http://periodicos.sbu.unicamp.br/ojs/index.php/parc
https://doi.org/10.20396/parc.v15i00.8670676

DAYLIGHT AND ENERGY PERFORMANCE OF SIDE LIGHTING SYSTEMS IN AN OFFICE ROOM IN A SUBTROPICAL CLIMATE

LUZ NATURAL E DESEMPENHO ENERGÉTICO DE SISTEMAS DE ILUMINAÇÃO LATERAL EM UMA SALA DE ESCRITÓRIO EM CLIMA SUBTROPICAL

Elaise Gabriel[1]

Giane de Campos Grigoletti[2]

Gabriela Meller[3]

Bruna Zambonato[4]

[1] Federal University of Santa Maria, Santa Maria, RS, Brazil, elaise.gabriel@ufsm.br
2 Federal University of Santa Maria, Santa Maria, RS, Brazil giane.c.grigoletti@ufsm.br
3 Federal University of Santa Maria, Santa Maria, RS, Brazil, gabriela.meller@ufpel.edu.br
4 Federal University of Santa Maria, Santa Maria, RS, Brazil, zambonato.bruna@acad.ufsm.br

Authors' contributions:
EG: conceptualization, data curation, formal analysis, investigation, methodology, project administration, validation, visualization, writing - original draft, writing - review and editing. **GCG**: conceptualization, methodology, project administration, supervision, validation, visualization, writing - original draft, writing - review and editing. **GM**: formal analysis, visualization, writing - original draft, writing - review and editing. **BZ**: formal analysis, visualization, writing - original draft, writing - review and editing.

Funding: Coordination for the Improvement of Higher Education Personnel
Conflict declaration: nothing was declared.

Responsible Editor:
Michele Marta Rossi

Abstract

In office buildings, daylight is an important natural resource, as it is profusely available during occupied hours. However, its use can increase energy consumption for air conditioning. Therefore, combining this resource with side lighting systems and promoting its integration with electric lighting is essential to obtain an energy balance. This paper aims to analyze daylight performance and the energy consumption for lighting and air conditioning considering four types of glazing, four orientations, from window-to-wall ratios varying between 40% to 100% for bare and shaded window models in an office room located in a subtropical city in southern Brazil. The methodology was based on Useful Daylight Illuminance levels of 500 to 2,500 lx, Daylight Autonomy levels of 500 lx, and total energy consumption through simulation in DesignBuilder software. The results showed that L13 glazing is not recommended for bare and shaded windows, regardless of window orientation. M76 presented the best performance for energy consumption for West shaded windows. For the West, shading is necessary irrespective of the glazing type (except L13, whose best performance is for bare windows) from WWR 50%. M76 and M52 had the lowest total energy consumption. The findings of this study add to an understanding of the energy savings and lighting performance of different types of glazing, combined with window apertures, and solar orientations for a subtropical climate. Furthermore, the study shows that the choice of glazing depends not only on the presence of shading but also on the orientation and WWR, without a linear behavior.

Palavras-chave: climate-based daylighting metrics, energy consumption, office room, glazing, simulation.

Resumo

Em escritórios, a luz natural é um importante recurso, pois está amplamente disponível durante as horas ocupadas. Todavia, seu uso pode aumentar o consumo de energia para ar-condicionado, portanto deve-se usar juntamente com sistemas de iluminação lateral para obter um balanço energético. O objetivo deste trabalho é analisar o desempenho de luz natural e o consumo de energia para iluminação e ar-condicionado considerando quatro tipos de vidros, quatro orientações, áreas de janela entre 40% e 100% para modelos expostos e sombreados em uma sala de escritório localizada no clima subtropical do sul do Brasil. A metodologia foi baseada nos níveis de Iluminação Útil da Luz do Dia de 500 a 2.500 lx, Autonomia da Luz do Dia de 500 lx e consumo de energia através de simulação computacional no DesignBuilder. Os resultados mostraram que o vidro L13 não é recomendado para janelas expostas e sombreadas independentemente da orientação da janela. O M76 apresentou melhor desempenho para consumo de energia em janelas sombreadas a oeste. Para oeste, o sombreamento é necessário independentemente do tipo de vidro (exceto L13 cujo melhor desempenho é para janela exposta) a partir de WWR 50%. M76 e M52 apresentaram menor consumo de energia. Os resultados obtidos contribuem para a compreensão da economia de energia e desempenho de luz natural, com diferentes vidros, aberturas de janelas e orientações solares no clima subtropical. Ainda, o estudo mostra que a escolha do vidro depende não apenas da presença de sombreamento, mas também da orientação e WWR, sem comportamento linear.

Keywords: *métricas de iluminação natural baseadas no clima, consumo de energia, escritório, vidros, simulação.*

How to cite this article:

GABRIEL, E.; GRIGOLETTI, G. de C.; MELLER, G.; ZAMBONATO, B. Daylight and energy performance of side lighting systems in an office room in a subtropical climate. **PARC Pesq. em Arquit. e Constr.**, Campinas, SP, v. 15, p. e024003, 2024. DOI: https://doi.org/10.20396/parc.v15i00.8670676

Submitted 10.08.2022 – Approved 17.10.2023 – Published 18.01.2024

Introduction

Daylight in buildings has some unique qualities that cannot be fully offset by electric lighting, such as constant changes in direction, intensity, and color, in addition to connecting building users to the outdoor landscape (Baker; Steemers, 2002; Edwards; Torcellini, 2002; Li, 2010). Daylight is also a passive energy source (Yu; Su, 2015), it is vital for humans to produce vitamin D and light-related hormones (Beute; Kort, 2018; Münch *et al.*, 2012), and is important for the metabolism, the entrainment of the biological clock, and the circadian rhythm (Li, 2010; Münch *et al.*, 2020). Furthermore, considering office buildings, daylight has great importance due to its abundant availability during occupied hours. However, electric lighting is responsible for a large part of the energy consumption, mainly because such buildings do not benefit from daylight. Even though the recent development of energy-efficient and intelligent lighting systems has significantly reduced the electric lighting demand, there is still room for daylight use (Asfour, 2020).

