 cases for the north orientation on March 22, June 21, and September 22. For Rio de Janeiro (22° south), a city with a higher latitude than Brasilia, a lack of circadian lighting was detected in 2 cases for the north, on June 21 and March 22.

As described by Fonseca *et al.* (2019, 2023), the availability of daylight and sky brightness was different and not according to latitude, and that might have impacted the results of the minimum criterion of Mel-EDI as well. To increase the understanding of the performance of electrochromic glazing as a function of variable city/latitude, more studies identifying the spectral irradiance data of the simulated six cities/latitudes in Brazil must be carried out, identifying similarities and differences considering daylight spectra.

In this context, the recommendations according to the performance of the electrochromic glazing regarding the achievement of 250 lux of Mel-EDI in at least 70% of the hours were reported separately for the six cities/latitudes and not clustered by the three latitude ranges as illustrated in Figure 27. The next section is dedicated to the categorization of the results for Mel-DER concerning the performance of electrochromic glazing and the other three glasses.

6.3.3. Categorization of results for Mel-DER: assessment of the performance of electrochromic glazing and the other three glasses

This section is dedicated to answering question 5.3.6 was related to the specific aim 1.3.4 regarding the performance of electrochromic glazing in comparison with two conventional and one reflective glass regarding visual and non-visual effects. Non-visual effects: What are the variations in the melanopic daylight efficacy ratio (Mel-DER) per city/latitude, orientation, glazing material, sensor/position, and date when the glazing material is modified?

Regarding the spectrum, the categorization of results of Mel-DER reported the melanopic efficacy of the simulated variables compared to the melanopic efficacy of CIE Illuminants D55 and D65, standard daylights. The general criterion, Mel-DER equal or greater than 0.904, was achieved in 73% of the cases, 25,180 cases from the total of 34,560 (100%), corresponding to the melanopic efficacy of CIE Illuminants CIE D55 and D65 (Daylight 5500 K and 6500 K). The details of the categorization for Mel-DER can be seen in Appendix J. To better understand the categorization of Mel-DER, results were reported with a combination of each of the two explanatory variables, i.e., two-by-two.

When results were disaggregated per city/latitude and orientation, the highest percentages for the minimum criterion for Mel-DER were found for the east, except for Bom Jesus da Lapa (13° south) and Brasilia (15° south), between 72% and 76%. For these two cities/latitudes, the highest percentages were for the south, but still with small differences. The lowest percentages were found to the west, with percentages varying from 58% in Santa Maria – 29° south (58%) to 76% in Bom Jesus da Lapa – 13° south.

The highest percentages regarding all cities/latitudes were found in Bom Jesus da Lapa (13° south) in all orientations, being the only city with a predominant condition of clear sky, an annual daily average of cloudiness of 34%. Additionally, to the north, in Bom Jesus da Lapa (13° south), Brasilia (15° south), and Manaus (3° south), the percentages were higher than 74%, and the lowest percentages to the same orientation were for Recife (8° south), Rio de Janeiro (22° south) and Santa Maria (29° south), between 65% and 68%. Results can be seen in Table 44.

Table 44 - Categorization of results for Mel-DER per city/latitude and orientation according to the achievement of the minimum of 0.904.

Mel-DER ≥ 0.904 (CIE Illuminants D55 and D65)					
City	**Latitude**	**East**	**North**	**West**	**South**
Manaus	3° south	75.9%	74.4%	64.8%	74.8%
Recife	8° south	72.1%	68.1%	61.0%	70.3%
Bom Jesus da Lapa	13° south	87.2%	83.3%	76.0%	89.1%
Brasilia	15 south	75.4%	76.4%	68.5%	79.0%
Rio de Janeiro	22° south	78.2%	67.4%	63.1%	76.0%
Santa Maria	29° south	72.4%	65.3%	58.3%	71.5%
Total number of cases		76.9%	72.5%	65.3%	76.8%

Note: Lower percentages were marked with yellow, and the highest highlighted with blue. Analysis included all four glasses. Source: The Author.

When the performance of electrochromic glazing was evaluated, differences among variables in cities/latitudes and window orientations were perceived. As can be seen in Table 45, the lowest results were for the west, varying from 35% in Rio de Janeiro (22° south) to 55% in Bom Jesus da Lapa (13° south). Exceptions were detected for Recife (8° south), with the lowest percentage of 5% for the north, and Santa Maria (29° south), with a percentage of 8% for the south over the four simulated four days. The predominance of the electrochromic glazing was a clear state, with the lowest M/P ratio – transmitting fewer short wavelengths of light, less blue light in comparison with longer wavelengths, and more yellow, green, and red light (Appendix B). This explained the reduced values of Mel-DER.

As described in Table 45 too, the highest results were for the east, in Bom Jesus da Lapa (13° south), Manaus (3° south), and Rio de Janeiro (22° south), varying from 49% in Rio de Janeiro to 80% in Bom Jesus da Lapa. Additionally, the highest results in Brasilia (15° south) and Santa Maria (29° south) for the north, with percentages of 57% and 38%, respectively. The highest results of the evaluated criterion for Mel-DER in Recife (8° south) were for the west, with a percentage of 30%. The highest results of Mel-DER to the east and the north coincided with the predominance of the electrochromic glazing in medium and dark tint states, as the lowering of tint states was required to prevent the incidence of direct sun, as mentioned in section 6.1, Appendix C and Appendix D.

Table 45 – Electrochromic glazing*:* categorization of results for Mel-DER per city/latitude and orientation according to the achievement of the minimum of 0.904.

Mel-DER ≥ 0.904 (CIE Illuminants D55 and D65)

City	Latitude	East	North	West	South
Manaus	3° south	50.0%	42.8%	32.5%	37.5%
Recife	8° south	25.6%	5.3%	30.0%	21.9%
Bom Jesus da Lapa	13° south	80.6%	60.3%	55.3%	67.2%
Brasilia	15 south	51.1%	57.5%	30.6%	32.8%
Rio de Janeiro	22° south	49.4%	38.3%	35.6%	28.1%
Santa Maria	29° south	25.6%	38.6%	20.0%	8.6%
Total number of cases		47.0%	40.5%	34.0%	32.7%

Note: Lower percentages were marked with yellow, and the highest highlighted with blue. Source: The Author.

No relationship between the results of Mel-DER and latitude was observed. To understand the performance of the electrochromic glazing considering city/latitudes and the sky spectral data of each site, more studies must be carried out to understand this issue within the Brazilian luminous context, identifying similarities and differences among these six cities/latitudes. As described by Inanici, Abboushi, and Safranek (2022), sky spectral data in ALFA varies according to atmospheric conditions, including trace gas and temperature profiles, aerosol particles and surface albedo, entered into libRadtran. The sky spectrum in this regard varied according to the chosen hour, site, latitude, longitude, sky condition, and ground albedo. For this reason, it was not possible to understand the profiles of each sky spectral data according to the simulated six cities/latitudes. Fortunately, as mentioned in Chapter 2, data packages of sky spectral data are being developed to address these issues.

Results of Mel-DER for electrochromic glazing were influenced by the generated shading schedule inputted in the simulations in ALFA, as described in Appendix C. Nazari, Matusiak, and Stefani (2023) identified lower results of Mel-DER for electrochromic glazing in a clear state, indicating less presence of blue light in comparison to clear glass. In the dark state, the light transmission of electrochromic glazing shifted, and more blue light was transmitted to the room.

Comparing with the shading schedules – lowering of states inputted in ALFA, described in Appendix C, the higher values of Mel-DER to the north and the east could be explained because the medium tint and dark tint states were required with more frequency when compared to the west and with low frequency to the south orientation, except for the cities with lower latitudes, from Manaus (3° south) to Brasilia (15° south) at specific hours during the summer months.

As described in section Appendix I, ANOVA did not identify equivalences in the means according to the glazing material/glass. It was possible to identify the highest percentages for the minimum criterion of Mel-EDI for the silver glass in all simulated cities/latitudes, meaning that this glass also contains one of the highest spectral transmissions for the blue wavelength (M/P ratio of 1.12). The lowest percentages were for electrochromic glazing, between 23% and 65%. The predominant state for electrochromic glazing was the ‘clear state’, with the lowest M/P ratio of the visible transmittance, 0.90. It is important to mention that in the medium dark state (M/P ratio of 1.28) and in the dark state (M/P ratio of 1.65), the electrochromic glazing transmitted more blue light (short wavelength) in relation to medium and long wavelengths. However, as discussed before, this was not the predominant state in the simulations. It is important to consider that minor differences in the absolute values of M/P ratios cause big impacts in the stimuli for visual and non-visual effects of light, modifying the light spectrum entering the room.

Comparing the other two glasses, the percentages for the criterion of Mel-DER were higher for neutral green glass (M/P ratio of 1.10), varying from 90% to 93% and lower for clear glass (M/P ratio of 1.01), varying from 58% and 82% regarding the six simulated cities/latitudes. More transmission in the visible spectrum for shorter wavelengths of light was already identified by Sacht et al. (2016) when studying solar control glasses. This was expected since these glasses were made to reduce the transmission and absorption of long wavelength radiation, allowing less infrared radiation and less red spectrum of visible light. Results can be visualized in Table 46.

Table 46 - Categorization of results for Mel-DER per city/latitude and glazing material/glass according to the achievement of the minimum of 0.904.

		Mel-DER ≥ 0.904 (CIE Illuminants D55 and D65)			
City	**Latitude**	**Electrochromic glazing**	**Silver glass**	**Clear glass**	**Green glass**
Manaus	3° south	40.7%	91.7%	66.5%	91.1%
Recife	8° south	20.7%	94.5%	62.1%	94.2%
Bom Jesus da Lapa	13° south	65.8%	94.0%	82.0%	93.9%
Brasilia	15 south	43.0%	92.8%	71.0%	92.4%
Rio de Janeiro	22° south	37.8%	90.7%	65.7%	90.5%
Santa Maria	29° south	23.2%	93.3%	58.4%	92.6%
Total number of cases		38.5%	92.8%	67.6%	92.5%

Note: Lower percentages were marked with yellow, and the highest highlighted with blue. Analysis separated per glazing material/glass. Source: The Author.

It is also important to note that the largest variation according to the percentages for the minimum criterion of Mel-DER was for electrochromic glazing due to variations in the shading schedule, with variations in the melanopic transmission per date, city/latitude, and window orientation. The highest percentages were for Bom Jesus da Lapa (13° south) and Brasilia (15° south) in the intermediate latitudes, as presented in Table 46. This happened due to the lowest percentages of cloudiness and high incidence of direct sunlight on March 22 and September 22, as described in the input data in Appendix C. Consequently, the electrochromic glazing was set to lower its visible state from clear to predominantly medium and dark tint states, transmitting more portions of the blue spectrum. As a result, results of Mel-DER increased for Bom Jesus da Lapa (13° south) and Brasilia (15° south), with this happening with less intensity in the other four cities/latitudes.

Regarding the cities with the lowest latitudes, the highest percentage for Manaus (3° south) was on September 22, with 83%, and for Recife (8° south) was on December 22, with 69%. As for the cities with the highest latitudes, in Rio de Janeiro (22° south) and in Santa Maria (29° south), the highest percentages were found on March 22, with 78% and 73%, respectively. For the cities with intermediate latitudes, Bom Jesus da Lapa (13° south) and Brasilia (15° south), the highest percentages were on September 22, varying from 91% to 86%, respectively. Results of the categorization of Mel-DER per city/latitude and date are presented in Table 47.

Table 47 - Categorization of results for Mel-DER per city/latitude and date according to the achievement of the minimum of 0.904.

Mel-DER ≥ 0.904 (CIE Illuminants D55 and D65)					
City	**Latitude**	Mar.	Jun.	Sept.	Dec.
Manaus	3° south	74.2%	66.8%	83.1%	65.8%
Recife	8° south	67.4%	67.1%	67.5%	69.4%
Bom Jesus da Lapa	13° south	76.5%	85.0%	91.2%	83.1%
Brasilia	15 south	81.1%	64.8%	86.3%	67.1%
Rio de Janeiro	22° south	78.1%	75.1%	62.2%	69.4%
Santa Maria	29° south	73.1%	63.3%	69.4%	61.8%
Total		75.1%	70.3%	76.6%	69.4%

Note: Lower percentages were marked with yellow, and the highest highlighted with blue. Analysis included all four glasses. Source: The Author.

Different results were found for the electrochromic glazing when they were disaggregated per city/latitude and date, as can be visualized in Table 48. Percentages for Mel-DER, minimum of 0.904, corresponding to melanopic efficacy of CIE illuminants D65 and D55 varied per city/latitude. The lowest percentages were found on December 22 in Brasilia (15° south), 5%; Manaus (3° south), 26%; and Santa Maria (29° south), 2.5%. The lowest percentage in Bom Jesus da Lapa (13° south) was found on March 22 with 37%, Recife (8° south) on June 21, 10%, and Rio de Janeiro (22° south) on September 22, 6%.

The highest percentages varied per city/latitude, as seen in Table 48. In Brasilia (15° south) and Manaus (3° south), these were on September 22, with 74% and 63%, respectively. The highest percentages in Bom Jesus da Lapa (13° south) and Rio de Janeiro (22° south) were on June 21, with 84% and 65%, respectively. In Recife (8° south), the highest percentages were on December 22, with 35%, and in Santa Maria (29° south) on March 22, with 41%.

Table 48 – Electrochromic glazing: categorization of results for Mel-DER per city/latitude and date according to the achievement of the minimum of 0.904.

Mel-DER ≥ 0.904 (CIE Illuminants D55 and D65)					
City	**Latitude**	Mar.	Jun.	Sept.	Dec.
Manaus	3° south	37.5%	36.1%	63.1%	26.1%
Recife	8° south	18.6%	10.0%	18.6%	35.6%
Bom Jesus da Lapa	13° south	37.5%	84.4%	81.9%	59.4%
Brasilia	15 south	60.6%	31.9%	74.4%	5.0%
Rio de Janeiro	22° south	53.9%	65.6%	6.7%	25.3%
Santa Maria	29° south	41.1%	18.3%	30.8%	2.5%
Total		41.5%	41.1%	45.9%	25.6%

Note: Lower percentages were marked with yellow, and the highest highlighted with blue. Source: The Author.

Differences were noted when the glasses were contrasted with the dates. As discussed, electrochromic glazing presented the lowest percentages of the minimum criterion of Mel-DER, and silver glass had the highest. September 22 presented the highest percentages, an average of 77%, followed by March 22, 75%, and June 21, with 70%. The lowest percentages including all four glasses/glazing materials were found on December 22. Results combining variables glazing material/glass and date are described in Table 49.

Table 49 - Categorization of results for Mel-DER per glazing material/glass and date according to the achievement of the minimum of 0.904.

Mel-DER ≥ 0.904 (CIE Illuminants D55 and D65)				
Glazing material/glass	Mar.	Jun.	Sept.	Dec.
Electrochromic glazing	41.5%	41.1%	45.9%	25.6%
Reflective silver glass	94.2%	88.2%	94.2%	94.7%
Clear glass	70.7%	64.3%	72.5%	63.0%
Neutral green glass	93.8%	87.7%	93.8%	94.4%
Total	75.1%	70.3%	76.6%	69.4%

Note: Lower percentages were marked with yellow, and the highest highlighted with blue. Source: The Author.

According to the results shown in Table 50, the worst percentages were for electrochromic glazing, with 39%. The best percentages were for reflective silver glass with 92%, and for neutral green glass with 92% of the cases with Mel-DER equal or greater than 0.904. For clear glass, the percentage of achievement was 68%. As discussed before, these differences were explained by the spectral transmissions of each of the four simulated glazing materials/glasses.

Table 50 – Categorization of results for Mel-DER per glazing material/glass to the achievement of the minimum of 0.904.

Mel-DER ≥ 0.904 (CIE Illuminants D55 and D65)			
Glazing material/glass	Yes	Total	Percentage
Electrochromic glazing	3330	8640	39%
Reflective silver glass	8020	8640	93%
Clear glass	5842	8640	68%
Neutral green glass	7988	8640	92%
Total	25180	34560	73%

Note: Lower percentages were marked with yellow, and the highest highlighted with blue. Source: The Author.

As for the sensors/position in the room, higher melanopic efficacy according to the minimum criterion for Mel-DER was found for positions P1 to P3, with percentages varying from 66% to 81% at a distance of 0.50 m from the window. In P4 to P7, the percentages varied between 67% and 79% at a distance of 3m from the window. The lowest percentages were for the positions at the distance of 5.50m from the window, in P7 to P9, with percentages varying from 60% to 71%. These observations applied to all four orientations and apply to all glasses. The results can be visualized in Table 51.

Table 51 - Categorization of results for Mel-DER per orientation and sensor/positions according to the achievement of the minimum of 0.904.

Mel-DER ≥ 0.904 (CIE Illuminants D55 and D65)									
	Sensor/position in the room								
Window orientation	P1	P2	P3	P4	P5	P6	P7	P8	P9
East	81.1%	80.1%	79.2%	79.3%	79.7%	78.9%	71.4%	71.3%	70.9%
North	80.4%	77.2%	77.3%	75.6%	75.6%	74.4%	64.2%	64.1%	63.6%
West	66.4%	67.1%	67.4%	67.7%	68.5%	68.6%	60.5%	60.9%	60.5%
South	80.4%	81.6%	83.5%	78.4%	80.3%	79.7%	68.5%	69.7%	68.9%
Total	77.1%	76.5%	76.8%	75.3%	76.0%	75.4%	66.1%	66.5%	66.0%

Note: Lower percentages were marked with yellow, and the highest highlighted with blue. Source: The Author.

Similarly, results for the electrochromic glazing indicated higher melanopic efficacy according to the minimum criterion for Mel-DER for positions P1 to P3, with percentages varying from 35% to 53% at a distance of 0.50 m from the window. In P4 to P7, the percentages varied between 32% and 46%, at the distance of 3m from the window. The lowest percentages were for the positions at the distance of 5.50m from the window, in P7 to P9, with percentages varying from 30% to 42%. These observations applied to all four orientations. These differences according to the positions in the room according to the distance from the window were identified in the literature review. Categorizing results for electrochromic glazing for Mel-DER per orientation and position in the room can be seen in Table 52.

Table 52 – Electrochromic glazing: categorizing results for Mel-DER per orientation and sensor/position according to the achievement of the minimum of 0.904.

Mel-DER ≥ 0.904 (CIE Illuminants D55 and D65)									
	Sensor/position in the room								
Window orientation	P1	P2	P3	P4	P5	P6	P7	P8	P9
East	52.1%	53.8%	52.5%	46.3%	45.8%	44.6%	42.9%	42.5%	42.9%
North	45.4%	44.6%	42.9%	42.9%	42.9%	42.1%	34.6%	34.6%	34.2%
West	33.8%	34.6%	35.0%	33.8%	33.8%	33.8%	33.8%	33.8%	33.8%
South	33.8%	34.2%	36.7%	32.5%	32.9%	32.9%	30.0%	30.8%	30.4%
Total	41.3%	41.8%	41.8%	38.9%	38.9%	38.3%	35.3%	35.4%	35.3%

Note: Lower percentages were marked with yellow, and the highest highlighted with blue.
Source: The Author.

Overall, electrochromic glazing showed the lowest percentages in achieving the minimum criterion for Mel-DER, with only 39% of all simulated cases meeting the threshold. The reported findings indicated that neutral green and reflective silver glass performed the best in terms of meeting the Mel-DER criterion due to their higher blue light transmission compared to clear glass and electrochromic glazing. Moreover, electrochromic glazing exhibited the highest variations in Mel-DER, due to its ability to transition between distinct states, from clear (M/P ratio in transmission of 0.90) to dark (M/P ratio of 1.65).

Regarding the spectral analysis of simulated glasses, including electrochromic glazing, differences in Mel-DER results can be attributed to wavelength transmission, as seen in Appendix B. Another useful indicator to compare with Mel-DER results is the M/P ratio in transmissions for each glazing material. Higher M/P ratios are related to higher Mel-DER results, indicating greater transmission of blue-spectrum light (Alight; Jakubiec, 2021; Carmon, Altomonte, 2021).

In general, the differences in the results of Mel-DER could be explained directly by the spectral transmissions of each glazing material/glass. In the case of electrochromic glazing, results of Mel-DER also varied not only according to the spectral transmission of each state but also according to the shading schedule – lowering of visible states described in section 6.1. In general, **these differences of Mel-DER were also perceived per city/latitude combined with the seasonal variations represented by the solstices and equinoxes for the electrochromic glazing. Seasonal differences of Mel-DER were detected in the study of Nazari, Matusiak, and Stefani (2023), and similar variations in this thesis were detected according to the season of the year.**

The next section will report detailed spectral analyses of the four simulated glazing materials/glasses regarding the five photoreceptors of the human eye.

6.4. Spectral analysis of the simulated glazing materials/glasses (categorization)

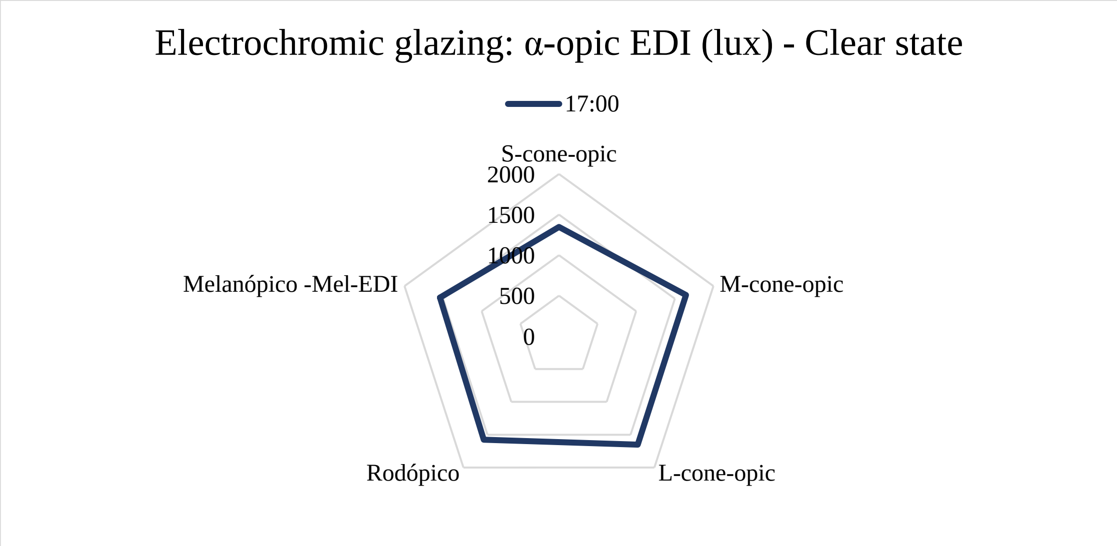
Results of 16 selected cases were reported using α-opic EDI using the CIE Toolbox, considering the city/latitude of Brasilia (15° south), north orientation, in the middle position/sensor (P5), on September 22, at 9 a.m., 12 p.m., 2 p.m., and 5 p.m. The detailed spectral analysis was done to answer questions 5.3.7 and 5.3.8.

- The first question is: What is the spectral distribution/stimulus according to color in the four states of the electrochromic glazing (clear, light tint, medium tint, and dark tint) considering the position in the room/sensor?
- The second question is: Are there significant changes in the spectral distribution of light/stimulus according to color related to the choice of glazing material/glass?

At first, the results for electrochromic glazing were reported per state, from clear to dark tint, and then the glazing materials/glasses comparisons were described and discussed. All the results of α-opic-EDI and Mel-DER for the 16 selected cases were shown in Appendix K.

Variations in the spectral distribution of electrochromic glazing were observed due to its dynamism and variation of the four states, from clear to dark tint, with a reduction in melanopic transmission. In the clear state (Tvis 0 – 0) of the electrochromic glazing, the distribution of α-opic EDI for the five photoreceptors was in general uniform, with slight differences for M-Cone-EDI, towards yellow and green, with 1,644 lux and towards red, L-cone-EDI of 1,651 lux. The lower transmission was towards blue, S-cone-EDI of 1,348 lux, rhodopic-EDI of 1,577 lux and Mel-EDI of 1,540 lux. For clear state, the value of Mel-DER was 0.93. Figure 45 illustrates the results of the α-opic-EDI for the clear state of the electrochromic glazing at 5 p.m. (17:00).

Figure 45 – Results of α-opic EDI for the clear state of the electrochromic glazing with units in lux.



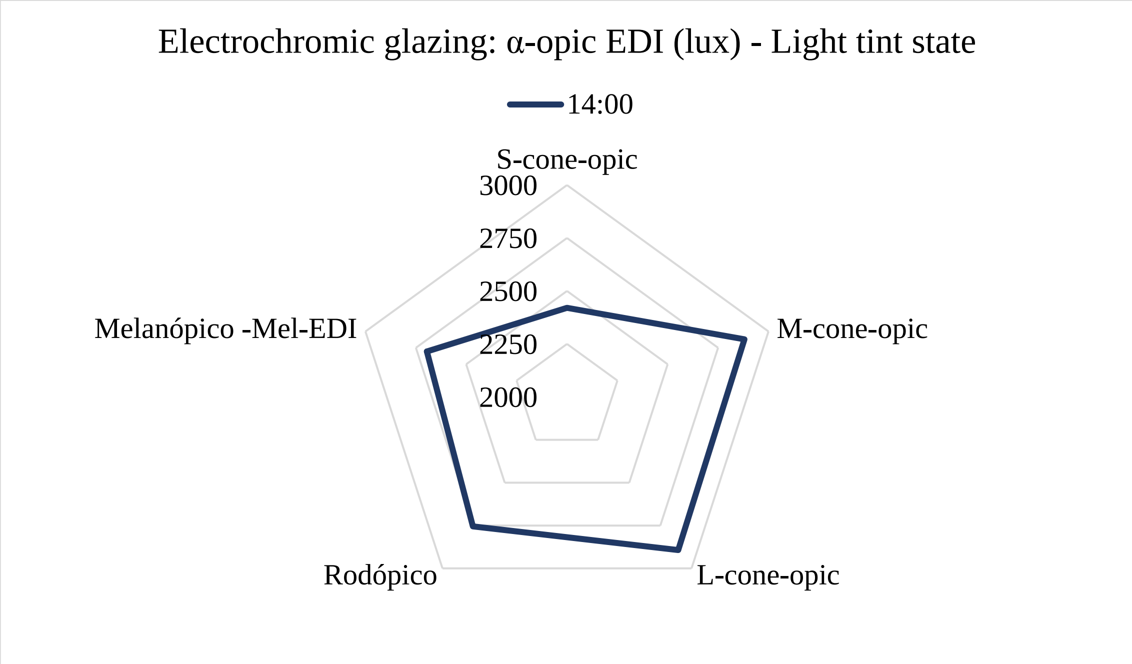
EC state	Hour	S-cone	M-cone	L-cone	Rhodopic	Mel-EDI	Mel-DER
Clear	17:00	1348	1644	1651	1577	1540	0.93

Note: *0 – Tint states - Tmel 0 55.7%/ 1- Tmel 1 37.4%/ 2- Tmel 2 7.0%/ 3- Tmel 3 1.8%.

Source: The Author.

Differences were found for the electrochromic glazing in light tint state (Tvis 1 – 1), with less stimulus for S-cone, with S-Cone-EDI of 2,421 lux, but higher values for rhodopic-EDI, 2,755 lux and Mel-EDI, 2,695 lux. According to the spectral transmission for blue wavelength (Appendix B), the stimulus for S-cones is 10% lower than for the iPRGCs, melanopsin. Almost no difference was found between M-cone-EDI, with a value of 2,881 lux, and L-cone-EDI, 2,893 lux. Results of α-opic EDI for the light tint state of the electrochromic glazing are illustrated in Figure 46.

Figure 46 - Results of α-opic EDI for the light tint state of the electrochromic glazing with units in lux.



EC state	Hour	S-cone	M-cone	L-cone	Rhodopic	Mel-EDI	Mel-DER
Light tint	14:00	2421	2881	2893	2755	2695	0.92

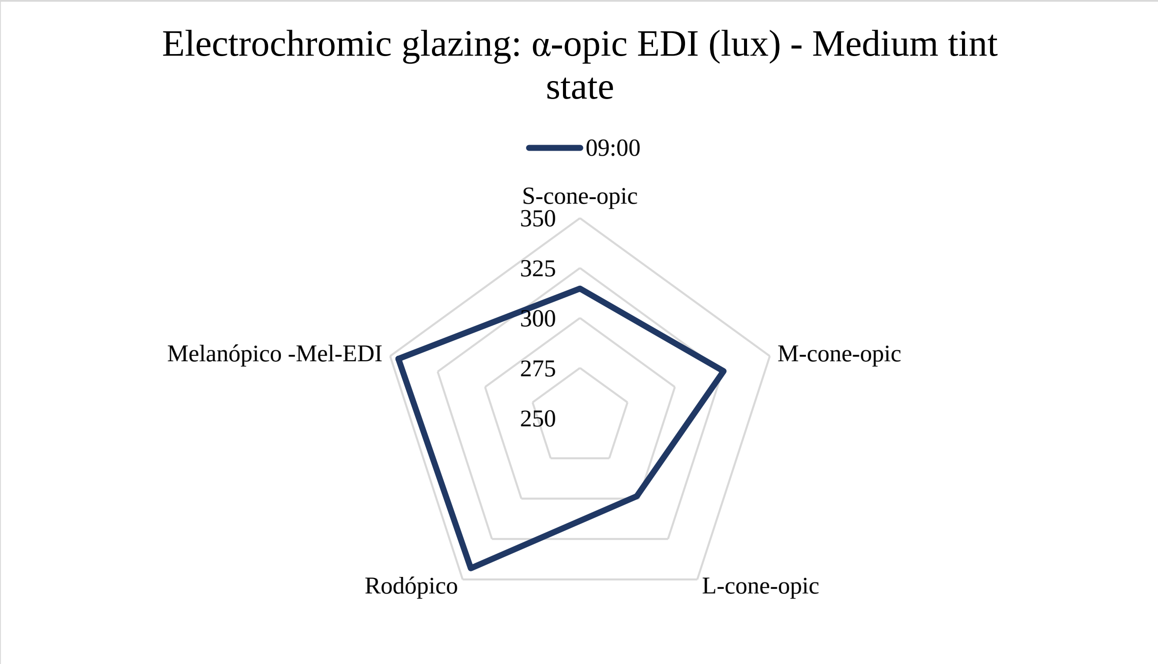
Note: *0 – Tint states - Tmel 0 55.7%/ 1- Tmel 1 37.4%/ 2- Tmel 2 7.0%/ 3- Tmel 3 1.8%.

Source: The Author.

These differences in the stimuli measured by the metric α-opic EDI for the five photoreceptors of the human eye confirmed the lower results of Mel-DER described in section 6.3.3. **The transmitted light through the electrochromic glazing in a clear tint and a light tint states transmitted 7% to 8% less blue light – measured by Mel-EDI and S-cone-EDI in comparison with L-Cone EDI – long wavelength of light, red and green light.**

As the tint states of the electrochromic glazing lowered to medium tint and dark tint states, the spectral transmission shifted to transmit more blue light in comparison with the other wavelengths. Differences were more visible for the electrochromic glazing in a medium tint state, and the stimulus of light was more intense for the rods, rhodopsin-EDI 343 lux, and melanopsin (ipRGCs), with Mel-EDI, 345 lux. The L-cone received less stimulus, with L-Cone-EDI of 298 lux, and the values for S-cone-EDI and M-Cone-EDI were similar, with 314 lux and 325 lux, respectively. In the medium tint state of the electrochromic glazing, Mel-DER was 1.14, 22% higher than for the clear state. However, all values of α-opic-EDI did not overtake 345 lux of Mel-EDI, in comparison of 1,540 lux of Mel-EDI – in the clear state. The melanopic transmission is 7% in clear states, compared with 55.7% for clear states and 37.4% for light tints. Results for α-opic EDI for medium tint state are illustrated in Figure 47.

Figure 47 - Results of α-opic EDI for the medium tint state of the electrochromic glazing with units in lux.

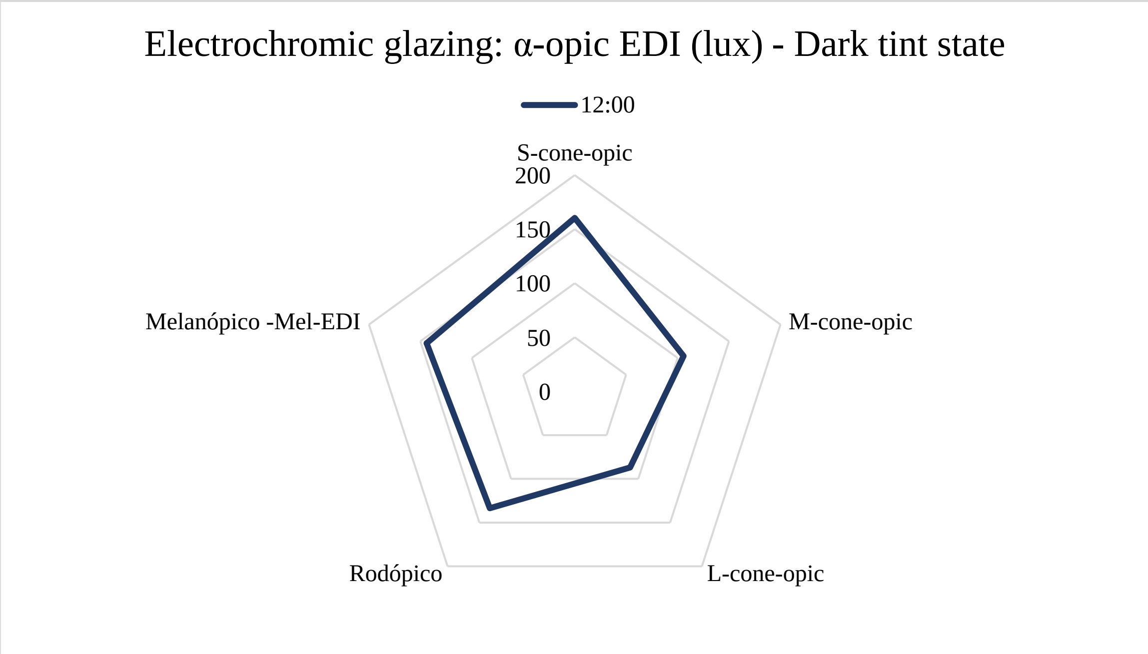


EC state	Hour	S-cone	M-cone	L-cone	Rhodopic	Mel-EDI	Mel-DER
Light tint	09:00	314	325	298	343	345	1.14

Note: *0 – Tint states - Tmel 0 55.7%/ 1- Tmel 1 37.4%/ 2- Tmel 2 7.0%/ 3- Tmel 3 1.8%.
Source: The Author.

Differences were visible in the distribution of light stimulus for the electrochromic glazing in the dark tint state. Despite the high value of Mel-DER, of 1.65, the minimum threshold of 250 lux of Mel-EDI was not achieved. This meant that the circadian lighting in the selected position P5 was not enough to stimulate non-visual effects from daylight alone, and the stimulus was more due to the blue spectrum than to the two others, red and green. The melanopic transmission (Tmel-3 of 1.8%) was the lowest compared to the other three transmissions of the three states. The results for S-cone-EDI were 160 lux, rhodopic-EDI 133 lux, and Mel-EDI, 143 lux. M-cone-EDI was 105 lux, and L-cone-EDI was 87 lux. This meant less stimulus for green and red light. Figure 48 illustrates the results of α-opic EDI for the dark tint state of the electrochromic glazing.

Figure 48 - Results of α-opic EDI for the dark tint state of the electrochromic glazing with units in lux.



EC state	Hour	S-cone	M-cone	L-cone	Rhodopic	Mel-EDI	Mel-DER
Dark tint	12:00	160	105	87	133	143	1.65

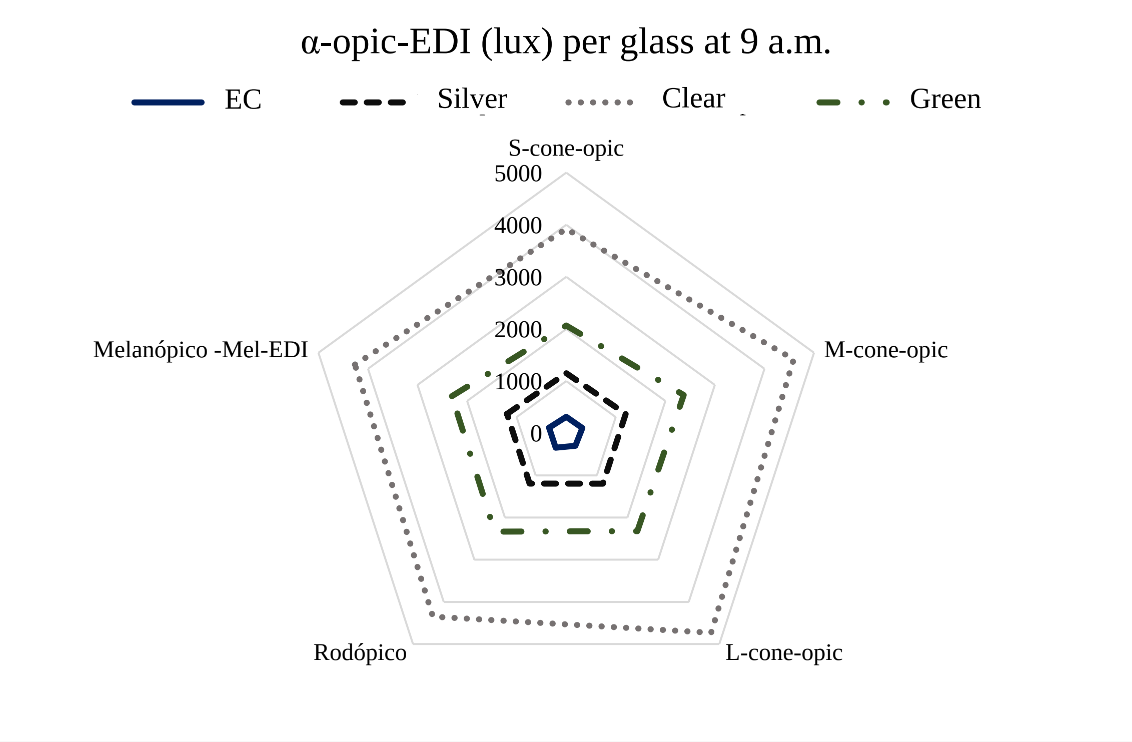
Note: *0 – Tint states - Tmel 0 55.7%/ 1- Tmel 1 37.4%/ 2- Tmel 2 7.0%/ 3- Tmel 3 1.8%.
Source: The Author.

These differences in the spectral transmissions of the four states of the electrochromic glazing were identified by Nazari, Matusiak, and Stefani (2023).

After the comparison of the spectrum of the four states of electrochromic glazing, the four glasses were compared per hour, 9 a.m., 12 p.m., 14 p.m., and 17 p.m., through the analysis of α-opic EDI. The idea was to contrast the analyzed results of the four states of the electrochromic glazing with clear, silver, and green glass.

As illustrated in Figure 49, the results of α-opic EDI for electrochromic glazing in the medium tint state were the lowest, with more stimulus to the blue spectrum, as already described. This meant that electrochromic glazing provided 71% less circadian lighting (Mel-EDI) compared to reflective silver glass. The distribution of α-opic EDI for reflective silver and neutral green glass was more uniform than for the clear glass, with S-cone-EDI of 2,066 lux and M-Cone-, L-cone-, Rhodopic and Mel-EDI between 2,321 lux and 2,370 lux. This meant that the electrochromic glazing provided less circadian lighting than the other glasses. This applied to all stimulus of the five photoreceptors as well.

Figure 49 - Results of α-opic EDI for all simulated glasses at 9 a.m. with units in lux.



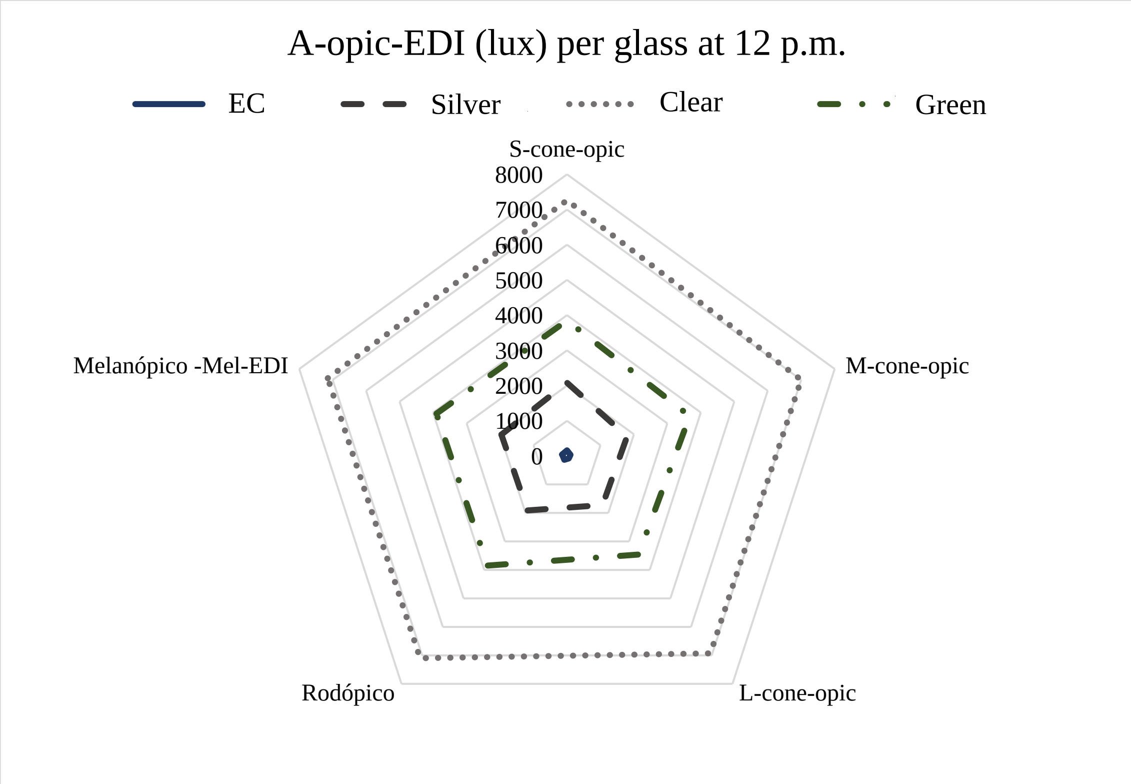
	α-opic EDI				
Glass	**S-cone**	**M-cone**	**L-cone**	**Rhodopic**	**Melanopic**
EC – Medium tint*	314.7358	325.6456	298.4516	343.0792	345.6546
Reflective Silver	1152.233	1200.1	1196.815	1196.289	1194.432
Clear	3919.505	4589.518	4732.005	4351.835	4263.892
Neutral green	2066.208	2370.789	2321.601	2334.043	2305.94

Note: *Tint states - Tmel 0 55.7%/ 1- Tmel 1 37.4%/ 2- Tmel 2 7.0%/ 3- Tmel 3 1.8%.

Source: The Author.

As illustrated in Figure 50, the results of α-opic EDI for electrochromic glazing in the dark tint state were the lowest, with more stimulus to the blue spectrum, as already described. The distribution of α-opic EDI for clear, neutral green glass and reflective silver glass was more uniform than for electrochromic glazing, as already described. This meant that the electrochromic glazing provided 93% less circadian lighting (Mel-EDI) compared to reflective silver glass and less stimulus for the five photoreceptors than the other glasses, and the results of α-opic EDI were not even on the same scale as the other glasses.

Figure 50 - Results of α-opic EDI for all simulated glasses at 12 p.m.