Air conditioning is also responsible for consuming large amounts of energy in buildings, and the admittance of daylight can increase this consumption. Therefore, optimizing daylighting systems is essential to achieve energy savings (Ahmad; Reffat, 2018; Pilechiha *et al.*, 2020). Energy consumption for lighting and air conditioning ranges from country to country due to climatic and design conditions, available technologies, and economic development. In Brazil, for example, according to the National Energy Balance report, with the base year of 2020, the commercial sector was responsible for 15.7% of the total energy consumed, becoming the third-largest consumer sector in the country (Brasil, 2021). According to the Energy Research Office (Brasil, 2021) (EPE in Portuguese), the commercial and service sectors will be able to achieve 37% of energy efficiency gains by 2029, demonstrating the issue's relevance in the economic and social context. Besides that, another factor that influences energy consumption and savings is the building envelope, which has a crucial role regarding losses and gains of energy, solar radiation, involving glazing solutions (Evola; Costanzo; Infantone; Marletta, 2021).

Considering this, studies on buildings' envelopes show that the definition of an ideal window varies in different environmental conditions (Cellai; Carletti; Sciurpi; Secchi, 2014; Troup; Phillips; Eckelman; Fannon, 2019; Ye; Meng; Xu, 2012). However, the need to increase the window area to improve daylighting and avoid excessive glazing to reduce cooling and heating demand causes a conflict. For the combination of natural and electric lighting to be efficient, it is necessary to select the window-to-wall ratio (WWR) properly and other factors that affect heat transfer, such as window orientation (Ahmad; Reffat, 2018; Shaeri; Yaghoubi; Habibi; Chokhachian, 2019), room dimension and geometry (Ghisi; Tinker; Ibrahim, 2005), the characteristics and types of glazing (Fasi; Budaiwi, 2015; Taleb; Antony, 2020). Therefore, the common practice is to perform a parametric analysis of different WWR values considering the local climatic conditions and available technologies (Asfour, 2020).

The effective integration of electric lighting systems and daylight occurs only when the electric lighting can be switched on or off as a function of daylight levels reaching the working surface (Ghisi; Tinker; Ibrahim, 2005). In addition to that, shading devices are an appropriate strategy to control the balance of heat loads and daylight levels, mainly in hot and temperate climates. Since windows allow suitable entry and exit of thermal load in the building, it is important to correctly define openings' characteristics, such as glazing types (Chi; Moreno; Navarro, 2017; Didoné; Bittencourt, 2008; Didoné; Pereira, 2010; Fang; Cho, 2019; Ghisi; Tinker, 2001; Ghosh; Neogi, 2018; Li; Lam, 2000; Poirazis; Blomsterberg; Wall, 2008; Xue *et al*., 2019). The main glazing properties to consider are thermal transmittance (U), solar heat gain coefficient (SHGC), and visual transmittance (VT). The simultaneous analysis of these three glazing properties is crucial when considering visual comfort and energy efficiency (Fasi; Budaiwi, 2015).

The daylight levels can be evaluated using dynamic daylight metrics, such as Useful Daylight Illuminance (UDI) and Daylight Autonomy (DA). UDI indicates the useful daylight levels for the occupant, that is, the percentage of occupied hours within a range considered "useful" by occupants. The range limits are to a certain degree flexible depending on the application, usually avoiding too dark (<100 lx) and too bright (> 2,500 lx) illuminances. The upper limit intends to detect excess daylight supply, which can lead to visual and thermal discomfort. Besides that, a UDI autonomous can be set (500-2,500 lx) to reduce UDI and DA to one parameter (Mardaljevic; Heschong; Lee, 2009; Nabil; Mardaljevic, 2005). DA indicates sufficient daylight in the work plane for an occupant to work without electric lighting. DA expresses the percentage of occupied hours in a year in which a minimum illuminance value in the work plane, equal to 300 lx or 500 lx, is maintained only by daylight (Reinhart; Mardaljevic; Rogers, 2006).

Most studies were carried out using specific computer programs that simulate the lighting and energy-building performance. They can assess the potential for electric energy savings to propose solutions and guidelines for design decisions. WWR, UDI, and DA have been widely used to analyze the energy efficiency of daylighting. Research highlights the potential for electricity savings when electric and daylighting are integrated with air conditioning (Ahmad; Reffat, 2018; Asfour, 2020; Atzeri; Cappelletti; Gasparella, 2014; Bodart; Herde, 2002; Marcondes Cavaleri, Cunha; Gonçalves, 2018; Chi, Moreno; Navarro, 2017; Didoné; Pereira, 2010; Fang; Cho, 2019; Ghisi; Tinker, 2001; Ghosh; Neogi, 2018; Li; Lam, 2000; Pellegrino; Cammarano; Loverso; Corrado, 2017; Poirazis, Blomsterberg; Wall, 2008; QIu; Yang, 2020; Rupp; Ghisi, 2017; Shaeri; Yachoubi; Habibi, Chokhachian, 2019; Xue *et al.*, 2019).

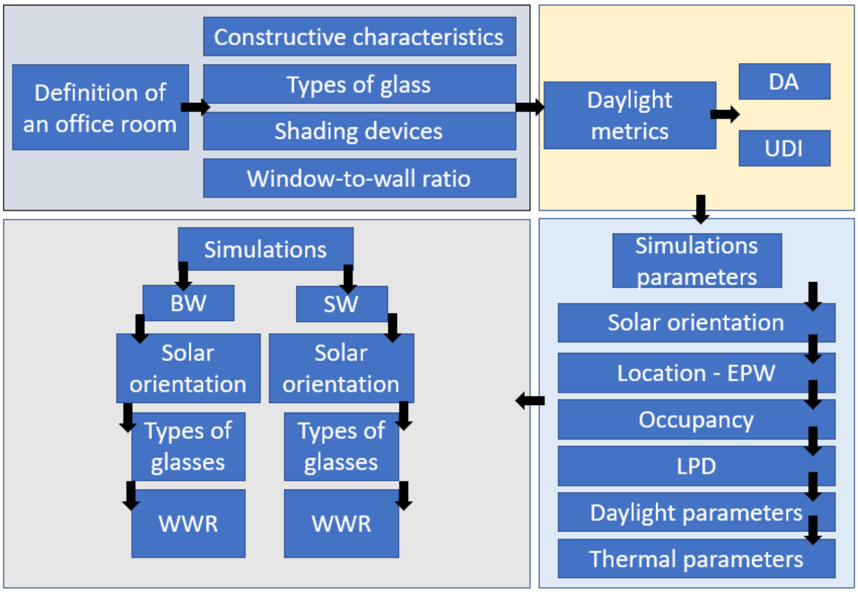
Considering the above, the objective of this paper is to analyze the daylight performance and the energy consumption for lighting and air conditioning considering four types of glazing, in four orientations, from window-to-wall ratios varying between 40% to 100% for bare and shaded window models in an office room in the subtropical city of Santa Maria, in southern Brazil.

Methods

The context of this study is an office room in Santa Maria, southern Brazil. According to Köppen's classification, Santa Maria has a Cfa humid subtropical climate, with an average temperature of 19.3 °C. During hot humid summers, temperatures frequently exceed 30 °C, with average lows dropping to 19°C (Köppen; Geiger, 1928). In winter, the maximum temperature reaches 19 °C, the minimum achieves 9 °C, and sub-zero temperatures are uncommon (Löbler; Sccoti; Werlang, 2015). The availability of solar radiation and sunshine (time in hours of solar glare on the surface) in Santa Maria is affected by the high frequency of fog (92 days a year), mainly in the morning. From June to August, sunshine is available for about 5,1 hours per day and, from December to January, it is over 8 hours per day (Heldwein; Buriol; Streck, 2009).

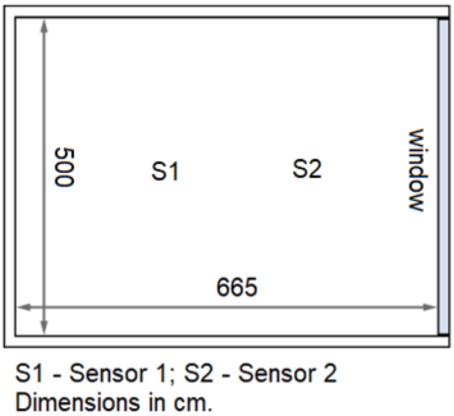
Figure 1 shows the steps adopted in the methodology. At first, a 33.25 m^2 (5.00 x 6.65 m) generic office room model was defined, with a ceiling height of 2.70 m (Figure 2) (Didoné; Wagner; Pereira, 2014). The room occupation was set from 8 am to 6 pm. DesignBuilder allows the definition of only two lighting areas, that is, two electric lighting points, S1 and S2, which were positioned at 0.75 m from the ground, and each sensor accounts for 50% of the floor area (Ghisi; Tinker, 2001). The physical properties of the building materials and the types of glazing are shown in Chart 1 and Table 1, respectively (Didoné; Wagner; Pereira, 2014). The glazing types represent the usual glazing used in office buildings in Brazil (ABRAVIDRO, 2021; INMETRO, 2013), and are abbreviated according to their nomenclature as L13, M76, M52, and M88. The types of glazing were applied to models with shaded windows (SW) (only horizontal for North, vertical, and horizontal for East and West) and models with bare windows (BW) for four orientations (North, South, East, and West).

Figure 1 – Methodology flow chart



Source: the authors.

Figure 2 - Plan view of the model and sensor positions.



Source: the authors.

Chart 1 – Characteristics of the model materials

Thermal transmittance [W/(m².K)] ((U)	Walls	2.47
	Ceiling	2.42
Thermal capacity [kJ/(m².K)] (C)	Walls	200
	Ceiling	187
Solar Absorbance	Walls	0.65
	Ceiling	0.7
Reflectance	Walls	0.7
	Ceiling	0.7
	Floor	0.4

Source: the authors.