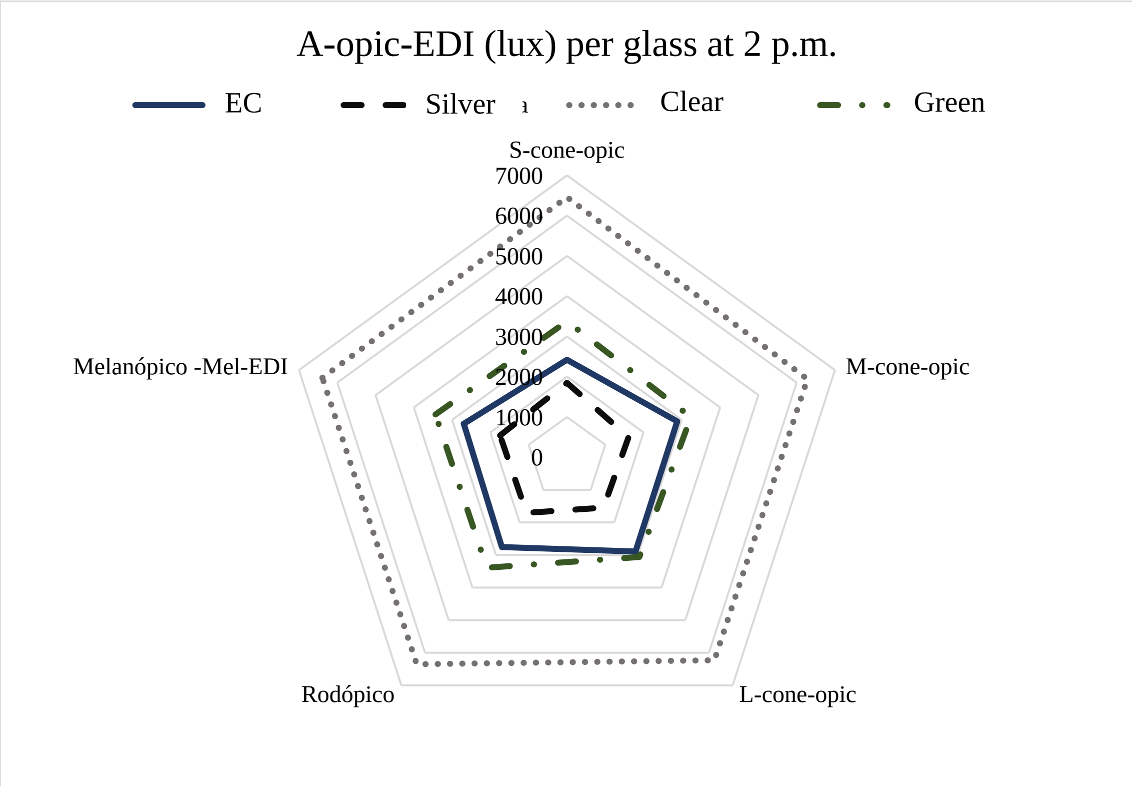
	α-opic EDI				
Glass	**S-cone**	**M-cone**	**L-cone**	**Rhodopic**	**Melanopic**
EC – Dark tint*	160.4492	105.834	87.01709	133.5827	143.9608
Reflective Silver	2081.515	1795.497	1722.18	1911.695	1958.922
Clear	7262.972	6998.099	6932.09	7099.586	7149.141
Neutral green	3848.505	3667.956	3462.245	3847.778	3900.655

Note: *Tint states - Tmel 0 55.7%/ 1- Tmel 1 37.4%/ 2- Tmel 2 7.0%/ 3- Tmel 3 1.8%.

Source: The Author.

As illustrated in Figure 51, the results of α-opic EDI for electrochromic glazing in the light tint state were within the same scale as the others due to its higher melanopic transmission of 37.4%. The results of Mel-EDI for the electrochromic glazing were 36% higher than for reflective silver glass. Despite small differences in the stimulus of α-opic EDI among the five photoreceptors, the distribution was generally uniform. The biggest difference observed was already discussed for the electrochromic glazing, with approximately 16% less stimulus for the S-Cone in relation to the M-cone-EDI and the other three photoreceptors.

Figure 51 - Results of α-opic EDI for all simulated glasses at 2 p.m.



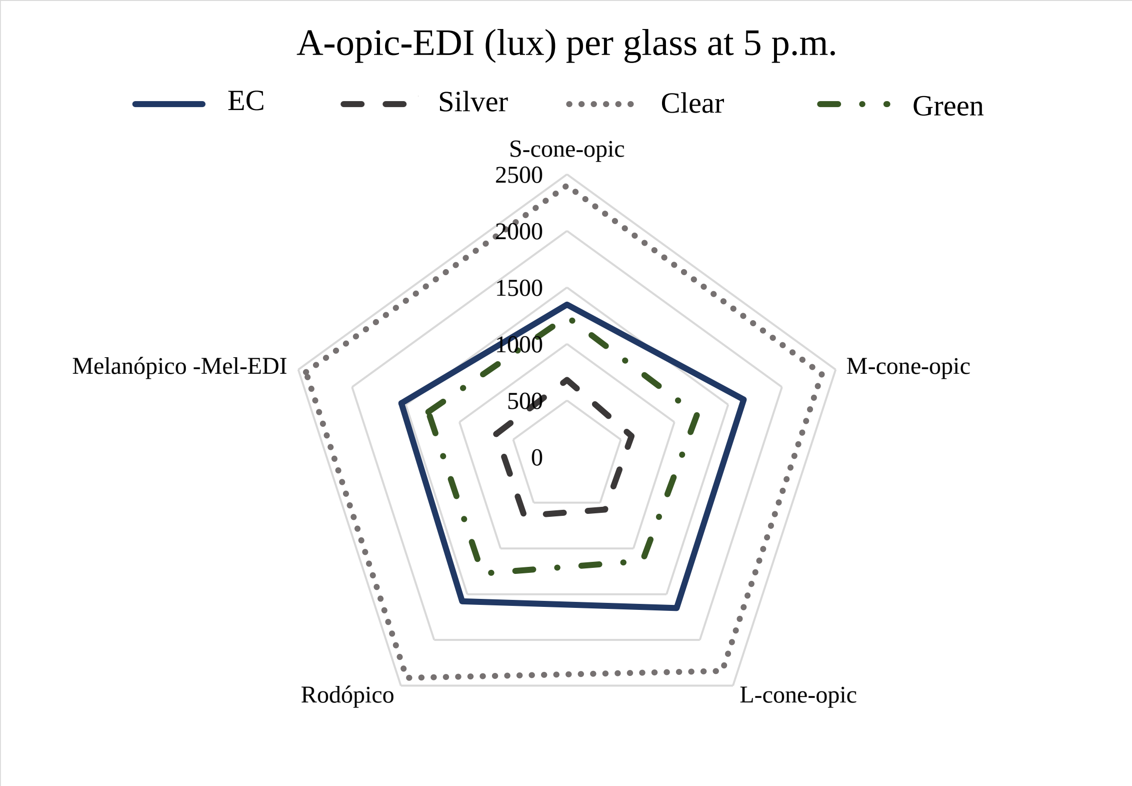
	α-opic EDI				
Glass	**S-cone**	**M-cone**	**L-cone**	**Rhodopic**	**Melanopic**
EC – Light tint*	2420.742	2880.795	2893.181	2755.367	2695.145
Reflective Silver	1847.133	1608.033	1544.868	1707.334	1747.527
Clear	6458.079	6279.747	6230.56	6353.308	6390.195
Neutral green	3375.46	3237.945	3059.156	3390.864	3434.868

Note: *Tint states - Tmel 0 55.7%/ 1- Tmel 1 37.4%/ 2- Tmel 2 7.0%/ 3- Tmel 3 1.8%.

Source: The Author.

As illustrated in Figure 52, the results of α-opic EDI for electrochromic glazing in the clear state were within the same scale as the others due to its higher melanopic transmission for the clear state, of 55.7%. The results of Mel-EDI for the electrochromic glazing were 45% higher than for reflective silver glass. Despite small differences in the stimulus of α-opic EDI among the five photoreceptors according to the glasses, the distribution was generally uniform. The biggest difference observed was already discussed for the electrochromic glazing, with approximately 16% less stimulus for the S-Cone in relation to the M-cone-EDI and the other three photoreceptors. The same difference between S-Cone-EDI and M-Cone-EDI was observed in the electrochromic glazing for the light tint state.

Figure 52 - Results of α-opic EDI for all simulated glasses at 5 p.m.



α-opic EDI					
Glass	**S-cone**	**M-cone**	**L-cone**	**Rhodopic**	**Melanopic**
EC – Clear state*	2420.742	2880.795	2893.181	2755.367	2695.145
Reflective Silver	1847.133	1608.033	1544.868	1707.334	1747.527
Clear	6458.079	6279.747	6230.56	6353.308	6390.195
Neutral green	3375.46	3237.945	3059.156	3390.864	3434.868

Note: *Tint states - Tmel 0 55.7%/ 1- Tmel 1 37.4%/ 2- Tmel 2 7.0%/ 3- Tmel 3 1.8%.

Source: The Author.

The largest variability in the spectral distribution of received light was for the electrochromic glazing due to its dynamism and variation of the four states, from clear to dark tint, with a reduction in melanopic transmission. Despite the high value of Mel-DER in the dark state of 1.65, the minimum threshold of 250 lux of Mel-EDI was not achieved. This meant that the dark state provided more stimulus to S-Cones, Rods, and iPRGCs (melanopsin), but the intensity of the values of Mel-EDI was at least 93% lower compared to reflective silver glass. The melanopic transmission was really low in the dark state, at 1.8%.

The same observation can be made for the electrochromic glazing in the medium tint state, with melanopic transmission of 7%. Despite the higher value of Mel-DER, of 1.14, the intensity of the values of Mel-EDI was at least 71% lower than for reflective silver glass, with melanopic transmission of 23.4%. This observation in the analyses of spectral distribution was the opposite for the electrochromic glazing in light tint and clear state. The observed stimulus was generally lower for the photoreceptors, which were more sensitive to the blue spectrum of light, particularly s-cones, and with less difference for iPRGCs - melanopsin and rods. The results of Mel-EDI for the electrochromic glazing for the light tint state were 36% higher than for reflective silver glass, and for the clear state, this difference was 45% in favor of the dynamic glazing.

In relation to the other three simulated glasses, clear, neutral green, and reflective glass, the observed results of α-opic EDI were more uniform, despite small differences in the stimulus for the five photoreceptors in relation to the electrochromic glazing. Consequently, results demonstrated that the choice of glazing material/glass significantly influenced the results of spectral distribution of the received light in the simulated model.

Among these three glasses, most of the differences were found in the intensity and quantity of the stimulus of α-opic-EDI, and this quantity was due to the differences in their melanopic transmissions. For clear, neutral green, and reflective silver glass, the melanopic transmissions were 89%, 47.3%, and 23.4%, respectively. For example, at 2 p.m., the results of α-opic EDI for clear glass was between 6,230 lux and 6,458 lux, for neutral green glass, between 3,059 lux and 3,434 lux, and for reflective silver, 1,544 lux, and 1,847 lux. In general, for neutral green and reflective silver glass, the lower α-opic-EDI levels were to L-Cone-EDI. As identified in the study of Sacht *et al.* (2016), **solar control glasses were made to reduce the transmission and absorption of long wavelength radiation, transmitting less infrared radiation and less red spectrum of visible light**. In this study, the differences between L-Cone-EDI and Mel-EDI for neutral green glass and reflective silver glass were in general 13% in favor of Mel-EDI. **Additionally, clear glass presented the most uniform spectral transmission in relation to the other three simulated glasses**. The uniformity of clear glass related to the spectral transmission was identified by Nazari, Matusiak and Stefani (2023) as well.

For these reasons, it was possible to observe that the most significant differences in the spectral transmission among the simulated glasses were for electrochromic glazing. In clear and light tint states, the stimulus was more intense in the M-cones and L-cones, meaning slightly higher transmission for green and red spectra, with 16% less intensity in the stimulus for S-cone (blue light), in particular. This explained the reduced values of

Mel-DER, between 0.91 and 0.93. However, the difference in the stimulus of the blue light for the sensitivities of the rods and iPRGCs was only 4%.

On the other hand, in medium and dark tint states, the opposite occurred in terms of the spectrum for the electrochromic glazing. The stimulus was less intense in the M-cones and L-cones, meaning lower transmissions for green and red spectra, with 34% more intensity for the stimulus for the S-cone (blue light). The difference between L-Cone-EDI and Mel-EDI for the medium tint state was 14%, and for the dark tint state, this difference was 40%. Nevertheless, the intensity of circadian lighting – Mel-EDI for the electrochromic glazing in a medium tint and a dark tint states is limited, jeopardizing the stimulus of non-visual effects of light.

These differences in the spectral transmissions of the four states of the electrochromic glazing were similar to the findings of Nazari, Matusiak, and Stefani (2023) in experiments conducted in Norway. In the light tint state, electrochromic glazing transmitted less blue light – measured by Mel-EDI and S-cone-EDI compared to L-Cone EDI – long wavelength of light, red light. According to the authors, the positive effect of electrochromic glazing is the color shift towards yellow in a clear state, which may contribute to a more joyful atmosphere in the room. The negative effect was that in the dark tint state, the vividness of all colors was strongly reduced, and vertical illuminance and Mel-EDI were also diminished. Besides that, the shift to blue light and the low intensity of light inside the office room was a source of criticism coming from large commercial buildings within the United States, as described by Day *et al.* (2019).

As described by Mardaljevic, Waskett and Painter (2016), users prefer a neutral or a slightly warm spectrum – i.e. with a uniform spectral distribution. The perception of transmitted blue light of electrochromic glazing in the dark tint state can be a source of criticism if parts of the window do not remain in a clear state or with clear glass.

In this study, **the results of response variable Mel-EDI related to the lack of circadian lighting - section 6.3.2 – and the shift to blue light detected in the spectral analyses confirmed that similar problems and criticisms coming from users may occur if similar technologies of the simulated electrochromic glazing are implemented in non-residential buildings in Brazil, as a neutral and more uniform spectrum is preferred.**

The discussion regarding the performance of electrochromic glazing is presented in the next section.

6.5. Discussion: Overall performance of electrochromic glazing regarding visual and non-visual effects of light

The focus of this section is to clearly indicate in which situations the evaluated technology of electrochromic glazing presented the best performance regarding the representative highly glazed model of a non-residential room in the Brazilian luminous context, represented by six cities according to the three latitude ranges. Additionally, recommendations were made to guide professionals, such as architects, engineers, and designers, among others, to optimize and improve the performance of electrochromic glazing concerning visual and non-visual effects within Brazilian latitudes.

6.5.1. Summary of the performance of electrochromic glazing regarding visual and non-visual effects of light

As discussed in section 6.2, variable window orientation did not present statistically significant differences regarding the response variables of visual effects of light: DA, UDI, and annual glare (DGP < 40%), including the performance of electrochromic glazing. Therefore, the results were summarized per city/latitude including all four orientations.

Regarding the results of non-visual effects of light, variable Mel-EDI presented differences according to city/latitude and window orientation and they were discussed in section 6.3.2, regarding the cases with lack of circadian lighting. For variable Mel-DER, the differences in the window orientations per city/latitude were summarized in Table 53 with the described information from section 6.3.

Comparing with the shading schedules – lowering of states inputted in ALFA, described in Appendix C, the higher values of Mel-DER to the north and the east could be explained because the medium tint and dark tint states were required with more frequency when compared to the west and with low frequency to the south orientation, except for the cities with lower latitudes, from Manaus (3° south) to Brasilia (15° south) at specific hours during the summer months. Table 53 summarizes the performance of electrochromic glazing regarding visual and non-visual effects of light.

Table 53 - Summary of the performance of electrochromic glazing regarding visual and non-visual effects of light.

City/latitude	DA* 300 lux/50%)	UDI* – 100-3000 lux	Annual glare* (DGP < 40%)	Mel-EDI**	Mel-DER**
Manaus (-3°)	100% achieving minimum criterion	72% achieving minimum criterion	67% achieving minimum criterion	Intermediate performance (90% of achievement)	Varied performance: Best (east) - 50%/Worst (west) - 32%
Recife (-8°)	100% achieving minimum criterion	78% achieving minimum criterion	67% achieving minimum criterion	Worst performance (85% of achievement)	Varied performance: Best (west) - 30%/Worst (north) - 5%
Bom Jesus da Lapa (-13°)	100% achieving minimum criterion	81% achieving minimum criterion	67% achieving minimum criterion	Best performance (93% of achievement)	Varied performance: Best (east) - 80%/Worst (west) - 55%
Brasilia (-15°)	100% achieving minimum criterion	81% achieving minimum criterion	67% achieving minimum criterion	Intermediate performance (88% of achievement)	Varied performance: Best (north) - 57%/Worst (west) - 30%
Rio de Janeiro (-22°)	100% achieving minimum criterion	86% achieving minimum criterion	67% achieving minimum criterion	Intermediate performance (89% of achievement)	Varied performance: Best (east) - 49%/Worst (south) -28%
Santa Maria (29°)	92% achieving minimum criterion	89% achieving minimum criterion	67% achieving minimum criterion	Intermediate performance (90% of achievement)	Varied performance: Best (north) - 38%/Worst (south) - 8%

Note: * Visual effects: Equivalent results according to the window orientation. **Non-visual effects: Different results according to the window orientation. Source: The Author.

The general criterion for Mel-EDI, equal or greater than 250 lux, was achieved in 95% of the cases. For this reason, the differences in the performance of electrochromic glazing regarding response variable Mel-EDI was better described when the cases considering a lack of circadian lighting were analyzed. Lack of circadian lighting was considered when the minimum of 250 lux of Mel-EDI was not achieved in at least 70% per day. Variations occurred considering variables city/latitude, window orientation and date. Table 54 describes the performance of electrochromic glazing regarding the cases of lack of circadian lighting.

Table 54 – Performance of electrochromic glazing regarding non-visual effects of light: cases with a lack of circadian lighting per city/latitude, window orientation and date.

City/latitude	North	South	East	West
Manaus (-3°)	June 21 (1)	December 21 (1)	June 21 (1)	No cases (0)
Recife (-8°)	No cases (0)	December 21 (1)	No cases (0)	March 22, September 22, December 22 (3)
Bom Jesus da Lapa (-13°)	June 21 (1)	No cases (0)	No cases (0)	No cases (0)
Brasilia (-15°)	March 22, June 21, September 22 (3)	No cases (0)	No cases (0)	No cases (0)
Rio de Janeiro (-22°)	March 22, June 21 (2)	No cases (0)	June 21 (1)	No cases (0)
Santa Maria (29°)	March 22, September 22 (2)	No cases (0)	March 22, June 21 (2)	No cases (0)

Note: Cases without achieving the minimum criterion of Mel-EDI were highlighted in orange. Source: The Author.

The overall performance of electrochromic glazing and recommendations for improvement regarding visual effects of light are described in the next section.

6.5.2. Overall performance of electrochromic glazing and recommendations for improvement regarding visual effects of light

The idea in this section was to summarize the main findings describing the performance of electrochromic glazing regarding response variables of visual effects of light. Then, recommendations were made based on its overall performance regarding visual and non-visual effects of light. Concerning the performance of electrochromic glazing related to the visual effects of light, the main findings per explanatory variable were summarized per city/latitude, window orientation, and position in the room.

- Latitude range 1 from 5° north to 9.9° south: Manaus (3° south) and Recife (8° south)
    - Daylight autonomy (DA 300 lux/50%): good compliance with 100% of the cases achieving minimum criterion
    - Useful daylight illuminance (UDI 100-3000 lux): lowest percentages of achievement of minimum criterion with 72% for Manaus and 78% for Recife
    - Annual glare (DGP lower than 40%): no significative differences in relation to the cities/latitudes of ranges 2 and 3. The percentage of achievement of the minimum criterion is 67%.
- Latitude range 2 from 10° south to 19.9° south: Bom Jesus da Lapa (13° south) and Brasilia (15° south)
    - Daylight autonomy (DA 300 lux/50%): good compliance with 100% of the cases achieving minimum criterion
    - Useful daylight illuminance (UDI 100-3000 lux): intermediate performance in relation to ranges 1 and 3 with percentages of achievement for a minimum criterion of 81% in both cities/latitudes.
    - Annual glare (DGP lower than 40%): no significative differences in relation to the cities/latitudes of ranges 1 and 3. The percentage of achievement of the minimum criterion is 67%.
- Latitude range 3 from 20° south to 34° south: Rio de Janeiro (22° south) and Santa Maria (29° south)
    - Daylight autonomy (DA 300 lux/50%): 100% of achievement of minimum criterion for Rio de Janeiro and 92% for Santa Maria, city/latitude with lower availability of natural light – lower daily

averages of global illuminance and solar radiation in relation to the cities within ranges 1 and 2.

- Useful daylight illuminance (UDI 100-3000 lux): best performance in relation to the other cities of latitude ranges 1 and 2 with percentages of achievement of minimum criterion of 86% in Rio de Janeiro and 89% in Santa Maria.
- Annual glare (DGP lower than 40%): no significative differences in relation to the cities/latitudes of ranges 1 and 2. The percentage of achievement of the minimum criterion is 67%.

- Window orientation: north, east, south, and west. Differences of performance according to the shading schedules – lowering of tint states and visible transmittances described in section 6.1.
    - Daylight autonomy (DA 300 lux/50%): worst performance for the north orientation with 94% of achievement percentage for minimum criterion. To the east, the west, and the south, this percentage was 100%, with equal performance.
    - Useful daylight illuminance (UDI 100-3000 lux): worst performance for the south, with the percentage of achievement for the minimum criterion of 67%, with electrochromic glazing remaining in a clear state. To the east and the west, there was a similar performance with percentages of achievement for the minimum criterion of 87% and 76%, respectively. The best performance was to the north with a percentage of 94%. To the east, the west, and the north, the tint states of electrochromic glazing were lowered, hence a decrease in the problems related to excess light entering the room on the horizontal grid.
    - Annual glare (DGP lower than 40%): no significant differences in window orientation. Percentages of achievement of minimum criterion to the south 69%; the west and the north, 63%; and the east, 64%. Even lowering its state and the visible transmittance, electrochromic glazing was not enough to prevent glare in the positions close to the window in all four orientations.

- Sensor/position in the room according to the distance from the window.
  - P1, P2, and P3 (0.50m from the window – close to the window): good compliance with criterion DA 300 lux/50% and worst performance in relation to UDI 100-3000 lux and annual glare (DGP).
  - P4 to P6 (3m from the window – middle of the room): good compliance with criterion DA 300lux/50% and good performance in relation to UDI 100-3000 lux and annual glare (DGP)
  - P7 to P9 (5.50m from the window – back of the room): worst performance in relation to criterion DA 300 lux/50% with 92% of achievement for minimum criterion, but only in Santa Maria (29° south) to the north. In all other cities/latitudes for the north, the minimum criterion of DA 300 lux/50% is achieved.
  - There was good compliance with criterion DA 300 lux/50% of the time to the east, the north and the west. Good compliance with variables UDI 100-3000 lux and annual glare (DGP).

Based on the discussion the results, the recommendations for the performance of electrochromic glazing were divided into three latitude ranges according to the Brazilian luminous zoning illustrated in Figure 27. They are shown in Figure 53. The recommendations in the use of electrochromic glazing according to the city/latitude and window orientation were as a function of the shading schedules - lowering of states with reductions in the visible transmittance described in section 6.1.

Figure 53 – Recommendations for improvement in the performance of electrochromic glazing related to visual effects of light.

Latitude range 1: from 5° north to 9.9° south

- Cities/latitudes: Manaus (3° south) and Recife (5° south)
  - Good compliance regarding criterion DA 300 lux/50% - no recommendation required.
  - UDI and DGP: accurate glare controls (shading schedules) required to prevent glare next to the window.
  - Window orientation: recommended use to the north. Not properly recommended to the south with benefits mostly found during summer months, as the lowering of states is required, but not in the other three seasons of the year. To the east and the west, the use is not properly recommended due to the frequent deep penetration of direct sunlight.

Latitude range 2: from 10° south to 19.9° south

- Cities/latitudes: Bom Jesus da Lapa (13° south) and Brasilia (15° south)
- Good compliance regarding criterion DA 300lux/50% - no recommendation required.

UDI and DGP: accurate glare controls (shading schedules) required to prevent glare next to the window.

Window orientation: recommended use to the north. Use not recommended to the south, with few periods required of lowering of states. To the east and the west, the use is not properly recommended due to the frequent deep penetration of direct sunlight.

Latitude range 3: from 20° south to 34° south

- Cities/latitudes: Rio de Janeiro (22° south) and Santa Maria (29° south)
- Good compliance regarding criterion DA 300lux/50% for Rio de Janeiro and Santa Maria with attention required for the north orientation regarding minimum illuminance levels at the back of the room.
- UDI and DGP: accurate glare controls (shading schedules) required to prevent glare next to the window.
- Window orientation: recommended use to the north. Use not recommended for the south. To the east and the west, the use is not properly recommended due to the frequent deep penetration of direct sunlight.

Note: Shading refers to the shading schedule – lowering of states required as described in section 6.1. Source: The Author.

Overall, for cities within latitude ranges 1 and 2, from 5° north to 9.9° south and from 10° south to 19.9° south, the performance of electrochromic glazing regarding the minimum criterion of DA 300 lux/50% of the time will be adequate. However, for the cities within latitude range 3, from 20° south to 34° south, problems related to the achievement of the minimum criterion of DA 300 lux 50% of the time in the positions at the back of the room can be a potential problem, particularly for the cities with the highest latitudes. In this regard, alterations in the shading schedule – lowering of states are required in Brazilian cities with higher latitudes (range 3). An increase in the tint states from dark tint state (Tvis 1.1%) to medium tint state (Tvis 5.4%) is recommended to increase visible transmittance when the minimum target of 300 lux in 50% of the time is not achieved.

As discussed in Chapter 2, electrochromic glazing was utilized for window orientations with high incidence of direct sunlight. For this reason, the use of electrochromic glazing in Brazil presents more advantages for the north. For the east and the west orientations, the use of electrochromic glazing is not properly recommended and these orientations should not be chosen as a first option in a project. As seen in the shading schedules in section 6.1, there is a high risk of a deep penetration of direct sunlight inside the work environment for the east in the morning and the west in the afternoon if the control systems of electrochromic glazing are not properly designed. For the south orientation regarding all three latitude ranges, the use of electrochromic glazing is not recommended as this technology required few periods of shading – lowering of states only during summer months. It is acknowledged that the incidence of direct solar radiation for the cities/latitudes of Manaus (3° south) and Recife (8° south) is high during summer months. However, in the other three seasons the lowering of states of electrochromic glazing is not required.

As discussed in section 6.2, the recommendation to improve the performance of electrochromic glazing related to the visual effects of light is to utilize more accurate glare controls. As described by Wu *et al.* (2019) and Jain, Karmann, and Wienold (2022), more accurate glare controls are based not only on controlling the incidence of direct sunlight but also on monitoring the luminance distribution of the sky. Accurate glare controls are recommended to the Brazilian latitudes as well.

If these recommendations are followed, the performance of electrochromic glazing related to the visual effects of light can improve. Moreover, this technology can be more attractive to be used than the other three simulated glasses (neutral green, reflective silver, and clear glass) – which are commonly used in non-residential buildings in Brazil. The recommendations for improvement regarding non-visual effects of light are described next.

6.5.3. Overall performance of electrochromic glazing and recommendations for improvement regarding non-visual effects of light

As discussed in section 6.3, no relationships between the results of Mel-EDI and Mel-DER were found as a function of latitude. Additionally, spectral differences for each of the six city/latitudes were detected. Data packages and tools to predict spectral sky conditions among different sites are still under development, making comparisons to the six evaluated Brazilian cities/latitudes difficult. Thus, more studies are needed to understand the spectral differences and similarities among the simulated cities/latitudes (Inanici; Abboushi; Safranek, 2023). For this reason, the summary of results and recommendations regarding the performance of electrochromic glazing related to non-visual effects of light had to be reported per city/latitude.

For the assessment of non-visual effects, two criteria were utilized: a minimum of 250 lux of Mel-EDI (potency of circadian lighting) and a minimum of 0.904 of Mel-DER corresponding to the spectral power distribution and the melanopic efficacy of CIE standard daylight D55 and D65. Regarding the performance of electrochromic glazing related to non-visual effects of light, the main findings per explanatory variable were summarized per city/latitude, window orientation, and position in the room.

- Manaus (3° south)
    - Mel-EDI: 90% of achievement for minimum criterion – intermediate performance
    - Mel-DER: varied performance, with better results to the east, with 50%, and worse results to the west, with 32% of achievement for minimum criterion.
- Recife (8° south)
    - Mel-EDI: 85% of achievement for minimum criterion – worst performance in relation to the other five cities/latitudes
    - Mel-DER: varied performance, with better results to the west, with 30%, and worse results to the north, with 5% of achievement for minimum criterion.
- Bom Jesus da Lapa (13° South)
    - Mel-EDI: 93% of achievement for minimum criterion – best performance in relation to the other five cities/latitudes

  - Mel-DER: varied performance, with better results to the east, with 80%, and worse results to the west, with 55% of achievement for minimum criterion. In general, Mel-DER performs best in relation to the other five cities/latitudes.

- Brasilia (15° South)
  - Mel-EDI: 88% of achievement for minimum criterion – intermediate performance in relation to the other five cities/latitudes
  - Mel-DER: varied performance, with better results to the north, with 57%, and worse results to the west, with 30% of achievement for minimum criterion.
- Rio de Janeiro (22° South)
  - Mel-EDI: 89% of achievement for minimum criterion – intermediate performance in relation to the other five cities/latitudes
  - Mel-DER: varied performance, with better results to the east, with 49%, and worse results to the south, with 28% of achievement for minimum criterion.
- Santa Maria (29° South)
  - Mel-EDI: 89% of achievement for minimum criterion – intermediate performance in relation to the other five cities/latitudes
  - Mel-DER: varied performance, with better results to the north, with 38%, and worse results to the south, with 8% of achievement for minimum criterion.
- Window orientation: north, east, south, and west. Differences of performance according to the shading schedules – lowering of tint states and visible transmittances described in section 6.1 and variations explained by the different spectral transmissions of the four states (Appendix B).
  - Mel-EDI: Best performance to the south, with 95% of achievement for minimum criterion (250 lux), followed by the west, with 89%, the east, with 88%, and the north, with 86% - with the worst performance. Details of the results of Mel-EDI are described in sections 6.3.1 and 6.3.2.
  - Mel-DER: Best performance for the east and the north, with percentages of achievement of minimum criterion (0.904 – CIE

Illuminants D55 and D65) of 47% and 40%, respectively. To the west, the percentage was 34%. The worst performance was for the south, with 32%. Details related to the results of Mel-DER are described in section 6.3.3.

- Sensor/position in the room according to the distance from the window.
  - P1, P2, and P3 (0.50m from the window – close to the window: best performance regarding variable Mel-EDI, with 98% of achievement for minimum criterion. There is no problem related to the supply of circadian lighting. Best performance regarding variable Mel-DER.
  - P4 to P6 (3m from the window – middle of the room): intermediate performance regarding variable Mel-EDI, with 88% of achievement for minimum criterion. Varied results, but in general, intermediate performance regarding variable Mel-DER.
  - P7 to P9 (5.50m from the window – back of the room): minimum criterion achieved in 80% to 81% of the cases related to variable Mel-EDI. The cases related to the lack of circadian lighting are better detailed in section 6.3.2. Worst performance in relation to variable Mel-DER.

Based on the answer to the questions related to the non-visual effects of light, the recommendations for the performance of electrochromic glazing were according to the six evaluated cities because variations between the two cities within the same latitude range occurred. As discussed in section 6.2, most of the problems regarding the performance of electrochromic glazing were related to the lack of circadian lighting. These problems varied according to the city/latitude, window orientation, date - season of the year, and position in the room. The percentage of achievement of variable Mel-EDI, as described in section 6.3, was detected in 95% of the cases. Adding to the lack of circadian lighting, spectral analyses identified the shift of blue light in the evaluated glazing, as mentioned in section 6.4. Therefore, recommendations were made to prevent these issues if electrochromic glazing technology is implemented in Brazil. The recommendations are mostly based on changes in the shading schedule - lowering states. As shown in section 6.4, the increase in the tint states, from dark tint state (Tmel – 1.8%) to medium tint state (Tmel-7%), can enhance the supply of minimum circadian lighting – 250 lux of Mel-EDI. The recommendations are shown in Figure 54.

Figure 54 – Recommendations regarding the performance of electrochromic glazing to improve the minimum supply of circadian lighting – non-visual effects.

Latitude range 1
Manaus (3° south)

- Shading schedule: increase in tint state from dark (T_{mel} 1.8%) to medium tint (T_{mel} 7%) recommended:
  - To the north in winter
  - To the east in the morning and to the west in the afternoon
  - To the south in summer

Latitude range 1
Recife (8° south)

- Shading schedule: increase in tint state from dark (T_{mel} 1.8%) to medium tint (T_{mel} 7%) recommended:
  - To the north in winter
  - To the east in the morning and to the west in the afternoon
  - To the south in summer

Latitude range 2
Bom Jesus da Lapa (13° south)

- Shading schedule: increase in tint state from dark (T_{mel} 1.8%) to medium tint (T_{mel} 7%) recommended:
  - To the north in winter
  - To the east in the morning and to the west in the afternoon

Latitude range 2
Brasilia (15° south)

- Shading schedule: increase in tint state from dark (T_{mel} 1.8%) to medium tint (T_{mel} 7%) recommended:
  - To the north in autumn, winter, and spring
  - To the east in the morning and to the west in the afternoon

Latitude range 3
Rio de Janeiro (22° south)

- Shading schedule: increase in tint state from dark (T_{mel} 1.8%) to medium tint (T_{mel} 7%) recommended:
  - To the north in autumn and winter
  - To the east in the morning and to the west in the afternoon

Latitude range 3
Santa Maria (29° south)

- Shading schedule: increase in tint state from dark (T_{mel} 1.8%) to medium tint (T_{mel} 7%) recommended:
  - To the north in autumn, winter and spring
  - To the east in the morning and to the west in the afternoon

Note: Each season is represented by a solstice or equinox: autumn on March 22, winter on June 21, spring on September 22, and summer on December 22. Source: The Author.

As commented in section 6.5.2, the recommended use of electrochromic glazing is for the north in all six cities/latitudes, as this is an orientation with high incidence of direct sunlight. To the south, an increase in the melanopic transmission is recommended for the cities/latitudes of Manaus (3° south) and Recife (8° south) during summer months. As for the east and the west, the penetration of direct sunlight can be deep in the working environment and the lowering of states will be required in the morning and in the afternoon, respectively. Consequently, the melanopic transmission will reduce jeopardizing the access of direct sunlight, particularly in the positions of the middle and at the back of the room. Therefore, increase in the melanopic transmission from dark tint state (T_{mel} 1.8%) to medium tint state (T_{mel} 7%) is highly recommended for the east and the west in all simulated cities/latitudes in the mentioned periods of the day.

As mentioned in section 6.3.2, no cases of lack of circadian lighting occurred for clear and neutral green glass, with higher melanopic transmittances. For the cities within higher latitudes, Rio de Janeiro (22° south) and Santa Maria (29° south), only a few cases to the south and the west were related to the lack of circadian lighting for reflective silver glass, with lower melanopic transmission in comparison with clear and neutral green glass. In light of these results, it was possible to identify that the worst performance according to glass/glazing material regarding the supply of non-visual effects was for electrochromic glazing in the three latitude ranges.

Regarding the spectrum, the current generation of electrochromic glazing, including the simulated one, still presents problems related to the shift to blue light. In this context, new generations of electrochromic glazing are emerging and offering different colors than blue tints, such as black, with more uniform spectral distribution and more sophisticated daylight controls, as mentioned in a recent report by Matusiak (2020). The investigation of these emerging technologies in the near future will be of paramount importance.

Consequently, these recommendations and summaries provided an overview of where a lack of circadian light is most likely to occur based on the three latitude ranges and window orientation for this dynamic glazing. Based on these predictions, alterations in the shading schedule considering the increase in the melanopic transmission can improve the performance of electrochromic glazing regarding access to circadian lighting – non-visual effects. This summary will be useful in making informed decisions for optimizing the use of electrochromic glazing if implemented in non-residential buildings in Brazil. The conclusions are reported in the next chapter.

Chapter 7. Conclusions

This section summarizes the key contributions and findings of this study. The achievement of the general and specific aims, and the confirmation of the hypothesis are discussed. Then, potentialities and problems related to the use of electrochromic glazing in highly glazed facades of non-residential buildings in the evaluated climates in Brazil are described. At the end the limitations of the research are discussed and suggestions for futures studies are made.

The originality of this research was to consider the influence of daylight, analyzing the impacts of innovative materials, particularly electrochromic glazing, on visual and non-visual effects in Brazilian latitudes. Technologies of smart windows, including electrochromic glazing, are not commercialized in Brazil. Therefore, **the importance of this work lies in the exhaustive simulation tests conducted to determine whether the analyzed electrochromic glazing can be appropriately used concerning visual and non-visual effects in the Brazilian context.**

It was found in the literature review that electrochromic glazing offered potentialities to mitigate problems related to glare caused by the intense use of glass on facades in non-residential buildings in Brazil. The negative aspect was the lack of circadian lighting when electrochromic glazing was in the dark state. In this respect, the main research gap was that it was unclear how the performance of electrochromic glazing was considering non-residential buildings in Brazilian climates.

Consequently, the aim of this research was achieved, and the performance of electrochromic glazing was determined for the daylighting conditions, including visual and non-visual effects, in a representative model of non-residential rooms within the Brazilian climatic context. Specific aim 1.3.1 was to select criteria for visual and non-visual effects of light. This was discussed in Chapter 4, and the assessment criteria for visual and non-visual effects were defined in Chapter 5 - method. For this reason, it was possible to evaluate the performance of electrochromic glazing considering both aspects of visual comfort. Specific aims 1.3.2 to 1.3.4 were achieved, and the questions related to the performance of electrochromic glazing concerning visual and non-visual effects and comparisons regarding its performance with two conventional and one reflective glass were answered.

In this respect, the hypothesis of this research was confirmed and limitations regarding the use of electrochromic glazing to balance user daylight conditions related to visual and non-visual effects were observed. The employment of electrochromic glazing was able to improve the daylighting conditions for users including visual effects of light in relation to two conventional and one reflective glass. However, the use of electrochromic glazing in comparison with clear, neutral green and reflective silver glasses worsened visual comfort conditions related to non-visual effects of light. Lack of circadian lighting, and distortions in the spectral distribution due to the shift to blue light were observed with the use of electrochromic glazing.

The main contribution of the method was predicting the performance of electrochromic glazing for the daylighting conditions, including visual and non-visual effects in a representative model of a non-residential room within the Brazilian climatic context. **In this context, a broader context was considered, including six different cities/latitudes, from Manaus (3° south) to Santa Maria (29° south), four window orientations, north, east, south, and west, nine positions in the room and according to the distance from the window, different dates and hours.**

In this context, it was possible to predict the performance of electrochromic glazing regarding visual and non-visual effects considering all the mentioned variables. **In the context of highly glazed façades in Brazil, electrochromic glazing can improve daylight conditions related to visual effects of light, daylight autonomy, and useful daylight illuminance compared with reflective silver, neutral green, and clear glass.** It is important to mention that this conclusion is limited to the context of highly glazed façades.

Despite problems related to the occurrence of disturbing and intolerable glare in the positions next to the window, controls for electrochromic glazing can still be improved by more accurate ones, considering the luminance distribution of the sky, besides the incidence of direct sunlight on the horizontal grid. **The first problem related to the use of electrochromic glazing within the simulated Brazilian latitudes is the occurrence of glare in the positions close to the window, when the electrochromic glazing is in the clear and a light tint states**. Occurrence of glare was not seen for electrochromic glazing for the conditions of medium tint and dark tint states, as the visible transmittances in both states were reduced to 5.4% and 1.1% respectively. In this context, shading schedules based on accurate glare controls are recommended, considering the incidence of direct sunlight and monitoring of the luminance distribution of the sky.

On the other hand, decreasing the visible transmittance according to the shading schedule for the purpose of glare mitigation may jeopardize the access of circadian lighting particularly in the positions at the back of the room. **Consequently, the second problem is related to the lack of circadian lighting when using electrochromic glazing in the medium tint and dark tint states.** Changes in the shading schedule must balance avoiding glare with more accurate glare controls and the minimum supply of circadian lighting. This is a challenge, but the different aspects of visual comfort must be considered, including visual and non-visual light.

To solve the issues concerning the lack of circadian lighting, it is highly recommended that adjustments be made in the shading schedules of electrochromic glazing based on city/latitude and window orientation. **To allow more circadian lighting entering the room, an increase in the melanopic transmission is suggested. This can be achieved by transitioning the electrochromic glazing from the dark tint state to medium tint state.**

It was seen in this study that electrochromic glazing in a clear state transmitted a more neutral spectrum in relation to dark tint or medium tint states. Unfortunately, it is common among the technology of electrochromic glazing the shift to blue light. This is the major negative aspect. These aspects related to the spectrum were also confirmed in the literature. As commented in Chapter 2 – literature review, users in office environments with electrochromic glazing prefer a neutral or slightly warm spectrum. In this regard, the achievement of a neutral spectrum concerning the different states of electrochromic glazing must be investigated concerning all latitudes in Brazil.

The main contribution of this study was to discuss the potentialities and limitations if similar technologies of smart windows like electrochromic glazing are imported into Brazil. Based on that, **recommendations were made for the three latitude ranges** about the use of the dynamic glazing to **improve its performance regarding visual and non-visual effects of light**. They were thought to guide professionals, such as architects, engineers, and designers, among others, to optimize the use of electrochromic glazing concerning visual effects in Brazilian latitudes. Consequently, this discussion is extremely useful in making informed decisions for optimizing the use of electrochromic glazing if implemented in non-residential in Brazil. The summary of recommendations for the use of electrochromic glazing regarding visual and non-visual effects in Brazil is presented in Figure 55.

Figure 55 – Summary of recommendations for the use of electrochromic glazing regarding visual and non-visual effects in Brazil.

Zone 1	**Latitude range 1: from 5° north to 9.9° south**
	**Orientation**: recommended use to the north. Not properly recommended to the south with required lowering of states only during summer months. To the east and the west, the use is not properly recommended due to the frequent deep penetration of direct sunlight. **Visual effects**: accurate glare controls (shading schedules) required. **Non-visual effects**: increase in tint state from dark (T_{mel} 1.8%) to medium tint (T_{mel}) 7%) required: • To the north in winter and to the south in summer. • To the east in the morning and to the west in the afternoon.
Zone 2	**Latitude range 2: from 10° south to 19.9° south**
	**Orientation**: recommended use to the north. Use not recommended to the south, with few periods required of lowering of states. To the east and the west, the use is not properly recommended due to the frequent deep penetration of direct sunlight. **Visual effects**: accurate glare controls (shading schedules) required. **Non-visual effects**: increase in tint state from dark (T_{mel} 1.8%) to medium tint (T_{mel}) 7%) required: • To the north in autumn, winter and spring • To the east in the morning and to the west in the afternoon.
Zone 3	**Latitude range 3: from 20° south to 34° south**
	**Orientation**: recommended use to the north. Not recommended to the south. To the east and the west, the use is not properly recommended due to the frequent deep penetration of direct sunlight. **Visual effects**: shading schedules must be based on accurate glare controls, while ensuring minimum illuminance levels of 300 lux at the back of the room for the north orientation. **Non-visual effects**: increase in tint state from dark (T_{mel} 1.8%) to medium tint (T_{mel}) 7%) required: • To the north in autumn, winter and spring. • To the east in the morning and to the west in the afternoon.

Source: The Author.

All in all, the performance of electrochromic glazing regarding visual and non-visual effects within the six simulated Brazilian latitudes showed limitations to balance visual and non-visual effects. In general, the evaluated performance of the dynamic glazing in highly glazed non-residential buildings can be improved with more accurate glare controls. The best performance for electrochromic glazing was for the north in the six evaluated cities/latitudes. Only a few benefits to the south were seen for the cities/latitudes of Manaus (3° south) and Recife (8° south), where the lowering of states were only required during summer months. To the east and the west, the use of electrochromic glazing is not properly recommended because in both orientations a deep penetration of direct sunlight occur in the morning and in the afternoon, respectively. If the shading schedules – lowering of states are not properly designed for the east and the west orientations, problems related to disturbing and intolerable glare can occur in the work environment.

Regarding visual effects of light, the main limitation of the majority of glazings, including the simulated ones and electrochromic glazing, is that these technologies are limited when the directionality of energy is considered. **That affected the distribution of daylight inside the simulated model. That explained the differences in the received daylight in the nine positions inside the simulated non-residential room.**

Consequently, according to Felippe (2016), to improve this issue, the combination of adequately designed shading devices, such as brise-soleil among other daylight redirecting systems, with other glazings can improve the distribution of daylight inside the room. This aspect considering sun shading devices and sunlight redirection was not investigated in this study. In this context, the prediction of the performance of electrochromic glazing combined with sun shading devices and other daylight redirecting systems must be further investigated in Brazilian latitudes.

Related to non-visual effects of light, changes in the shading schedule are highly recommended in order to allow more circadian lighting to enter the room. In this context, the increase from dark tint state to medium tint state is highly recommended.

The contributions through publications of parts of this research are shown in Appendix L.

Among the limitations of this thesis, the following points are noteworthy.

The method of this research was based on theoretical models to predict the performance of electrochromic glazing concerning visual and non-visual effects of light. The computer simulations conducted in Climate Studio and Alfa allowed the analysis of 864 cases and 34,560 cases regarding visual and non-visual effects, a broader context, including six sites/cities covering three different latitude ranges in Brazil. Nevertheless, it is recognized that the monitoring of its performance in real case studies must be carried out, if importation of electrochromic glazing or similar technologies is possible.

The software ALFA was restricted to point-in-time simulations. Therefore, to represent the variations of daylight throughout the year, four days close to the solstices and equinoxes were chosen to represent the beginning of each of the four yearly seasons. As daylight presents variations according to the seasons of the year, a more dynamic approach for future simulations of non-visual effects should be considered.

Similarities and differences regarding the performance of electrochromic glazing regarding non-visual effects per city/latitude were not related to any of the three proposals of the Brazilian luminous zoning, as described by Fonseca *et al.* (2023). These proposals were made considering visual effects of light, more precisely, the photopic illuminance. In this context, Inanici, Abboushi, and Safranek (2023) highlighted that recently developed sky models presented progress compared to colorless sky models, but further research is needed to increase the understanding of the sky spectral data of different locations. This observation is applied to the different Brazilian luminous contexts and latitudes as well.

The focus of this study was to understand the performance of electrochromic glazing considering a broader range of climates within the Brazilian context. The subjective assessment and users' acceptability regarding the use of electrochromic glazing must be considered in further studies, particularly in Brazil, if this technology is made commercially available.

The main limitation of this research is that experiments were not conducted to test the performance of electrochromic glazing regarding visual and non-visual effects of light. This is a technology that is not commonly commercialized in Brazil and the importation of this technology is extremely difficult.