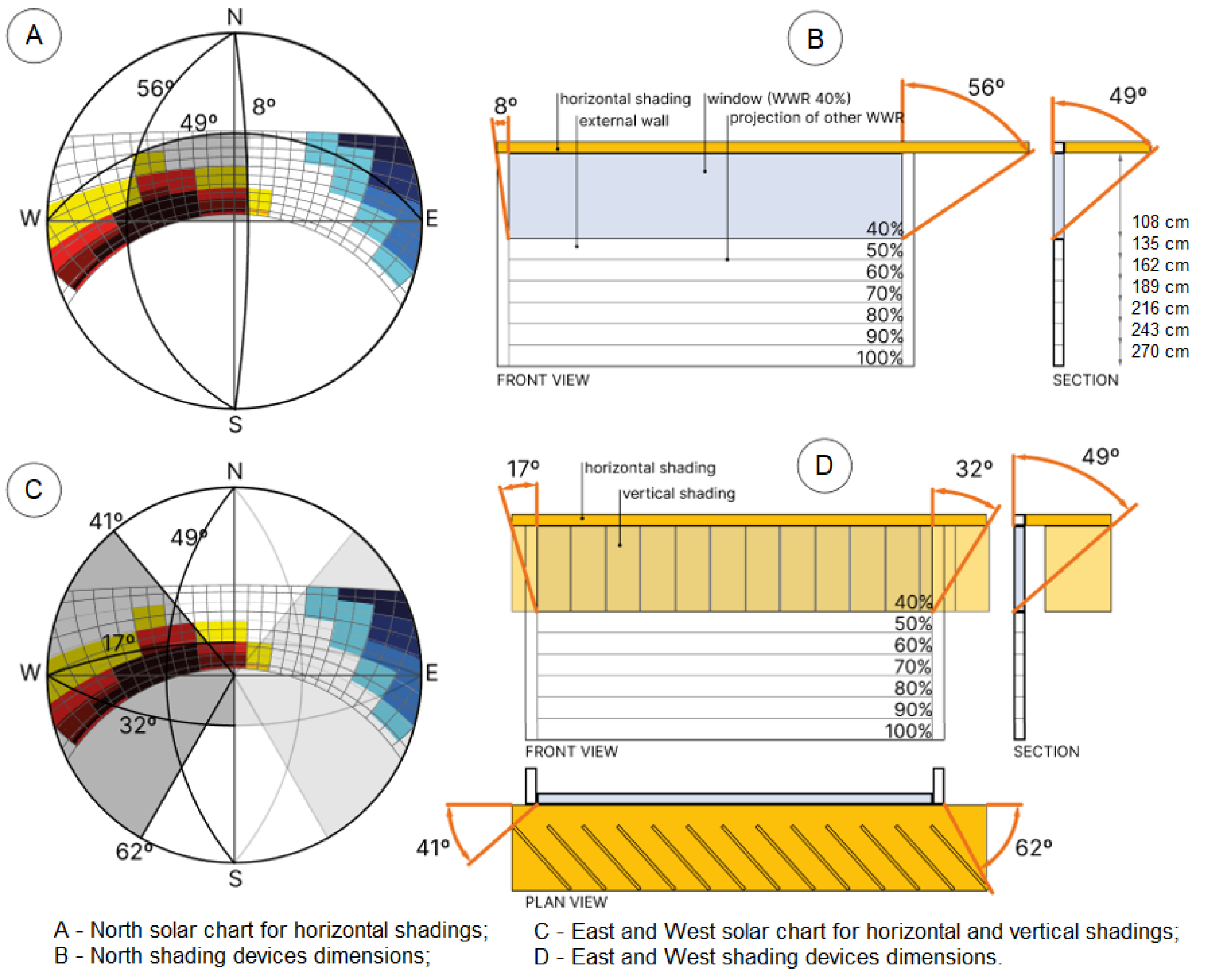
Table 1 – Glazing characteristics

Glazing types	Thickness	U (W/m²K)	SHGC (g-value)	VT
Laminated (L13)	8 mm	5.70	0.27	0.13
Monolithic (M76)	6 mm	3.23	0.43	0.76
Monolithic (M52)	6 mm	5.60	0.58	0.52
Monolithic (M88)	3 mm	5.82	0.82	0.88

Source: the authors.

The geometry of the shading devices is defined to protect the window from solar radiation throughout the year. It is designed as simply fixed overhangs because this system is cheaper, requires less maintenance, and does not need occupant interaction, which is suitable for a developing country such as Brazil (Figure 3). Since the RTQ-C (INMETRO, 2010) does not determine the calculation of shading devices for offices, the method adopted for calculating these devices in residential buildings was used. The typologies were dimensioned according to the critical temperatures of the solar charts from the Bioclimatic Zone 2 (INMETRO, 2012). In order to simplify the geometry for simulation, for the West, the East, and the North, the windows are shaded throughout the year from 21st July to 21st May (the highest temperatures of the year). The window-to-wall ratio varied from 40%, the minimum aperture allowed by local laws (Santa Maria, 2018), to 100%, in 10% increments (Ghisi; Tinker, 2001).

Figure 3 – Geometry progression of the shading devices for WWR from 40% to 100%, for North, East, and West orientations.



Source: the authors.

The UDI-autonomous (500-2,500 lx) was adopted with a range between 0 to 500 lx taken as the short range, 500 to 2,500 lx as the desirable range, and illuminance more than 2,500 lx as the oversupply (Asfour, 2020; Marcondes Cavaleri; Cunha; Gonçalves, 2018; Fernandes; Ruivo; Cunha; Krebs, 2018; Mardaljevic; Heschong; Lee, 2009; Qiu; Yang, 2020; Queiroz; Westphal; Pereira, 2020). The DA (500 lx) was based on the Brazilian standard that determines the minimum level considering activities such as medical service; reading and writing; computer-aided design, among others, which are everyday tasks developed in offices (ABNT, 2013). The level of 2,500 lx was based on literature that applies 500 lx as the lower level (Mardaljevic; Heschong; Lee, 2009).

The simulations were performed on the DesignBuilder software, 6.1.3.008 version (DESIGNBUILDER, 2020). The parameters considered for the UDI and DA level simulations were ambient bounces = 5; ambient accuracy = 0.1; ambient resolution = 512; ambient division = 2,048; and ambient super-samples = 1,024 (Reinhart, 2006). The parameters for the thermal simulations were lighting power density (LPD) equal to 6.74 W/m² and equipment power density equal to 9.7 W/m² (Didoné; Wagner; Pereira, 2014; Carlo, 2008; Santana, 2006). The total heat release in the space is 130 W/person (ASHRAE, 2001). Therefore, for the occupancy of one person per 14.7 m², the thermal load is 8.84 W/m².

The air conditioning system is a split type, classified as level A of energy efficiency, with a coefficient of performance higher than 3.81 (INMETRO, 2021; INMETRO, 2013). The adopted cooling setpoint was 23.5 °C, and the heating setpoint was 20.5 °C (INMETRO, 2012). The weather file *.EPW* (TMY) used for the simulation was developed by the Energy Efficiency in Buildings Laboratory (LABEEE, 2019) and corresponds to the city of Santa Maria, located in southern Brazil, at latitude 29°42' S, longitude 53°42' W, and altitude of 95 m. In addition, the standard sky was adopted for sky conditions, as suggested by the International Commission on Illumination (CIE, 2014).

The thermal exchange was considered only in the studied façade, while the other façades were adiabatic. After that, the simulation allowed the identification of the ideal WWR based on UDI and DA levels and energy consumption. Simulations were divided into two parts. In the first one, the BW was the model combined with the four glazing, four orientations, and seven WWR (40% to 100%) for UDI, DA, and energy consumption. In the second part, the SW model was combined with the four glazing types with the seven opening percentages defined in stage one and for the three orientations (South does not need shading). In total, 392 simulations were performed. The results present the performance of each combination according to the annual energy consumption and UDI and DA levels.

Results

In this section, the results are presented regarding the daylight performance and the energy consumption. The analysis of the efficiency of the solutions was based on energy consumption only, not on the sufficiency of daylight for users. The analyses made for UDI and DA were comparative to understand the comparative behavior between the solutions according to these two metrics.

Daylight analysis

Table 2 demonstrates the UDI and DA levels for the four types of glazing considering BW. These results indicate the percentage of occupied hours in which the threshold levels were achieved. The highest values are highlighted in green according to WWR, and the lowest are in red. For glazing with the most increased VT (M76 and M88), DA levels are higher than those with lower VT (L13) in all cases, as expected.

Table 2 – DA and UDI for bare windows, according to the type of glazing, WWR, and orientations, in percentage of occupied hours.

ORIENT.	GLAZ.	40		50		60		70		80		90		100	
		DA	UDI	DA	UDI	DA	UDI	DA	UDI	DA	UDI	DA	UDI	DA	UDI
NORTH	L13	0	0	8	0	18	8	21	15	21	15	23	16	23	16
	M76	78	61	97	72	100	68	100	66	100	66	100	63	100	61
	M52	59	58	68	54	74	53	80	58	79	57	95	72	97	73
	M88	93	70	100	67	100	63	100	60	100	61	100	57	100	56
EAST	L13	0	0	0	0	7	0	0	12	12	0	14	0	13	0
	M76	67	61	78	62	93	69	99	72	98	73	100	72	100	71
	M52	47	44	58	56	63	53	68	52	67	51	75	58	77	60
	M88	75	63	95	73	100	71	100	69	100	69	100	67	100	65
WEST	L13	0	0	0	0	10	0	15	2	15	2	16	3	17	4
	M76	71	64	85	65	98	71	100	71	100	72	100	69	100	68
	M52	51	48	62	59	55	56	74	56	73	56	83	63	83	64
	M88	81	66	98	75	100	68	100	66	100	66	100	64	100	63
SOUTH	L13	0	0	0	0	0	0	6	6	6	6	6	6	6	6
	M76	58	58	68	64	74	60	81	63	81	62	95	76	95	76
	M52	39	39	50	50	69	56	59	52	58	52	63	55	63	56
	M88	66	66	76	65	90	69	98	74	98	74	100	75	100	75

Source: the authors.

DA and UDI are strongly influenced by the opening area for BW. WWR allows more or less sunlight to enter, increasing or decreasing DA and UDI according to the illumination levels within the useful range. Taking into account the DA levels, it increased as the WWR increased. On the other hand, UDI decreases if illuminance values are not within the useful range (from 500 lx to 2,500 lx), which can happen according to the WWR.

Considering the North orientation, for M88 and M76, the minimum DA is 93% and 78%, respectively, for 40% WWR. For UDI, the minimum levels are 56% for M88 and 61% for M76, for 100% WWR, indicating an excess of daylight entry since in the larger window opening (100% WWR), these types of glazing allowed more natural light to enter, causing lower percentages of occupied hours with UDI levels within the useful range. By increasing the opening, more daylight enters the room and, consequently, illuminance ranges above 2,500 lx, which causes a decrease in the percentage of occupied hours in which only useful levels are reached (between 500 and 2,500 lx). Contrariwise, M76 also presents 61% UDI for 40% WWR (in this case, insufficient daylight) as there is not enough natural light to increase the percentage of occupied hours within useful daylight levels. Regarding UDI and DA levels, M76 showed the best performance, reaching higher levels within the useful illuminance range, followed by M88, which is an expected result due to high VT. On the other hand, L13 glass presented the lowest levels of illuminance, 0% of the occupied hours with at least 500 lx in some cases, and a maximum of 23%.

In general, UDI decreases for 90% and 100% WWR, indicating an increase in excessive daylight levels for all types of glazing. This behavior can be associated with direct solar radiation, as the sun's rays strike the ground with angles between 35 degrees at the winter solstice and nearly 82 degrees at the summer solstice.

In the South, the best performance was M88 glazing (minimum 66% DA and 65% UDI), as direct solar radiation is not present in this direction for most of the hours of the year. For larger WWR (90% and 100%), glazing with high VT, such as M76, also presented better performances for UDI. Considering East and West orientations, M76 and M8 performed better, M76 for high window areas (above 60%), and M88 for small ones (below 60%). The minimum values found for M76 were 67% DA and 61% UDI in the East. For M88, DA levels reached at least 75% in the East, and UDI, 63% in the East and West. If the aim is to take advantage of daylight, and electric lighting is not considered, L13 is not recommended in this climate context. However, M76 and M88 are recommended according to WWR and orientation. Table 3 presents results for SW according to orientation, glazing, and WWR. This table highlights the highest DA and UDI values in green and the lowest in red, according to WWR.

Table 3 – DA and UDI for shaded windows, according to glazing types, WWR, and orientations, in percentage of occupied hours.

ORIENT.	GLAZ.	40		50		60		70		80		90		100	
		DA	UDI	DA	UDI	DA	UDI	DA	UDI	DA	UDI	DA	UDI	DA	UDI
NORTH	L13	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	M76	75	68	75	75	67	68	71	63	74	29	77	31	87	31
	M52	55	55	52	52	46	46	52	52	52	31	52	31	53	53
	M88	97	84	91	92	77	76	91	80	98	29	100	31	100	31
EAST	L13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M76	0	0	0	0	0	0	0	0	1	1	1	1	1	0
	M52	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M88	0	0	0	0	0	0	0	0	2	2	2	1	1	1
WEST	L13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M76	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	M52	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M88	0	0	0	0	0	0	0	0	2	2	1	1	1	1

Source: the authors.

When the windows are shaded, the DA and UDI levels decreased, mainly for the East and West orientations, as the North-facing window receives direct solar radiation between May 21st to July 21st due to the sun's path during the year. Similar results were found by Cellai, Carletti, Sciurpi and Secchi (2014), which demonstrated a significant reduction of daylight, for the overcast sky condition, in the West and East when shading devices are applied on façades through UDI metric. In the case studied, the region presents cloudiness on only a few days of the year, mainly in the mornings, which may have determined the glazing behavior and the need for electric lighting.

For the North, M88 presented the highest UDI levels (due to its high VT), except for WWRs equal to or greater than 80%, indicating that excessive daylight entry may occur. Even when shaded, M88 allows visible light to enter the room at adequate levels. L13 presents the worst performance (low VT), as expected. These results corroborate the inadequacy of the concomitant use of L13 and fixed shading devices. However, M76 and M52 also present acceptable DA and UDI in the North. Considering that WWR is equal to or greater than 90% for UDI, M76, M52, and M88 presented similar performances. Additionally, the difference between the lowest value and the highest value of DA and UDI considering WWR exceeds, for M76, 23% and 61% of the highest value, respectively, for M52, 16% and 44%, and M88, 23% and 68%. In other words, the opening area influenced UDI more than DA.

The percentage of occupied hours of the year that reached a minimum illuminance value of 500 lx in the work plan was lower for models with shading devices than without, according to the glazing type. For East and West-facing SW, electric lighting should be provided regardless of the type of glazing. This result mainly occurred due to the dimension of shading devices, which can influence the lower daylight levels in the room for those orientations.

Energy consumption analysis

Tables 4 and 6 show the total energy consumption for the four glazings in different orientations for BW and SW. The lowest (green color) and highest (red color) values are highlighted in these tables according to each orientation. Tables 5 and 7 present energy consumption according to the final lighting or air conditioning use. In these tables, higher consumptions are highlighted.

Table 4 - Energy consumption in kWh/m²/year for models with bare windows according to WWR and orientation.