Additionally, the spectral analysis was limited to specific cases, in Brasilia (15° south – intermediate latitude) in one day at specific hours to cover all four states of the dynamic glazing. The spreadsheet CIE α-opic Toolbox is limited to the analysis of one case at a time. As variations in the spectral distribution of electrochromic glazing occurred according to city/latitude, window orientation, position in the room, date/season of the year, and hour confirmed by the variations in Mel-DER, more cases must be selected to understand them.

In view of these limitations further studies are recommended:

- The understanding of the performance of electrochromic glazing related to glare mitigation in Brazilian latitudes must be deepened. For this reason, studies considering more accurate glare controls based on monitoring the sky luminance distribution in different sites/latitudes in Brazil must be developed.
- The Brazilian luminous zoning must consider the sky spectral data to deal with non-visual effects. In this respect, further studies focused on understanding the sky spectral data in different sites/latitudes covering the national territory are highly recommended.
- Studies must be focused on a more dynamic approach considering simulation studies to predict the performance of electrochromic glazing regarding non-visual effects of light considering longer periods than 4 days representing solstices and equinoxes in Brazil. Fortunately, simulations tools considering non-visual effects of light are rapidly being developed and this will be possible in the upcoming years.
- The users' subjective assessment must be considered. This will increase the acceptability if similar technologies of electrochromic glazing are imported and used in Brazilian latitudes.
- More experimental approaches are highly recommended, such as testbeds or real case studies, if the importation or commercialization of this technology is possible in Brazil.
- The spectral analysis of electrochromic glazing must consider more cases than the ones selected for this study. Mardaljevic, Waskett, and Painter (2016) indicated that approximately one eighth of the area containing the electrochromic glazing must remain in a clear state to achieve a more neutral spectrum. In this context, further studies are recommended to verify if the same proportion is required considering all three latitude ranges in Brazil.

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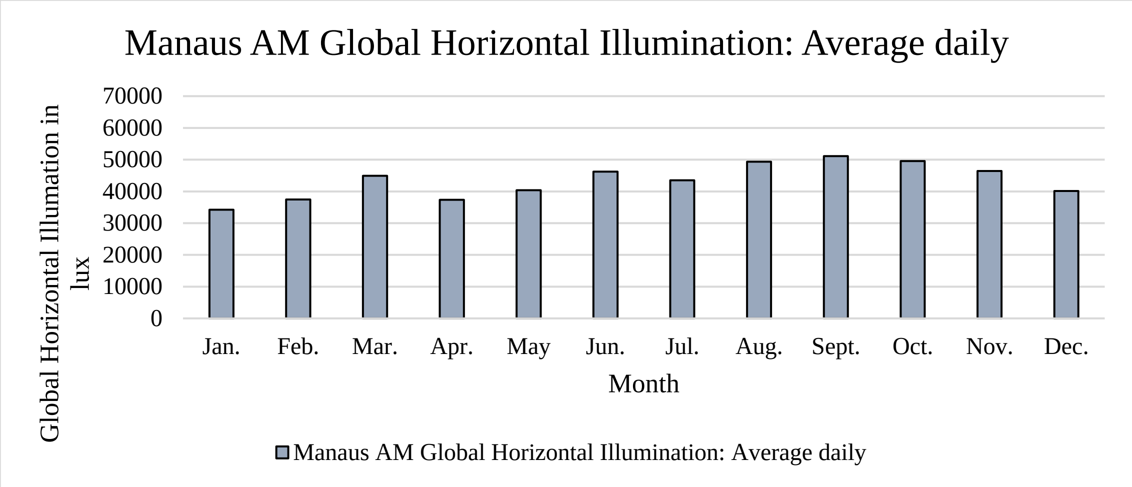
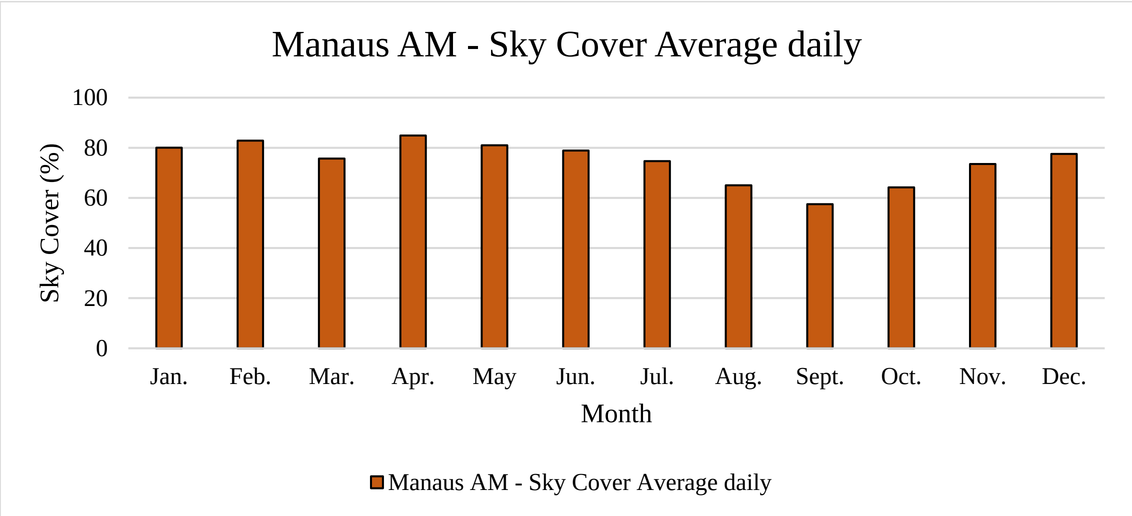
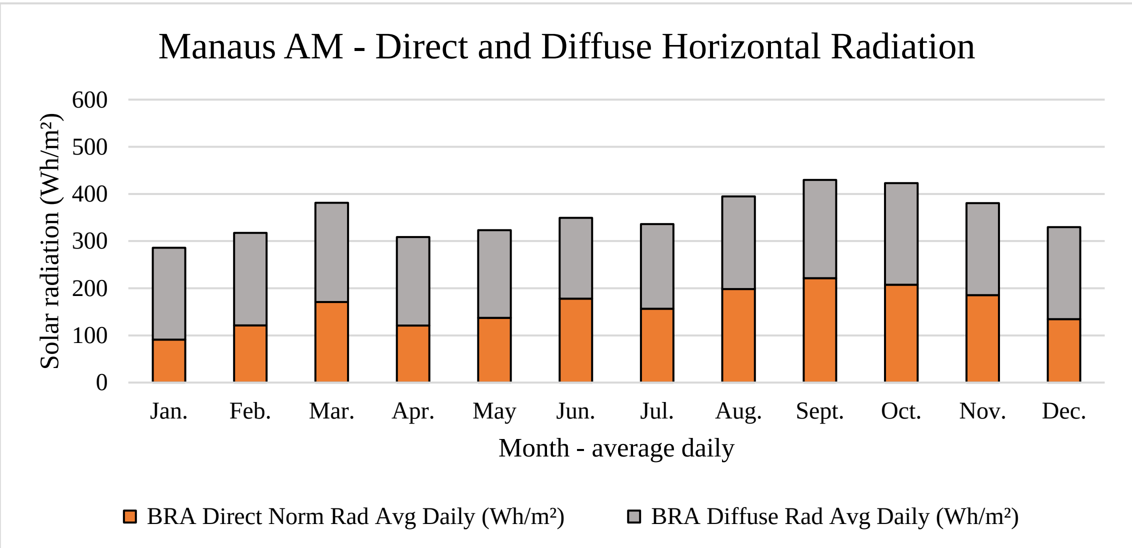
Appendix A. Global horizontal illuminance, cloudiness and direct and diffuse radiation of the simulated cities

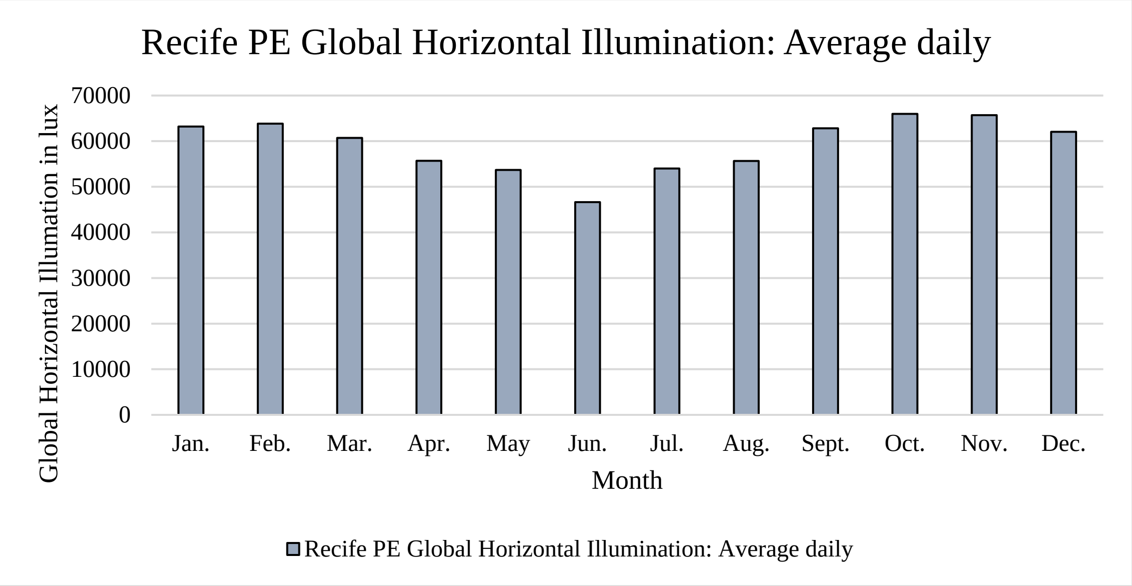
A1) Manaus (3° S/60° W)

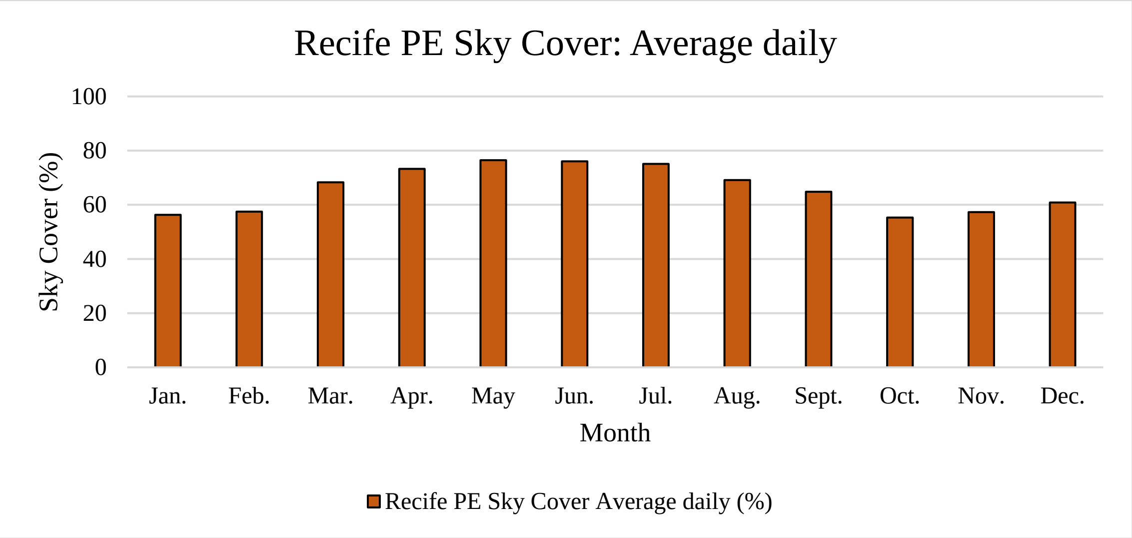


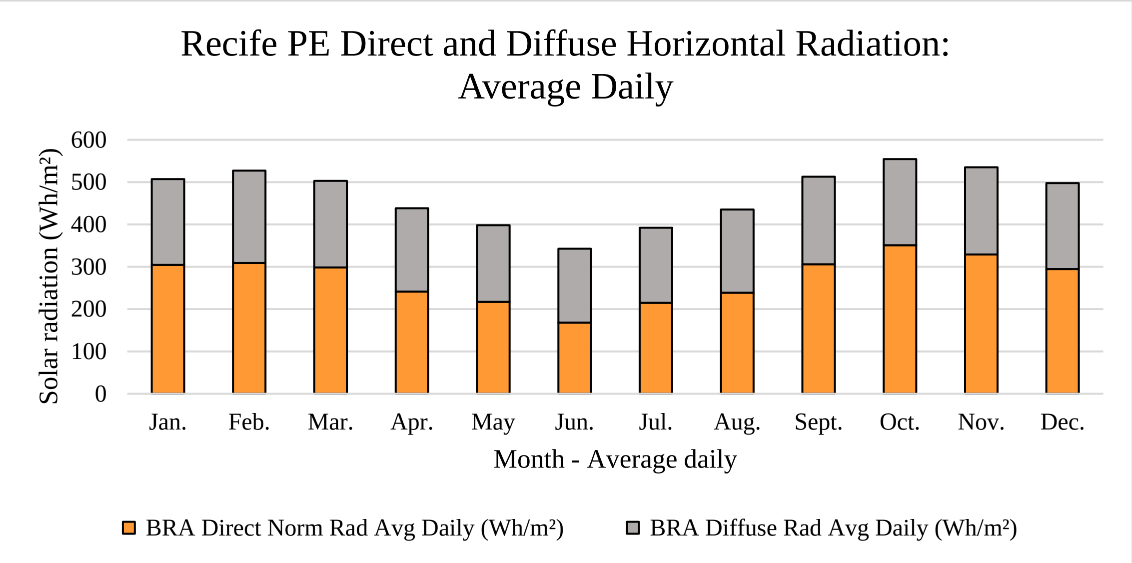




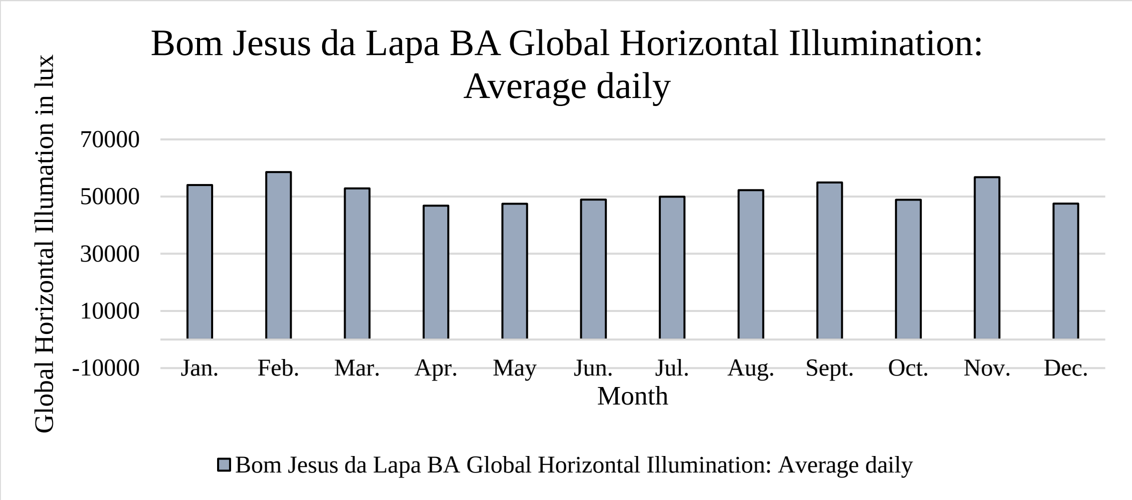
A2) Recife (8°S/ 34° W)

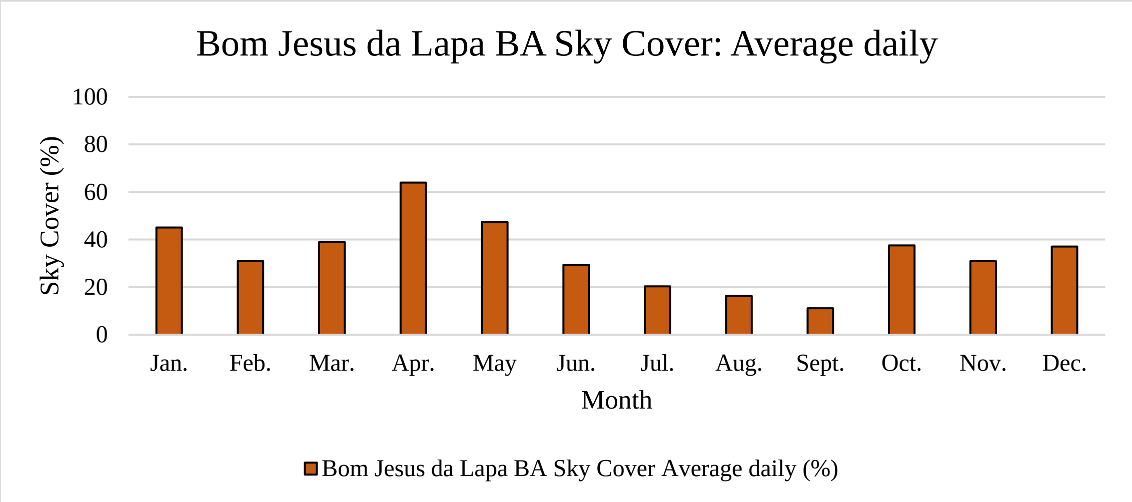


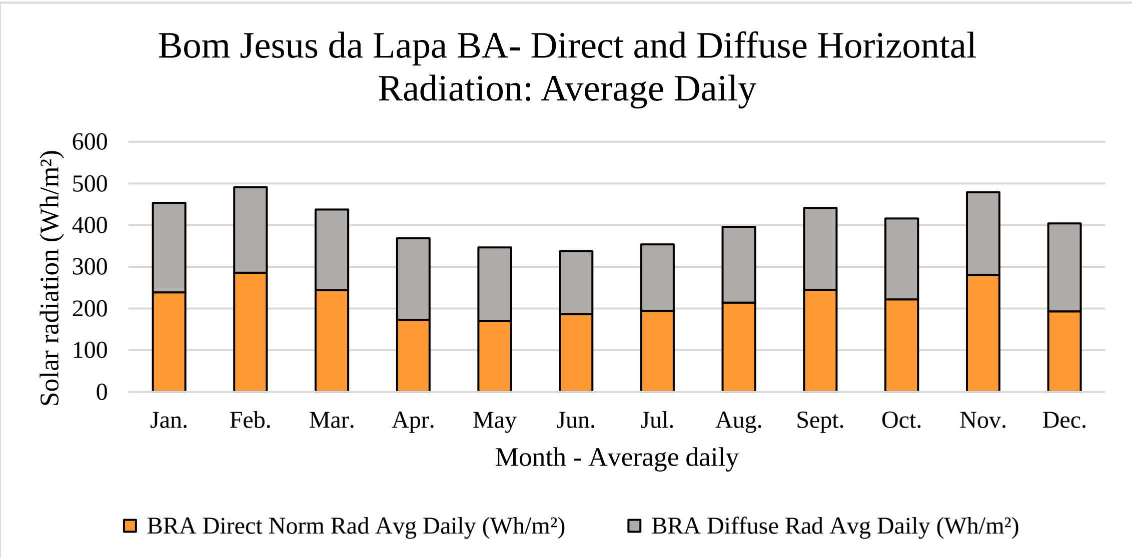




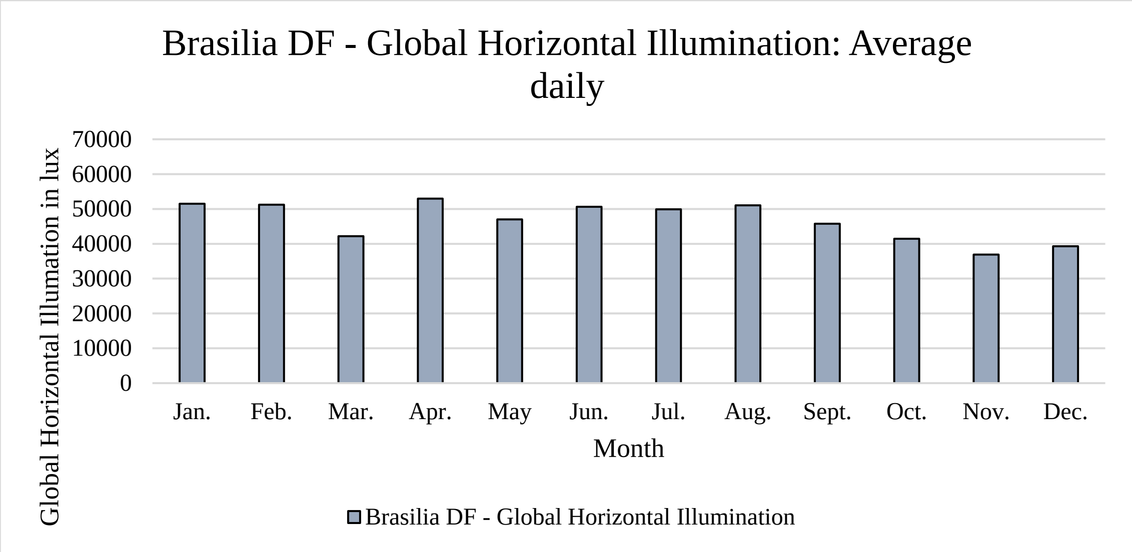
A3) Bom Jesus da Lapa (13° S/43° W)

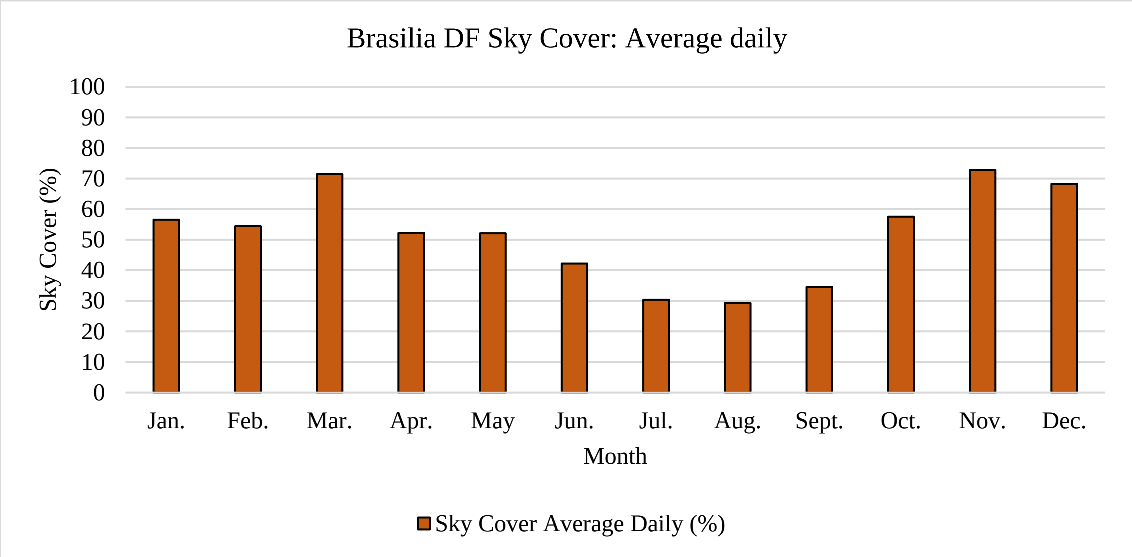


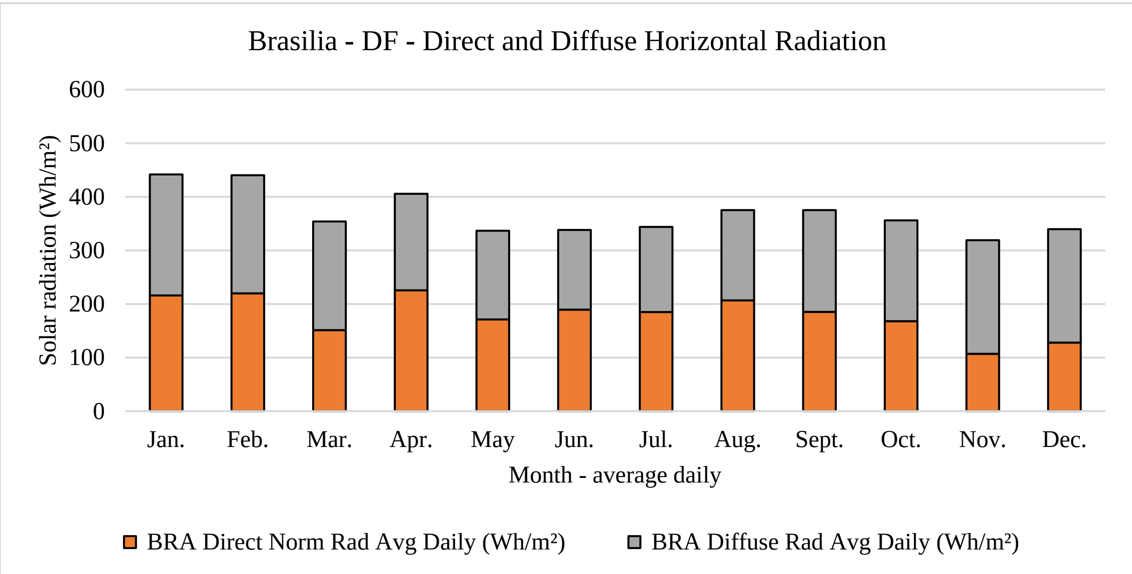




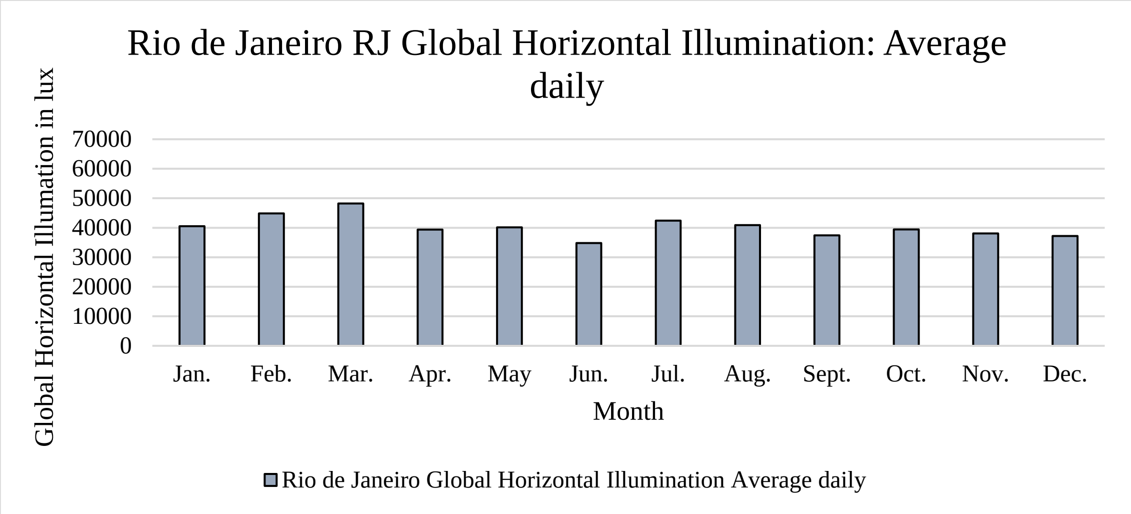
A4) Brasília (15° S/47° W)

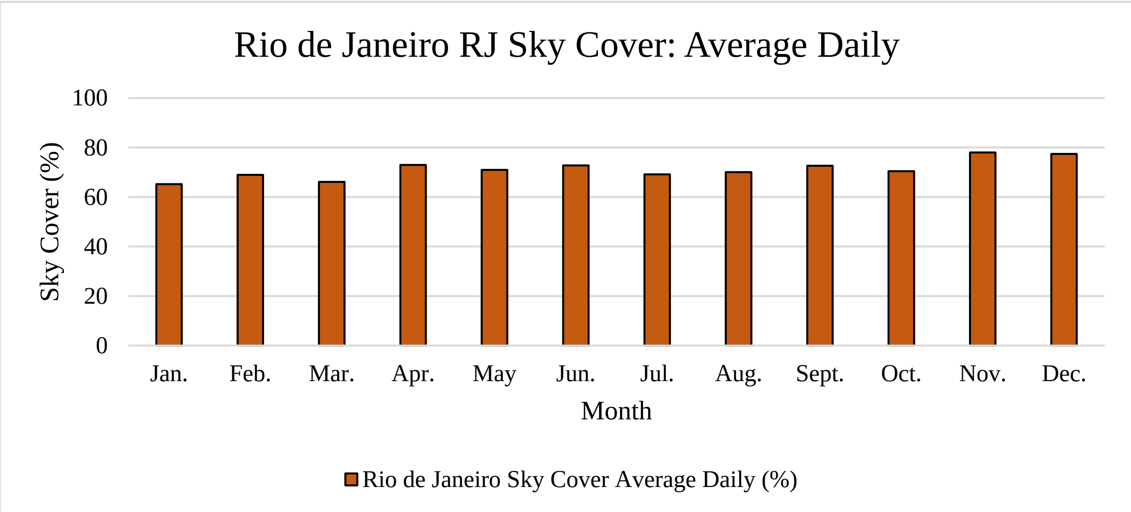


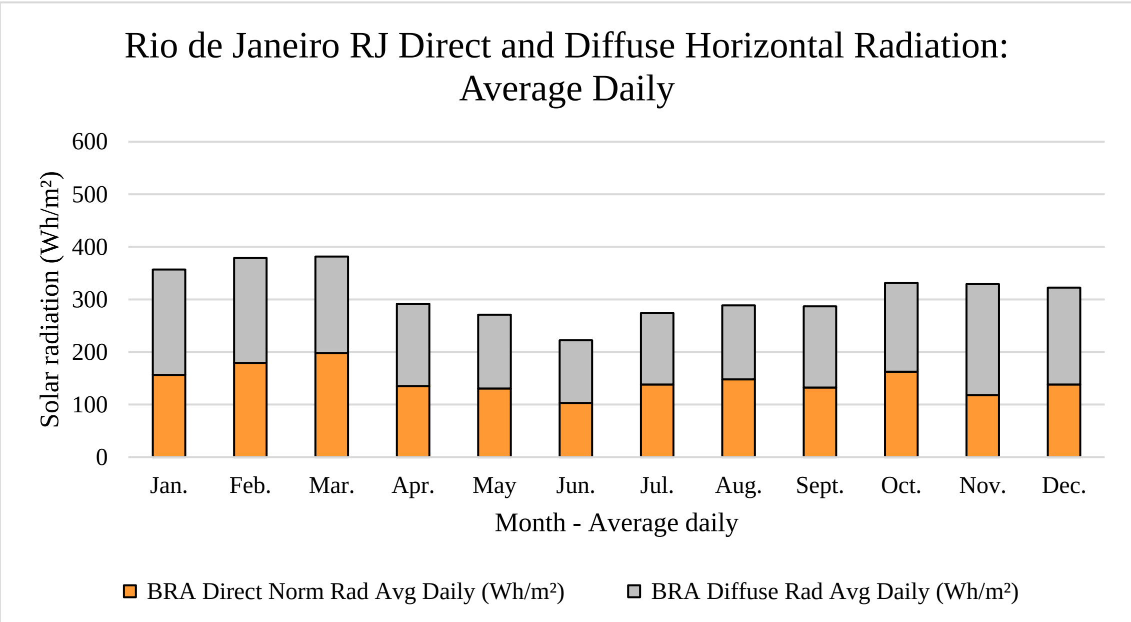




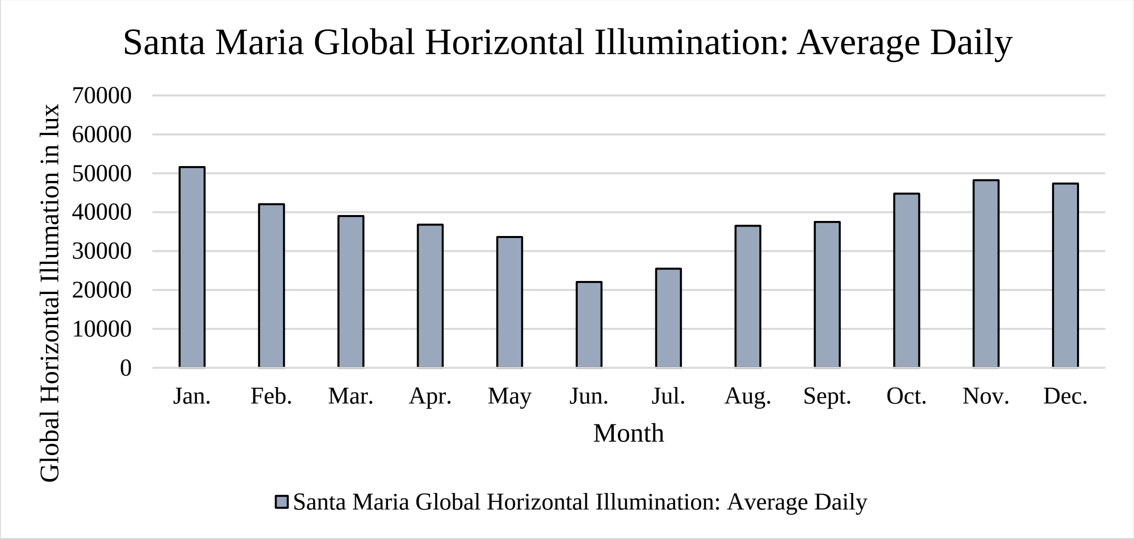
A5) Rio de Janeiro (22° S/43° W)

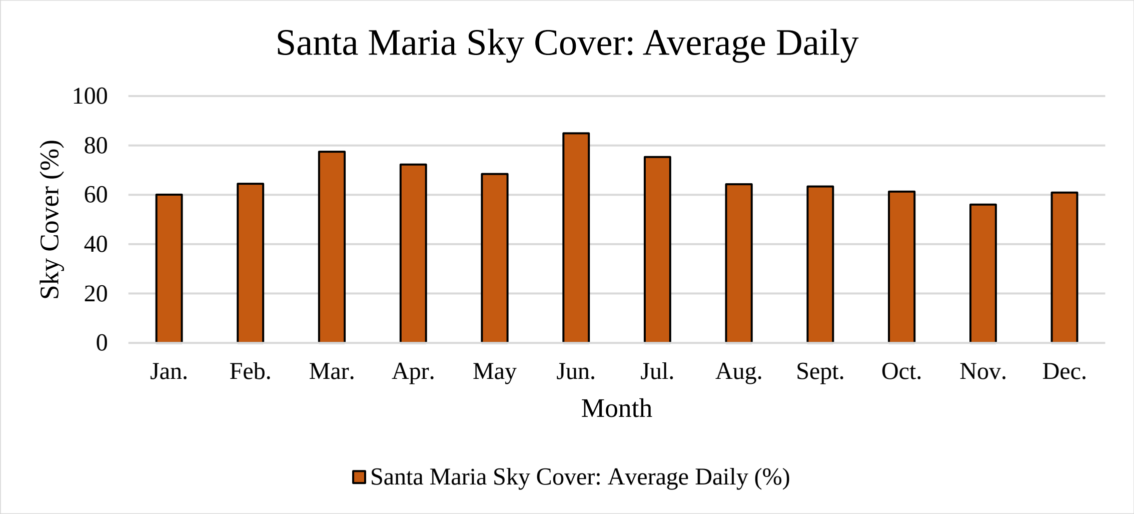


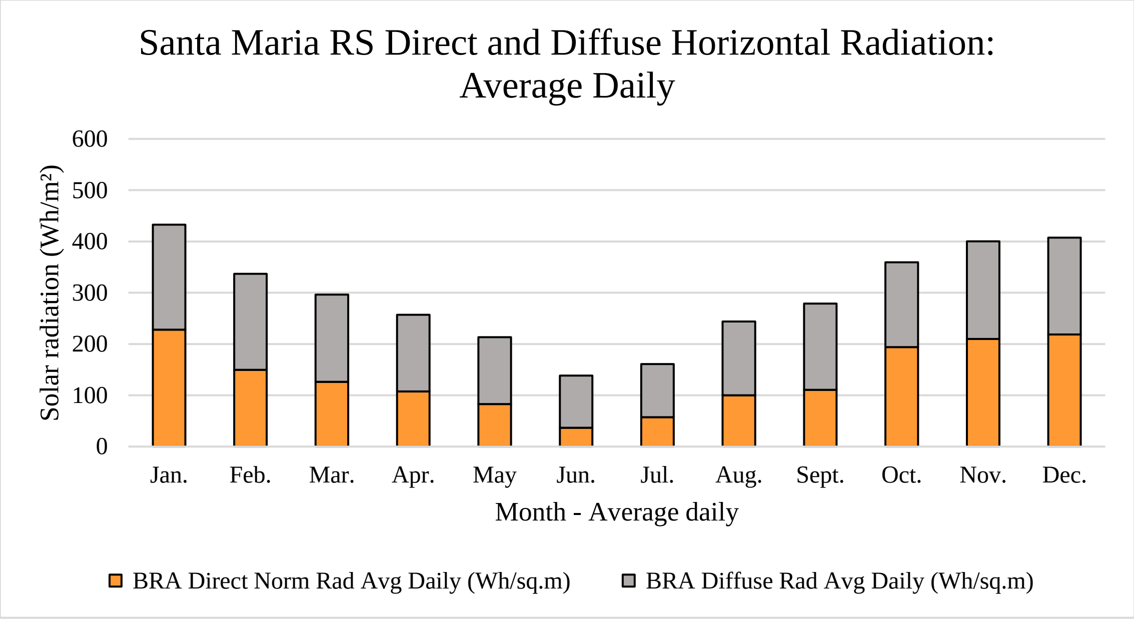




A6) Santa Maria (29° S/53° W)







A7) Summary of the data regarding global horizontal illuminance, cloudiness and direct and diffuse radiation of the simulated cities

Global horizontal illuminance (lux) - Average daily per month

City	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Mean (daily aver. per month)	Std. Dev.
Manaus	34.234	37.471	44.928	37.379	40.374	46.250	43.529	49.376	51.136	49.540	46.418	40.146	43.398	5.228
Recife	63.212	63.835	60.724	55.701	53.687	46.628	54.011	55.647	62.814	65.984	65.681	62.051	59.165	5.696
Bom Jesus da Lapa	54.056	58.548	52.845	46.806	47.502	48.932	49.954	52.224	54.952	48.871	56.755	47.568	51.584	3.735
Brasília	51.520	51.220	42.196	52.985	47.010	50.635	49.870	51.029	45.758	41.426	36.909	39.313	46.656	5.220
Rio de Janeiro	40.506	44.883	48.230	39.384	40.135	34.818	42.420	40.883	37.448	39.422	38.077	37.233	40.287	3.451
Santa Maria	51.588	42.066	39.000	36.794	33.623	22.060	25.493	36.490	37.506	44.765	48.235	47.343	38.747	8.500

Source: National Institute of Meteorology - INMET (2018).

Cloudiness (%) - Average daily per month

City	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Mean (daily aver. per month)	Std. Dev.
Manaus	80	83	76	85	81	79	75	65	58	64	74	78	75	8
Recife	56	58	68	73	76	76	75	69	65	55	57	61	66	8
Bom Jesus da Lapa	45	31	39	64	47	29	20	16	11	38	31	37	34	13
Brasília	57	54	71	52	52	42	30	29	35	58	73	68	52	14
Rio de Janeiro	65	69	66	73	71	73	69	70	73	70	78	77	71	4
Santa Maria	60	64	77	72	68	85	75	64	63	61	56	61	67	8

Source: National Institute of Meteorology - INMET (2018).

Direct Normal Radiation (Wh/m²) - Average daily per month														
City	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Mean (daily aver. per month)	Std. Dev.
Manaus	91,17	121,34	170,67	120,85	137,18	178,02	156,62	198,44	221,31	207,46	185,51	134,6	160	37
Recife	304,43	308,91	298,28	241,44	217,29	167,95	214,98	238,57	306,02	350,81	329,1	294,51	273	51
Bom Jesus da Lapa	239,02	286,02	243,86	172,97	169,66	186,26	194,49	214,4	244,48	222,04	279,76	193,37	221	36
Brasília	216,11	219,91	151,33	225,46	171,14	189,56	185,11	206,86	185,15	168,01	107,06	127,97	179	34
Rio de Janeiro	156,55	179,16	197,75	135,1	130,57	103,12	138,07	147,85	132,37	162,58	117,98	138,1	145	24
Santa Maria	228,1	149,54	126,12	107,45	82,829	36,784	57,307	100,16	110,63	194,12	209,89	218,59	135	59

Source: National Institute of Meteorology - INMET (2018).

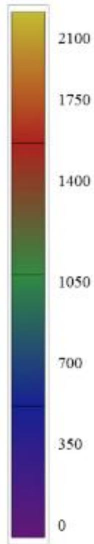
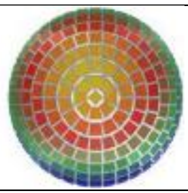
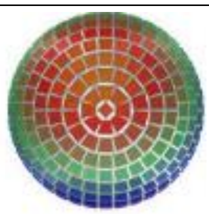
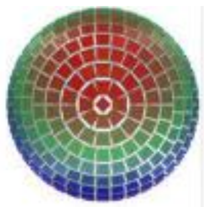
Diffuse Radiation (Wh/m²) - Average daily per month														
City	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Mean (daily aver. per month)	Std. Dev.
Manaus	194,54	195,97	210,7	187,88	186,12	171,33	179,34	196,28	208,47	215,51	195,15	195,12	195	12
Recife	202,59	218,25	204,63	196,87	180,99	174,52	177,36	196,74	206,74	203,45	205,94	203,09	198	12
Bom Jesus da Lapa	214,39	205,32	193,78	195,42	176,83	151,12	159,54	181,67	196,99	193,81	199,1	210,93	190	18
Brasília	225,57	220,36	202,72	180,18	165,43	148,71	158,77	168,4	189,92	188,19	211,93	211,74	189	23
Rio de Janeiro	200,42	199,55	183,67	156,7	140,28	119,24	136,03	140,88	154,37	168,84	211,1	184,35	166	27
Santa Maria	204,55	187,24	170,14	149,65	130,58	101,65	103,59	143,69	168,09	165,14	190,49	188,89	159	31

Source: National Institute of Meteorology - INMET (2018).

Global Horizontal Radiation (Wh/m²) - Average daily per month														
City	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**	**Mean (daily aver. per month)**	**Std. Dev.**
Manaus	307,14	341,72	414,05	336,79	359,68	408,23	386,13	446,91	471,86	458,79	421,13	360,98	393	48
Recife	582,77	594,35	564,58	501,97	476,16	408,92	476,06	502,45	581,36	623,94	609,14	569,83	541	61
Bom Jesus da Lapa	499,95	548,65	489,41	418,51	418,49	429,14	444,78	473,24	505,68	456,42	533,09	441,13	472	41
Brasília	479,64	479,05	385,57	474,67	411,35	439,57	436,44	454,89	418,8	385,23	339,74	362,85	422	43
Rio de Janeiro	384,79	413,66	435,12	346,03	346,69	296,49	365,93	357,63	333,45	363,7	352,38	349,79	362	33
Santa Maria	481,03	381,78	347,51	323,77	287,29	184,49	216,59	318,63	333,32	411,24	448,95	449,56	349	84

Source: National Institute of Meteorology - INMET (2018).