ORIENT.	GLAZ.	40	50	60	70	80	90	100
NORTH	L13	621.2	619.2	620.0	609.0	609.0	593.8	597.8
	M76	259.4	309.0	368.7	420.8	420.8	505.1	512.7
	M52	535.0	575.7	659.6	745.8	745.8	930.2	968.3
	M88	609.6	731.9	851.8	977.2	977.2	1,237.3	1,294.2
EAST	L13	594.0	600.8	612.2	631.9	631.9	669.8	674.2
	M76	310.2	367.4	430.6	480.2	480.2	565.1	572.3
	M52	521.1	580.1	594.1	593.9	593.9	673.5	698.9
	M88	579.2	585.3	615.4	702.2	702.2	825.6	848.7
WEST	L13	811.0	805.2	817.5	843.3	843.3	925.6	942.1
	M76	580.5	641.9	686.0	733.5	733.5	851.0	875.8
	M52	743.6	838.0	939.8	1,032.7	1,032.7	1,200.9	1,235.4
	M88	826.2	967.3	1,093.0	1,208.6	1,208.6	1,422.1	1,467.3
SOUTH	L13	607.3	582.6	573.6	582.1	582.1	609.6	610.1
	M76	223.8	248.5	274.1	310.4	310.4	392.4	409.1
	M52	340.3	369.9	413.0	457.2	457.2	532.8	546.0
	M88	324.9	392.7	457.4	509.2	509.2	580.5	581.4

Source: the authors.

As expected, energy consumption was lower for South-facing BW, as the South received the lowest solar radiation levels during the year. However, due to the sun's path, the simulated climate is characterized by high solar radiation values in the West and the East orientations during summer and the whole year in the North. Therefore, the highest energy consumption occurred for the West, followed by the North and the East.

Considering the BW models and orientations with direct solar radiation (West, North, and East), the total energy consumption was higher for glazings with higher U, i.e., M88, L13, and M52. Furthermore, it increased with WWR, as expected, except for L13 in the North, with the lowest VT. On the other hand, M76 had the lowest total energy consumption, regardless of window orientation and WWR, mainly because this glazing allows less sun heat in the room and provides higher insulation (U equals 3.23 W/m².K), compared to the other glazings.

Table 5 - Energy consumption in kWh/m²/year considering lighting and air conditioning for bare windows according to orientation and WWR.

GLAZ.	40		50		60		70		80		90		100		%	
	L	AC	L	AC	L	AC	L	AC	L	AC	L	AC	L	AC	L	AC
NORTH																
L13	306	315	269	350	244	376	227	382	227	382	205	389	199	398	39	61
M76	102	157	97	212	94	275	92	329	92	329	90	415	89	423	25	75
M52	118	417	108	467	103	557	100	646	100	646	97	834	96	872	15	85
M88	96	514	92	640	89	762	88	889	88	889	87	1151	86	1208	10	90
EAST																
L13	356	238	316	284	288	324	271	361	271	361	247	423	241	433	45	55
M76	115	195	107	261	102	329	99	381	99	381	96	469	95	477	24	76
M52	137	384	124	456	116	478	111	483	111	483	106	568	105	594	19	81
M88	105	474	99	486	96	520	94	609	94	609	91	734	91	758	14	86
WEST																
L13	347	464	306	499	277	541	259	584	259	584	236	690	230	712	32	68
M76	105	475	97	544	93	593	91	643	91	643	88	763	88	788	13	87
M52	127	617	113	725	105	834	101	932	101	932	97	1104	95	1140	11	89
M88	96	730	91	876	88	1005	86	1122	86	1122	85	1337	84	1383	8	92
SOUTH																
L13	432	175	387	196	354	220	334	248	334	248	305	304	297	313	59	41
M76	121	102	110	138	104	170	100	210	100	210	96	296	96	313	36	64
M52	152	188	133	237	122	291	116	341	116	341	109	424	107	439	29	71
M88	108	217	101	292	96	361	94	415	94	415	91	489	91	491	21	79

Source: the authors.

Considering that the total energy consumption accounts for the sum of electric lighting and air conditioning, M88 presented the highest values for air conditioning consumption. On the other hand, the BW with L13 showed the highest energy demand for lighting, as seen in Table 3, as expected, as this glazing has the lowest VT, and the shading allowed less visible light into the room. Although L13 does not account for high energy consumption for air conditioning, electric lighting was a determinant of its behavior. M88, with high U, SHGC, and VT, was only better than L13 when it was South-oriented, which shows that for orientations with lower direct radiation, higher VT is more important than lower SHGC or U. This reinforces the importance of choosing a glazing with minimum U and SHGC and maximum VT, in this case, represented by M76, for BW.

Table 6 - Energy consumption in kWh/m²/year for models with shaded windows according to WWR and orientation.

ORIENT.	GLAZ.	40	50	60	70	80	90	100
NORTH	L13	654.5	561.5	643.5	637.5	688.1	662.3	652.1
	M76	477.0	349.4	331.7	417.0	426.1	432.9	469.6
	M52	419.7	468.6	479.8	466.1	498.5	522.4	565.7
	M88	438.8	478.7	461.0	510.9	576.9	642.8	726.3
EAST	L13	758.7	821.1	850.5	884.9	893.7	893.6	907.7
	M76	844.8	858.8	851.5	840.4	864.1	870.0	891.5
	M52	884.7	855.6	886.0	886.4	909.2	921.3	943.7
	M88	844.6	798.8	862.1	859.2	886.4	890.1	916.1
WEST	L13	668.2	793.2	839.1	888.6	897.9	901.9	913.3
	M76	843.1	850.5	882.4	815.9	808.4	827.7	819.7
	M52	897.3	882.5	907.1	911.6	932.3	947.1	891.4
	M88	843.0	834.0	894.3	896.3	922.6	929.0	822.6

Source: the authors.

Performance according to the glazing type strongly depends on the window's orientation and the balance between lighting and air conditioning. If the window was shaded, in some cases, more energy was spent on lighting, and the M76 glazing, for the North, was the best option because, even when shaded, this glazing allows more visible light in and less demand for cooling. For the East and West, M76 presented a better performance, for WWR greater than 70%. Overall, for both orientations, M52 resulted in the highest consumption. Moreover, the energy consumption was not linear in WWR; this effect can be better seen in Table 7. For BW models, regarding the two intermediate glazings, L13 and M52, even though M52 has better insulation than L13, the latter allows less sun heat to enter the room, indicating that lower air conditioning demand is required to compensate for the heat entry (Table 4).

Table 7 - Energy consumption in kWh/m²/year considering lighting (L) and air conditioning (AC) for shaded windows according to orientation and WWR.

GLAZ.	40		50		60		70		80		90		100		%	
	L	AC	L	AC	L	AC	L	AC	L	AC	L	AC	L	AC	L	AC
NORTH																
L13	459	195	383	178	461	182	416	221	419	269	379	283	362	290	64	36
M76	90	387	109	240	120	211	113	304	113	313	105	328	103	367	27	73
M52	144	275	131	338	150	330	136	330	135	363	122	400	118	448	28	72
M88	105	334	101	378	109	352	104	407	104	473	98	545	96	630	19	81
EAST																
L13	658	101	655	167	652	198	646	239	635	259	629	265	642	266	75	25
M76	573	272	567	292	551	300	519	321	516	348	495	375	489	403	62	38
M52	601	283	566	290	584	302	560	326	559	351	543	379	537	406	63	37
M88	546	298	488	311	518	344	479	380	473	413	447	443	437	479	56	44
WEST																
L13	668	0	660	133	655	184	660	229	644	253	643	259	654	260	79	21
M76	594	249	564	287	589	294	512	304	482	327	473	355	443	377	62	38
M52	629	268	597	286	613	294	597	314	592	340	579	368	508	383	65	35
M88	550	293	532	302	561	333	532	365	522	401	500	429	379	444	58	42

Source: the authors.

Table 8 shows the performance of each type of glazing considering its shading condition according to WWR, and orientation (grey indicates the lowest values).

Table 8 - Total energy consumption in kWh/m²/year considering bare and shaded windows according to orientation and WWR. BW stands for bare windows, and SW for shaded windows.

ORIENT	GLAZ.	40		50		60		70		80		90		100	
		BW	SW	BW	SW	BW	SW	BW	SW	BW	SW	BW	SW	BW	SW
NORTH	L13	621.2	654.5	619.2	561.5	620.0	643.5	609.0	637.5	609.0	688.1	593.8	662.3	597.8	652.1
	M76	259.4	477.0	309.0	349.4	368.7	331.7	420.8	417.0	420.8	426.1	505.1	432.9	512.7	469.6
	M52	535.0	419.7	575.7	468.6	659.6	479.8	745.8	466.1	745.8	498.5	930.2	522.4	968.3	565.7
	M88	609.6	438.8	731.9	478.7	851.8	461.0	977.2	510.9	977.2	576.9	1237.3	642.8	1294.2	726.3
EAST	L13	594.0	758.7	600.8	821.1	612.2	850.5	631.9	884.9	631.9	893.7	669.8	893.6	674.2	907.7
	M76	310.2	844.8	367.4	858.8	430.6	851.5	480.2	840.4	480.2	864.1	565.1	870.0	572.3	891.5
	M52	521.1	884.7	580.1	855.6	594.1	886.0	593.9	886.4	593.9	909.2	673.5	921.3	698.9	943.7
	M88	579.2	844.6	585.3	798.8	615.4	862.1	702.2	859.2	702.2	886.4	825.6	890.1	848.7	916.1
WEST	L13	811.0	668.2	805.2	793.2	817.5	839.1	843.3	888.6	843.3	897.9	925.6	901.9	942.1	913.3
	M76	580.5	843.1	641.9	850.5	686.0	882.4	733.5	815.9	733.5	808.4	851.0	827.7	875.8	819.7
	M52	743.6	897.3	838.0	882.5	939.8	907.1	1032.7	911.6	1032.7	932.3	1200.9	947.1	1235.4	891.4
	M88	826.2	843.0	967.3	834.0	1093.0	894.3	1208.6	896.3	1208.6	922.6	1422.1	929.0	1467.3	822.6

Source: the authors.

If only energy consumption is considered, BW presented a better performance in some cases than SW, which is not an expected result. An example is that, for the East orientation, all glazings showed better performance for BW. This can be explained by the substantial increase in energy consumption for electric lighting in SW, which is much more considerable than the decrease in cooling demand in the same models (Table 7). Besides that, the East orientation presents the lowest direct solar radiation, compared to the West and the North, showing that the shading devices are not so efficient for this case.

When considering the North orientation, M52 and M88 presented better performances for SW, and between them, the best performance varied according to the balance of electric lighting and air conditioning consumptions. Differences in total energy consumption between M52 and M88 increase with WWR, in which the air conditioning demand is more significant than electric lighting (Tables 7 and 8). However, East-facing BW showed better results, primarily due to the lower direct solar radiation in this orientation, compared to the North.

Although M88 has the lowest insulation performance and allows the highest heat gains, this glazing presented the best energy performance for North-facing SW as it also allowed more elevated daylight levels in the room, reducing the electric lighting demand and balancing the total energy consumption. M52 has similar performance due to similar characteristics.

For the West orientation, M76 presented the best energy performance for BW. This glazing allows significant daylight levels in the room and avoids the entry of solar heat, providing good thermal insulation. Therefore, M76 is an appropriate choice for West-facing BW. In the context of this study, considering the West orientation, shading is desirable for WWR above 50%, with M52, due to the high demand for air conditioning when the window is bare, and the demand for electric lighting is lower.

The difference between total energy consumption for BW and SW was more evident for M88 and M76, as shown in Table 9 (negative sign indicates that the total energy was higher for SW than for BW, and the higher absolute differences are highlighted in grey, according to the glazing type, for each WWR). Additionally, for M76, the smallest WWRs had the highest differences in energy consumption. Contrariwise, for M88, the highest WWRs resulted in the most significant differences for North and West orientations. These results reinforce the importance of taking WWR, orientation, shading device, and type of glazing into account in a joint analysis as the behavior is not linear.

Table 9 - Difference between total energy for bare and shaded windows.