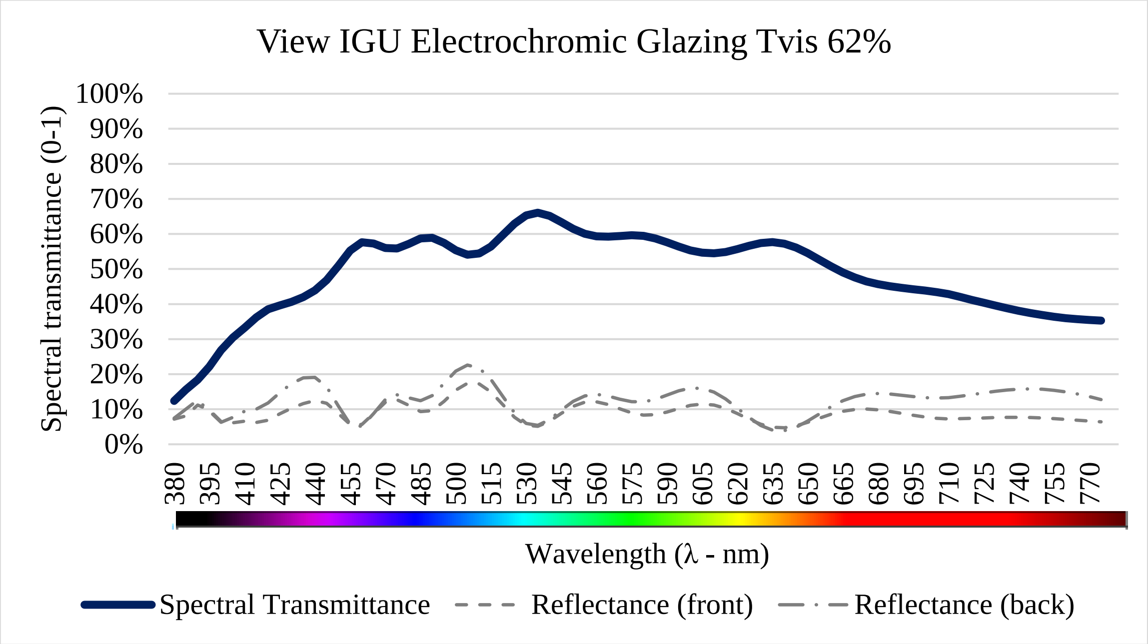
A8) Global annual radiation received by the semisphere representing the sky dome

Global annual radiation received by the semisphere representing the sky dome		
Manaus -03° 06’	Recife -08° 03’	
		Radiation [kWh/m²]
Bom Jesus da Lapa -13° 15’	Brasília -15° 46’	
		
Rio de Janeiro -22° 54’	Santa Maria -29° 41’	
		

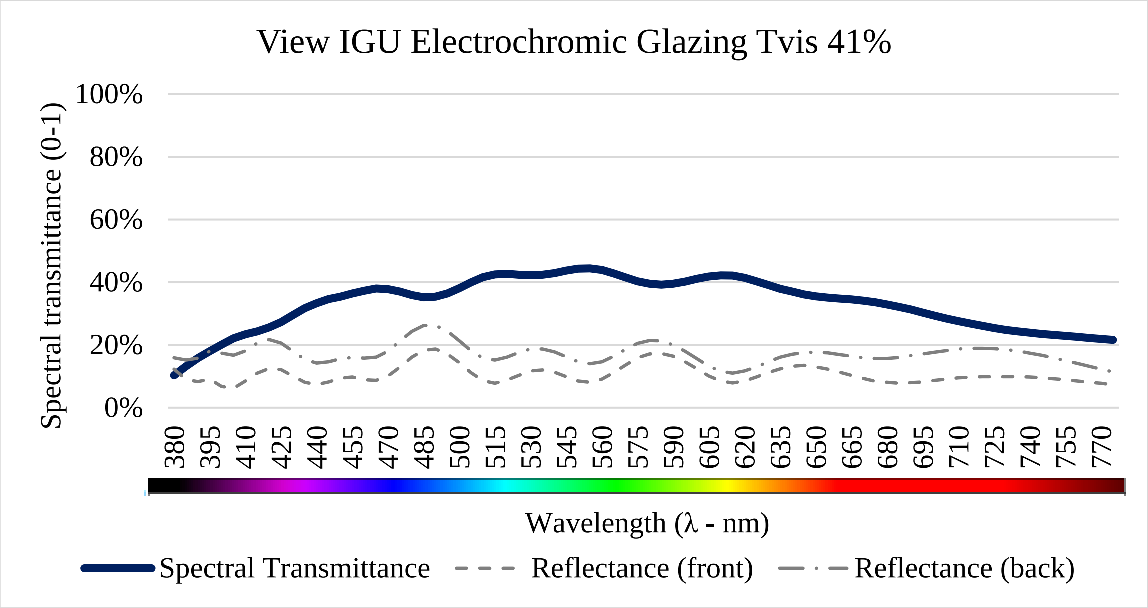
Source: Adapted from Fonseca *et al.* (2019).

Appendix B. Spectral transmittance and reflectance of the simulated glasses

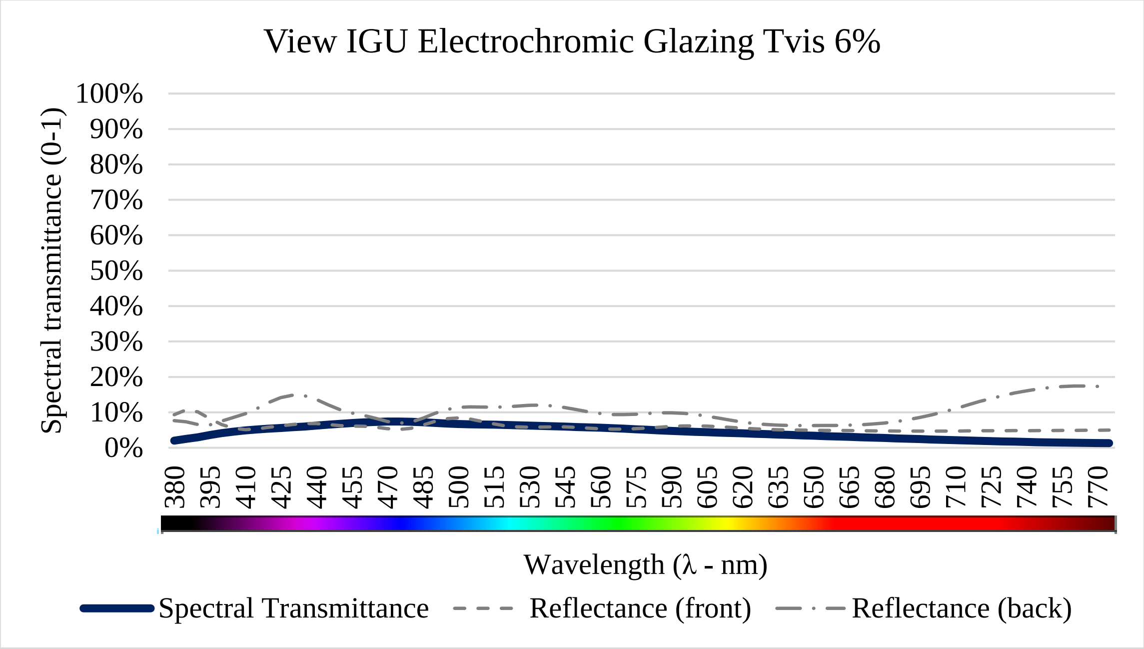
B1) Electrochromic glazing: Clear State



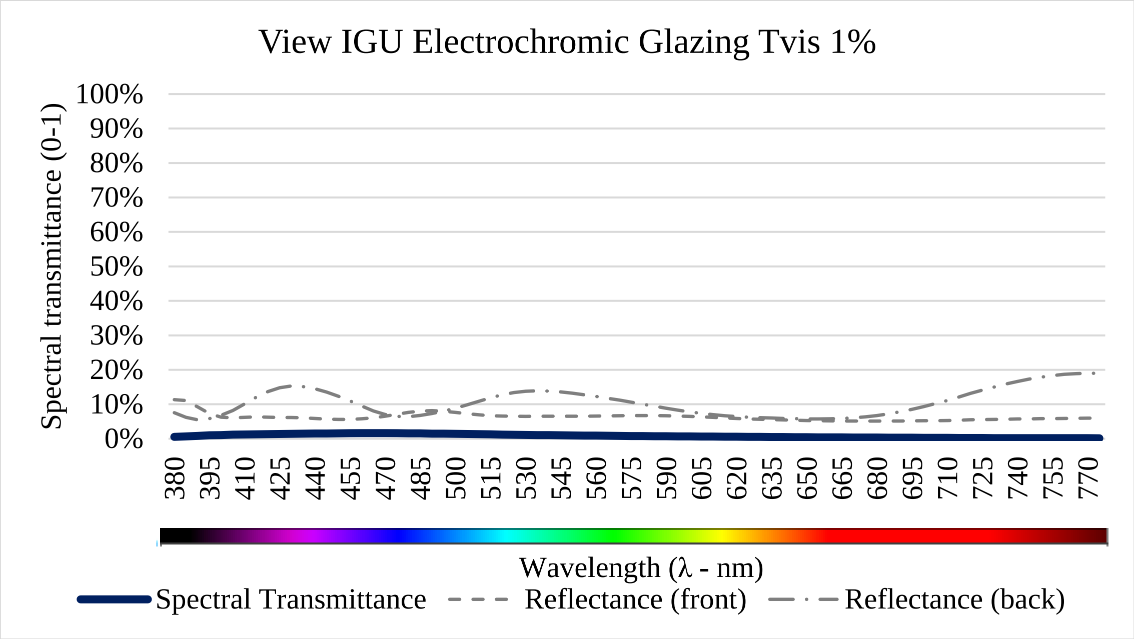
B2) Electrochromic glazing: Light Tint State



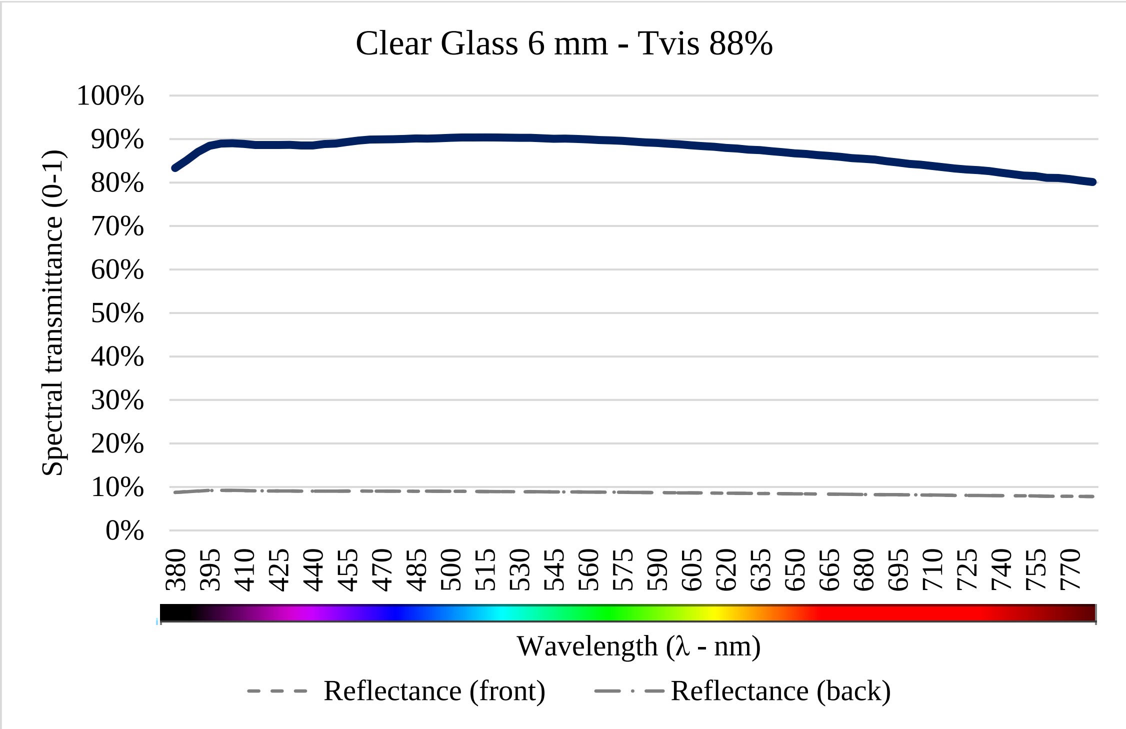
B3) Electrochromic glazing: Medium Tint State



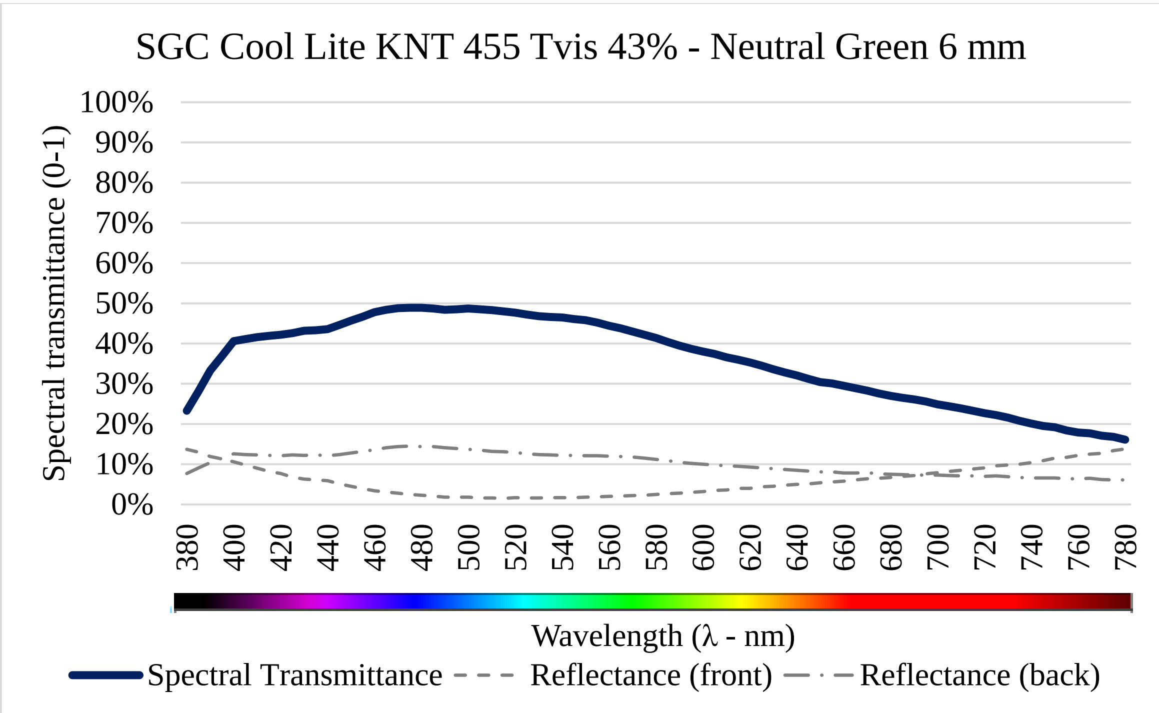
B4) Electrochromic glazing: Dark Tint State



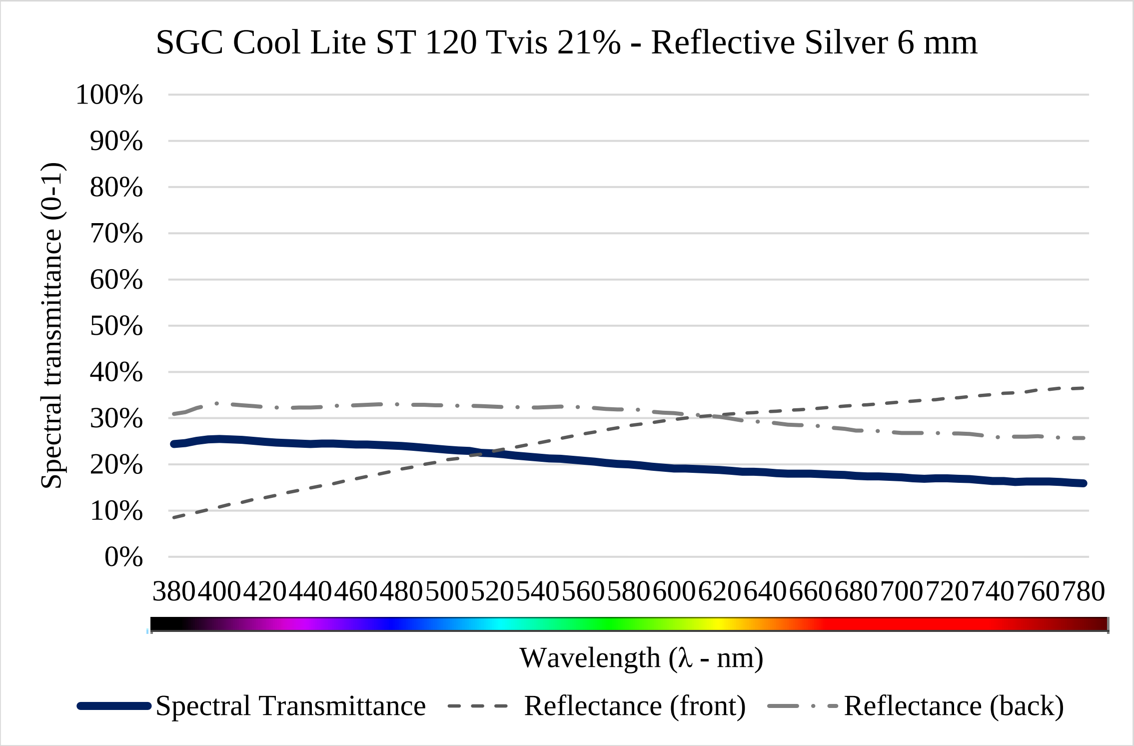
B5) Clear glass 6 mm



B6) Neutral green glass



B7) Reflective silver glass



Appendix C. Input data for simulations in ALFA

Month	Day	Hour	Cloudiness	Sky Condition	EC North	EC East	EC South	EC West
Manaus	AM	BRA						
3°6' S/60°1' W			Cloudiness	Sky condition	Vidro EC View	Vidro EC View	Vidro EC View	Vidro EC View
month	day	hour	%	Classification	Operation Schedule North	Operation Schedule East	Operation Schedule South	Operation Schedule West
3	22	8	70	Partly cloudy	0	2	0	0
3	22	9	50	Partly cloudy	0	3	0	0
3	22	10	30	Partly cloudy	0	3	0	0
3	22	11	30	Partly cloudy	0	0	0	0
3	22	12	30	Partly cloudy	0	0	0	0
3	22	13	30	Partly cloudy	0	0	0	3
3	22	14	20	Clear	0	0	0	3
3	22	15	20	Clear	0	0	0	2
3	22	16	20	Clear	0	0	0	0
3	22	17	30	Partly cloudy	0	0	0	0
6	21	8	80	Overcast	2	2	0	0
6	21	9	60	Partly cloudy	2	3	0	0
6	21	10	50	Partly cloudy	3	3	0	0
6	21	11	50	Partly cloudy	2	0	0	0
6	21	12	50	Partly cloudy	3	0	0	0
6	21	13	40	Partly cloudy	3	0	0	2
6	21	14	40	Partly cloudy	2	0	0	2
6	21	15	40	Partly cloudy	2	0	0	2
6	21	16	40	Partly cloudy	0	0	0	0
6	21	17	50	Partly cloudy	0	0	0	0
9	22	8	60	Partly cloudy	0	2	0	0
9	22	9	40	Partly cloudy	0	2	0	0
9	22	10	20	Clear	0	3	0	0
9	22	11	30	Partly cloudy	0	0	0	0
9	22	12	20	Clear	0	0	0	0
9	22	13	20	Clear	0	0	0	3
9	22	14	20	Clear	0	0	0	3
9	22	15	20	Clear	0	0	0	2
9	22	16	20	Clear	0	0	0	0
9	22	17	30	Partly cloudy	0	0	0	0
12	22	8	90	Overcast	0	0	0	0
12	22	9	70	Partly cloudy	0	2	2	0
12	22	10	60	Partly cloudy	0	2	2	0
12	22	11	40	Partly cloudy	0	0	2	0
12	22	12	40	Partly cloudy	0	0	2	0
12	22	13	40	Partly cloudy	0	0	3	3
12	22	14	30	Partly cloudy	0	0	0	0
12	22	15	50	Partly cloudy	0	0	2	2
12	22	16	30	Partly cloudy	0	0	0	0
12	22	17	70	Partly cloudy	0	0	0	0

Month	Day	Hour	Cloudiness	Sky Condition	EC North	EC East	EC South	EC West
Recife	PE	BRA						
8°4'S/ 34°55' W			Cloudiness	Sky condition	Vidro EC View	Vidro EC View	Vidro EC View	Vidro EC View
Month	Day	Hour	%	Classification	Operation Schedule North	Operation Schedule East	Operation Schedule South	Operation Schedule West
3	22	8	80	Overcast	0	2	0	0
3	22	9	60	Partly cloudy	0	3	0	0
3	22	10	40	Partly cloudy	0	0	0	0
3	22	11	40	Partly cloudy	0	0	0	0
3	22	12	40	Partly cloudy	0	0	0	3
3	22	13	40	Partly cloudy	0	0	0	3
3	22	14	40	Partly cloudy	0	0	0	3
3	22	15	40	Partly cloudy	0	0	0	2
3	22	16	40	Partly cloudy	0	0	0	0
3	22	17	60	Partly cloudy	0	0	0	0
6	21	8	90	Overcast	0	0	0	0
6	21	9	90	Overcast	0	0	0	0
6	21	10	90	Overcast	0	0	0	0
6	21	11	90	Overcast	0	0	0	0
6	21	12	90	Overcast	0	0	0	0
6	21	13	90	Overcast	0	0	0	0
6	21	14	90	Overcast	0	0	0	0
6	21	15	90	Overcast	0	0	0	0
6	21	16	80	Overcast	0	0	0	0
6	21	17	90	Overcast	0	0	0	0
9	22	8	60	Partly cloudy	0	3	0	0
9	22	9	50	Partly cloudy	0	3	0	0
9	22	10	50	Partly cloudy	0	0	0	0
9	22	11	50	Partly cloudy	0	0	0	0
9	22	12	50	Partly cloudy	0	0	0	3
9	22	13	50	Partly cloudy	0	0	0	3
9	22	14	60	Partly cloudy	0	0	0	3
9	22	15	50	Partly cloudy	0	0	0	0
9	22	16	60	Partly cloudy	0	0	0	0
9	22	17	60	Partly cloudy	0	0	0	0
12	22	8	50	Partly cloudy	0	3	3	0
12	22	9	40	Partly cloudy	0	3	3	0
12	22	10	30	Partly cloudy	0	0	3	0
12	22	11	30	Partly cloudy	0	0	0	0
12	22	12	30	Partly cloudy	0	0	3	3
12	22	13	30	Partly cloudy	0	0	3	3
12	22	14	30	Partly cloudy	0	0	3	3
12	22	15	30	Partly cloudy	0	0	2	2
12	22	16	40	Partly cloudy	0	0	0	0
12	22	17	50	Partly cloudy	0	0	0	0

Month	Day	Hour	Cloudiness	Sky Condition	EC North	EC East	EC South	EC West
Bom Jesus da Lapa	BA	BRA						
13°14' S/43°24' W			Cloudiness	Sky condition	Vidro EC View	Vidro EC View	Vidro EC View	Vidro EC View
Month	Day	Hour	%	Classification	Operation Schedule North	Operation Schedule East	Operation Schedule South	Operation Schedule West
3	22	8	80	Overcast	0	0	0	0
3	22	9	70	Partly cloudy	0	1	0	0
3	22	10	60	Partly cloudy	0	3	0	0
3	22	11	30	Partly cloudy	0	0	0	0
3	22	12	30	Partly cloudy	0	0	0	0
3	22	13	20	Clear	0	0	0	3
3	22	14	10	Clear	0	0	0	3
3	22	15	0	Clear	0	0	0	2
3	22	16	0	Clear	0	0	0	0
3	22	17	40	Partly cloudy	0	0	0	0
6	21	8	30	Partly cloudy	2	2	0	0
6	21	9	10	Clear	2	2	0	0
6	21	10	0	Clear	3	3	0	0
6	21	11	0	Clear	3	0	0	0
6	21	12	0	Clear	3	0	0	0
6	21	13	0	Clear	3	0	0	2
6	21	14	0	Clear	2	0	0	2
6	21	15	0	Clear	2	0	0	2
6	21	16	0	Clear	0	0	0	0
6	21	17	0	Clear	0	0	0	0
9	22	8	0	Clear	0	2	0	0
9	22	9	0	Clear	0	3	0	0
9	22	10	0	Clear	0	3	0	0
9	22	11	0	Clear	0	0	0	0
9	22	12	0	Clear	0	0	0	0
9	22	13	0	Clear	0	0	0	3
9	22	14	0	Clear	0	0	0	3
9	22	15	0	Clear	0	0	0	0
9	22	16	0	Clear	0	0	0	0
9	22	17	0	Clear	0	0	0	0
12	22	8	50	Partly cloudy	0	0	0	0
12	22	9	50	Partly cloudy	0	0	0	0
12	22	10	40	Partly cloudy	0	3	0	0
12	22	11	10	Clear	0	0	0	0
12	22	12	0	Clear	0	0	0	0
12	22	13	0	Clear	0	0	0	2
12	22	14	0	Clear	0	0	2	3
12	22	15	0	Clear	0	0	2	2
12	22	16	0	Clear	0	0	0	0
12	22	17	0	Clear	0	0	0	0

Month	Day	Hour	Cloudiness	Sky Condition	EC North	EC East	EC South	EC West
Brasilia	DF	BRA						
15°46' S/47°55' W			Cloudiness	Sky condition	Vidro EC View	Vidro EC View	Vidro EC View	Vidro EC View
Month	Day	Hour	%	Classification	Operation Schedule North	Operation Schedule East	Operation Schedule South	Operation Schedule West
3	22	8	60	Partly cloudy	0	2	0	0
3	22	9	50	Partly cloudy	2	3	0	0
3	22	10	50	Partly cloudy	3	3	0	0
3	22	11	40	Partly cloudy	3	0	0	0
3	22	12	30	Partly cloudy	3	0	0	0
3	22	13	20	Clear	3	0	0	3
3	22	14	20	Clear	3	0	0	3
3	22	15	20	Clear	2	0	0	2
3	22	16	10	Clear	0	0	0	0
3	22	17	10	Clear	0	0	0	0
6	21	8	100	Overcast	0	0	0	0
6	21	9	100	Overcast	2	2	0	0
6	21	10	70	Partly cloudy	3	2	0	0
6	21	11	50	Partly cloudy	3	0	0	0
6	21	12	30	Partly cloudy	3	0	0	0
6	21	13	30	Partly cloudy	3	0	0	2
6	21	14	30	Partly cloudy	2	0	0	2
6	21	15	30	Partly cloudy	2	0	0	2
6	21	16	30	Partly cloudy	0	0	0	0
6	21	17	30	Partly cloudy	0	0	0	0
9	22	8	30	Partly cloudy	0	2	0	0
9	22	9	30	Partly cloudy	2	3	0	0
9	22	10	20	Clear	3	3	0	0
9	22	11	10	Clear	3	0	0	0
9	22	12	0	Clear	3	0	0	0
9	22	13	0	Clear	3	0	0	3
9	22	14	0	Clear	1	0	0	2
9	22	15	0	Clear	0	0	0	0
9	22	16	0	Clear	0	0	0	0
9	22	17	0	Clear	0	0	0	0
12	22	8	80	Overcast	0	0	0	0
12	22	9	50	Partly cloudy	0	0	0	0
12	22	10	50	Partly cloudy	0	2	0	0
12	22	11	40	Partly cloudy	0	0	0	0
12	22	12	40	Partly cloudy	0	0	0	0
12	22	13	40	Partly cloudy	0	0	0	2
12	22	14	60	Partly cloudy	0	0	0	0
12	22	15	90	Overcast	0	0	0	0
12	22	16	90	Overcast	0	0	0	0
12	22	17	90	Overcast	0	0	0	0

Month	**Day**	**Hour**	**Cloudiness**	**Sky Condition**	**EC North**	**EC East**	**EC South**	**EC West**
Rio de Janeiro	RJ	BRA						
22°54’ S/43°12’ W			Cloudiness	Sky condition	Vidro EC View	Vidro EC View	Vidro EC View	Vidro EC View
Month	Day	Hour	%	Classification	Operation Schedule North	Operation Schedule East	Operation Schedule South	Operation Schedule West
3	22	8	80	Overcast	1	2	0	0
3	22	9	70	Partly cloudy	2	2	0	0
3	22	10	50	Partly cloudy	3	3	0	0
3	22	11	30	Partly cloudy	3	0	0	0
3	22	12	20	Clear	2	0	0	0
3	22	13	20	Clear	3	0	0	3
3	22	14	10	Clear	2	0	0	3
3	22	15	20	Clear	1	0	0	2
3	22	16	40	Partly cloudy	0	0	0	0
3	22	17	30	Partly cloudy	0	0	0	0
6	21	8	50	Partly cloudy	2	2	0	0
6	21	9	30	Partly cloudy	2	2	0	0
6	21	10	10	Clear	3	2	0	0
6	21	11	0	Clear	3	0	0	0
6	21	12	0	Clear	3	0	0	0
6	21	13	0	Clear	2	0	0	2
6	21	14	20	Clear	2	0	0	2
6	21	15	50	Partly cloudy	0	0	0	0
6	21	16	50	Partly cloudy	0	0	0	0
6	21	17	60	Partly cloudy	0	0	0	0
9	22	8	90	Overcast	0	0	0	0
9	22	9	80	Overcast	0	0	0	0
9	22	10	70	Partly cloudy	0	0	0	0
9	22	11	70	Partly cloudy	0	0	0	0
9	22	12	50	Partly cloudy	0	0	0	0
9	22	13	40	Partly cloudy	2	0	0	2
9	22	14	30	Partly cloudy	0	0	0	0
9	22	15	40	Partly cloudy	0	0	0	1
9	22	16	40	Partly cloudy	0	0	0	0
9	22	17	50	Partly cloudy	0	0	0	0
12	22	8	80	Overcast	0	3	0	0
12	22	9	60	Partly cloudy	0	3	0	0
12	22	10	50	Partly cloudy	0	3	0	0
12	22	11	30	Partly cloudy	0	0	0	0
12	22	12	20	Clear	0	0	0	0
12	22	13	30	Partly cloudy	0	0	0	3
12	22	14	30	Partly cloudy	0	0	0	3
12	22	15	30	Partly cloudy	0	0	0	2
12	22	16	30	Partly cloudy	0	0	0	0
12	22	17	70	Partly cloudy	0	0	0	0

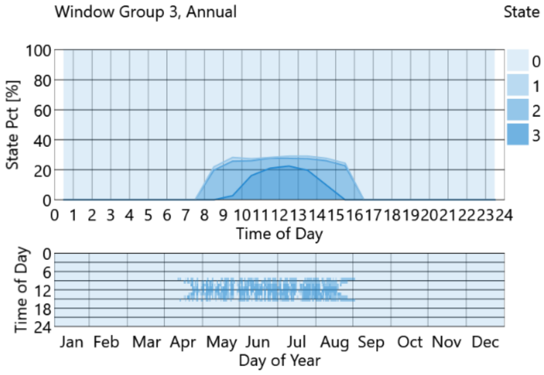
Month	**Day**	**Hour**	**Cloudiness**	**Sky Condition**	**EC North**	**EC East**	**EC South**	**EC West**
Santa Maria	RS	BRA						
29°41’ S/53°48’ W			Cloudiness	Sky Condition	Vidro EC View	Vidro EC View	Vidro EC View	Vidro EC View
Month	Day	Hour	%	Classification	Operation Schedule North	Operation Schedule East	Operation Schedule South	Operation Schedule West
3	22	8	80	Overcast	0	1	0	0
3	22	9	70	Partly cloudy	2	2	0	0
3	22	10	60	Partly cloudy	3	3	0	0
3	22	11	60	Partly cloudy	3	3	0	0
3	22	12	50	Partly cloudy	3	0	0	0
3	22	13	40	Partly cloudy	3	0	0	0
3	22	14	30	Partly cloudy	2	0	0	2
3	22	15	30	Partly cloudy	2	0	0	2
3	22	16	20	Clear	0	0	0	0
3	22	17	20	Clear	0	0	0	0
6	21	8	90	Overcast	0	0	0	0
6	21	9	90	Overcast	0	0	0	0
6	21	10	100	Overcast	0	0	0	0
6	21	11	100	Overcast	0	0	0	0
6	21	12	100	Overcast	0	0	0	0
6	21	13	90	Overcast	0	0	0	0
6	21	14	70	Partly cloudy	2	0	0	2
6	21	15	70	Partly cloudy	0	0	0	0
6	21	16	70	Partly cloudy	0	0	0	0
6	21	17	70	Partly cloudy	0	0	0	0
9	22	8	90	Overcast	0	0	0	0
9	22	9	80	Overcast	1	2	0	0
9	22	10	70	Partly cloudy	2	2	0	0
9	22	11	60	Partly cloudy	2	2	0	0
9	22	12	60	Partly cloudy	3	0	0	0
9	22	13	60	Partly cloudy	3	0	0	3
9	22	14	60	Partly cloudy	2	0	0	2
9	22	15	60	Partly cloudy	2	0	0	2
9	22	16	50	Partly cloudy	0	0	0	1
9	22	17	60	Partly cloudy	0	0	0	0
12	22	8	100	Overcast	0	0	0	0
12	22	9	90	Overcast	0	0	0	0
12	22	10	80	Overcast	0	0	0	0
12	22	11	80	Overcast	0	0	0	0
12	22	12	80	Overcast	0	0	0	0
12	22	13	80	Overcast	0	0	0	0
12	22	14	60	Partly cloudy	0	0	0	2
12	22	15	60	Partly cloudy	0	0	0	0
12	22	16	70	Partly cloudy	0	0	0	1
12	22	17	70	Partly cloudy	0	0	0	0

Appendix D. Shading schedule of electrochromic glazing per city and window orientation

D1) Manaus

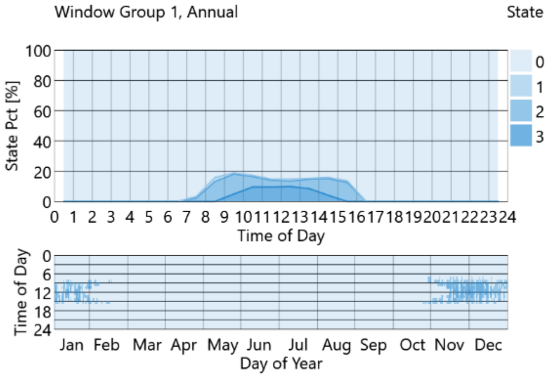
Manaus (3°6’ S/60°1’ W)

North



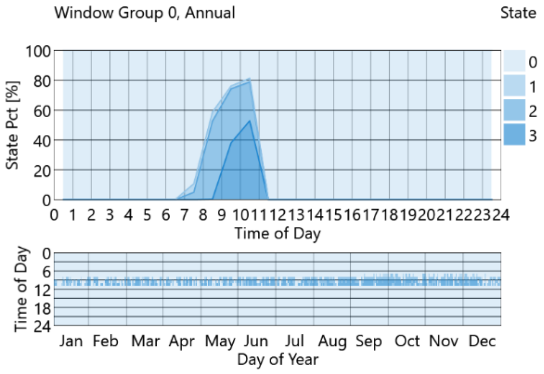
Clear state – 78% of the year

South



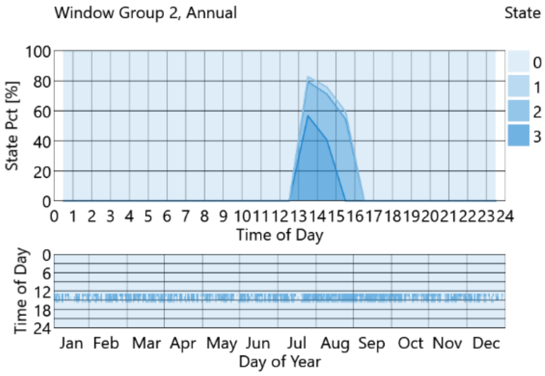
Clear state – 87% of the year

East



Clear state – 78% of the year

West



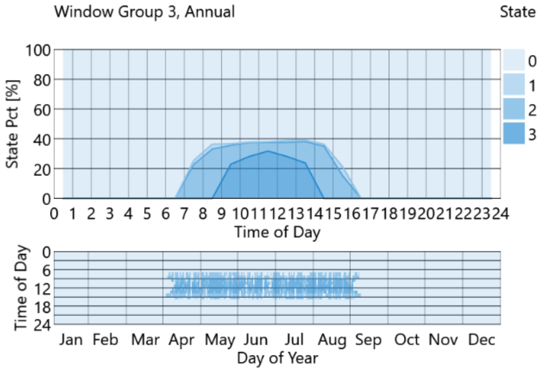
Clear state – 78% of the year

Note: *0 – Tint states: Tvis 0 62.1%/ 1- Tvis 1 41.4%/ 2- Tvis 2 5.4%/ 3- Tvis 3 1.1%.

D2) Recife

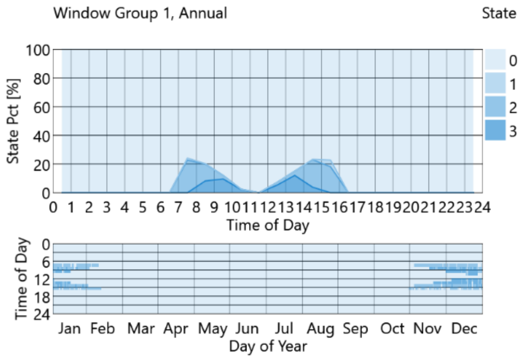
Recife (8°4’S/ 34°55’ W)

North



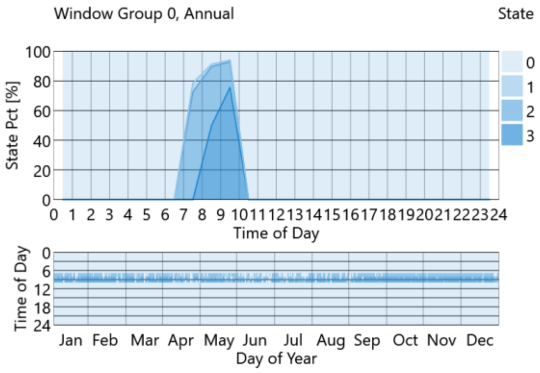
Clear state – 69% of the year

South



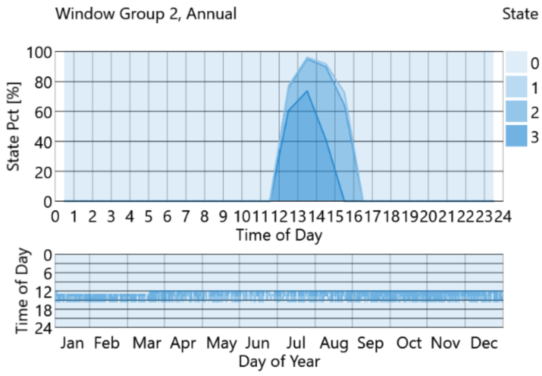
Clear state – 90% of the year

East



Clear state – 77% of the year

West



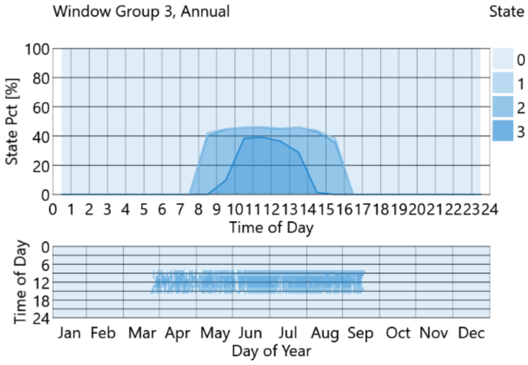
Clear state – 66% of the year

Note: *0 – Tint states: Tvis 0 62.1%/ 1- Tvis 1 41.4%/ 2- Tvis 2 5.4%/ 3- Tvis 3 1.1%.

D3) Bom Jesus da Lapa

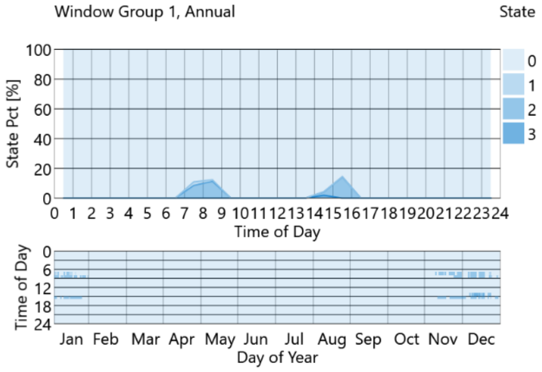
Bom Jesus da Lapa (13°14’ S/43°24’ W)

North



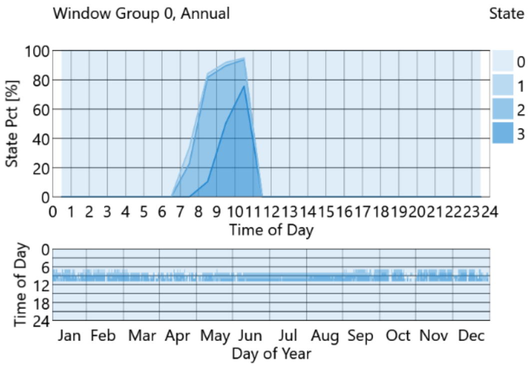
Clear state – 65% of the year

South



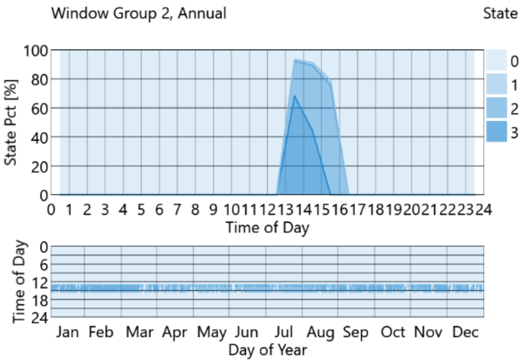
Clear state – 97% of the year

East



Clear state – 72% of the year

West



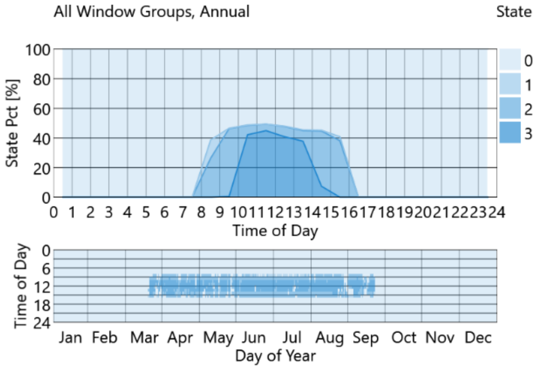
Clear state – 74% of the year

Note: *0 – Tint states: Tvis 0 62.1%/ 1- Tvis 1 41.4%/ 2- Tvis 2 5.4%/ 3- Tvis 3 1.1%.

D4) Brasilia

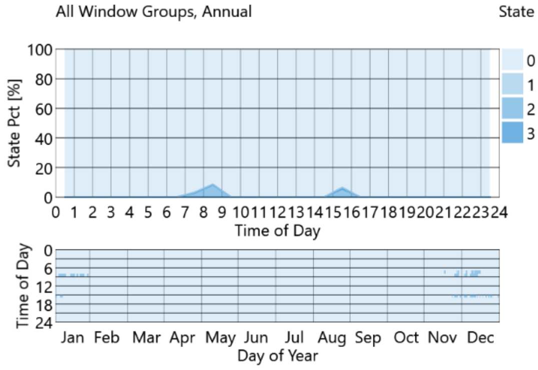
Brasilia (15°46’ S/47°55’ W)

North



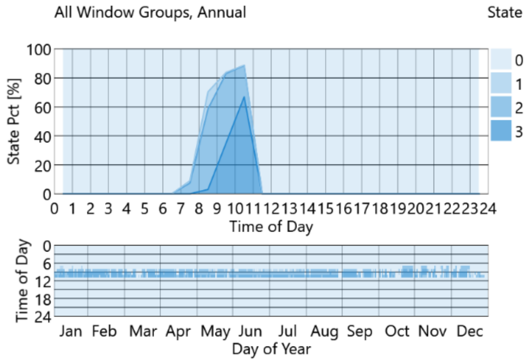
Clear state – 64% of the year

South



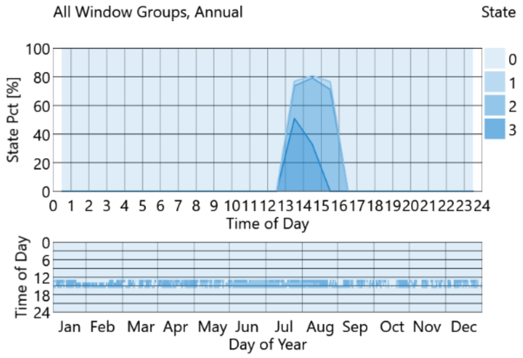
Clear state – 98% of the year

East



Clear state – 75% of the year

West



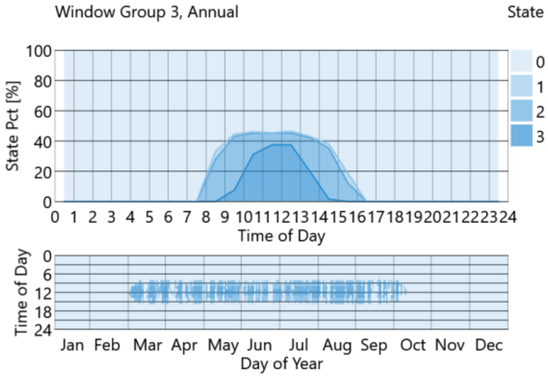
Clear state – 77% of the year

Note: *0 – Tint states: Tvis 0 62.1%/ 1- Tvis 1 41.4%/ 2- Tvis 2 5.4%/ 3- Tvis 3 1.1%.

D5) Rio de Janeiro

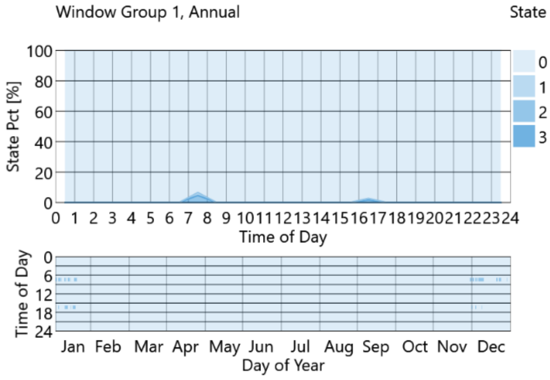
Rio de Janeiro (22°54’ S/43°12’ W)

North



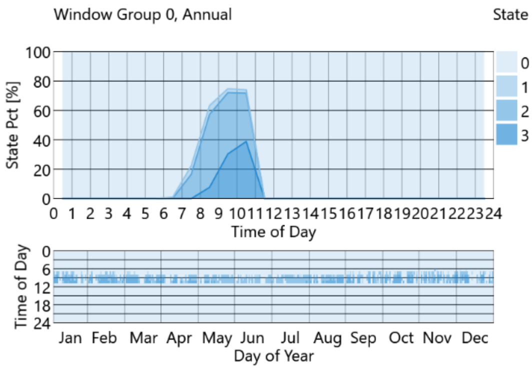
Clear state – 68% of the year

South



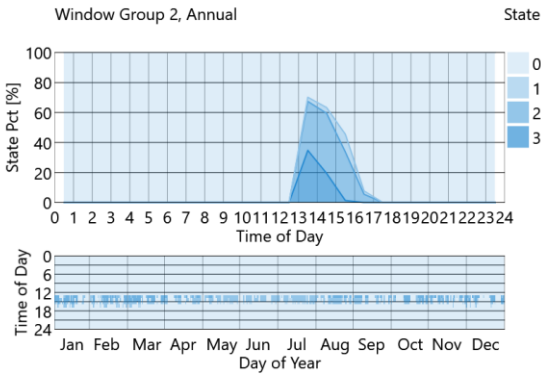
Clear state – 100% of the year

East



Clear state – 78% of the year

West



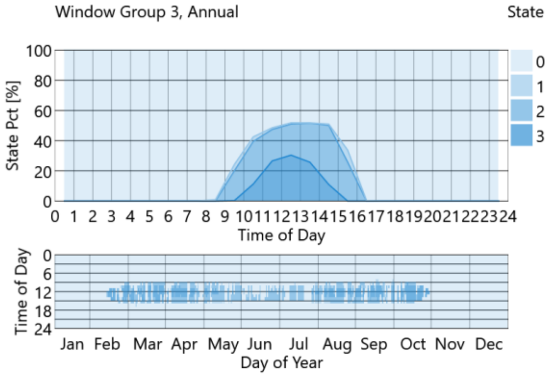
Clear state – 81% of the year

Note: *0 – Tint states: Tvis 0 62.1%/ 1- Tvis 1 41.4%/ 2- Tvis 2 5.4%/ 3- Tvis 3 1.1%.

D6) Santa Maria

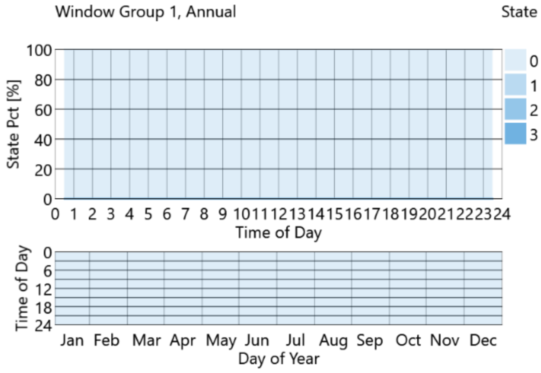
Santa Maria (29°41' S/53°48' W)

North



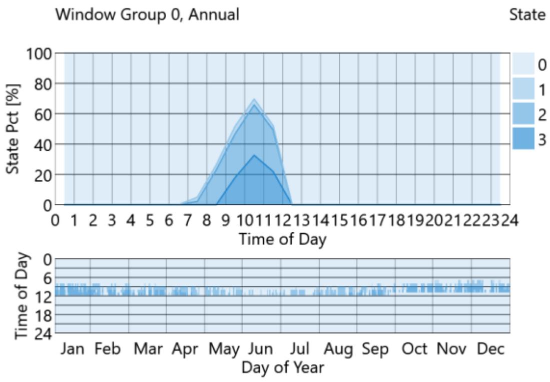
Clear state – 70% of the year

South



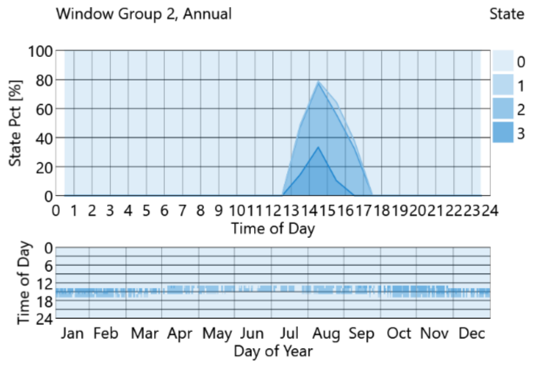
Clear state – 100% of the year

East



Clear state – 80% of the year

West



Clear state – 77% of the year

Note: *0 – Tint states: Tvis 0 62.1%/ 1- Tvis 1 41.4%/ 2- Tvis 2 5.4%/ 3- Tvis 3 1.1%.

Appendix E. Summary of results of visual effects response variables

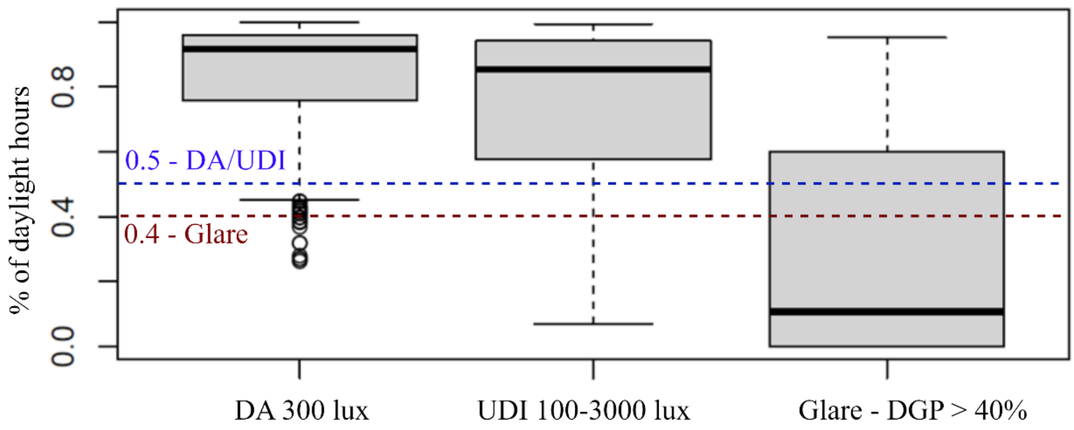
Visual effects of light

Summary of results of daylight autonomy (DA), useful daylight autonomy (UDI) and annual glare (DGP > 40%).

Variable	**DA 300 Lux**	**UDI 100 - 3000 Lux**	**Annual glare (DGP > 40%)**
Minimum	0.263	0.07096	0
1st Quartile	0.7581	0.57966	0
Median	0.9174	0.85479	0.1077
Mean	0.8438	0.73797	0.285
3º Quartile	0.9614	0.94226	0.6005
Maximum	0.9995	0.99452	0.9518
Standard deviation	0.1541	0.264	0.3224
Coefficient of variation	18.2%	35.8%	131.1%

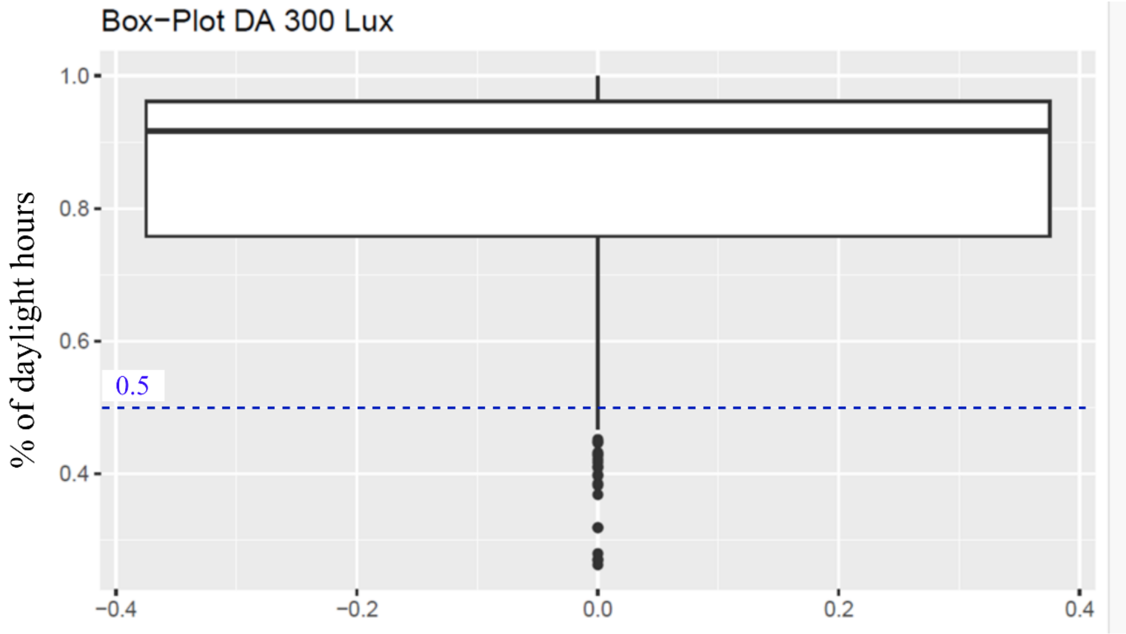
Source: The Author.

Boxplot chart summarizing results of daylight autonomy (DA), useful daylight autonomy (UDI) and annual glare (DGP).



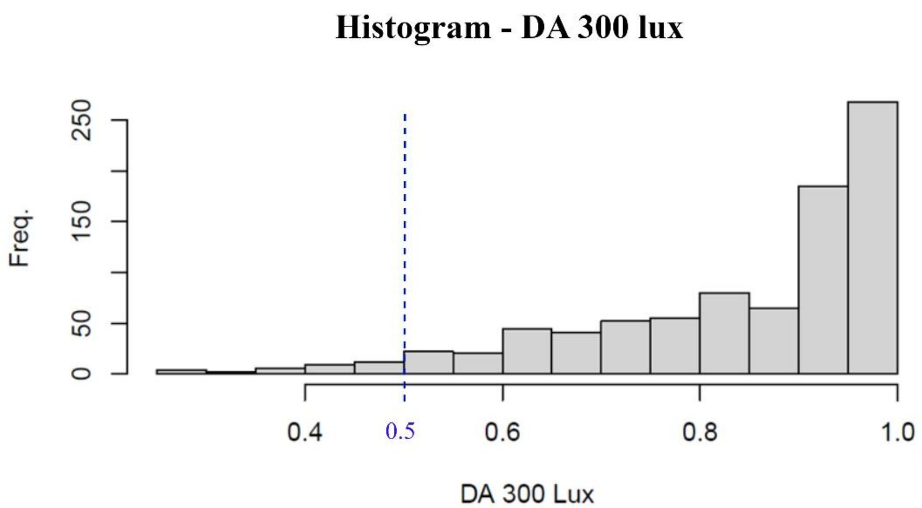
Source: The Author.

Boxplot of daylight autonomy with a highlighted minimum threshold of 50% of the time – daylight hours.



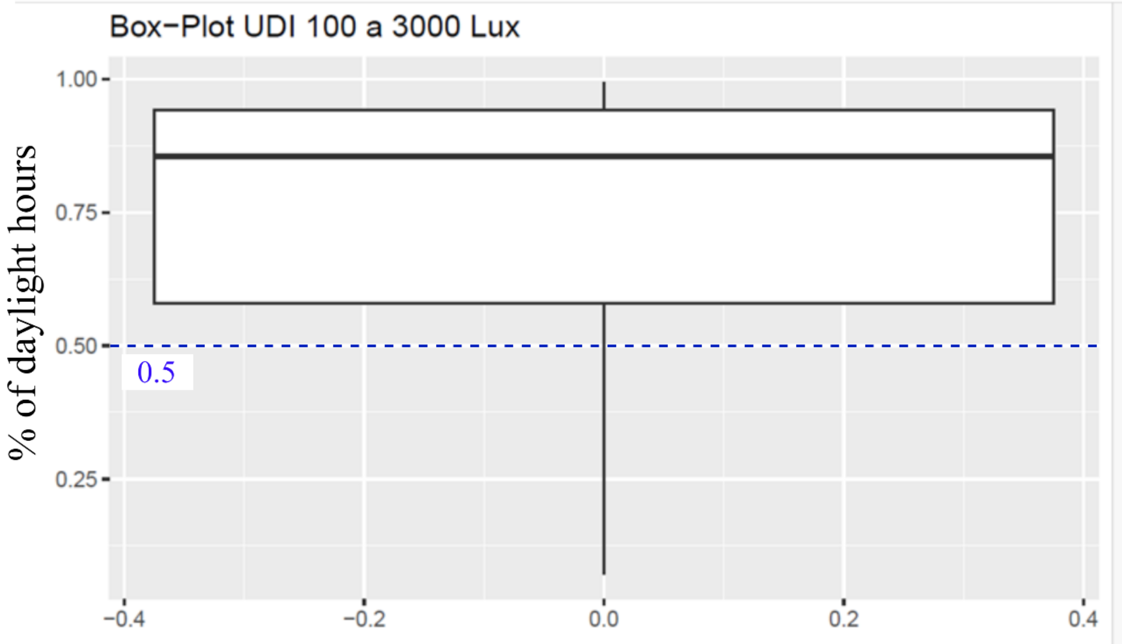
Source: The Author.

Histogram of results of daylight autonomy of 300 lux between 8 a.m. and 6 p.m. for all analyzed explanatory variables.



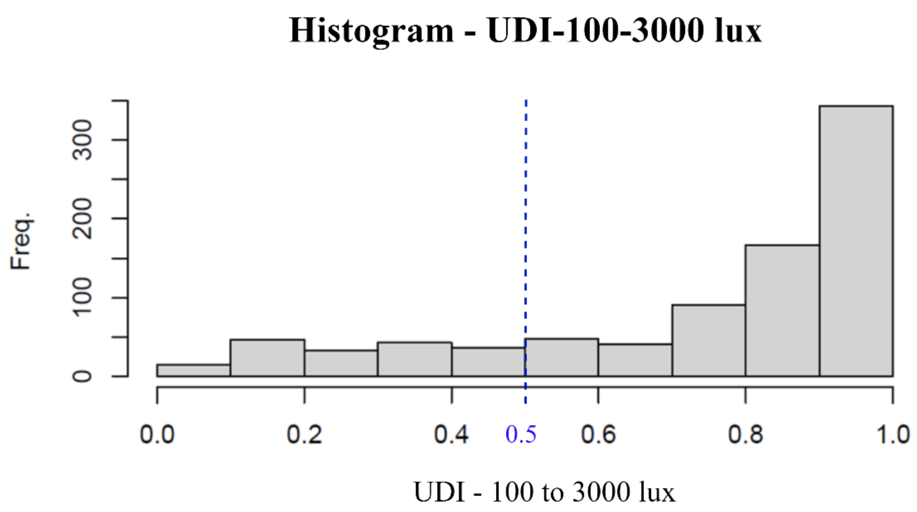
Source: The Author.

Boxplot of useful daylight illuminance with highlighted minimum threshold of 50% of the time – daylight hours.



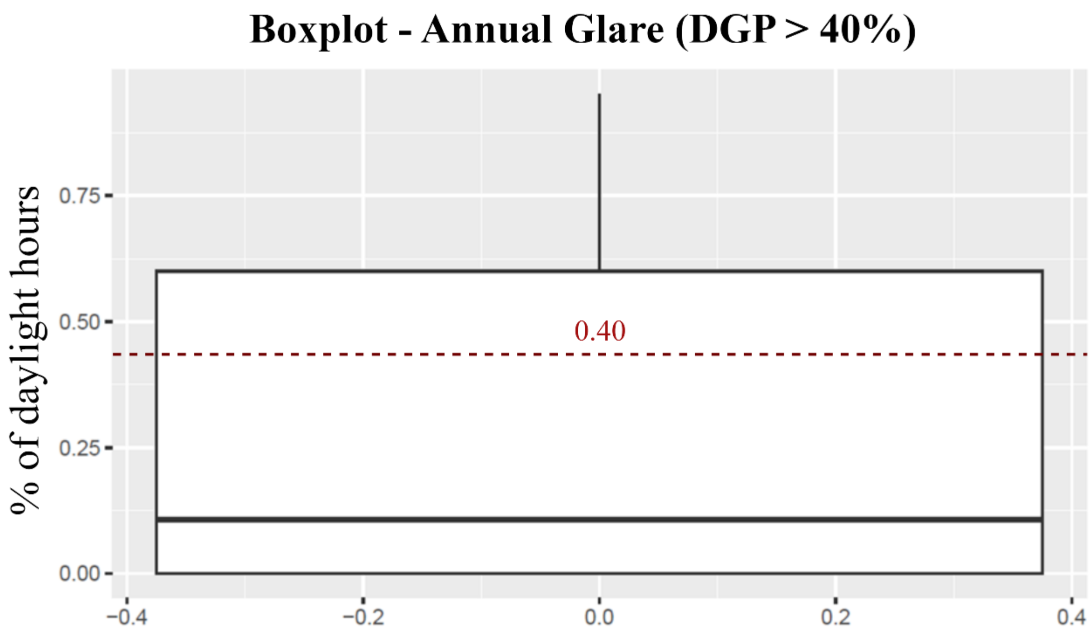
Source: The Author.

Histogram of results of useful daylight autonomy between 100 and 3,000 lux for all simulated cases.



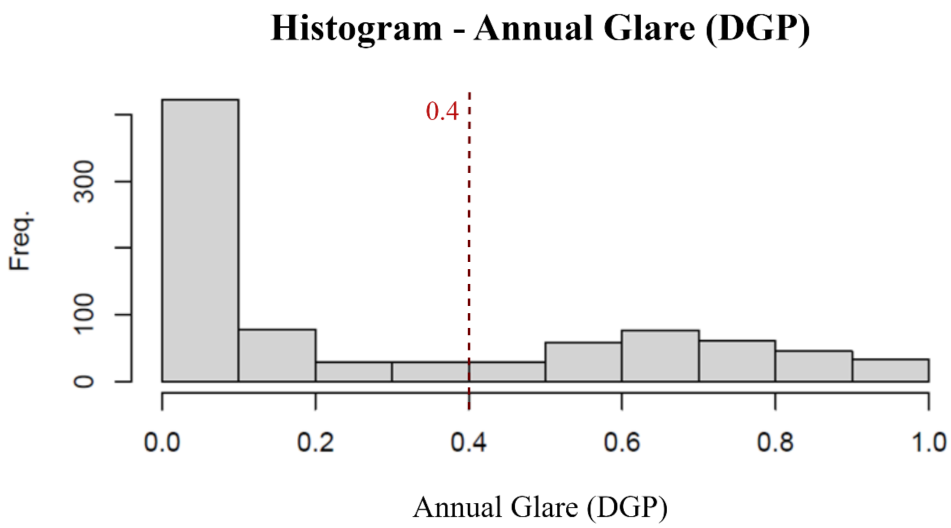
Source: The Author.

Boxplot of annual glare (DGP > 40%) with highlighted maximum threshold of 40% of the time – daylight hours.



Source: The Author.

Histogram of results of annual glare for all simulated cases with highlight to the maximum threshold of 40%.



Source: The Author.

The correlation between response variables was significant but only strong in the case of UDI and annual glare (DGP > 40%). A strong negative correlation was found between the response variables annual glare (DGP > 40%) and useful daylight autonomy (UDI – 100 to 3000 lux), with the corresponding result of -0.8883821. A linear regression model was adjusted between the variables UDI and annual glare (DGP > 40%), and this model explains almost 79% of the simulated cases, as described in Equation 6. The model indicates that for each point of variation of UDI, annual glare decreases by 0.72.

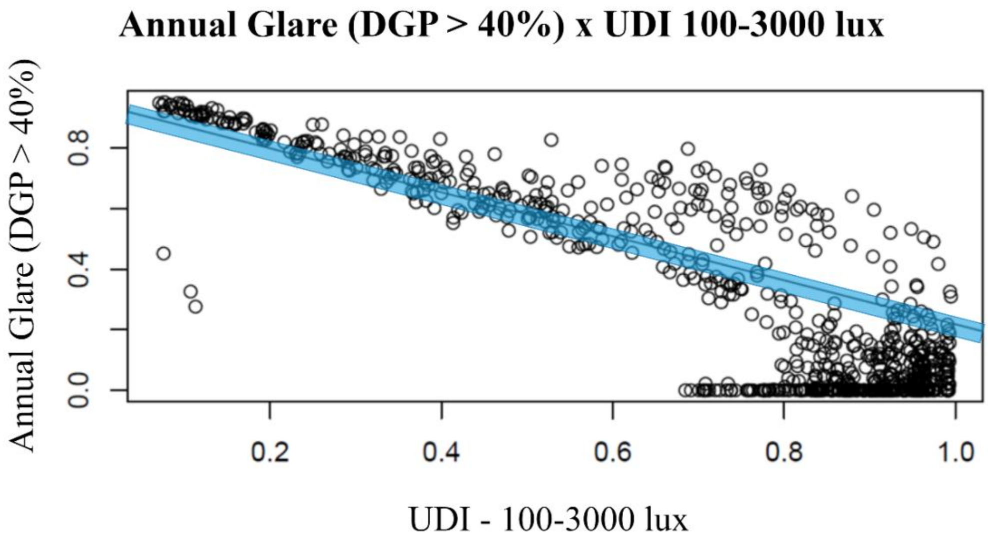
Equation 6 – Linear regression model for the response variables annual glare (DGP) as function of UDI – 100-3000 lux.

$$\text{Annual Glare (DGP} > 40\%) = 0.945251 - 0.727316\, x\, UDI$$

Note: Coefficient of determination (% of explanation): 78.92%. Significance of regression: F = 3.228.0; P < 0.001. Significance coefficients: a = 0.945251; t = 171.63; P < 0.001; b = -0.727316; t = -56.81; P < 0.001

Source: The Author.

Scatter chart between variables annual glare and UDI.



Source: The Author.

As described in section 4.1, Mardaljevic *et al.* (2012) identified a robust relationship between annual glare (DGP) and UDI, and the same relationship between these two variables was identified in this study. The same reasoning was observed: the relationship between annual glare (DGP > 40%) occurred with higher frequency for lower values of annual glare.

Appendix F. Results of visual effects: comparison between explanatory and response variables

In this appendix, the results of response variables DA, UDI, and annual glare (DGP) were compared. This process was done to verify if there were differences in the means of the described response variables of visual effects of light, i.e., per city/latitude, orientation, glazing material, and sensor/position in the room.

DA 300 lux

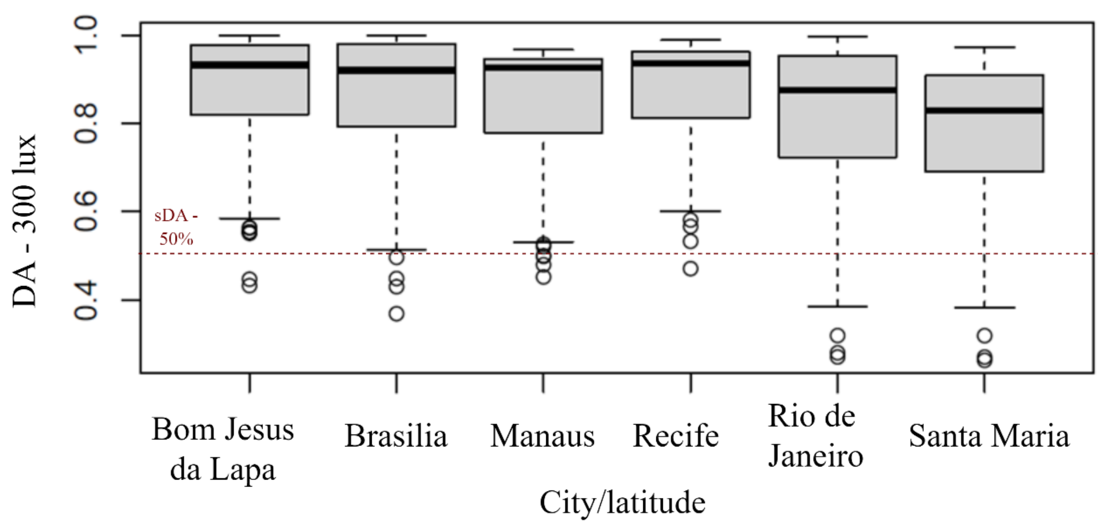
PER CITY/LATITUDE

Means of daylight autonomy, number of analyzed cases, and standard deviation per city/latitude.

City	Latitude	Mean (average)	Number of cases	Standard deviation
Manaus	3° south	0.8560122	144	0.1304093
Recife	8° south	0.8701408	144	0.1305325
Bom Jesus da Lapa	13° south	0.8705879	144	0.1444567
Brasilia	15 south	0.8612100	144	0.1529506
Rio de Janeiro	22° south	0.8214973	144	0.1743399
Santa Maria	29° south	0.7830537	144	0.1690863
Total		0.8437503	864	0.1541397

Note: All four glasses included. Source: The Author.

Results of daylight autonomy per city.



Note: All four glasses included. Source: The Author.

Comparison of means using Analysis of Variance (ANOVA) indicated significative differences (F=7,616; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001)

Cities	P value
Brasília-Bom Jesus da Lapa BA	0.9951390
Manaus-Bom Jesus da Lapa BA	0.9643160
Recife-Bom Jesus da Lapa BA	1.0000000
Rio de Janeiro-Bom Jesus da Lapa BA	0.0661689
Santa Maria RS-Bom Jesus da Lapa BA	0.0000161
Manaus-Brasília	0.9997173
Recife-Brasília	0.9961383
Rio de Janeiro-Brasília	0.2260608
Santa Maria RS-Brasília	0.0001895
Recife-Manaus	0.9687990
Rio de Janeiro-Manaus	0.3807356
Santa Maria RS-Manaus	0.0006631
Rio de Janeiro-Recife	0.0707271
Santa Maria RS-Recife	0.0000182
Santa Maria RS-Rio de Janeiro	0.2595403

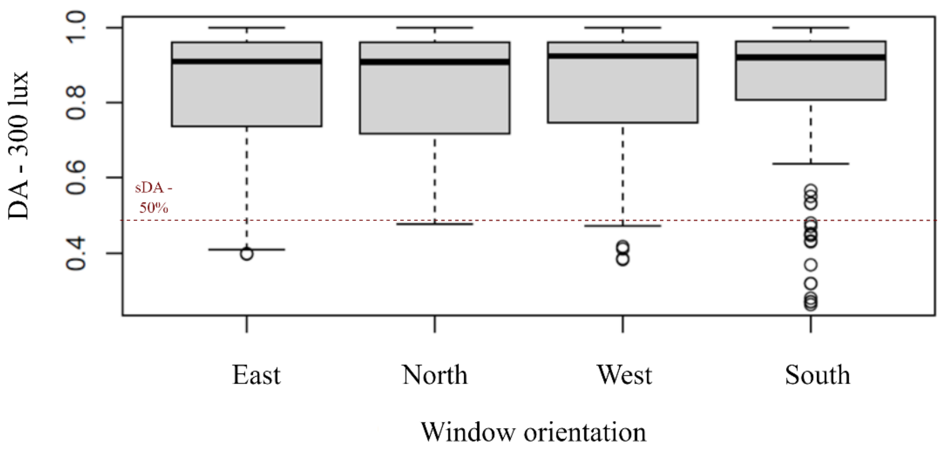
PER ORIENTATION

Means and standard deviations of daylight autonomy per window orientation.

Orientation	Mean	N	Standard deviation
East	0.8362861	216	0.1510544
North	0.8315348	216	0.1578666
West	0.8535845	216	0.1450873
South	0.8535959	216	0.1617951
Total	0.8437503	864	0.1541397

Note: All four glasses included. Source: The Author.

Boxplot of results of DA per window orientation for all cities/latitudes.



Note: All four glasses included in the analysis. Source: The Author.

No significative differences were found among the means through ANOVA (F=1,209; P = 0,305).

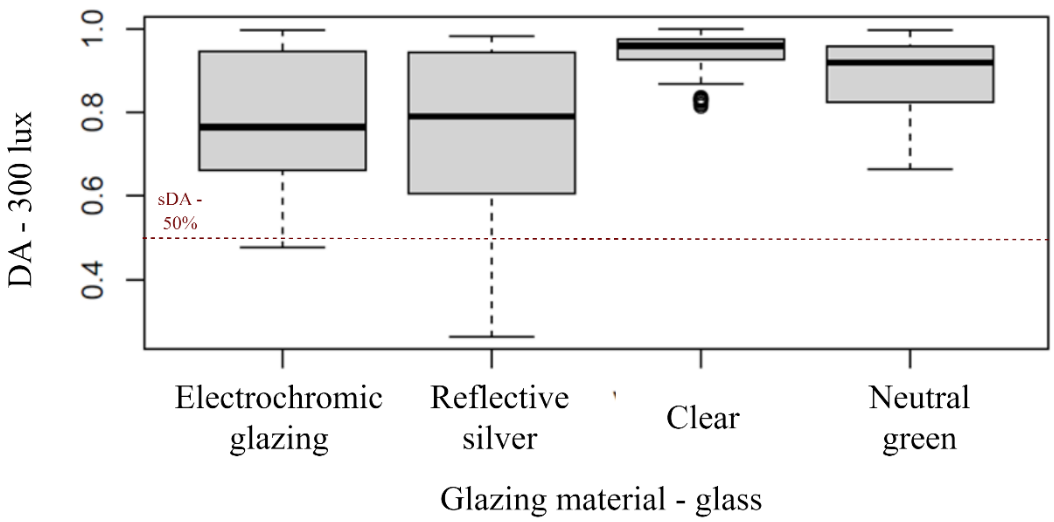
PER GLAZING MATERIAL/GLASS

Means and standard deviations of daylight autonomy per glazing material.

Glazing material	Mean	N	Standard deviation
Electrochromic glazing	0.7894850	216	0.15267228
Reflective silver glass	0.7508067	216	0.19582031
Clear glass	0.9459741	216	0.04405509
Neutral green glass	0.8887354	216	0.08720055
Total	0.8437503	864	0.15413970

Source: The Author.

Boxplot showing results of DA per glazing material.



Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA indicated significative differences (F=97,31; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001)

Glazing/glass	P-value
Silver glass -EC glazing	0.0141523
Clear glass – EC glazing	0.0000000
Green glass – EC glazing	0.0000000
Clear glass – silver glass	0.0000000
Green glass – silver glass	0.0000000
Green glass – clear glass	0.0000552

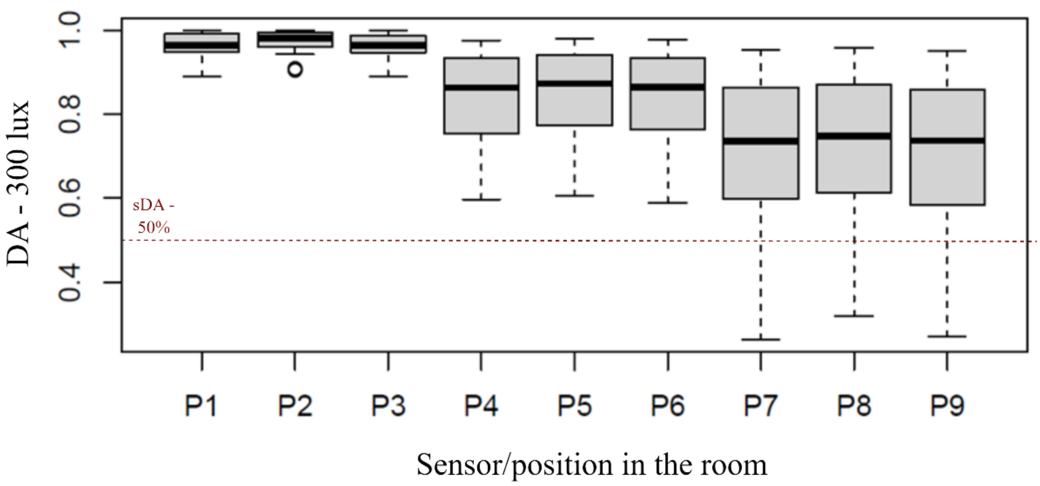
POR SENSOR/POSITION IN THE ROOM

Means and standard deviations of DA per sensor/position in the room.

Position/sensor	Mean	N	Standard deviation
P1	0.9647289	96	0.02704195
P2	0.9750343	96	0.02247545
P3	0.9644378	96	0.02681821
P4	0.8407962	96	0.10742060
P5	0.8498573	96	0.10314742
P6	0.8407449	96	0.10634817
P7	0.7139098	96	0.17421028
P8	0.7307163	96	0.16042661
P9	0.7135274	96	0.17388852
Total	0.8437503	864	0.15413970

Note: All four glasses included in the analysis. Source: The Author.

Boxplot showing results of DA per sensor/position in the room.



Note: All four glasses included in the analysis. Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA indicated significative differences (F=82,56; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001)

Sensor/Position	P-value
P2-P1	0.9995365
P3-P1	1.0000000
P4-P1	0.0000000
P5-P1	0.0000000
P6-P1	0.0000000
P7-P1	0.0000000
P8-P1	0.0000000
P9-P1	0.0000000
P3-P2	0.9994307
P4-P2	0.0000000
P5-P2	0.0000000
P6-P2	0.0000000
P7-P2	0.0000000
P8-P2	0.0000000
P9-P2	0.0000000
P4-P3	0.0000000
P5-P3	0.0000000
P6-P3	0.0000000
P7-P3	0.0000000
P8-P3	0.0000000
P9-P3	0.0000000
P5-P4	0.9998227
P6-P4	1.0000000
P7-P4	0.0000000
P8-P4	0.0000000
P9-P4	0.0000000
P6-P5	0.9998149
P7-P5	0.0000000
P8-P5	0.0000000
P9-P5	0.0000000
P7-P6	0.0000000
P8-P6	0.0000000
P9-P6	0.0000000
P8-P7	0.9857992
P9-P7	1.0000000
P9-P8	0.9835890

UDI – 100-3000 lux

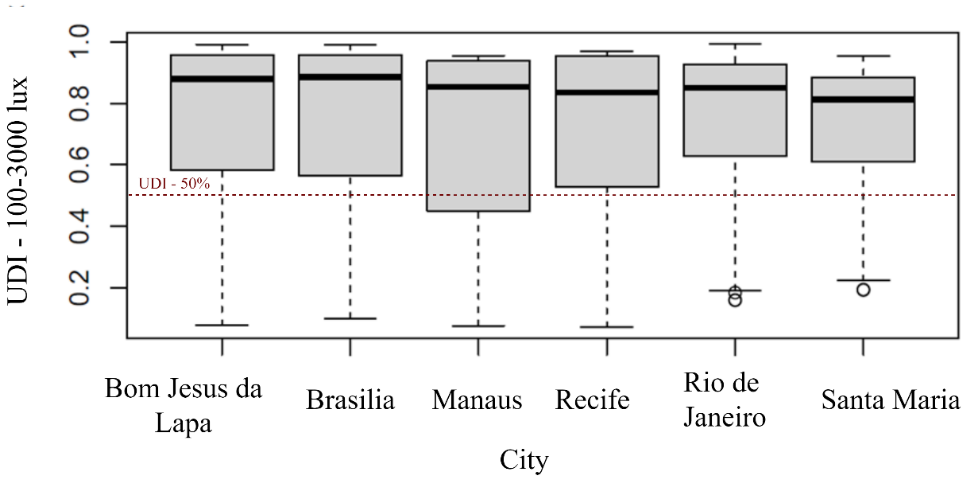
PER CITY/LATITUDE

Means of UDI-100-3000 lux, number of analyzed cases and standard deviation per city.

City	Latitude	Mean (average)	Number of cases	Standard deviation
Manaus	3° south	0.7124734	144	0.2853544
Recife	8° south	0.7219711	144	0.2770200
Bom Jesus da Lapa	13° south	0.7455251	144	0.2810259
Brasilia	15 south	0.7503482	144	0.2781883
Rio de Janeiro	22° south	0.7641134	144	0.2398413
Santa Maria	29° south	0.7334132	144	0.2160027
Total		0.7379741	864	0.2639790

Note: All four glasses included in the analysis. Source: The Author.

Boxplot of the results of UDI per city.



Note: All four glasses included in the analysis. Source: The Author.

No significant differences were detected through analysis of Variance - ANOVA (F=0,751; P = 0,585).

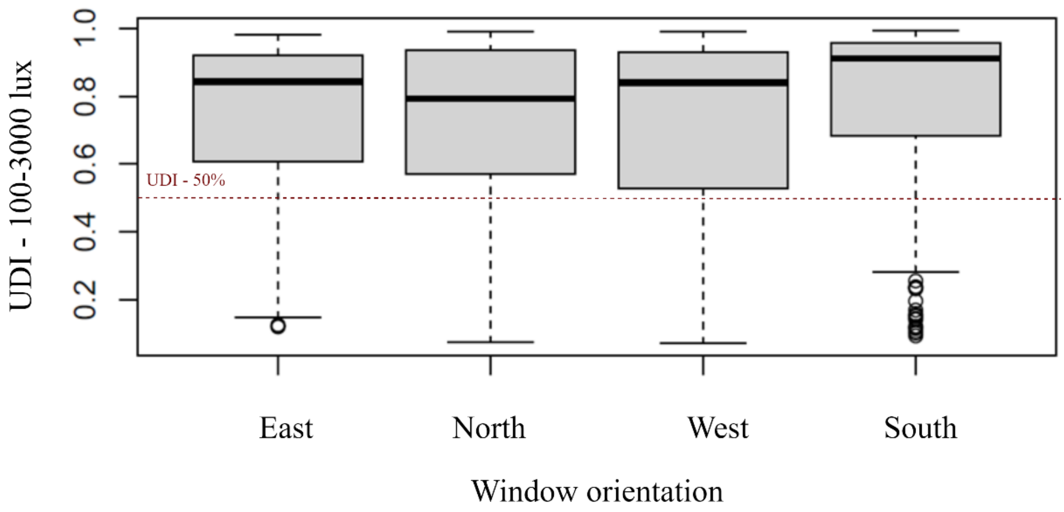
PER WINDOW ORIENTATION

Means and standard deviations of UDI per window orientation.

Orientation	Mean (average)	Number of cases	Standard deviation
East	0.7375292	216	0.2402048
North	0.7134221	216	0.2664718
West	0.7232204	216	0.2744447
South	0.7777245	216	0.2706926
Total	0.7379741	864	0.2639790

Note: All four glasses included in the analysis. Source: The Author.

Results of UDI 100-3000 lux per orientation.



Note: All four glasses included in the analysis. Source: The Author.

No significant differences were detected among the means through ANOVA (F=2,493; P = 0,0588).

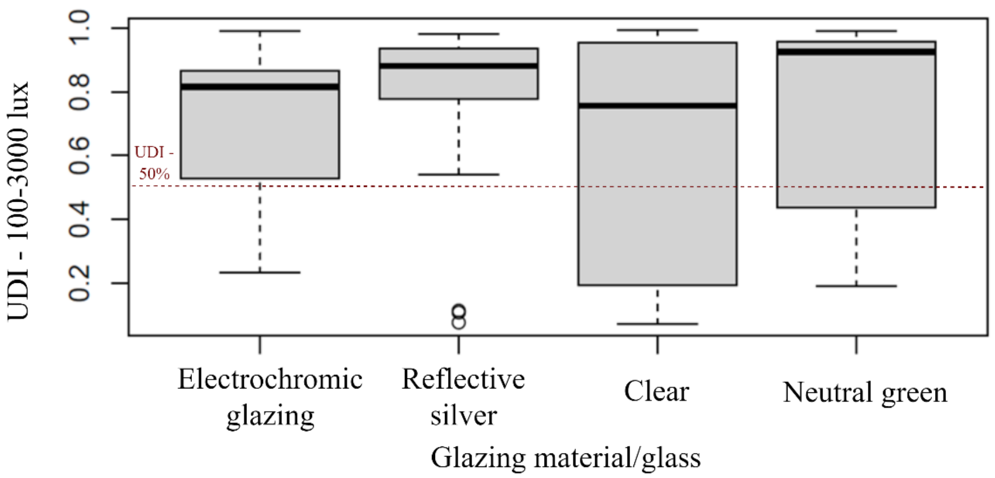
PER GLAZING MATERIAL/GLASS

Means and standard deviations of UDI – 100-3000 lux per glazing material.

Glazing material	Mean (average)	Number of cases	Standard deviation
Electrochromic glazing	0.7239434	216	0.1995975
Reflective silver glass	0.8409006	216	0.1338562
Clear glass	0.6294229	216	0.3519441
Neutral green glass	0.7576294	216	0.2739040
Total	0.7379741	864	0.2639790

Source: The Author.

Results of UDI-100-3000 lux per glazing material.



Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA indicated significative differences (F=25,77; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001):

GLAZING/GLASS	P-value
Silver glass – EC glazing	0.0000112
Clear glass – EC glazing	0.0006544
Green glass – EC glazing	0.5109598
Clear glass – silver glass	0.0000000
Green glass – silver glass	0.0037051
Green glass – clear glass	0.0000011

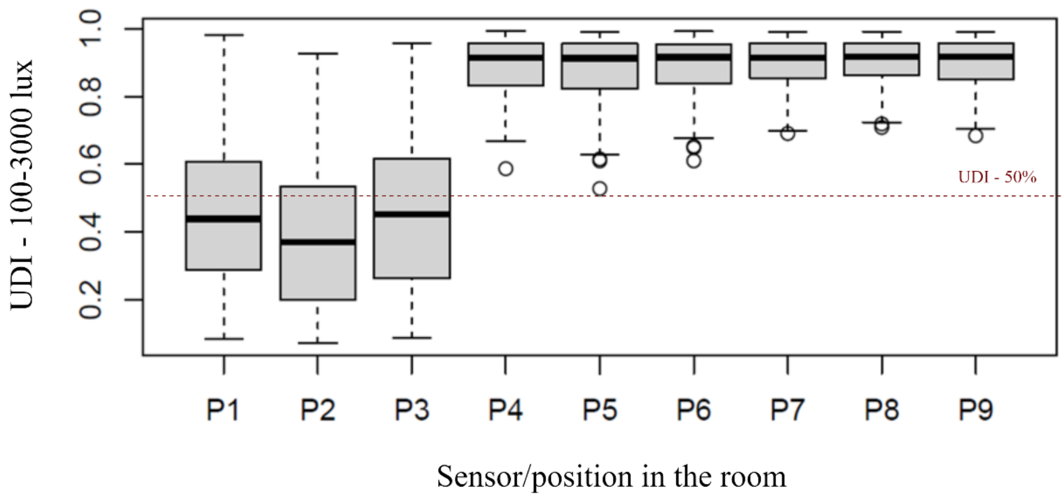
POR SENSOR/POSITION

Results of UDI-100-3000 lux per position.

Position/sensor	**Mean**	**N**	**Standard deviation**
P1	0.4550942	96	0.23469040
P2	0.3877369	96	0.22383788
P3	0.4546718	96	0.23531966
P4	0.8857734	96	0.09202992
P5	0.8739555	96	0.10861676
P6	0.8865896	96	0.08997489
P7	0.8981678	96	0.07504709
P8	0.9026855	96	0.06932786
P9	0.8970919	96	0.07573199
Total	0.7379741	864	0.26397895

Note: All four glasses included in the analysis. Source: The Author.

Results of UDI-100-3000 lux according to sensor/position in the room.



Note: All four glasses included in the analysis. Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA indicated significative differences (F=223,0; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001):

Sensor	P-value
P2-P1	0.0527712
P3-P1	1.0000000
P4-P1	0.0000000
P5-P1	0.0000000
P6-P1	0.0000000
P7-P1	0.0000000
P8-P1	0.0000000
P9-P1	0.0000000
P3-P2	0.0558336
P4-P2	0.0000000
P5-P2	0.0000000
P6-P2	0.0000000
P7-P2	0.0000000
P8-P2	0.0000000
P9-P2	0.0000000
P4-P3	0.0000000
P5-P3	0.0000000
P6-P3	0.0000000
P7-P3	0.0000000
P8-P3	0.0000000
P9-P3	0.0000000
P5-P4	0.9998159
P6-P4	1.0000000
P7-P4	0.9997368
P8-P4	0.9974680
P9-P4	0.9998671
P6-P5	0.9996964
P7-P5	0.9725750
P8-P5	0.9258219
P9-P5	0.9793204
P7-P6	0.9998423
P8-P6	0.9982172
P9-P6	0.9999247
P8-P7	0.9999999
P9-P7	1.0000000
P9-P8	0.9999994

Annual glare (DGP > 40%)

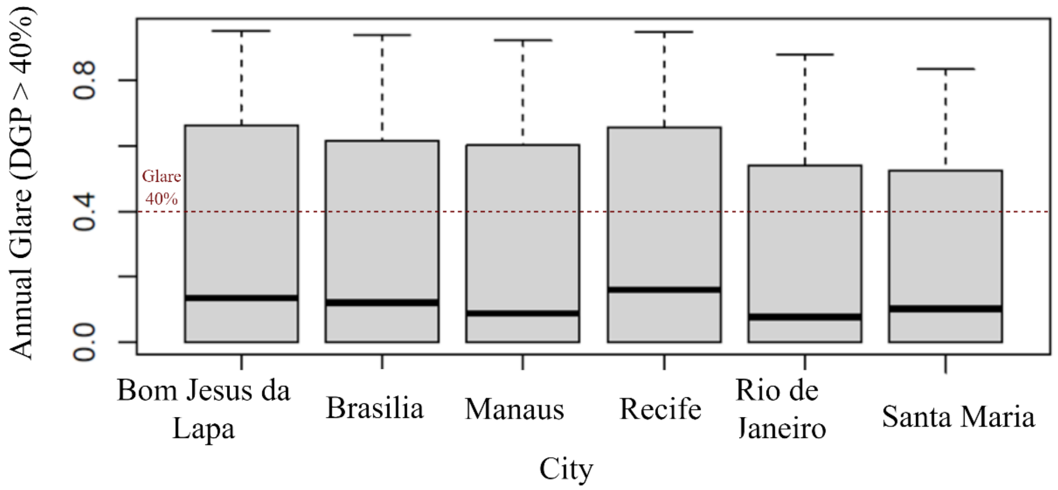
POR CIDADE

Means of annual glare (DGP > 40%), number of analyzed cases and standard deviation per city.