ORIENT.	GLAZING	40	50	60	70	80	90	100
NORTH	L13	-33.3	57.7	-23.5	-28.5	-79.1	-68.5	-54.3
	M76	-217.6	-40.4	37.0	3.8	-5.3	72.2	43.1
	M52	115.3	107.1	179.8	279.7	247.3	407.8	402.6
	M88	170.8	253.2	390.8	466.3	400.3	594.5	567.9
EAST	L13	-164.7	-220.3	-238.3	-253.0	-261.8	-223.8	-233.5
	M76	-534.6	-491.4	-420.9	-360.2	-383.9	-304.9	-319.2
	M52	-363.6	-275.5	-291.9	-292.5	-315.3	-247.8	-244.8
	M88	-265.4	-213.5	-246.7	-157.0	-184.2	-64.5	-67.4
WEST	L13	142.8	12.0	-21.6	-45.3	-54.6	23.7	28.8
	M76	-262.6	-208.6	-196.4	-82.4	-74.9	23.3	56.1
	M52	-153.7	-44.5	32.7	121.1	100.4	253.8	344.0
	M88	-16.8	133.3	198.7	312.3	286.0	493.1	644.7

Source: the authors.

The definition of the glazing type should consider not only the presence of shading devices, as Prowler (2016) indicates, but also the climatic characteristics, WWR, and window orientation (Ahmad; Reffat, 2018; Chua; Chou, 2010; Fasi; Budaiwi, 2015; Reffat; Ahmad, 2020). According to Rezaei, Shannigrahi and Ramakrishna (2017), the SHGC should be as low as possible, and the VT should be as high as possible in cold climates; in contrast, in hot climates, SHGC should be lower to avoid overheating as the direct solar radiation is more elevated. This effect can be seen in the lowest air conditioning energy consumption for L13 and M76, the two glazings with the smallest SHGC. It should be noted that although L13 has a lower SHGC than M76 (0.27 and 0.43, respectively), the latter has a better insulation performance (U equals 3.23 $W/m^2.K$), which results in lower energy consumption for air conditioning. This corroborates with the previous literature that affirms that the simultaneous analysis of glazing properties is crucial when visual comfort and energy efficiency are considered (Chi; Moreno; Navarro, 2017; Fang; Cho, 2019; Fasi; Budaiwi, 2015; Ghosh; Neogi, 2018; Xue *et al*., 2019).

Chua and Chou (2010) demonstrated, for multi-story housing in Singapore, with a tropical climate, that energy savings depend not only on window orientation but also on the geometry of shading devices. For the same shaded façade, the devices' geometry was determinant for the cooling energy savings. In the study, the geometry of shading devices played a key role in some unexpected results. An example of this is shown in Tables 5 and 7. The energy consumption for electric lighting is significantly higher for SW than for BW. These demands depend mostly on the size of shading as the results for East and West are considerably close to each other.

Conclusions

The present study contributes to complex side lighting system solutions considering fixed shading devices, four different glazing types, and a climate with hot and humid summers and mild winters, classified as a subtropical climate, considering available technologies for a developing country such as Brazil. Furthermore, different side lighting systems were performed on the total energy consumption of air conditioning and electric lighting and the daylight performance of an office room.

The results corroborate the importance of jointly considering WWR, glazing type, shading devices, and specific local climate conditions in the performance analysis.

Regarding the orientation, South-facing windows presented the lowest energy consumption for bare cases, and the North and West, the highest. Higher levels of UDI and DA were also for the North and West orientations. When analyzing the influence of shading devices, the SW presented higher lighting consumption. However, in some situations, they caused a decrease in air conditioning demand, resulting in lower global energy consumption. At the same time, SW showed a lower performance regarding the UDI and DA levels. In general, when considering WWR, the smaller the window, the lower the energy consumption. The opposite occurs when analyzing daylight levels, the higher the WWR, the better the daylight performance.

L13 was not recommended under the simulated conditions, regardless of window orientation. M76 presented the best performance for total energy consumption for the West and SW. For the West, shading is necessary regardless of the glazing type (except L13 whose best performance is for BW) from WWR 50%. M76 and M52, with medium values of VT and SHGC presented the lowest total energy consumption. The choice of glazing depends not only on the presence or absence of shading but also on orientation and WWR without a linear behavior.

This work is an initial study of Santa Maria and its social, economic, and climatic context. As limitations and recommendations for future research, the metrics of supplementary and autonomous UDI levels could improve the understanding of energy-efficient solutions for the city. Additionally, this study did not consider external obstructions due to complex situations in the urban environment. Moreover, it is essential to consider this feature, and complementary studies should be able to achieve this characteristic. Finally, visual daylight glare probability (DGP) could clarify this critical aspect of visual comfort. It is also important to note that all results were obtained using a validated program, DesignBuilder. All modules used in this work were validated for similar situations (office buildings with air conditioning and daylighting) (Ghisi; Tinker; Ibrahim, 2005; Rupp; Ghisi, 2017). However, this work did not perform an experimental study to validate the simulations; therefore, future works could be performed to compare simulation results and field studies. Besides that, this research considered the analysis of the efficiency of the solutions based on energy consumption only, not on the sufficiency of daylight for users. Therefore, for future works, it is recommended to analyze different levels/limits of daylight including satisfactory, acceptable and unsatisfactory performance.

Finally, this method can be helpful in the preliminary building design process, helping the design team choose the appropriate window area combined with the glazing and solar orientations.

Acknowledgments

The authors would like to thank the Brazilian agency Coordination for the Improvement of Higher Education Personnel (CAPES) for the financial support.

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1 **Elaise Gabriel**
Engenheira Civil. Doutora em Engenharia Civil. Professora Adjunta da Coordenação Acadêmica da Universidade Federal de Santa Maria. Endereço postal: Rodovia Taufik Germano 3013, Cachoeira do Sul, Rio Grande do Sul, Brasil, 96503-205.

2 **Giane de Campos Grigoletti**
Arquiteta e Urbanista. Doutora em Engenharia Civil. Professora do Programa de Pós-Graduação em Engenharia Civil e do Programa de Pós-Graduação em Arquitetura, Urbanismo e Paisagismo da Universidade Federal de Santa Maria. Endereço postal: Av. Roraima 1000, Santa Maria, Rio Grande do Sul, Brasil, 97105-900.

3 **Gabriela Meller**
Engenheira Civil. Doutora em Engenharia Civil. Professora Adjunta do Centro de Engenharias da Universidade Federal de Pelotas. Endereço postal: Rua Benjamin Constant 989, Pelotas, Rio Grande do Sul, Brasil, 96010-450.

4 **Bruna Zambonato**
Arquiteta e Urbanista. Mestra em Arquitetura e Urbanismo. Egressa do Programa de Pós-Graduação em Arquitetura e Urbanismo da Universidade Federal de Santa Maria. Endereço postal: Av. Roraima 1000, Santa Maria, Rio Grande do Sul, Brasil, 97105-900.