City	Latitude	Mean (average)	Number of cases	Standard deviation
Manaus	3° south	0.2833531	144	0.3272930
Recife	8° south	0.3230445	144	0.3400727
Bom Jesus da Lapa	13° south	0.3054763	144	0.3415323
Brasilia	15 south	0.2925813	144	0.3338172
Rio de Janeiro	22° south	0.2565930	144	0.3008919
Santa Maria	29° south	0.2488891	144	0.2863256
Total		0.2849895	864	0.3224380

Note: All four glasses included in the analysis. Source: The Author.

Boxplot of the results of annual glare (DGP > 40%) per city.



Note: All four glasses included in the analysis. Source: The Author.

No significant differences were detected among the means through ANOVA (F=1,119; P = 0,348).

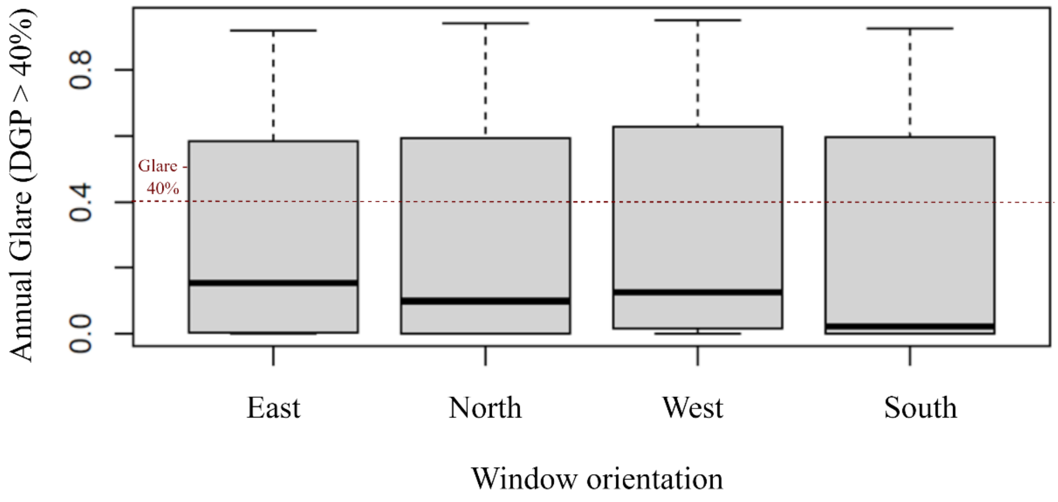
PER WINDOW ORIENTATION

Means and standard deviations of annual glare (DGP > 40%) per window orientation.

Orientation	**Mean (average)**	**Number of cases**	**Standard deviation**
East	0.2937827	216	0.3047656
North	0.2902948	216	0.3270094
West	0.3057934	216	0.3329775
South	0.2500872	216	0.3238207
Total	0.2849895	864	0.3224380

Note: All four glasses included in the analysis. Source: The Author.

Results of annual glare (DGP) per orientation.



Note: All four glasses included in the analysis. Source: The Author.

No significant differences were detected among the means through ANOVA (F=1,217; P = 0,302).

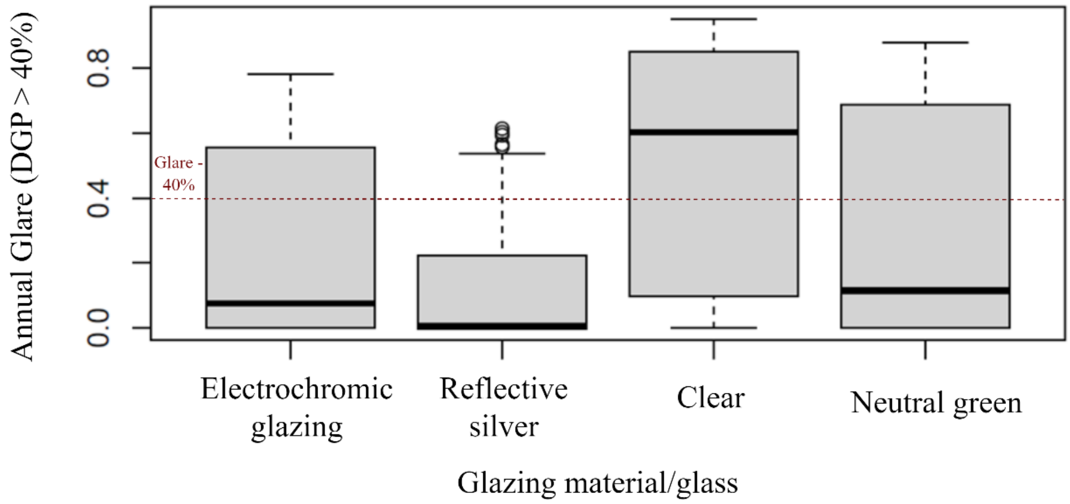
PER GLAZING MATERIAL/GLASS

Means and standard deviations of annual glare (DGP > 40%) per glazing material.

Glazing material	Mean (average)	Number of cases	Standard deviation
Electrochromic glazing	0.2288432	216	0.2707890
Reflective silver glass	0.1143100	216	0.1722243
Clear glass	0.5139028	216	0.3491437
Neutral green glass	0.2829021	216	0.3276324
Total	0.2849895	864	0.3224380

Source: The Author.

Results of annual glare (DGP > 40%) per glazing material.



Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA indicated significative differences (F=73,41; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001):

Glazing/glass	P-value
Silver glass – EC glazing	0.0002325
Clear glass – EC glazing	0.0000000
Green glass – EC glazing	0.2083590
Clear glass – silver glass	0.0000000
Green glass – silver glass	0.0000000
Green glass – clear glass	0.0000000

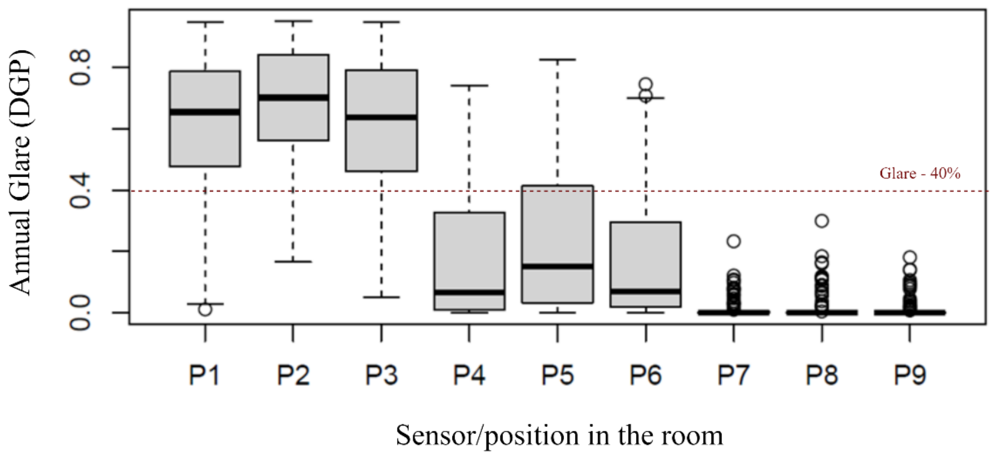
PER SENSOR/POSITION

Results of annual glare (DGP > 40%) per position.

Position/sensor	Mean	N	Standard deviation
P1	0.61072073	96	0.23297013
P2	0.68483369	96	0.19285447
P3	0.60872406	96	0.23471849
P4	0.18232358	96	0.23748333
P5	0.24311228	96	0.25299253
P6	0.18588107	96	0.23825343
P7	0.01492787	96	0.03621467
P8	0.02066314	96	0.05011587
P9	0.01371939	96	0.03463809
Total	0.28498954	864	0.32243798

Note: All four glasses included in the analysis. Source: The Author.

Results of annual glare (DGP > 40%) according to sensor/position in the room.



Note: All four glasses included in the analysis. Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA indicated significative differences (F=200,2; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001):

Sensor	P-value
P2-P1	0.1540676
P3-P1	1.0000000
P4-P1	0.0000000
P5-P1	0.0000000
P6-P1	0.0000000
P7-P1	0.0000000
P8-P1	0.0000000
P9-P1	0.0000000
P3-P2	0.1293679
P4-P2	0.0000000
P5-P2	0.0000000
P6-P2	0.0000000
P7-P2	0.0000000
P8-P2	0.0000000
P9-P2	0.0000000
P4-P3	0.0000000
P5-P3	0.0000000
P6-P3	0.0000000
P7-P3	0.0000000
P8-P3	0.0000000
P9-P3	0.0000000
P5-P4	0.4041602
P6-P4	1.0000000
P7-P4	0.0000001
P8-P4	0.0000002
P9-P4	0.0000001
P6-P5	0.4915046
P7-P5	0.0000000
P8-P5	0.0000000
P9-P5	0.0000000
P7-P6	0.0000000
P8-P6	0.0000001
P9-P6	0.0000000
P8-P7	0.9999999
P9-P7	1.0000000
P9-P8	0.9999995

Considerations regarding statistical relationships among variables DA, UDI, and annual glare (DGP > 40%)

The results of daylight autonomy presented a mean higher than 50%. This was expected as the simulated room was highly glazed – with a WWR of 85%. Variable DA 300 lux showed averages/means of the same order of magnitude between the cities. Even so, there were statistically significant differences. These differences occurred when comparing the cities/latitudes of Santa Maria (29° south) with Bom Jesus da Lapa (13° south), Brasilia (15° south), and Manaus (3° south). The other pairs of averages compared by city were statistically equivalent: among Manaus (3° south), Recife (8° south), Bom Jesus da Lapa (13° south), and Rio de Janeiro (22° south).

The lowest results of daylight autonomy were for the cities with the highest latitudes, which were Rio de Janeiro (22° south) and Santa Maria (29° south), with values of global horizontal illuminance across the sky dome of 40 klux and 38 klux, and global radiation of, 362 kWh/m² and 349 kWh/m², respectively. Among the possible reasons, the annual daily averages of the global horizontal illuminance and radiation of the six simulated cities/latitudes were lower for the two mentioned cities with higher latitudes. Among the cities with lower latitudes, from Manaus (3° south) to Brasilia (15° south), no statistically significant differences in the results of daylight autonomy were found. As described in section 5.1, the values of global horizontal illuminance and global radiation of these other four cities are higher, indicating higher results for daylight autonomy. These results confirmed the fact that variable latitude can possibly affect daylight entering the room, as reported by Fonseca *et al.* (2023). It is not clear, however, how strong this relationship between latitude and daylight autonomy is.

Variable UDI-100-3000 lux presented statistically similar results when comparing cities/latitudes and orientations. The lower results for Manaus (3° south) and Santa Maria (29° south) were possibly explained by the reduction in the illuminance levels from January to March in Manaus and in June and July in Santa Maria, with higher values of cloudiness in both cities, daily averages above 75% in both cities. This happened in specific periods of the year in these two cities/latitudes: summer months in Manaus and during winter months in Santa Maria. When analyzing the whole year, ANOVA did not indicate significative differences in the results of UDI per city/latitude, with this equivalence applying to the six cities/latitudes, including Manaus (3° south) and Santa Maria (29° south) as well. ANOVA did not detect significative differences in the results of UDI per window orientation due to the low variation of the results. Additionally, no significative differences in the results of DGP were detected per city/latitude and window orientation, with minor variations of the results.

When comparing the results of DA per city/latitude, the consideration of latitude ranges made sense (Fonseca *et al.*, 2023), as described in section 5.1. The highest results of DA were for the cities within the latitudes of Manaus (3° south) to Brasilia (15° south), and the lowest results were for the cities of Rio de Janeiro (22° south) and Santa Maria (29° south). These differences per city/latitude were detected through ANOVA. However, as discussed in section 4.3, differences in sky brightness, global illuminance, and solar radiation per city/latitude possibly affected the results of UDI and DGP. For example, Bom Jesus da Lapa (13° south) presented an annual daily average of 59 klux and Manaus (3° south) 43 klux, a city with a lower latitude. Therefore, when analyzing the results of UDI and annual glare, no relationships between the results were found as a function of latitude. This corroborated the findings of Fonseca et al. (2023) that **when the difference in the sky brightness conditions was significant, it was impossible to establish a relationship to latitude** In this study, it was detected through ANOVA no statistically significant differences in the results of UDI and annual glare as a function of city/latitude.

No significative differences were found through ANOVA for the results of DA, UDI and annual glare (DGP > 40%) for the north, the east, the south, and the west. Since the simulated room was highly glazed, excess of light was the most recurrent problem. This confirmed the discussion in the studies of Lima *et al.* (2022), Ciappina, Urbano, and Giglio (2022), and Passos (2019), regarding the problems related to the excessive use of glass on facades of non-residential buildings.

The glazing materials/glasses differed from each other, **with equivalence only occurring between the reflective silver glass and the electrochromic glazing and this was the case for variable DA**. This equivalence was explained by the reduction in the visible transmittance by the electrochromic glazing, from 62.1% to 1.1%. The visible transmittance of reflective silver glass is 20.8%, transmitting less light than clear glass, VT - 88%, and neutral green glass, VT - 43%.

Moreover, there was an equivalence between neutral green glass and electrochromic glazing for annual glare and UDI variables. This was explained by the dynamism of the electrochromic glazing, which could lower and increase the visible transmittance. That was the reason for the equivalence of the electrochromic glazing with neutral green glass (VT – 43%), with higher visible transmittance than reflective silver glass (VT – 20.8%). In this context, the electrochromic glazing presented worse performance than reflective silver glass considering mitigation of glare (DGP lower than 40%), but better when compared with clear glass. Regarding visual effects of light, the better performance of electrochromic glazing in comparison with clear glass was confirmed in the study of Nazari, Matusiak and Stefani (2023) concerning the control of excessive illuminance levels on the horizontal grid.

Equivalent results were found among the positions depending on their position and the differences between positions at the three different distances from the window, front, middle, and back of the room. Positions P1, P2 and P3 were equivalent, as were P4, P5 and P6 and, likewise, P7, P8 and P9. Significant differences occurred between the positions at different distances from the windows, 0.50m, 3m, and 5.5m. This observation applied to all three variables: DA, UDI-100-3000 lux, and annual glare (DGP > 40%). These same equivalences of the results in the positions/sensors at the same distance from the window were observed in the study of Saiedlue *et al.* (2019).

Common results to all three variables were: (1) **equivalence between reflective silver glass and electrochromic glazing for variable DA**; (2) **equivalence between neutral green and electrochromic glazing for variables UDI and annual glare (DGP > 40%)**, both of which differed from the other glasses; (3) **equivalence between positions at the same distance from the window** and differences by positions, closer (P1 to P3), intermediate (P4 to P6) and at the back of the room (P7 to P9). **For the cities/latitudes, only the DA variable showed a significant difference in Rio de Janeiro (22° south) and Santa Maria (29° south)**. In contrast, the **window orientations (north, east, south, and west) were equivalent for all three response variables**: DA, UDI, and annual glare (DGP > 40%). These three variables are categorized according to the defined assessment criteria for visual effects of light in the next section.

Appendix G. Categorization of response variables of visual effects

DA 300 lux in at least 50% of the hours between 8 a.m. and 6 p.m.

Total

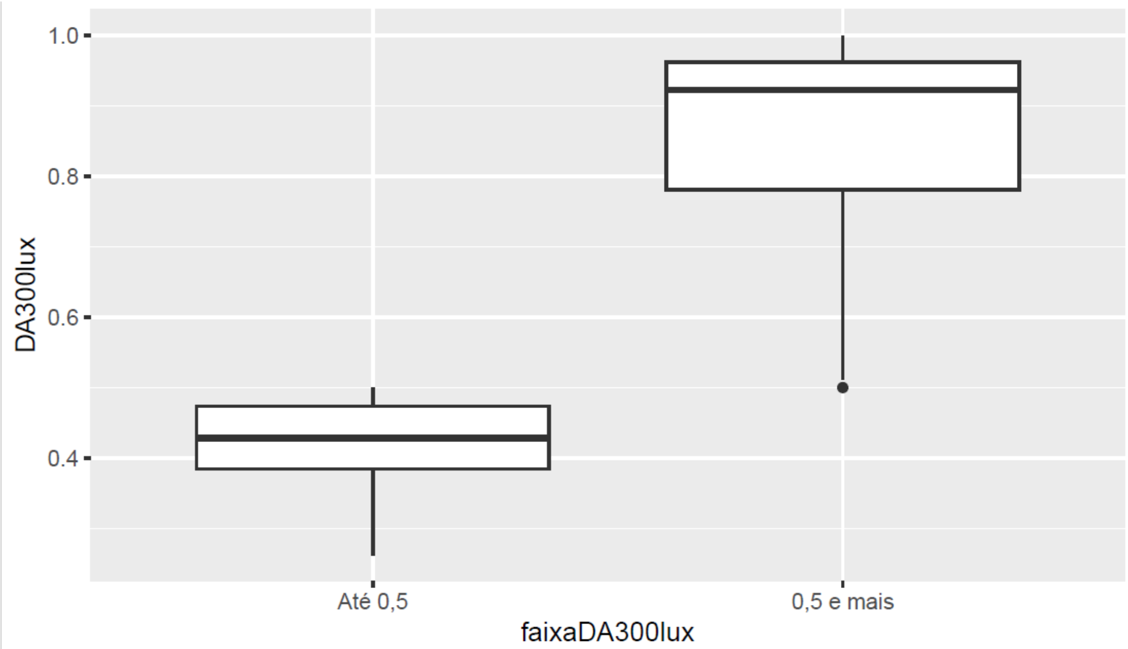
832 cases (96%) meet the minimum criterion

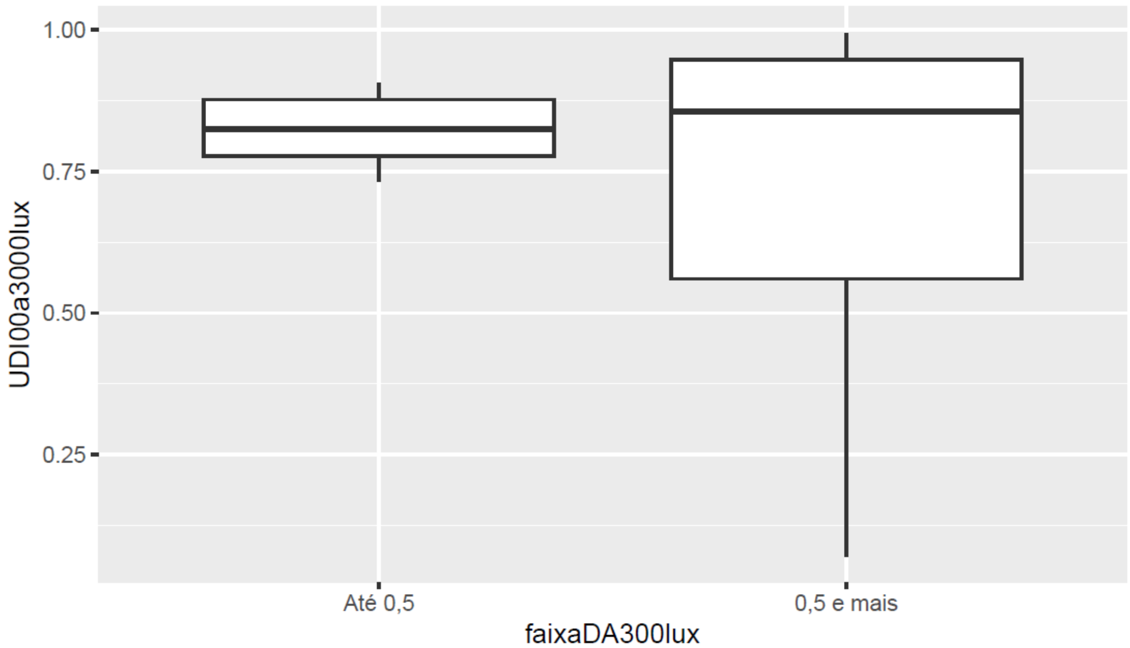
The following 32 records did not meet the criterion

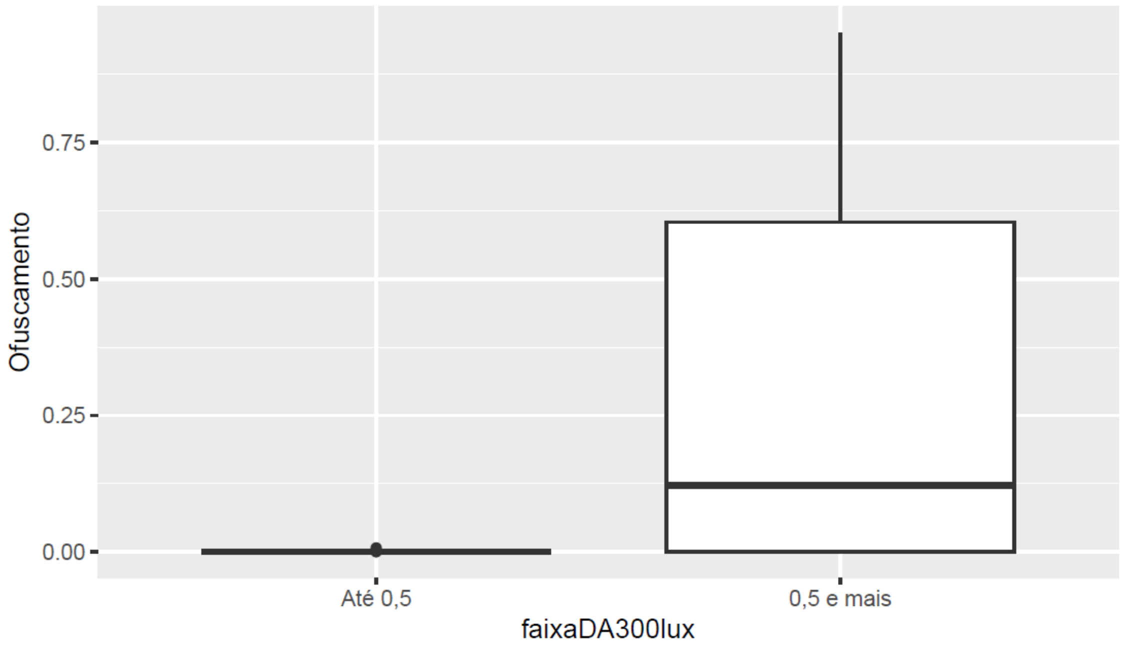
Bom Jesus da Lapa BA	South	Silver glass	P7
Bom Jesus da Lapa BA	South	Silver glass	P9
Brasília	West	Silver glass	P9
Brasília	South	Silver glass	P7
Brasília	South	Silver glass	P8
Brasília	South	Silver glass	P9
Manaus	North	Silver glass	P9
Manaus	South	Silver glass	P7
Manaus	South	Silver glass	P9
Recife	South	Silver glass	P7
Rio de Janeiro	East	Silver glass	P7
Rio de Janeiro	East	Silver glass	P8
Rio de Janeiro	East	Silver glass	P9
Rio de Janeiro	West	Silver glass	P7
Rio de Janeiro	West	Silver glass	P8
Rio de Janeiro	West	Silver glass	P9
Rio de Janeiro	South	Silver glass	P7
Rio de Janeiro	South	Silver glass	P8
Rio de Janeiro	South	Silver glass	P9
Santa Maria RS	East	Silver glass	P7
Santa Maria RS	East	Silver glass	P8
Santa Maria RS	East	Silver glass	P9
Santa Maria RS	North	EC glazing	P7
Santa Maria RS	North	EC glazing	P8
Santa Maria RS	North	EC glazing	P9
Santa Maria RS	North	Silver glass	P7
Santa Maria RS	West	Silver glass	P7
Santa Maria RS	West	Silver glass	P8
Santa Maria RS	West	Silver glass	P9
Santa Maria RS	South	Silver glass	P7
Santa Maria RS	South	Silver glass	P8
Santa Maria RS	South	Silver glass	P9

Means of the variables per category of DA 300 lux

Category of DA 300 lux	No (0)	Yes (1)	Total
DA 300 Lux	0,415	0,860	0,844
UDI 100 a 3000 Lux	0,825	0,735	0,740
Annual glare (DGP>40%)	0,0004	0,296	0,285







Per city

	Da 300 Lux >= 0,5			
City	0	1	Total	Yes %
Bom Jesus da Lapa BA	2	142	144	99%
Brasília	4	140	144	97%
Manaus	3	141	144	98%
Recife	1	143	144	99%
Rio de Janeiro	9	135	144	94%
Santa Maria RS	13	131	144	91%
Total	32	832	864	96%

Per window orientation

	Da 300 Lux >= 0,5			
Orientation	0	1	Total	Yes %
East	6	210	216	97%
North	5	211	216	98%
West	7	209	216	97%
South	14	202	216	94%
Total	32	832	864	96%

Por Glazing

Glazing	0	1	Total	Yes - %
EC glazing	3	213	216	99%
Silver glass	29	187	216	87%
Clear glass	0	216	216	100%
Green glass	0	216	216	100%
Total	32	832	864	96%

Por Sensor/Position

Sensor/Position	0	1	Total	Yes - %
P1		96	96	100%
P2		96	96	100%
P3		96	96	100%
P4		96	96	100%
P5		96	96	100%
P6		96	96	100%
P7	12	84	96	88%
P8	8	88	96	92%
P9	12	84	96	88%
Total	32	832	864	96%

Sensor/EC glazing	No	Yes	% Yes	Total
P1	0	24	100%	24
P2	0	24	100%	24
P3	0	24	100%	24
P4	0	24	100%	24
P5	0	24	100%	24
P6	0	24	100%	24
P7	1	23	96%	24
P8	1	23	96%	24
P9	1	23	96%	24
Total	3	213	99%	216

Sensor/Silver glass	No	Yes	% Yes	Total
P1	0	24	100%	24
P2	0	24	100%	24
P3	0	24	100%	24
P4	0	24	100%	24
P5	0	24	100%	24
P6	0	24	100%	24
P7	11	13	54%	24
P8	7	17	71%	24
P9	11	13	54%	24
Total	29	187	87%	216

Sensor/Clear glass	No	Yes	% Yes	Total
P1	0	24	100%	24
P2	0	24	100%	24
P3	0	24	100%	24
P4	0	24	100%	24
P5	0	24	100%	24
P6	0	24	100%	24
P7	0	24	100%	24
P8	0	24	100%	24
P9	0	24	100%	24
Total	0	216	100%	216

Sensor/Green glass	No	Yes	% Yes	Total
P1	0	24	100%	24
P2	0	24	100%	24
P3	0	24	100%	24
P4	0	24	100%	24
P5	0	24	100%	24
P6	0	24	100%	24
P7	0	24	100%	24
P8	0	24	100%	24
P9	0	24	100%	24
Total	0	216	100%	216

UDI – 100 a 3000 lux in at least 50% of the hours between 8 a.m. and 6 p.m.

Total

690 cases (80%) met the minimum criterion

Per city: ANOVA detected no differences in the means of UDI among cities (see below)

City	No	Yes	% Yes	Total
Bom Jesus da Lapa BA	29	115	80%	144
Brasília	29	115	80%	144
Manaus	37	107	74%	144
Recife	32	112	78%	144
Rio de Janeiro	24	120	83%	144
Santa Maria RS	23	121	84%	144
Total	174	690	80%	864

Per window orientation: ANOVA detected no significant differences in the means of UDI among orientations (see above)

Orientation	No	Yes	% Yes	Total
East	37	179	83%	216
North	43	173	80%	216
West	50	166	77%	216
South	44	172	80%	216
Total	174	690	80%	864

Per glass: ANOVA detected differences among the means for UDI per orientation - green glass equivalent to EC glazing and all the others differed from each other (see above).

Glass	No	Yes	% Yes	Total
EC glazing	41	175	81%	216
Silver glass	3	213	99%	216
Clear glass	72	144	67%	216
Green glass	58	158	73%	216
Total	174	690	80%	864

Per Sensor: ANOVA detected differences in UDI between the sensors; those at the same distance from the window were equivalent (P1 = P2 = P3; P4 = P5 = P6 = P7 = P8 = P9); the sensors differed depending on their distance from the window. The lowest UDI values of 100-3000 lux were found at points P1 to P3. In the sensors furthest from the window, from P5 to P8, the UDI criterion was met in all cases (100%).

Sensor	No	Yes	% Yes	Total
P1	55	41	43%	96
P2	65	31	32%	96
P3	54	42	44%	96
P4	0	96	100%	96
P5	0	96	100%	96
P6	0	96	100%	96
P7	0	96	100%	96
P8	0	96	100%	96
P9	0	96	100%	96
Total	174	690	80%	864

Sensor/EC glazings	No	Yes	% Yes	Total
P1	12	12	50%	24
P2	18	6	25%	24
P3	11	13	54%	24
P4	0	24	100%	24
P5	0	24	100%	24
P6	0	24	100%	24
P7	0	24	100%	24
P8	0	24	100%	24
P9	0	24	100%	24
Total	41	175	81%	216

Sensor/Green glass	No	Yes	% Yes	Total
P1	18	6	25%	24
P2	22	2	8%	24
P3	18	6	25%	24
P4	0	24	100%	24
P5	0	24	100%	24
P6	0	24	100%	24
P7	0	24	100%	24
P8	0	24	100%	24
P9	0	24	100%	24
Total	58	158	73%	216

Sensor/Silver glass	No	Yes	% Yes	Total
P1	1	23	96%	24
P2	1	23	96%	24
P3	1	23	96%	24
P4	0	24	100%	24
P5	0	24	100%	24
P6	0	24	100%	24
P7	0	24	100%	24
P8	0	24	100%	24
P9	0	24	100%	24
Total	3	213	99%	216

Sensor/Clear glass	No	Yes	% Yes	Total
P1	24	0	0%	24
P2	24	0	0%	24
P3	24	0	0%	24
P4	0	24	100%	24
P5	0	24	100%	24
P6	0	24	100%	24
P7	0	24	100%	24
P8	0	24	100%	24
P9	0	24	100%	24
Total	72	144	67%	216

Annual glare (DGP < 40%) in at least 60% of the time

Total

559 cases (65%) met the minimum criterion

Per city: ANOVA did not detect any significant difference in the mean glare among the cities (see below)

City	No	Yes	% Yes	Total
Bom Jesus da Lapa BA	53	91	63%	144
Brasília	51	93	65%	144
Manaus	51	93	65%	144
Recife	54	90	63%	144
Rio de Janeiro	47	97	67%	144
Santa Maria RS	49	95	66%	144
Total	305	559	65%	864

Por Orientation: ANOVA did not detect any significant difference in the mean glare among the cities (see below)

Orientation	No	Yes	% Yes	Total
East	77	139	64%	216
North	80	136	63%	216
West	80	136	63%	216
South	68	148	69%	216
Total	305	559	65%	864

Por glass: ANOVA detected differences among the means: green glass equivalent to EC glazing and all the others different from each other; the highest occurrence of is for single glass and the lowest for silver glass (see below):

Glass	No	Yes	% Yest	Total
EC Glazing	72	144	67%	216
Silver glass	20	196	91%	216
Clear glass	140	76	35%	216
Green glass	73	143	66%	216
Total	305	559	65%	864

Per Sensor: ANOVA detected significative differences in annual glare among the sensors; those at the same distance from the window were equivalent (P1 = P2 = P3; P4 = P5 = P6; P7 = P8 = P9); the sensors differed depending on their distance from the window. The closer they were, the more glare or the lower the percentage of hours without glare during the day.

Sensor	No	Yes	% Yes	Total
P1	75	21	22%	96
P2	86	10	10%	96
P3	75	21	22%	96
P4	22	74	77%	96
P5	25	71	74%	96
P6	22	74	77%	96
P7		96	100%	96
P8		96	100%	96
P9		96	100%	96
Total	305	559	65%	864

Sensor – EC glazing	No	Yes	% Yes	Total
P1	24	0	0%	24
P2	24	0	0%	24
P3	24	0	0%	24
P4	0	24	100%	24
P5	0	24	100%	24
P6	0	24	100%	24
P7	0	24	100%	24
P8	0	24	100%	24
P9	0	24	100%	24
Total	72	144	67%	216

Sensor – Silver glass	No	Yes	% Yes	Total
P1	3	21	88%	24
P2	14	10	42%	24
P3	3	21	88%	24
P4	0	24	100%	24
P5	0	24	100%	24
P6	0	24	100%	24
P7	0	24	100%	24
P8	0	24	100%	24
P9	0	24	100%	24
Total	20	196	91%	216

Sensor – Clear glass	No	Yes	% Yes	Total
P1	24	0	0%	24
P2	24	0	0%	24
P3	24	0	0%	24
P4	22	2	8%	24
P5	24	0	0%	24
P6	22	2	8%	24
P7	0	24	100%	24
P8	0	24	100%	24
P9	0	24	100%	24
Total	140	76	35%	216

Sensor – Green glass	No	Yes	% Yes	Total
P1	24	0	0%	24
P2	24	0	0%	24
P3	24	0	0%	24
P4	0	24	100%	24
P5	1	23	96%	24
P6	0	24	100%	24
P7	0	24	100%	24
P8	0	24	100%	24
P9	0	24	100%	24
Total	73	143	66%	216

Appendix H. Summary of results of non-visual effects response variables

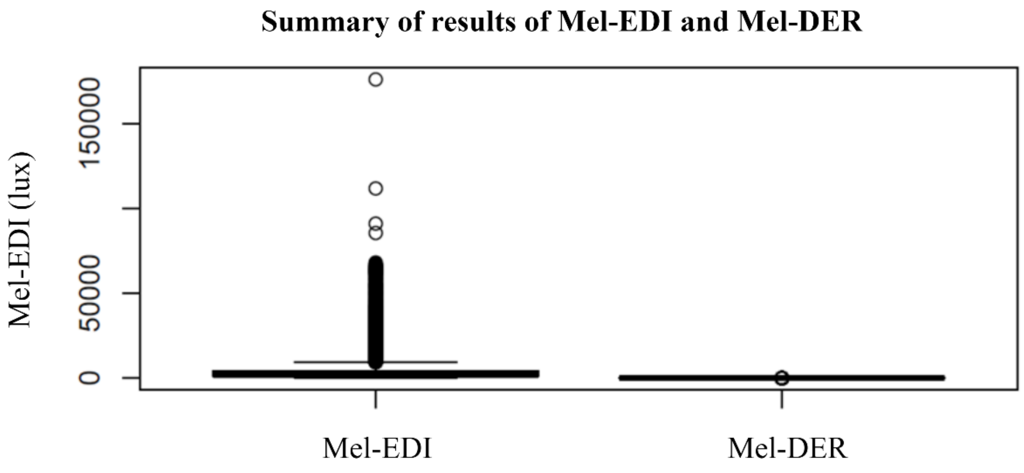
Non-visual effects

Summary of results of melanopic equivalent daylight illuminance (Mel-EDI) and melanopic daylight efficacy ratio (Mel-DER).

Variable	Mel-EDI (lux)	Mel-DER
Minimum	19.48	0.5056
1st Quartile	935.76	0.8954
Median	2022.5	0.981
Mean	3879.25	0.9843
3º Quartile	4344.87	1.0563
Maximum	176309.1	1.7224
Standard deviation	6143.043	0.1376
Coefficient of variation	158.4%	14.0%

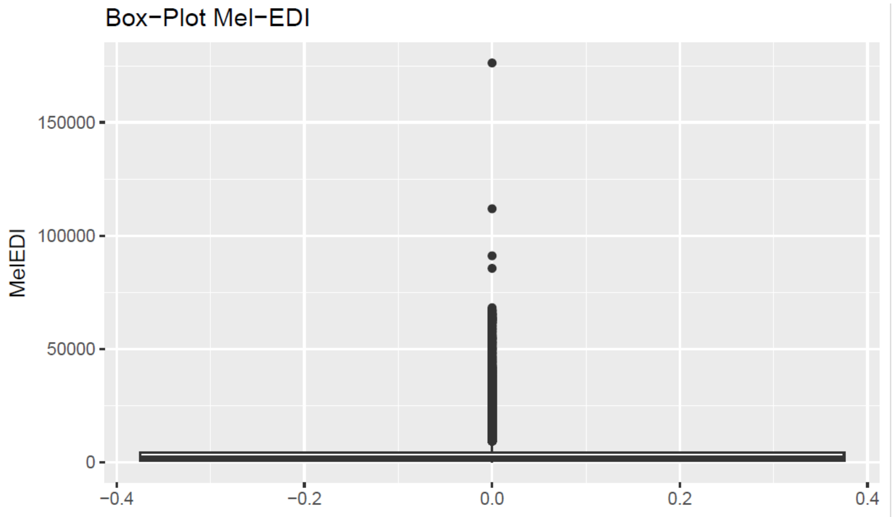
Source: The Author.

Boxplot chart summarizing results of Mel-EDI and Mel-DER illustrating the differences between the two scales.



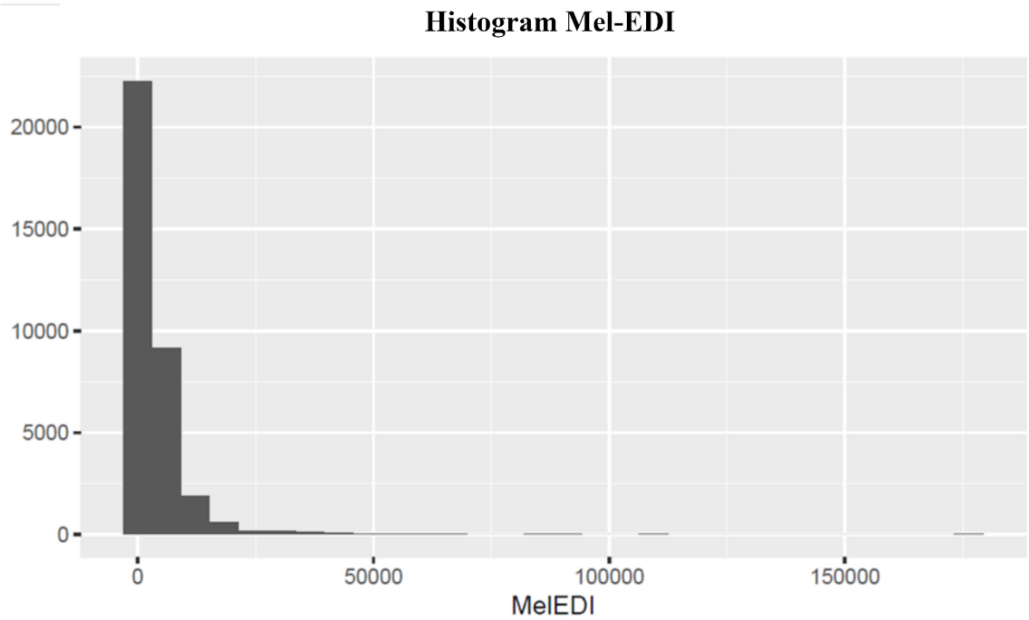
Source: The Author.

Boxplot summarizing the results of Mel-EDI.



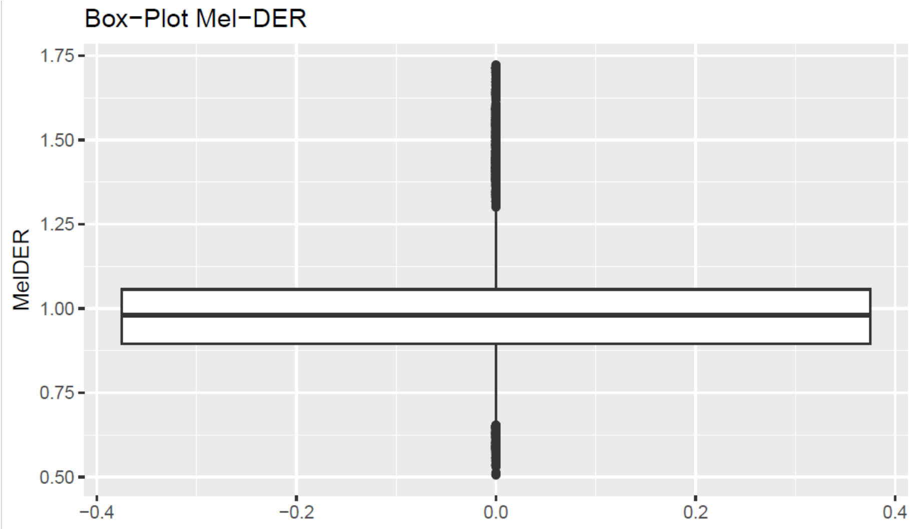
Source: The Author.

Histogram of the results for Mel-EDI.



Source: The Author.

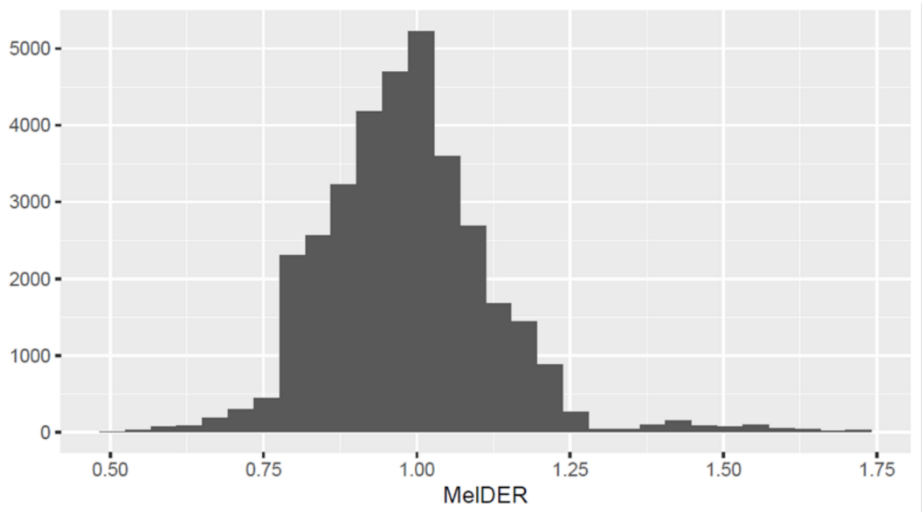
Boxplot summarizing the results of Mel-DER.



Source: The Author.

Histogram of the results of Mel-DER.

Histogram Mel-DER



Source: The Author.

Pearson linear correlation between Mel-EDI and Mel-DER

r-Pearson = – 0,1708525, significative at 1% (t=-32,235; P-value < 0,001)

Pearson linear correlation results for variables Mel-EDI and Mel-DER.

Variables	**Mel-DER**
Mel-EDI	-0.1708525* - No correlation!

Note: **Significant correlation at 1%. Source: The Author.

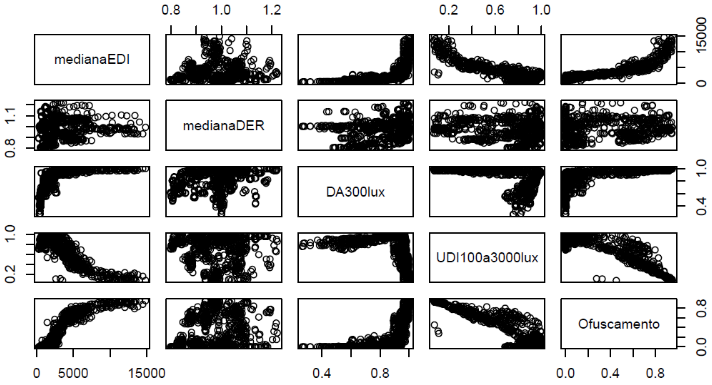
Negative (one variable increases while the other decreases), significative, however, weak. Therefore, this correlation does not indicate adjustments for a linear model.

Relationships among response variables of visual and non-visual effects of light were tested using the Pearson linear correlation matrix. Correlations were reported between each of the two correlations related to visual effects of light, which were daylight autonomy, useful daylight autonomy, and annual glare (DGP). As presented in section 5.4, for the strong positive or negative correlations, the values 0.70 or -0.70 were considered. Otherwise, it was considered that no strong correlations were found.

As described in section 5.4.2, each of the 40 results of non-visual effects was represented by the medians, including 4 dates and 10 hours to represent one case. Each record represented 40 values of Mel-EDI and Mel-DER in the merged file, totaling 864 records. After this process, the visual and non-visual effects variables were correlated to identify possible relationships. Pearson linear correlation matrix regarding the variables of visual and non-visual effects of light is show below:

Pearson linear correlation matrix regarding variables of visual effects of light.

	Median Mel-EDI	**Median Mel-DER**	**DA300lux**	**UDI00-3000lux**	**Annual glare**
Median Mel-EDI	1.000	0.103**	0.617**	-0.876**	0.896**
Median Mel-DER		1.000	0.219**	-0.082*	0.144**
DA300lux			1.000	-0.433**	0.666**
UDI00-3000lux				1.000	-0.888**
Annual glare (DGP)					1.000



Note: *Significative correlation at 5%. **Significant correlation at 1%. Source: The Author.

A strong negative correlation was found between variable annual glare (DGP) and UDI-100-3000 lux. The first model of linear regression was made, and it was described in Appendix E. **As commented, this relationship was also found by Mardaljevic *et al.* (2012), and the relationship between annual glare and DGP occurred with higher frequency for lower values of annual glare**. Among Mel-DER and Mel-EDI, no correlation was found and this lack of relationship between these two variables had been identified by Englezou and Michael (2023).

The main contribution of the correlation matrix was to quantify the relationships among annual glare (DGP), UDI 100-3000 lux and median of Mel-EDI. The relationships among these three responsible variables were not quantified in the studies mentioned in the literature review. Therefore, two more linear regression models were created relating them.

The second linear regression model was made for correlations between UDI-100-3000 lux as a function of the Median of Mel-EDI, and it was described in Equation 7. This model explained almost 77% of the simulated cases. **The model indicated that for each point of variation of UDI, Median-Mel-EDI decreases by $7.986 x 10^{-5}$.**

Equation 7 – Linear regression model for the response variables UDI – 100-3000 lux as a function of the medians of Mel-EDI.

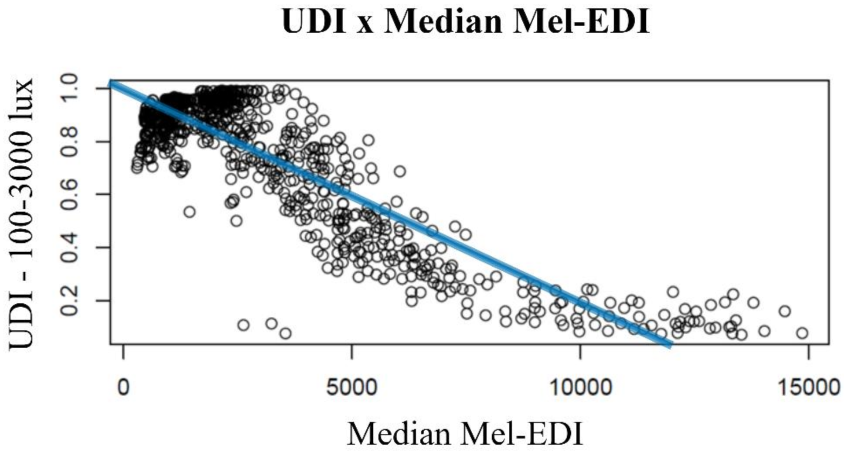
$$UDI100 - 3000\ lux = 9.949x10^{-1} - 7.986x10^{-5}\ x\ MedianMel - EDI$$

Note: Coefficient of determination (% of explanation): 76.74%. Significance of regression: F = 2.844,0; P < 0.001. Significance coefficients: a = $9.949x10^{-1}$; t = 153.53; P < 0,001; b = $-7.986x10^{-5}$; t = -53.33; P < 0.001.

Source: The Author.

The dispersion chart showed the numeric results of UDI in contrast with the results of the median of Mel-EDI. The straight line symbolizes the linear regression model.

Dispersion chart of numeric results of UDI in contrast with the results of the median of Mel-EDI.



Note: Scales were adjusted to fit both magnitudes of the variables represented in both axes. Source: The Author.

The third linear regression model was made for the correlation between annual glare (DGP) and median-Mel-EDI, and it was described in Equation 8. **This model explained 80% of the simulated cases. The model indicated that for each point of variation annual glare (DGP), Median-Mel-EDI increased by 9.980x10^{-5}.**

Equation 8 – Linear regression model for the response variables annual glare (DGP) as a function of the medians of Mel-EDI.

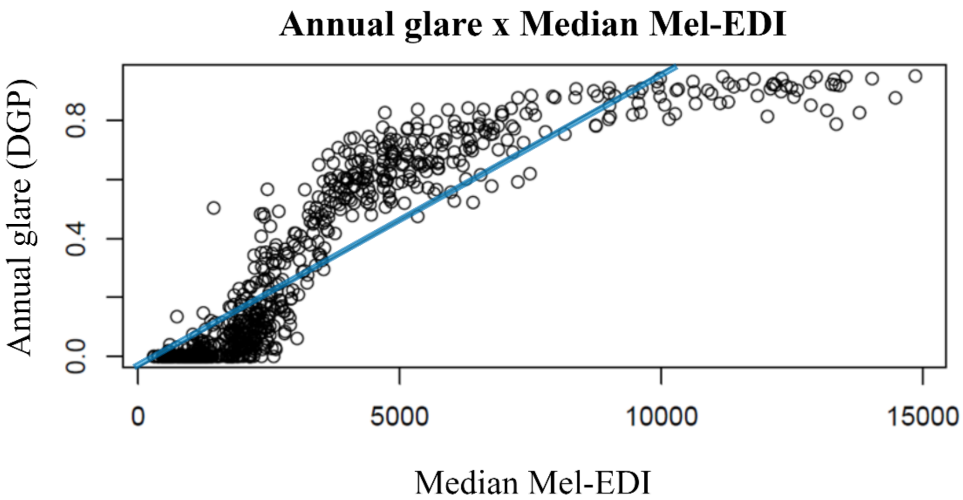
$$Annual\ glare\ (DGP) = -3{,}609x10^{-2} + 9{,}980x10^{-5}\ x\ MedianMel - EDI$$

Note: Coefficient of determination (% of explanation): 80.33%. Significance of regression: F = 3.520.0; P < 0.001. Significance coefficients: a = -3.609x10^{-2}; t = -4.958; P < 0.001; b = 9.980x10^{-5}; t = 59.332; P < 0.001

Source: The Author.

The dispersion chart showed the numeric results of UDI in contrast with the results of the median of Mel-EDI. The straight line symbolizes the linear regression model.

Dispersion chart of numeric results of UDI in contrast with the results of the median of Mel-EDI.



Note: Scales were adjusted to fit both magnitudes of the variables represented in both axes. Source: The Author.

Appendix I. Results of non-visual effects: comparison between explanatory and response variables

Variable Mel-EDI

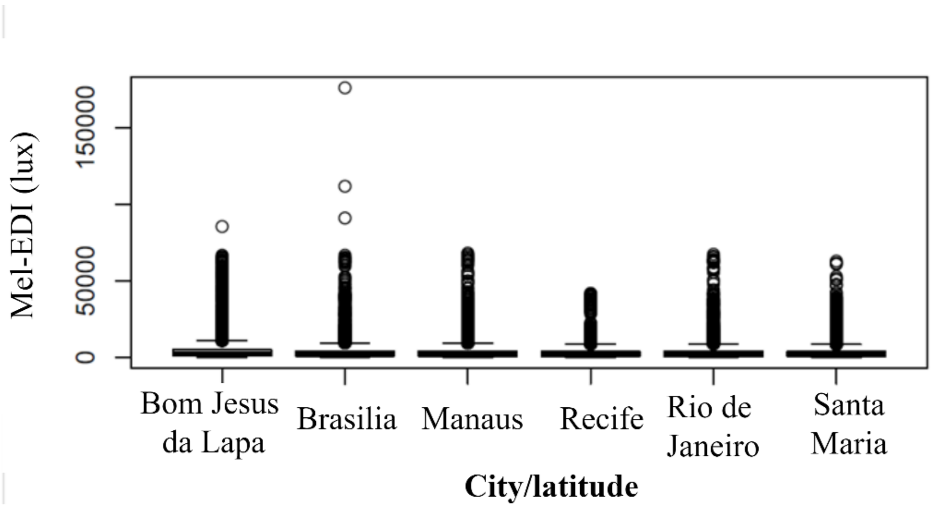
PER CITY/LATITUDE

Means of Mel-EDI, number of analyzed cases and standard deviation per city.

City	Latitude	Mean (average)	Number of cases	Standard deviation
Manaus	3° south	3914.580	5760	6095.930
Recife	8° south	3336.235	5760	4525.561
Bom Jesus da Lapa	13° south	4755.715	5760	7575.531
Brasilia	15 south	4039.161	5760	6863.519
Rio de Janeiro	22° south	3713.812	5760	5897.850
Santa Maria	29° south	3516.011	5760	5318.171
Total		3879.252	34560	6143.043

Note: All four glasses included in the analysis. Source: The Author.

Results of Mel-EDI per city.



Note: All four glasses included in the analysis. Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA) indicated significative differences (F=38,34; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001):

City	P-value
Brasília-Bom Jesus da Lapa BA	0.0000000
Manaus-Bom Jesus da Lapa BA	0.0000000
Recife-Bom Jesus da Lapa BA	0.0000000
Rio de Janeiro-Bom Jesus da Lapa BA	0.0000000
Santa Maria RS-Bom Jesus da Lapa BA	0.0000000
Manaus-Brasília	0.8850781
Recife-Brasília	0.0000000
Rio de Janeiro-Brasília	0.0499699
Santa Maria RS-Brasília	0.0000673
Recife-Manaus	0.0000060
Rio de Janeiro-Manaus	0.4927865
Santa Maria RS-Manaus	0.0063928
Rio de Janeiro-Recife	0.0121121
Santa Maria RS-Recife	0.6153117
Santa Maria RS-Rio de Janeiro	0.5099846

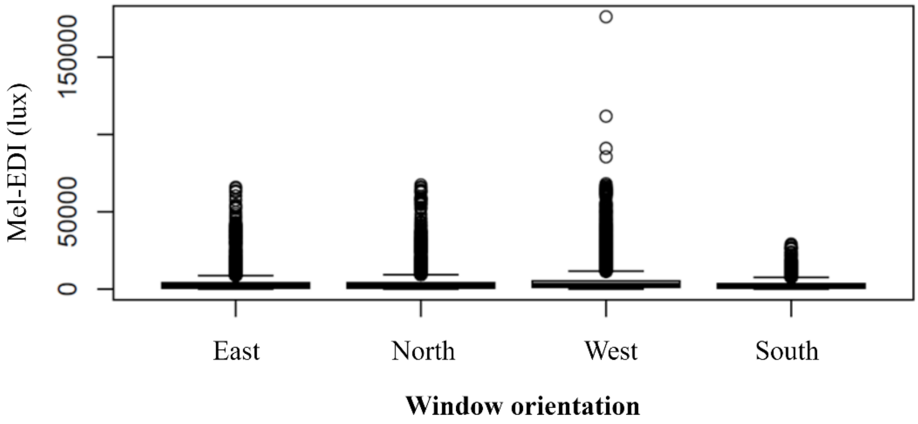
PER WINDOW ORIENTATION

Means and standard deviations of Mel-EDI per window orientation.

Orientation	**Mean**	**N**	**Standard deviation**
East	3679.606	8640	5537.506
North	3837.525	8640	5786.885
West	5089.339	8640	8630.515
South	2910.539	8640	3143.025
Total	3879.252	34560	6143.043

Note: All four glasses included in the analysis. Source: The Author.

Boxplot chart of results for Mel-EDI per window orientation.



Note: All four glasses included in the analysis. Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA) indicated significative differences (F=189,6; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001):

Orientation	P-value
North-East	0.3218194
West-East	0.0000000
South-East	0.0000000
West-North	0.0000000
South-North	0.0000000
South-West	0.0000000

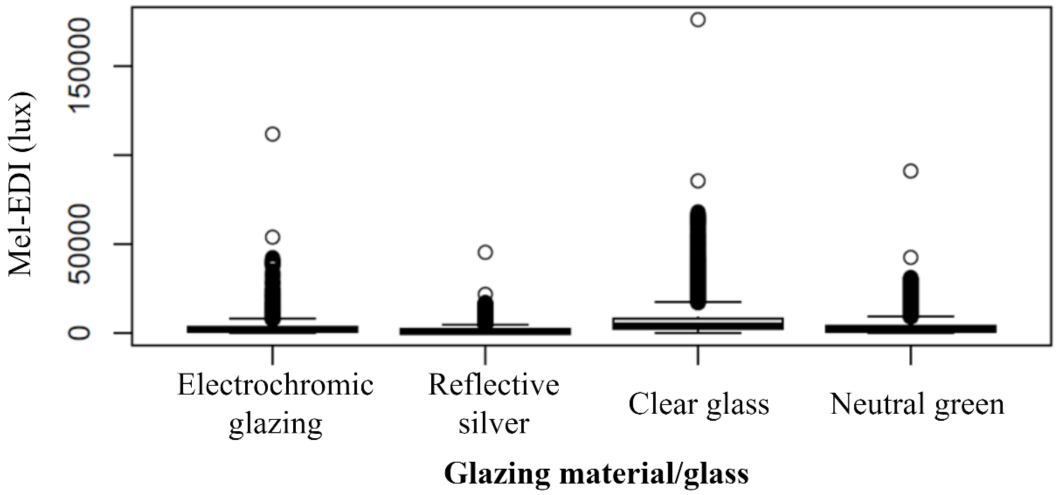
PER GLAZING MATERIAL/GLASS

Means and standard deviations of Mel-EDI per glazing material.

Glazing material	Mean	N	Standard deviation
Electrochromic glazing	2972.969	8640	4230.337
Reflective silver glass	1874.080	8640	2457.586
Clear glass	7034.627	8640	9550.079
Neutral green glass	3635.333	8640	4578.412
Total	3879.252	34560	6143.043

Source: The Author.

Boxplot chart showing results for Mel-EDI per glazing material.



Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA) indicated significative differences (F=1258,0; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001):

Glazing/glass	P-value
Silver glass – EC glazing	0.0000000
Clear glass – EC glazing	0.0000000
Green glass – EC glazing	0.0000000
Clear glass – silver glass	0.0000000
Green glass – silver glass	0.0000000
Green glass – clear glass	0.0000000

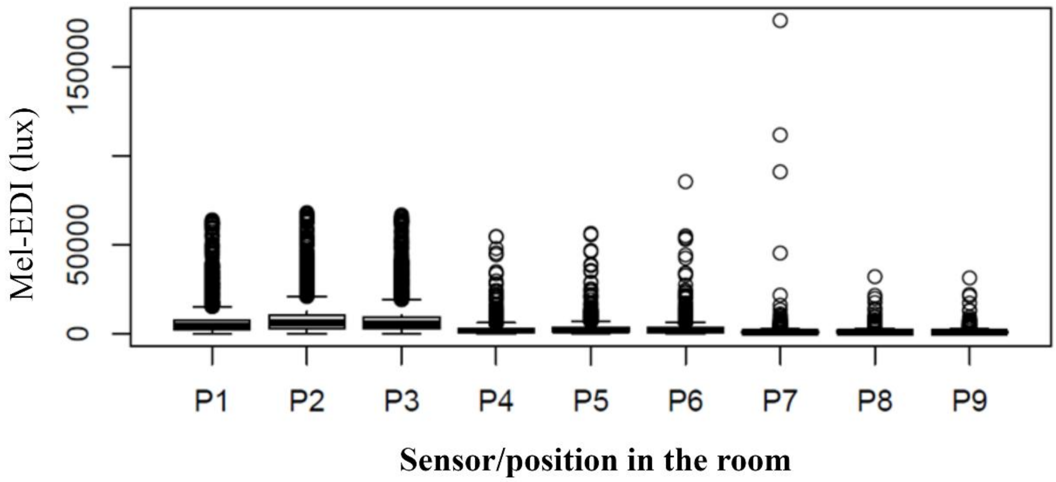
PER SENSOR/POSITION

Means and standard deviations of Mel-EDI per sensor/position in the room.

Sensor/position	**Mean**	**N**	**Standard deviation**
P1	6506.761	3840	7706.728
P2	8703.028	3840	9153.687
P3	7981.562	3840	8783.251
P4	2503.271	3840	2964.656
P5	2820.302	3840	3127.655
P6	2625.285	3840	3230.724
P7	1309.767	3840	3870.337
P8	1246.328	3840	1279.660
P9	1216.966	3840	1235.487
Total	3879.252	34560	6143.043

Note: All four glasses included in the analysis. Source: The Author.

Boxplot chart showing results of Mel-EDI per sensor/position in the room.



Note: All four glasses included in the analysis. Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA) indicated significative differences (F=1166,0; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001):

Sensor/Position	P-value
P2-P1	0.0000000
P3-P1	0.0000000
P4-P1	0.0000000
P5-P1	0.0000000
P6-P1	0.0000000
P7-P1	0.0000000
P8-P1	0.0000000
P9-P1	0.0000000
P3-P2	0.0000002
P4-P2	0.0000000
P5-P2	0.0000000
P6-P2	0.0000000
P7-P2	0.0000000
P8-P2	0.0000000
P9-P2	0.0000000
P4-P3	0.0000000
P5-P3	0.0000000
P6-P3	0.0000000
P7-P3	0.0000000
P8-P3	0.0000000
P9-P3	0.0000000
P5-P4	0.2090445
P6-P4	0.9876681
P7-P4	0.0000000
P8-P4	0.0000000
P9-P4	0.0000000
P6-P5	0.8226382
P7-P5	0.0000000
P8-P5	0.0000000
P9-P5	0.0000000
P7-P6	0.0000000
P8-P6	0.0000000
P9-P6	0.0000000
P8-P7	0.9998859
P9-P7	0.9981093
P9-P8	0.9999997

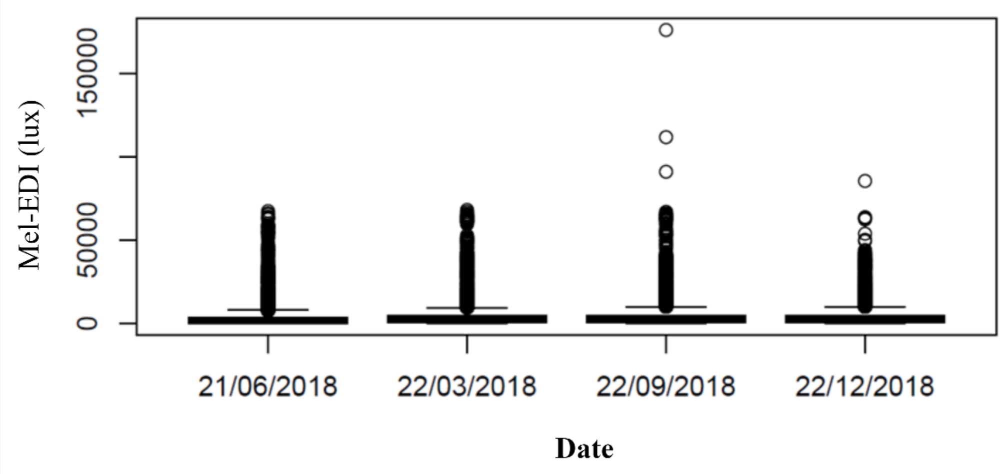
PER DATE

Means and standard deviations of Mel-EDI per date – close to solstices and equinoxes.

Date	Mean	N	Standard deviation
March 22	4021.572	8640	6409.076
June 21	3304.721	8640	5723.683
September 22	4252.203	8640	6996.734
December 22	3938.513	8640	5260.886
Total	3879.252	34560	6143.043

Note: All four glasses included in the analysis. Source: The Author.

Boxplot chart showing results of Mel-EDI per simulated dates.



Note: All four glasses included in the analysis. Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA) indicated significative differences (F=37,74; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001):

Date	P-value
22/03/2018-21/06/2018	0.0000000
22/09/2018-21/06/2018	0.0000000
22/12/2018-21/06/2018	0.0000000
22/09/2018-22/03/2018	0.0644203
22/12/2018-22/03/2018	0.8100232
22/12/2018-22/09/2018	0.0043107

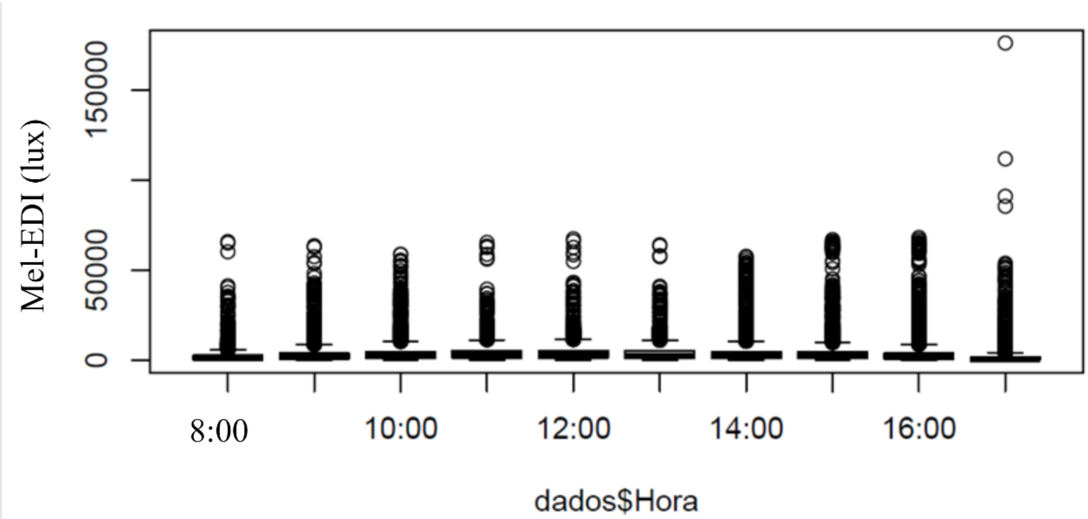
PER HOUR

Means and standard deviations of Mel-EDI per sensor/position in the room.

Hour	Mean	N	Standard deviation
08:00	2488.218	3456	4083.093
09:00	3705.740	3456	5792.085
10:00	4232.344	3456	5989.835
11:00	4311.940	3456	5094.070
12:00	4369.598	3456	5173.056
13:00	4114.132	3456	5050.623
14:00	4501.578	3456	6704.843
15:00	4444.681	3456	7498.488
16:00	4263.040	3456	7929.671
17:00	2361.249	3456	6584.556

Note: All four glasses included in the analysis. Source: The Author.

Boxplot chart showing results of Mel-EDI per hour.



Note: All four glasses included in the analysis. Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA) indicated significative differences (F=59,2; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001):

Hour	P-value
09:00-08:00	0.0000000
10:00-08:00	0.0000000
11:00-08:00	0.0000000
12:00-08:00	0.0000000
13:00-08:00	0.0000000

14:00-08:00	0.0000000
15:00-08:00	0.0000000
16:00-08:00	0.0000000
17:00-08:00	0.9974109
10:00-09:00	0.0122362
11:00-09:00	0.0014729
12:00-09:00	0.0002575
13:00-09:00	0.1416068
14:00-09:00	0.0000026
15:00-09:00	0.0000207
16:00-09:00	0.0056375
17:00-09:00	0.0000000
11:00-10:00	0.9999425
12:00-10:00	0.9953145
13:00-10:00	0.9985173
14:00-10:00	0.7124382
15:00-10:00	0.9120731
16:00-10:00	1.0000000
17:00-10:00	0.0000000
12:00-11:00	0.9999964
13:00-11:00	0.9421857
14:00-11:00	0.9555007
15:00-11:00	0.9963607
16:00-11:00	0.9999992
17:00-11:00	0.0000000
13:00-12:00	0.7715035
14:00-12:00	0.9965166
15:00-12:00	0.9999650
16:00-12:00	0.9993526
17:00-12:00	0.0000000
14:00-13:00	0.1982636
15:00-13:00	0.4197604
16:00-13:00	0.9914419
17:00-13:00	0.0000000
15:00-14:00	0.9999968
16:00-14:00	0.8355396
17:00-14:00	0.0000000
16:00-15:00	0.9662376
17:00-15:00	0.0000000
17:00-16:00	0.0000000

Variable Mel-DER

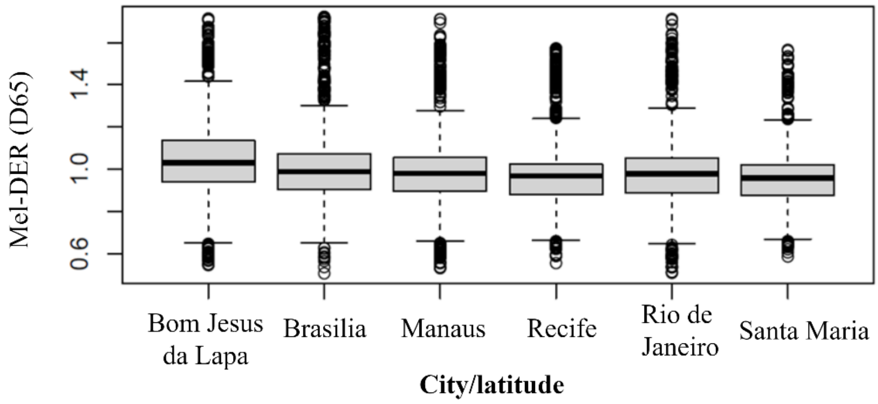
PER CITY/LATITUDE

Means of Mel-DER, number of analyzed cases and standard deviation per city.

City	Latitude	Mean (average)	Number of cases	Standard deviation
Manaus	3° south	0.9796612	5760	0.1343225
Recife	8° south	0.9629609	5760	0.1284924
Bom Jesus da Lapa	13° south	1.0339597	5760	0.1454572
Brasilia	15 south	0.9982605	5760	0.1473972
Rio de Janeiro	22° south	0.9771923	5760	0.1388982
Santa Maria	29° south	0.9535124	5760	0.1128904
Total		3879.252	34560	6143.043

Note: All four glasses included in the analysis. Source: The Author.

Results of Mel-DER per city.



Note: All four glasses included in the analysis. Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA) indicated significative differences (F=261,2; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001):

City	P-value
Brasília-Bom Jesus da Lapa BA	0.0000000
Manaus-Bom Jesus da Lapa BA	0.0000000
Recife-Bom Jesus da Lapa BA	0.0000000
Rio de Janeiro-Bom Jesus da Lapa BA	0.0000000
Santa Maria RS-Bom Jesus da Lapa BA	0.0000000
Manaus-Brasília	0.0000000
Recife-Brasília	0.0000000
Rio de Janeiro-Brasília	0.0000000
Santa Maria RS-Brasília	0.0000000
Recife-Manaus	0.0000000
Rio de Janeiro-Manaus	0.9241559
Santa Maria RS-Manaus	0.0000000
Rio de Janeiro-Recife	0.0000002
Santa Maria RS-Recife	0.0024024
Santa Maria RS-Rio de Janeiro	0.0000000

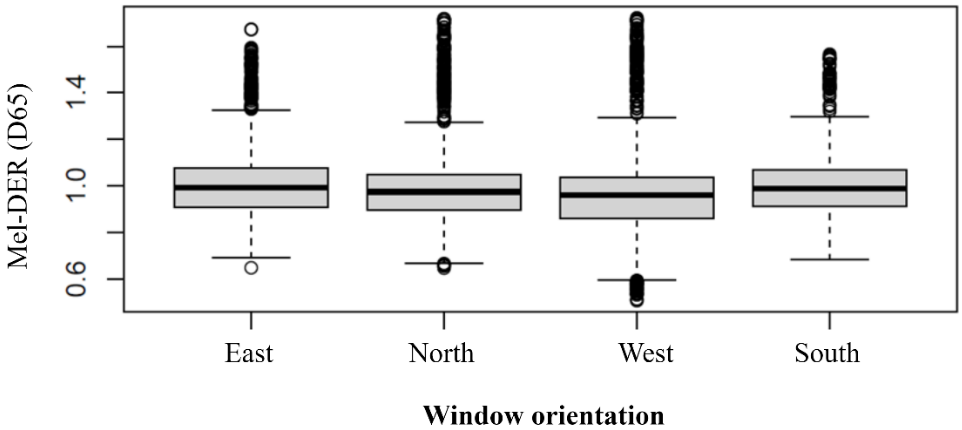
PER WINDOW ORIENTATION

Means and standard deviations of Mel-DER per window orientation.

Orientation	**Mean**	**N**	**Standard deviation**
East	1.0018407	8640	0.1303896
North	0.9837312	8640	0.1372735
West	0.9578923	8640	0.1576874
South	0.9935672	8640	0.1180414
Total	0.9842578	34560	0.1375948

Note: All four glasses included in the analysis. Source: The Author.

Boxplot of results of Mel-DER per window orientation.



Note: All four glasses included in the analysis. Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA) indicated significative differences (F=168,4; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001):

Orientation	P-value
North-East	0.0000000
West-East	0.0000000
South-East	0.0003996
West-North	0.0000000
South-North	0.0000132
South-West	0.0000000

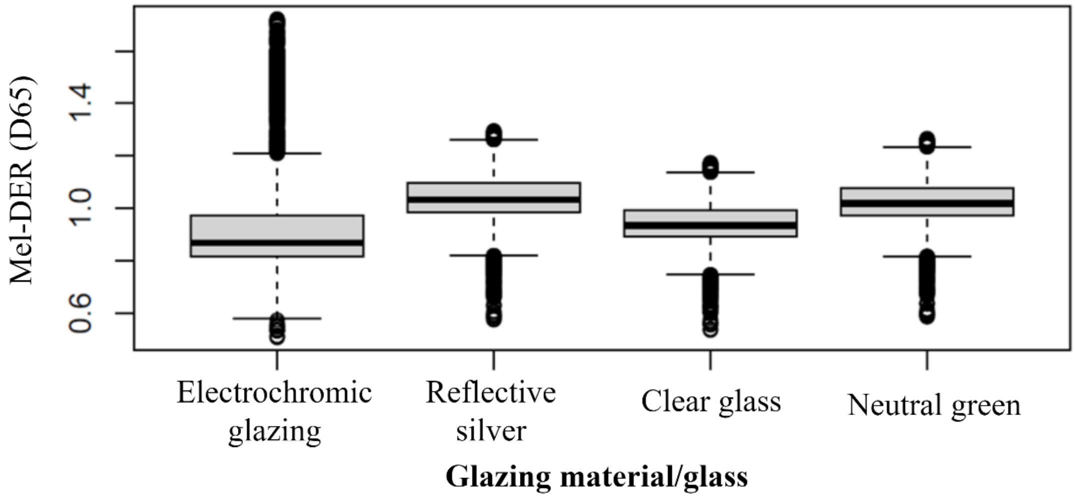
PER GLAZING MATERIAL/GLASS

Means and standard deviations of Mel-DER per glazing material.

Glazing material	**Mean**	**N**	**Standard deviation**
Electrochromic glazing	0.9314024	8640	0.19746547
Reflective silver glass	1.0393148	8640	0.10206865
Clear glass	0.9419661	8640	0.08923145
Neutral green glass	1.0243481	8640	0.09560957
Total	0.9842578	34560	0.13759483

Source: The Author.

Boxplot showing results of Mel-DER per glazing material.



Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA) indicated significative differences (F=1597,0; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001):

Glazing/glass	P-value
Silver glass – EC glazing	0.0000000
Clear glass – EC glazing	0.0000000
Green glass – EC glazing	0.0000000
Clear glass – silver glass	0.0000000
Green glass – silver glass	0.0000000
Green glass – clear glass	0.0000000

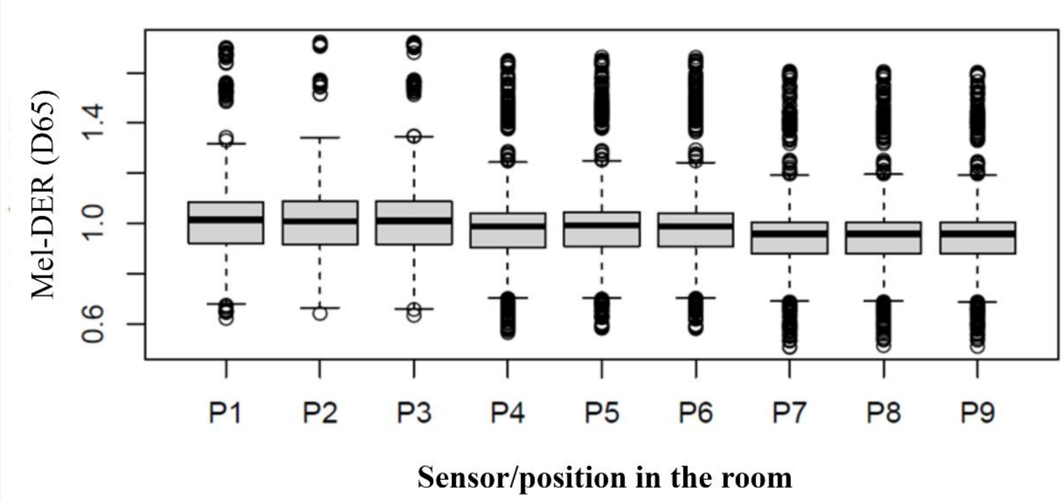
PER SENSOR/POSITION

Means and standard deviations of Mel-DER per sensor/position in the room.

Sensor/position	Mean	N	Standard deviation
P1	1.0117123	3840	0.1341927
P2	1.0124212	3840	0.1320299
P3	1.0125256	3840	0.1329499
P4	0.9848680	3840	0.1390455
P5	0.9887149	3840	0.1395623
P6	0.9862078	3840	0.1383898
P7	0.9539621	3840	0.1350765
P8	0.9540121	3840	0.1340039
P9	0.9538966	3840	0.1342523
Total	0.9842578	34560	0.1375948

Note: All four glasses included in the analysis. Source: The Author.

Boxplot showing results of Mel-DER per sensor/position in the room.



Note: All four glasses included in the analysis. Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA) indicated significative differences (F=133,9; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001):

Sensor/Position	P-value
P2-P1	0.9999998
P3-P1	0.9999993
P4-P1	0.0000000
P5-P1	0.0000000
P6-P1	0.0000000
P7-P1	0.0000000
P8-P1	0.0000000
P9-P1	0.0000000
P3-P2	1.0000000
P4-P2	0.0000000
P5-P2	0.0000000
P6-P2	0.0000000
P7-P2	0.0000000
P8-P2	0.0000000
P9-P2	0.0000000
P4-P3	0.0000000
P5-P3	0.0000000
P6-P3	0.0000000
P7-P3	0.0000000
P8-P3	0.0000000
P9-P3	0.0000000
P5-P4	0.9467617
P6-P4	0.9999672
P7-P4	0.0000000

P8-P4	0.0000000
P9-P4	0.0000000
P6-P5	0.9966013
P7-P5	0.0000000
P8-P5	0.0000000
P9-P5	0.0000000
P7-P6	0.0000000
P8-P6	0.0000000
P9-P6	0.0000000
P8-P7	1.0000000
P9-P7	1.0000000
P9-P8	1.0000000

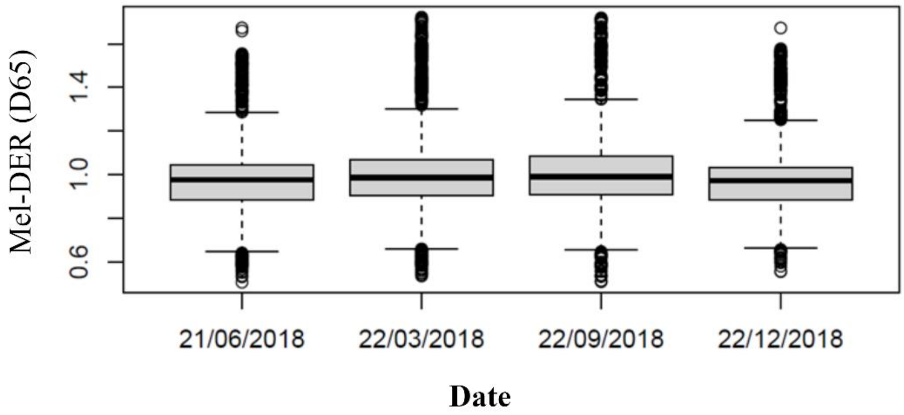
PER DATE

Means and standard deviations of Mel-DER per date – close to solstices and equinoxes.

Date	Mean	N	Standard deviation
March 22	0.9744520	8640	0.1349310
June 21	0.9941978	8640	0.1437415
September 22	0.9999280	8640	0.1435668
December 22	0.9684536	8640	0.1247643
Total	0.9842578	34560	0.1375948

Note: All four glasses included in the analysis. Source: The Author.

Boxplot chart showing results of Mel-DER per simulated dates.



Note: All four glasses included in the analysis. Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA) indicated significative differences (F=106,0; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001):

Date	P-value
22/03/2018-21/06/2018	0.0000000
22/09/2018-21/06/2018	0.0000000
22/12/2018-21/06/2018	0.0208479
22/09/2018-22/03/2018	0.0303942
22/12/2018-22/03/2018	0.0000000
22/12/2018-22/09/2018	0.0000000

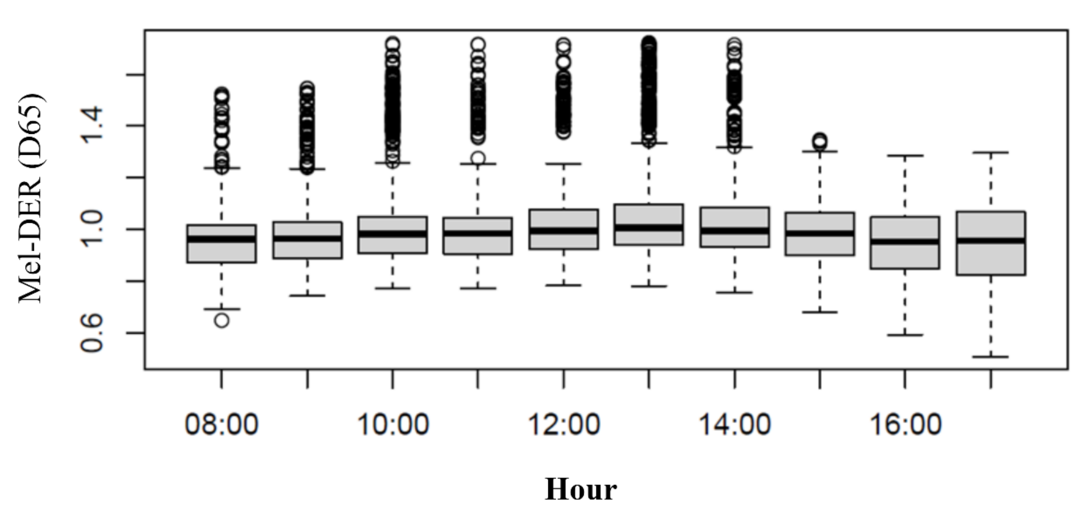
PER HOUR

Means and standard deviations of Mel-DER per sensor/position in the room.

Hour	**Mean**	**N**	**Standard deviation**
08:00	0.9530661	3456	0.1086392
09:00	0.9656628	3456	0.1137490
10:00	0.9973813	3456	0.1414332
11:00	0.9853756	3456	0.1191765
12:00	1.0090578	3456	0.1319658
13:00	1.0350714	3456	0.1608062
14:00	1.0159365	3456	0.1342299
15:00	0.9852786	3456	0.1182500
16:00	0.9528317	3456	0.1393757
17:00	0.9429167	3456	0.1653242

Note: All four glasses included in the analysis. Source: The Author.

Boxplot chart showing results of Mel-DER per hour.



Note: All four glasses included in the analysis. Source: The Author.

Comparison of the means through Analysis of Variance (ANOVA) indicated significative differences (F=178,0; P < 0,001).

Tukey Test for the comparison of two-by-two means (Sig. < 0,001):

Hour	P-value
09:00-08:00	0.0039326
10:00-08:00	0.0000000
11:00-08:00	0.0000000
12:00-08:00	0.0000000
13:00-08:00	0.0000000
14:00-08:00	0.0000000
15:00-08:00	0.0000000
16:00-08:00	1.0000000
17:00-08:00	0.0542978
10:00-09:00	0.0000000
11:00-09:00	0.0000001
12:00-09:00	0.0000000
13:00-09:00	0.0000000
14:00-09:00	0.0000000
15:00-09:00	0.0000001
16:00-09:00	0.0029470
17:00-09:00	0.0000000
11:00-10:00	0.0079169
12:00-10:00	0.0114859
13:00-10:00	0.0000000
14:00-10:00	0.0000004
15:00-10:00	0.0070772
16:00-10:00	0.0000000
17:00-10:00	0.0000000
12:00-11:00	0.0000000
13:00-11:00	0.0000000
14:00-11:00	0.0000000
15:00-11:00	1.0000000
16:00-11:00	0.0000000
17:00-11:00	0.0000000
13:00-12:00	0.0000000
14:00-12:00	0.5091795
15:00-12:00	0.0000000
16:00-12:00	0.0000000
17:00-12:00	0.0000000
14:00-13:00	0.0000002
15:00-13:00	0.0000000
16:00-13:00	0.0000000
17:00-13:00	0.0000000
15:00-14:00	0.0000000
16:00-14:00	0.0000000
17:00-14:00 -	0.0000000

16:00-15:00	0.0000000
17:00-15:00	0.0000000
17:00-16:00	0.0671182

Considerations regarding the comparisons of Mel-EDI and Mel-DER

The variability of the results for Mel-EDI and Mel-DER was entirely different. While the former showed high variability (CV=158%), the latter had results more concentrated around the average (CV=14%). Variable Mel-EDI showed outliers concentrated in the highest values, unlike Mel-DER. The number of cases as outliers for Mel-EDI was 1,130, or 3.3% of the simulated cases. Results of Mel-EDI presented outliers concentrated in the highest values, above 16,165.34 lux39. Only four outliers were detected above 69,000 lux of Mel-EDI, representing 0.01% of the total 34,560.

The distribution of Mel-EDI data was asymmetrical, with high concentration of data in the lowest values. This is also evident since the median (2022.5) is lower than the mean (3879.3).

Mel-DER also showed outliers, but these were distributed at the two extremes, both the highest, above 1.0563, and lowest values, below 0.8954. Outliers were concentrated on two extremes, above 1.25 in 839 cases and below 0.7048 in 417 cases. In total, 1,256 outliers were detected, representing 3.63% of the total simulated cases. Both variables presented weak correlation. For this reason, no linear regression model was adjusted.

The first analyzed response variable was melanopic daylight equivalent illuminance (Mel-EDI), analyzing the potency of circadian lighting inside the simulated room. **Results of Mel-EDI for Brasilia (15° south), Manaus (3° south), and Rio de Janeiro (22° south) were equivalent, with intermediate means** between 3,713 lux and 4,039 lux. **Another similar group was found among Recife (8° south), Rio de Janeiro (22° south), and Santa Maria (29° south), with the lowest means**, between 3,336 lux and 3,713 lux. **Bom Jesus da Lapa (13° south) differed from all the others, with the highest mean for Mel-EDI**, 4,755 lux. **The north and east orientations were equivalent for Mel-EDI, but all the others differed. The results of Mel-EDI for the north, west, and south differed from each other.**

Confronting these results with the existing proposals of luminous zoning in Brazil in sections 4.4 and 5.1, no relationships were found according to availability

[39] Outliers are calculated by the mean with the addition or subtraction of 2 times the value of the standard deviation (Diez; Rundel; Barr, 2022).

of daylight nor latitude. The Brazilian luminous zoning per latitude range was not created for this purpose.

The simulations in ALFA were restricted to four dates, representing the beginning of the four yearly seasons. Added to this, the sky models based on light spectrum and metrics are still being developed, as discussed in Chapter 4. **The spectral irradiance of the sky in ALFA was calculated for each city/latitude, hour, and sky condition, and this was defined by a set of historical atmospheric data and an atmospheric radiative transfer library (libRadtran)**. For this reason, more studies identifying the spectral irradiance data of the six cities/latitudes that were simulated must be carried out, identifying similarities and differences considering these atmospheric variables.

As mentioned in section 4.2, Inanici, Abboushi, and Safranek (2023) highlighted that recently developed sky models presented progress compared to colorless sky models, but further research is needed to simulate daylight spectra accurately. The same can be said within the context of the six Brazilian simulated cities/latitudes. **The similarities and differences among the different climates/sites of the Brazilian luminous zoning must take into account the light spectrum, particularly data containing spectral irradiance at different seasons and hours.** In this respect, it will be possible to identify possible relationships regarding the results of Mel-EDI per city/latitude.

Fortunately, as mentioned in section 4.2, data packages such as SKYSPECTRA have been proposed to encompass measurements from both long-term measurement sites and specific periods or experiments of spectral sky data, including the city of Sao Paulo - 23° south (Balakrishnan *et al.*, 2023). However, these tools have not yet been made available, and comparisons to the six evaluated Brazilian cities/latitudes could not be made.

ANOVA did not detect any equivalence among the results according to glazing material/glass. The four glasses, including electrochromic glazing, presented distinct results, with a P-value lower than 0.001. Clear glass (melanopic transmittance – 78%) presented the highest mean, with 7,034 lux, followed by neutral green glass (Tmel – 47%), 3,635 lux, electrochromic glazing (Tmel – 55% - 1.8%), 2,972 lux and at last reflective silver glass (Tmel – 23%), 1,874 lux. **This can be explained according to the difference in the melanopic transmittances of the four glasses.**

Positions P1 to P3 were not equivalent for Mel-EDI. Results for P4 to P6, 3m far from the window, and for P7 to P9, 5.5m far from the window, were equivalent, which indicated it was possible to study the room depth using any of the three positions at the same distance from the window in P4 to P9. These equivalences among positions at the same distance from the window were already identified in the results of the visual effects of light and the study conducted by Saiedlue *et al.* (2019).

The equivalences between March 22 and September 22 and March 22 and December 22 indicated that the worst results of Mel-EDI were during the winter months. The lowest mean was for June 21, with 3,304 lux. The means for March 22, September 22, and December 22 were similar, between 3,938 lux and 4,021 lux. Among the simulated hours, there was equivalence between 8 a.m. (8:00) with 5 p.m. (17:00), 9 a.m. (9:00) with 10 a.m. (10:00) and 1 p.m. (13:00). The means of Mel-EDI according to these three hours were, 4,083 lux for 8 a.m., 5,792 lux for 9 a.m., and 6,584 lux for 5 p.m. **A group of hours was formed and identified through ANOVA, from 10 a.m. (10:00) to 4 p.m. (16:00), with equivalent results**, with the means varying from 5,050 lux for 1 p.m. and 7,929 lux for 4 p.m. **In general, better results of Mel-EDI were found from 10 a.m. to 4 p.m., and the lowest results of Mel-EDI were found at 8 a.m. and 5 p.m.**

Englezou and Michael (2023) already identified both seasonal and hourly variations. In this study, the highest results of Mel-EDI were during the winter, with higher penetration of circadian light in the room. This happened because of the high latitude of Cyprus (35° north) and the sun's low angle. Within the Brazilian context, with lower latitudes, the lowest results of Mel-EDI occurred on June 21 (winter), with lower daylight availability. **The highest results occurred during autumn, spring, and summer, represented by March 22, September 22, and December 22, in general, due to more availability of daylight** – with detailed data per city/latitude of global horizontal illuminance, cloudiness, and solar radiation described in Appendix A.

The second evaluated response variable regarding non-visual effects of light was the melanopic daylight efficacy ratio (Mel-DER) testing the light source's melanopic efficacy in relation to CIE Illuminant D65. The lowest results were found in Santa Maria (29° south), with a mean of 0.95, and the highest ones were found in Bom Jesus da Lapa (13° south), 1.03. In the other four cities, Manaus (3° south), Brasilia (15° south), and Rio de Janeiro (22° south), the means were between 0.96 and 0.99. **No relationship with variable Mel-DER was seen as a function of latitude**. As discussed in section 4.2, results of Mel-DER were strongly related to correlated color temperature (CCT) and spectral distribution of the light source. **This indicated that there was possibly more blue light inside the room in Bom Jesus da Lapa (13° south) than in the other five cities/latitudes, caused by the spectral transmission of the electrochromic glazing in medium tint and dark tint states. The lowest means of Mel-DER were found in the**

cities/latitudes of Recife (8° south), with a mean of 0.96, and Santa Maria (29° south), 0.95, indicating a lower presence of blue light inside the room.

Despite the similar means, no equivalence was found through ANOVA among the four orientations for Mel-DER, with the P-valuer lower than 0.001 in all tested combinations. The highest mean was for the east, 1.001, followed by the south, 0.99; the north, 0.98; and finally, the west, 0.95. As described in section 4.2, variable Mel-DER was directly affected by the light spectrum – spectral power distribution of the light source. **This suggested that the higher results of Mel-DER for the north and the east orientations indicated more blue light. For the south and the west orientations, the lower results of Mel-DER indicated less presence of blue light**. As already commented for the results of variable Mel-EDI, **a better understanding of the similarities and differences among the different climates/sites of the Brazilian luminous zoning is needed, particularly considering the light spectrum**, specifically containing data of spectral irradiance at different seasons and hours of each site/latitude.

No equivalences of the results for Mel-DER were detected considering variable glazing material/glass. **The lowest results of Mel-DER were for electrochromic glazing because it was found in a clear state (M/P ratio of clear state 0.90) during most of the simulated hours**, as described in section 6.1. **Higher results of Mel-DER for the electrochromic glazing were found for the dark state, with an M/P ratio of 1.65, the highest transmission for blue wavelength in relation to the other three glasses**. The same observations were made by Nazari, Matusiak, and Stefani (2023), regarding the commented variable – Mel-DER for the electrochromic glazing. The lower results of Mel-DER for electrochromic glazing in a clear state indicated less presence of blue light in comparison to clear glass. In the dark state, the light transmission of electrochromic glazing shifted, and more blue light was transmitted to the room. The results of Mel-DER and the spectral transmission of all four glazing materials/glasses will be discussed in the next sections.

The highest results of Mel-DER were for reflective silver glass, followed by neutral green glass and clear glass, with means of 1.03, 1.02, and 0.94, respectively. As mentioned in Chapter 4, variable Mel-DER was affected by the spectral power distribution of the light source, hence these differences were explained by the spectral transmission of each glass (described in Appendix B).

The comparison between the positions for Mel-DER repeated the results of the previous variable, with the exception of positions P1 to P3, which were equivalent. At the same distance from the window, the results were similar to each other and different from the other positions. Thus, P1 to P3, P4 to P6, and P7 to P9 presented equivalent results. These equivalences in the positions at the same distance from the window were observed for Mel-EDI.

In the case of dates for Mel-DER, June 21 and December 22 and March 22 and September 22 were equivalent. All other comparisons resulted in statistically different means. The means for June 21 and December 22 were 0.97 and 0.96, respectively, indicating lower values of Mel-DER in the winter and summer equinoxes. The means for March 22 and September 22 were 0.97 and 0.99, respectively, indicating higher values of Mel-DER in the winter and summer equinoxes. Among the hours for Mel-DER, specific equivalences were found: 8 a.m., 4 p.m. and 5 p.m.; 10 a.m. and 12 p.m.; 11 a.m. and 3 p.m.; 12 p.m. and 2 p.m.; 4 p.m. and 5 p.m. There was no grouping of hours in sequence, as occurred in the results for Mel-EDI. Both seasonal and hourly variations of Mel-DER were already identified by Englezou and Michael (2023).

Appendix J. Categorization of response variables of non-visual effects

Non-visual effects

Variable Mel-EDI

Criterion: Mel-EDI ≥ 250 lux in 70% of the hours per day (from 8 a.m. to 6 p.m.)

General: minimum criterion met in 95% of the cases (32733/34560*100)

	MedEDI >= 250			% Hours	
Hour	0	1	Total	Yes	No
08	237	3219	3456	93%	7%
09	128	3328	3456	96%	4%
10	154	3302	3456	96%	4%
11	58	3398	3456	98%	2%
12	76	3380	3456	98%	2%
13	164	3292	3456	95%	5%
14	110	3346	3456	97%	3%
15	43	3413	3456	99%	1%
16	98	3358	3456	97%	3%
17	759	2697	3456	78%	22%
Total	1827	32733	34560	95%	5%

Hours with the HIGHEST percentage of hours meeting the criterion: 3 p.m. (99%)

Hours with the LOWEST percentage of hours that meet the criterion: 5 p.m. (78%)

Per city: in all cities (100%) the minimum criterion is met

Per city	MedEDI >= 250			Percent.	
City and hour	0	1	Total	Yes	No
Bom Jesus da Lapa BA	148	5612	5760	97%	3%
Brasília	237	5523	5760	96%	4%
Manaus	236	5524	5760	96%	4%
Recife	529	5231	5760	91%	9%
Rio de Janeiro	347	5413	5760	94%	6%
Santa Maria RS	330	5430	5760	94%	6%
Total	1827	32733	34560	95%	5%

City with the HIGHEST percentage of hours meeting the criterion: Bom Jesus da Lapa (97%)

City with the LOWEST percentage of hours meeting the criterion: Recife (91%)

PER ORIENTATION: in all orientations (100%) the criterion is met

	MedEDI >= 250			Percent.	
Orientation	0	1	Total	Yes	No
East	538	8102	8640	94%	6%
North	529	8111	8640	94%	6%
West	388	8252	8640	96%	4%
South	372	8268	8640	96%	4%
Total Geral	1827	32733	34560	95%	5%

Orientation with the HIGHEST percentage of hours meeting the criterion: South (95.7%)

Orientation with the LEAST percentage of hours meeting the criterion: East (93.8%)

PER SENSORS: all sensors meeting the minimum criterion

	MedEDI >= 250			Percent.	
Sensor	0	1	Total	Yes	No
P1	39	3801	3840	99%	1%
P2	17	3823	3840	100%	0%
P3	21	3819	3840	99%	1%
P4	199	3641	3840	95%	5%
P5	181	3659	3840	95%	5%
P6	191	3649	3840	95%	5%
P7	401	3439	3840	90%	10%
P8	385	3455	3840	90%	10%
P9	393	3447	3840	90%	10%
Total	1827	32733	34560	95%	5%

Sensor with HIGHEST percentage of hours meeting the criterion: P2 (99.6%)

Sensor with LOWEST percentage of hours meeting the criterion: P7 (89.6%)

POR GLASS: all glasses/glazings met the minimum criterion

	MedEDI >= 250			Percent.	
Glass	0	1	Total	Yes	No
EC glazing	930	7710	8640	89%	11%
Silver glass	567	8073	8640	93%	7%
Clear glass	107	8533	8640	99%	1%
Green glass	223	8417	8640	97%	3%
Total	1827	32733	34560	95%	5%

Glass with the HIGHEST percentage of hours meeting the criterion: Clear glass (99%)

Glass with the LEAST percentage of hours meeting the criterion: EC glazing (89%)

PER DATE: In all dates the minimum criterion is met

	MedEDI >= 250			Percent.	
Date	0	1	Total	Yes	No
22/Mar.	408	8232	8640	95%	5%
21/Jun.	761	7879	8640	91%	9%
22/Sept.	385	8255	8640	96%	4%
22/Dec.	273	8367	8640	97%	3%
Total	1827	32733	34560	95%	5%

Date with the HIGHEST percentage of hours meeting the criterion: Dec. 22 (97%)

Date with LOWEST percentage of hours meeting the criterion: June 21 (91%)

CROSSING OF VARIABLES: Lack of circadian lighting

City and Orientation: 100% of combinations meet the criterion

City and Window/Glass: 100% of combinations meet the criterion

City and Sensor: 100% of combinations meet the criterion

City and Date: 100% of combinations meet the criterion

Orientation and Window/Glass: 100% of combinations meet the criterion

Orientation and Sensor: 100% of combinations meet the criterion

Orientation and Date: 100% of combinations meet the criterion

Window/Glass and Sensor: 100% of combinations meet the criterion

Window/glass and Date: 100% of combinations meet the criterion

Sensor and Date: 100% of combinations meet the criterion

City, Orientation and Window/Glass: 100% of combinations meet the criterion

City, Orientation and Sensor: 100% of combinations meet the criterion

City, Orientation and Date: 100% of combinations meet the criterion

Orientation, Window/Glass and Sensor: 100% of combinations meet the criterion

Orientation, Window/Glass and Date: 100% of combinations meet the criterion

Window, Sensor, Date: 100% of combinations meet the criterion

City, Orientation, Sensor and Date: 100% of combinations meet the criterion

City, Orientation, Window and Sensor: 99% of combinations meet the criterion. Not met in the: sensors P4 to P9 with EC glass in the north of Brasilia (6 cases); sensors P7 and P8 with EC glass in the west of Recife (2 cases); sensor P7 with EC glass in the north of Rio de Janeiro (1 case); sensors P7 to P9 with EC glass in the north of Santa Maria (3 cases).

City, Orientation, Window and Date: 98% of the combinations meet the criteria. Not met in: June, north, EC glass, Bom Jesus da Lapa (1 case); March, June and September, north, EC glass, Brasília (3 cases); June, north, EC glass, Manaus (1 case); December, south, EC glass, Manaus (1 case); December, south, EC glass, Recife (1 case); March, September, west, EC glass, Recife (1 case); June, east, EC glass, Rio de Janeiro (1 case); March, June, North, EC glass, Rio de Janeiro (2 cases); June, South, silver glass, Rio de Janeiro (1 case); March, June, East, EC glass, Santa Maria (2 cases); March, September, East, silver glass, Santa Maria (2 cases); March, September, North, EC glass, Santa Maria (2 cases); June, West, South, silver glass, Santa Maria (2 cases).

City, Window, Sensor and Date: 98% of the combinations meet the criteria. Not met in: Brasília, EC glass, P7 to P9, June (3 cases); Manaus, EC glass, P7 to P9, June (3 cases); Recife, EC glass, P7 to P9, June (3 cases); Rio de Janeiro, EC glass, P7, June (1 case); Rio de Janeiro, silver glass, P7 to P9, June (3 cases); Santa Maria, silver glass, P7 to P9, June (3 cases).

Orientation, Window, Sensor and Date: 98% of the combinations meet the criteria. Not met to the: north, EC glass, P4 to P6 in June, P7 and P8 in March and June, P9 in June (8 cases); south, silver glass, P7 to P9, June (3 cases)

LACK OF CIRCADIAN LIGHTING

City, Orientation, Window/Glass, Sensor and Date: 98% of combinations meet the criterion

Criterion: Mel-EDI ≥ 250 lux in at least 70% of daylight hours

Not achieved in 85 cases

City	Orientation	Glass	Sensor	Date	Cases
Bom Jesus da Lapa	North	EC glazing	P4	June	1
			P5	June	1
			P6	June	1
			P7	June	1
			P8	June	1
			P9	June	1
Brasília	North	EC glazing	P4	March	1
				June	1
				September	1
			P5	March	1
				June	1
				September	1
			P6	March	1
				June	1
				September	1

			P7	March	1
				June	1
				September	1
			P8	March	1
				June	1
				September	1
			P9	March	1
				June	1
				September	1
Manaus	East	EC glazing	P7	June	1
			P8	June	1
			P9	June	1
	North	EC glazing	P4	June	1
			P5	June	1
			P6	June	1
			P7	June	1
			P8	June	1
			P9	June	1
	South	EC glazing	P7	December	1
			P8	December	1
			P9	December	1
Recife	West	EC glazing	P4	September	1
			P5	September	1
			P6	September	1
			P7	March	1
				September	1
				December	1
			P8	March	1
				September	1
				December	1
			P9	March	1
				September	1
	South	EC glazing	P4	December	1
			P5	December	1
			P6	December	1
			P7	December	1
			P8	December	1
			P9	December	1
Rio de Janeiro	East	EC glazing	P7	June	1
	North	EC glazing	P4	June	1
			P5	June	1
			P6	June	1
			P7	March	1
				June	1
			P8	March	1
				June	1
			P9	March	1
				June	1

	South	Silver glass	P7	June	1
			P8	June	1
			P9	June	1
Santa Maria	East	EC glazing	P7	March	1
		Silver glass	P7	June	1
			P8	June	1
			P9	June	1
	North	EC glazing	P4	March	1
			P5	March	1
			P6	March	1
			P7	March	1
				September	1
			P8	March	1
				September	1
			P9	March	1
				September	1
	West	Silver glass	P7	June	1
			P8	June	1
			P9	June	1
	South	Silver glass	P7	June	1
			P8	June	1
			P9	June	1
					85

CONCLUSION: MelEDI, considering the positive criterion of 70% of the day with MelEDI ≥ 250, is not a good discriminating performance variable, as all the control variables (city, window orientation, date and time sensor) had above 90% positive performance.

Variable Mel-DER

Criterion: Mel-DER ≥ 0,904

1 = 0,000 ≤ MelDER < 0,404 – < Daylight 2000 K (Englezou; Michael, 2023)

2 = 0,404 ≤ MelDER < 0,562 – ~ Daylight 3000 K (Englezou; Michael, 2023)

3 = 0,562 ≤ MelDER < 0,904 – CIE Standard Daylight D55 (5500 K) – CIE, 2018

4 = 0,904 ≤ MelDER < 1,000 – CIE Standard Daylight D65 (6500 K) – CIE, 2018

5 = 1,000≤ MelDER ≥ Máximo observado

Criterion: count of the hours in the day when Mel-DER is in the intervals 4 and 5 (Mel-DER ≥ 0.904) - CIE D55 and D65

GENERAL: intervals 4 and 5 occur in 73% of cases

Mel-DER		Hours' count	
	1	0	0,0%
	2	26	0,1%
	3	9354	27,1%
	4	10828	31,3%
	5	14352	41,5%
Total		34560	100,0%

PER CITY: highest in Bom Jesus da Lapa (84%) and lowest in Santa Maria (67%)

City	2	3	4	5	Total	4 and 5	Percent.
Bom Jesus da Lapa	4	922	1544	3290	5760	4834	84%
Brasília	2	1448	1730	2580	5760	4310	75%
Manaus	9	1576	1821	2354	5760	4175	72%
Recife	1	1850	1959	1950	5760	3909	68%
Rio de Janeiro	10	1650	1792	2308	5760	4100	71%
Santa Maria	0	1908	1982	1870	5760	3852	67%
Total	26	9354	10828	14352	34560	25180	73%

PER ORIENTATION: highest to the East (76.9%) and lowest to the West (65.3%)

Orientation	2	3	4	5	Total	4 and 5	Percent.
Leste		1999	2666	3975	8640	6641	76,9%
Norte		2377	2900	3363	8640	6263	72,5%
Oeste	26	2972	2524	3118	8640	5642	65,3%
Sul		2006	2738	3896	8640	6634	76,8%
Total	26	9354	10828	14352	34560	25180	72,9%

PER SENSOR: higher in P1 (77.1%) and lower in P9 (66.0%)

Sensor	2	3	4	5	Total	4 and 5	Percent.
P1		880	938	2022	3840	2960	77,1%
P2		903	978	1959	3840	2937	76,5%
P3		889	966	1985	3840	2951	76,8%
P4		950	1190	1700	3840	2890	75,3%
P5		920	1152	1768	3840	2920	76,0%
P6		945	1180	1715	3840	2895	75,4%
P7	12	1288	1465	1075	3840	2540	66,1%
P8	7	1280	1484	1069	3840	2553	66,5%
P9	7	1299	1475	1059	3840	2534	66,0%
Total	26	9354	10828	14352	34560	25180	72,9%

PER GLAZING: higher in Silver Glass (93%) and lower in EC Glass (39%)

Glazing	2	3	4	5	Total	4 and 5	Percent.
EC Glazing	16	5294	1641	1689	8640	3330	39%
Silver glass		620	2184	5836	8640	8020	93%
Clear glass	10	2788	3917	1925	8640	5842	68%
Green glass		652	3086	4902	8640	7988	92%
Total	26	9354	10828	14352	34560	25180	73%

PER DATE: highest in September (77%) and lowest in December (69%)

DATE	2	3	4	5	Total	4 and 5	Percent.
Mar.	7	2148	2722	3763	8640	6485	75%
Jun.	5	2558	2617	3460	8640	6077	70%
Sept.	12	2010	2585	4033	8640	6618	77%
Dec.	2	2638	2904	3096	8640	6000	69%
Total	26	9354	10828	14352	34560	25180	73%

CROSSING VARIABLES (% of hours in which Mel-DER ≥ 0.904)

Higher / Lower

City and orientation

City	East	North	West	South
Bom Jesus da Lapa	87,2%	83,3%	76,0%	89,1%
Brasília	75,4%	76,4%	68,5%	79,0%
Manaus	75,9%	74,4%	64,8%	74,8%
Recife	72,1%	68,1%	61,0%	70,3%
Rio de Janeiro	78,2%	67,4%	63,1%	76,0%
Santa Maria	72,4%	65,3%	58,3%	71,5%
Total	76,9%	72,5%	65,3%	76,8%

City and glazing material/glass

	EC glazing	Silver glass	Clear glass	Green glass
Bom Jesus da Lapa	65,8%	94,0%	82,0%	93,9%
Brasília	43,0%	92,8%	71,0%	92,4%
Manaus	40,7%	91,7%	66,5%	91,1%
Recife	20,7%	94,5%	62,1%	94,2%
Rio de Janeiro	37,8%	90,7%	65,7%	90,5%
Santa Maria RS	23,2%	93,3%	58,4%	92,6%
Total	38,5%	92,8%	67,6%	92,5%

City and sensor/position

	P1	P2	P3	P4	P5	P6	P7	P8	P9
Bom Jesus da Lapa	85,3%	85,2%	85,5%	87,2%	86,9%	86,9%	79,5%	79,5%	79,4%
Brasília	78,0%	78,4%	78,0%	78,4%	78,4%	77,7%	68,0%	68,4%	68,1%
Manaus	76,4%	74,5%	75,9%	75,5%	75,5%	75,3%	66,1%	66,9%	66,3%
Recife	73,9%	74,2%	74,8%	69,7%	71,7%	70,5%	58,6%	58,8%	58,6%
Rio de Janeiro	75,9%	75,0%	75,5%	72,5%	74,2%	73,3%	64,5%	65,2%	64,5%
Santa Maria	73,0%	71,6%	71,4%	68,3%	69,5%	68,8%	60,2%	60,2%	59,1%
Total	77,1%	76,5%	76,8%	75,3%	76,0%	75,4%	66,1%	66,5%	66,0%

City and date

	Mar.	Jun.	Sept.	Dec.
Bom Jesus da Lapa	76,5%	85,0%	91,2%	83,1%
Brasília	81,1%	64,8%	86,3%	67,1%
Manaus	74,2%	66,8%	83,1%	65,8%
Recife	67,4%	67,1%	67,5%	69,4%
Rio de Janeiro	78,1%	75,1%	62,2%	69,4%
Santa Maria	73,1%	63,3%	69,4%	61,8%
Total	75,1%	70,3%	76,6%	69,4%

Orientation and glass/glazing material

	EC glazing	Silver glass	Clear glass	Green glass
Leste	47,0%	94,6%	72,1%	93,7%
Norte	40,5%	94,5%	60,6%	94,4%
Oeste	34,0%	83,3%	60,9%	83,1%
Sul	32,7%	98,8%	76,9%	98,7%
Total	38,5%	92,8%	67,6%	92,5%

Orientation and sensor

	P1	P2	P3	P4	P5	P6	P7	P8	P9
East	81,1%	80,1%	79,2%	79,3%	79,7%	78,9%	71,4%	71,3%	70,9%
North	80,4%	77,2%	77,3%	75,6%	75,6%	74,4%	64,2%	64,1%	63,6%
West	66,4%	67,1%	67,4%	67,7%	68,5%	68,6%	60,5%	60,9%	60,5%
South	80,4%	81,6%	83,5%	78,4%	80,3%	79,7%	68,5%	69,7%	68,9%
Total	77,1%	76,5%	76,8%	75,3%	76,0%	75,4%	66,1%	66,5%	66,0%

Orientation and date

	Mar.	Jun.	Sept.	Dec.
East	76,9%	76,4%	81,4%	72,6%
North	77,0%	62,9%	77,4%	72,6%
West	67,6%	63,1%	66,1%	64,4%
South	78,6%	79,0%	81,5%	68,1%
Total	75,1%	70,3%	76,6%	69,4%

Glass and sensor

	P1	P2	P3	P4	P5	P6	P7	P8	P9
EC Glazing	41,3%	41,8%	41,8%	38,9%	38,9%	38,3%	35,3%	35,4%	35,3%
Silver glass	91,7%	91,3%	91,6%	94,6%	94,7%	94,5%	92,4%	92,5%	92,3%
Clear glass	83,6%	81,0%	82,4%	73,2%	76,5%	74,5%	45,6%	46,6%	45,1%
Green glass	91,8%	91,9%	91,7%	94,4%	94,2%	94,3%	91,3%	91,5%	91,3%
Total	77,1%	76,5%	76,8%	75,3%	76,0%	75,4%	66,1%	66,5%	66,0%

Glass and date

	Mar.	Jun.	Sept.	Dec.
EC Glazing	41,5%	41,1%	45,9%	25,6%
Silver glass	94,2%	88,2%	94,2%	94,7%
Clear glass	70,7%	64,3%	72,5%	63,0%
Green glass	93,8%	87,7%	93,8%	94,4%
Total	75,1%	70,3%	76,6%	69,4%

Sensor and Date

	Mar.	Jun.	Sept.	Dec.
P1	77,8%	77,0%	78,9%	74,7%
P2	78,8%	73,1%	79,9%	74,2%
P3	78,1%	74,6%	79,5%	75,2%
P4	77,6%	72,3%	79,0%	72,2%
P5	78,0%	73,1%	79,8%	73,2%
P6	78,0%	71,8%	79,2%	72,6%
P7	69,1%	63,5%	71,0%	60,9%
P8	69,3%	63,9%	71,4%	61,5%
P9	68,9%	63,8%	70,8%	60,5%
Total	75,1%	70,3%	76,6%	69,4%

City, Orientation and Window/Glass

	EC glazing	Silver glass	Clear glass	Green glass
Bom Jesus da Lapa BA	66%	94%	82%	94%
East	81%	95%	79%	94%
North	60%	95%	83%	95%
West	55%	86%	76%	86%
South	67%	100%	90%	100%
Brasília	43%	93%	71%	92%
East	51%	92%	69%	90%
North	58%	92%	64%	92%
West	31%	88%	68%	88%
South	33%	100%	83%	100%
Manaus	41%	92%	66%	91%
East	50%	93%	70%	91%
North	43%	96%	63%	96%
West	33%	82%	64%	81%
South	38%	96%	69%	96%
Recife	21%	95%	62%	94%
East	26%	98%	69%	96%
North	5%	100%	67%	100%
West	30%	83%	49%	83%
South	22%	98%	63%	98%
Rio de Janeiro	38%	91%	66%	90%
East	49%	94%	76%	94%
North	38%	91%	49%	91%
West	36%	79%	59%	79%
South	28%	99%	79%	98%
Santa Maria RS	23%	93%	58%	93%
East	26%	98%	70%	96%
North	39%	93%	38%	92%
West	20%	83%	48%	82%
South	9%	100%	78%	100%
Total	39%	93%	68%	92%

City, orientation and sensor

	East	North	West	South
Bom Jesus da Lapa BA	87%	83%	76%	89%
P1	87%	89%	75%	90%
P2	88%	86%	75%	92%
P3	88%	87%	74%	93%
P4	91%	89%	78%	91%
P5	91%	88%	78%	91%
P6	90%	88%	79%	91%
P7	84%	75%	75%	84%
P8	84%	74%	75%	85%
P9	84%	74%	75%	84%
Brasília	75%	76%	69%	79%
P1	79%	81%	69%	83%
P2	79%	81%	71%	84%
P3	76%	80%	73%	84%
P4	79%	81%	71%	82%
P5	79%	81%	73%	82%
P6	78%	80%	72%	81%
P7	69%	69%	63%	71%
P8	71%	68%	63%	72%
P9	69%	67%	64%	73%
Manaus	76%	74%	65%	75%
P1	79%	83%	67%	78%
P2	78%	78%	65%	78%
P3	78%	79%	65%	83%
P4	79%	78%	68%	77%
P5	79%	77%	68%	78%
P6	79%	76%	68%	78%
P7	70%	67%	61%	66%
P8	71%	67%	62%	68%
P9	70%	66%	61%	68%
Recife	72%	68%	61%	70%
P1	76%	78%	68%	75%
P2	77%	78%	65%	78%
P3	77%	77%	65%	81%
P4	74%	71%	63%	71%
P5	75%	72%	64%	76%
P6	74%	69%	64%	75%
P7	66%	56%	53%	59%
P8	65%	56%	54%	59%
P9	66%	56%	54%	59%
Rio de Janeiro	78%	67%	63%	76%
P1	85%	76%	63%	80%
P2	82%	71%	66%	81%

P3	81%	71%	66%	83%
P4	79%	69%	65%	78%
P5	80%	69%	67%	81%
P6	78%	68%	67%	80%
P7	73%	61%	58%	67%
P8	73%	61%	59%	68%
P9	73%	61%	58%	67%
Santa Maria RS	72%	65%	58%	72%
P1	82%	76%	57%	77%
P2	77%	71%	61%	78%
P3	76%	70%	61%	78%
P4	74%	66%	61%	73%
P5	74%	68%	63%	74%
P6	74%	65%	63%	73%
P7	66%	58%	54%	64%
P8	64%	58%	53%	66%
P9	64%	58%	52%	63%
Total	77%	72%	65%	77%

Appendix K. Results of spectral analysis of the simulated glasses

Selected cases: Brasilia; North orientation; September 22 at 9 a.m., 12 p.m., 2 p.m. and 5p.m.

A-Opic EDI for the five photoreceptors of the human eye – Unity: lux

Selected cases			α-opic EDI and Mel-DER						
Glass	Hour	EC State North	**Ev (lux)**	**S-cone-opic**	**M-cone-opic**	**L-cone-opic**	**Rhodopic**	**Mel-EDI**	Mel-DER
EC	09:00	2	303,22	314,74	325,65	298,45	343,08	**345,65**	**1,14**
EC	12:00	3	87,16	160,45	105,83	87,02	133,58	**143,96**	**1,65**
EC	14:00	1	2915,18	2420,74	2880,80	2893,18	2755,37	**2695,15**	**0,92**
EC	17:00	0	1664,34	1348,02	1644,97	1651,54	1577,23	**1540,80**	**0,93**
Silver	09:00	N.A.	1198,06	1152,23	1200,10	1196,82	1196,29	**1194,43**	**1,00**
Silver	12:00	N.A.	1720,36	2081,52	1795,50	1722,18	1911,70	**1958,92**	**1,14**
Silver	14:00	N.A.	1543,44	1847,13	1608,03	1544,87	1707,33	**1747,53**	**1,13**
Silver	17:00	N.A.	573,66	681,88	601,14	573,78	642,65	**658,10**	**1,15**
Clear	09:00	N.A.	4733,88	3919,50	4589,52	4732,00	4351,83	**4263,89**	**0,90**
Clear	12:00	N.A.	6928,05	7262,97	6998,10	6932,09	7099,59	**7149,14**	**1,03**
Clear	14:00	N.A.	6227,45	6458,08	6279,75	6230,56	6353,31	**6390,20**	**1,03**
Clear	17:00	N.A.	2339,61	2401,17	2371,63	2338,83	2414,57	**2428,99**	**1,04**
Green	09:00	N.A.	2342,60	2066,21	2370,79	2321,60	2334,04	**2305,94**	**0,98**
Green	12:00	N.A.	3486,85	3848,50	3667,96	3462,25	3847,78	**3900,65**	**1,12**
Green	14:00	N.A.	3081,19	3375,46	3237,94	3059,16	3390,86	**3434,87**	**1,11**
Green	17:00	N.A.	1146,02	1241,25	1209,83	1136,99	1273,63	**1290,09**	**1,13**

Note: *0 – Tint states - Tmel 0 55.7%/ 1- Tmel 1 37.4%/ 2- Tmel 2 7.0%/ 3- Tmel 3 1.8%.

Spectral analysis

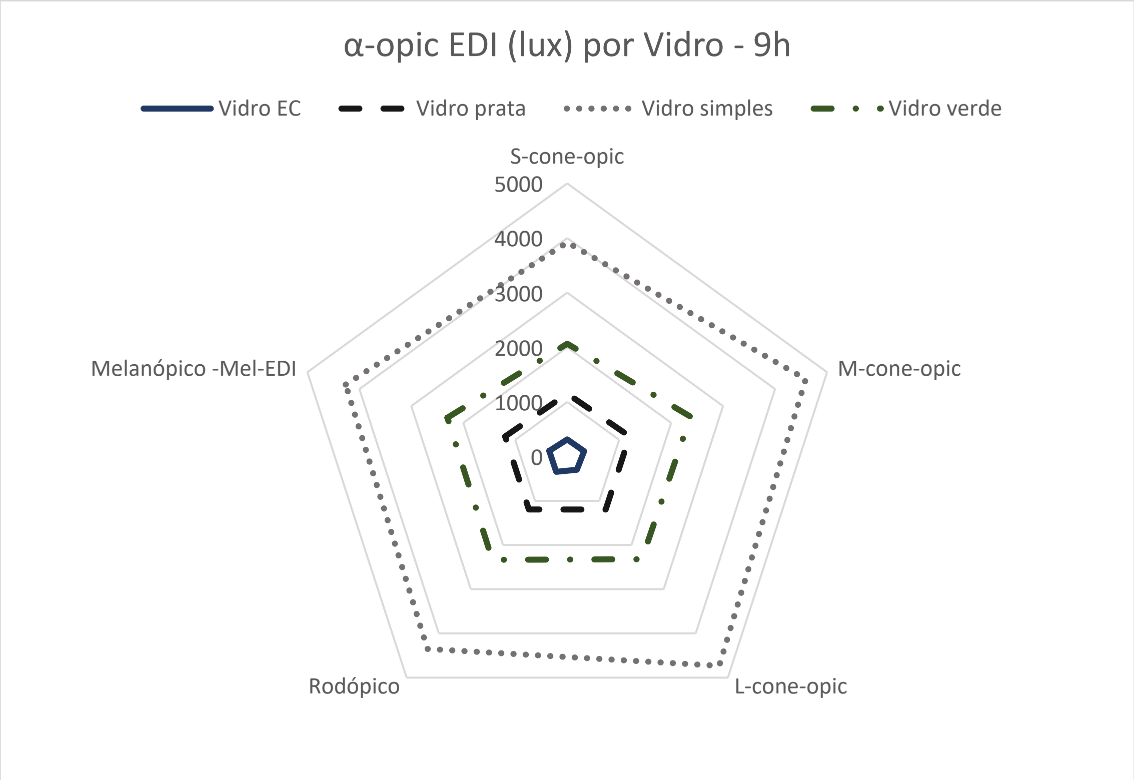
A-opic EDI – Unity: lux

Case selection: Brasilia; north orientation; September 22 at 9 a.m., 12 noon, 2 p.m. and 5 p.m.

PER GLASS

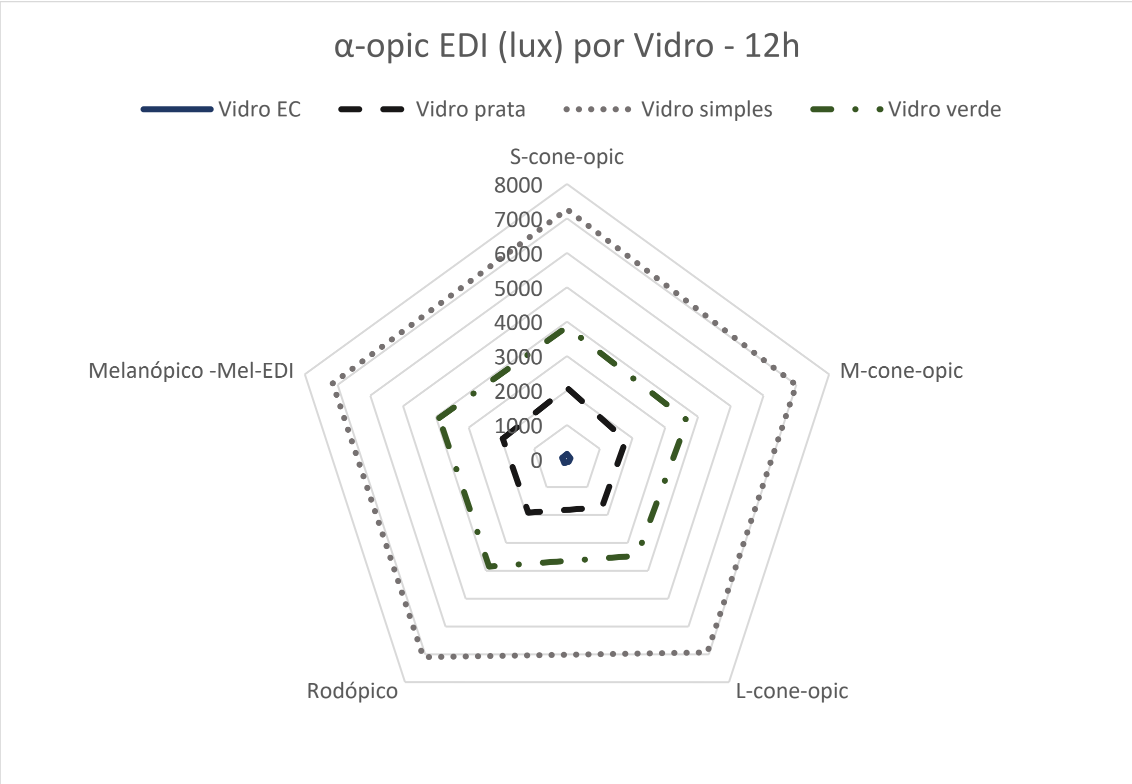
Hour: 9 a.m.

Glass	S-cone-opic	M-cone-opic	L-cone-opic	Rodopic	Mel-EDI
EC glazing	314,7358	325,6456	298,4516	343,0792	345,6546
Silver glass	1152,233	1200,1	1196,815	1196,289	1194,432
Clear	3919,505	4589,518	4732,005	4351,835	4263,892
Green glass	2066,208	2370,789	2321,601	2334,043	2305,94



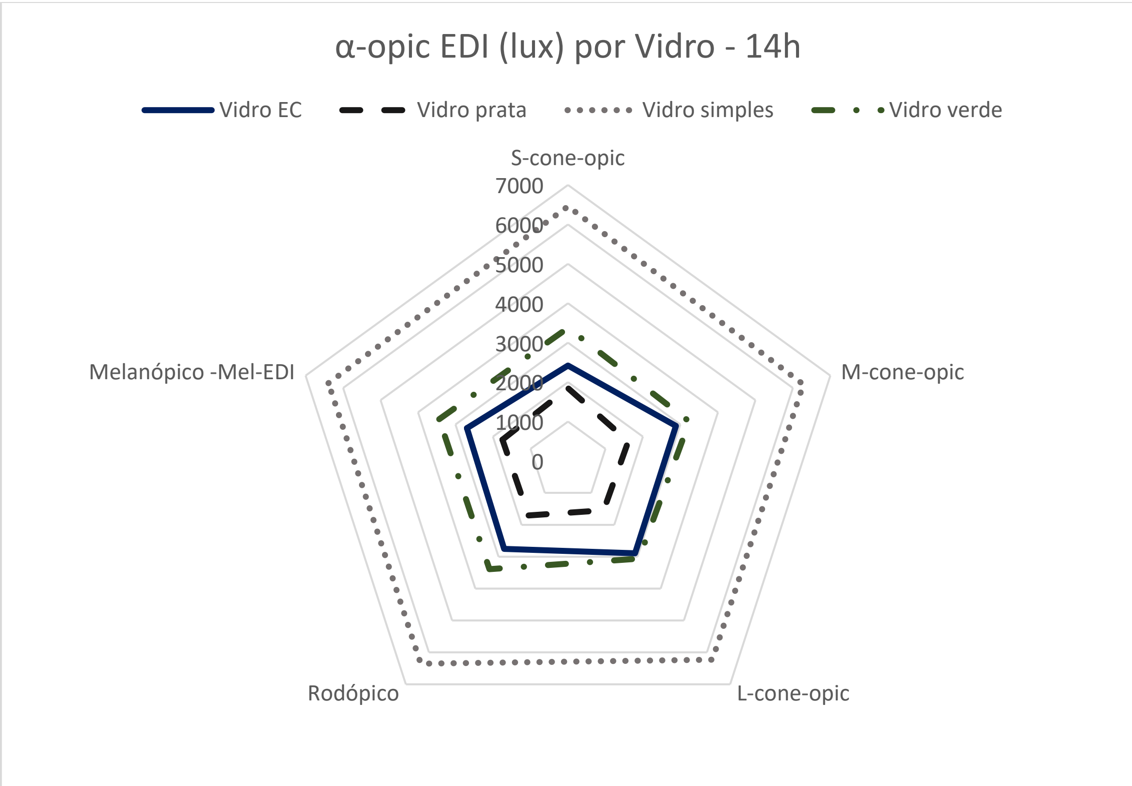
Hour: 12 p.m.

Glass	Glass	S-cone-opic	M-cone-opic	L-cone-opic	Rodopic
EC glazing	160,4492	105,834	87,01709	133,5827	143,9608
Silver glass	2081,515	1795,497	1722,18	1911,695	1958,922
Clear	7262,972	6998,099	6932,09	7099,586	7149,141
Green glass	3848,505	3667,956	3462,245	3847,778	3900,655



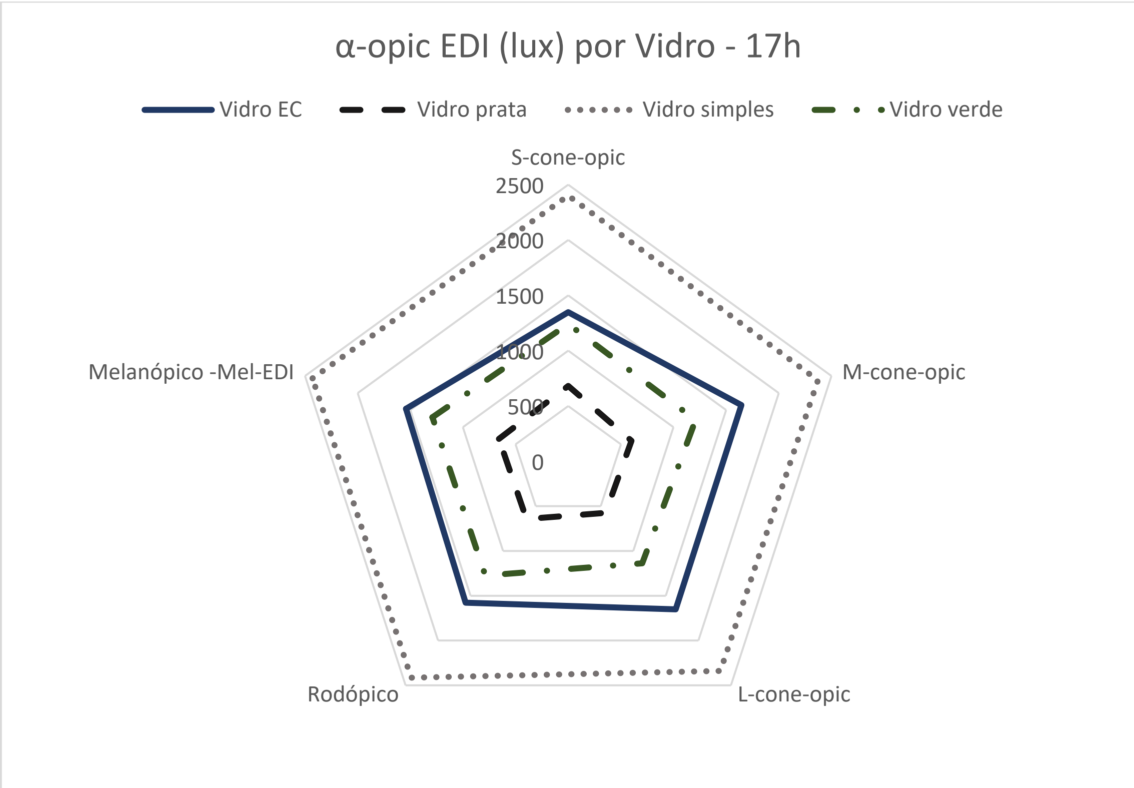
Hour: 2 p.m.

Glass	Glass	S-cone-opic	M-cone-opic	L-cone-opic	Rodopic
EC glazing	2420,742	2880,795	2893,181	2755,367	2695,145
Silver glass	1847,133	1608,033	1544,868	1707,334	1747,527
Clear	6458,079	6279,747	6230,56	6353,308	6390,195
Green glass	3375,46	3237,945	3059,156	3390,864	3434,868



Hour: 5 p.m.

Glass	Glass	S-cone-opic	M-cone-opic	L-cone-opic	Rodopic
EC glazing	1348,017	1644,972	1651,543	1577,226	1540,802
Silver glass	681,8798	601,1366	573,7821	642,6533	658,0952
Clear	2401,168	2371,634	2338,827	2414,573	2428,994
Green glass	1241,247	1209,825	1136,988	1273,626	1290,09



Appendix L. Contributions of the publications from this research

Two conference papers from this research were published at two important conferences in the field of Architecture, ENCAC and PLEA. Moreover, two journal articles were published, one in Ambiente Construido and one in the Journal of Daylighting, the latter with a high Cite Score and indexed in Scopus. The first conference paper was related to finding the most innovative transparent and translucent materials used on facades through the literature review (Costa; Amorim, 2021). The idea was to identify innovative materials to improve daylight and thermal comfort conditions in highly glazed non-residential buildings. Later, this paper was extended and published in the journal Ambiente Construido (Costa, Amorim, 2022). In these two publications, the potentialities of electrochromic glazing were first identified as promising in warm climates located in lower latitudes due to the dynamism of the tint states and more control of the properties of visible transmission. In this context, questions remained as to how the performance of electrochromic glazing would be in Brazilian climates regarding visual comfort.

Then, the second important aspect was identified and considered relevant to be investigated: the non-visual effects of light. The second conference paper was dedicated to investigating studies focused on innovative transparent and translucent materials related to metrics and calculation methods for non-visual effects of light (Costa; Amorim, 2022). The contents of this conference paper were extended, improved, and added in sections Chapter 3 and Chapter 4 of the literature review. These sections were crucial to identify and select assessment criteria of visual comfort regarding visual and non-visual effects of light.

The last article published in the Journal of Daylighting was the key contributor to the method related to the performance of electrochromic glazing for one Brazilian climate/latitude (Costa; Amorim, 2024). This publication was related to the first round of simulations using electrochromic glazing for the climate/latitude of Brasilia (15° south). The main contribution to the thesis was to adapt the metrics of non-visual effects of light to the CIE International Standard S026 (Commission…, 2018). In this publication, the first problems related to the lack of circadian lighting were detected in the climate of Brasilia (15° south), which was related to the use of electrochromic glazing. The section corresponding to the method of this article was later extended to evaluate the performance of electrochromic glazing for five other cities/latitudes within the Brazilian climatic context, comparing its performance with two conventional and one reflective glass.

Furthermore, two manuscripts will be submitted for consideration for publication in journals of high impact.[40] The first publication will focus on the performance of electrochromic glazing regarding visual effects in the context of the six simulated cities/latitudes and the comparison with the conventional, clear, and neutral green and reflective silver glass. The second publication will focus on the performance of electrochromic glazing regarding non-visual effects of light in the same context as the visual effects of Brazilian climates and compare it with the three other glasses. A combination of these two aspects of visual comfort and visual and non-visual effects is also considered for the two possible future publications regarding the performance of electrochromic glazing.

[40] At least A4, or equivalent as indicated in the report of Qualis Periódicos da CAPES (Brasil, 2019).