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LIGHTWELL IN RESIDENTIAL BUILDING: ARCHITECTURAL SOLUTIONS TO THE DAYLIGHTING PERFORMANCE THROUGH PARAMETRIC SIMULATION

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Abstract. The lightwell is an architectural solution to promote daylight into the internal spaces from the core of a building. The shaft configurations, such as geometry and reflectance can affect the performance of the daylighting entering the adjoining rooms under different conditions. This study aims to indicate the adequate architectural solutions to improve the daylighting performance of buildings with lightwells at three different southern latitudes. From a base model of 6-stories building, alternative cases were parametrically simulated using Rhinoceros, GrassHopper and ClimateStudio software. From variations in the lightwell geometry and walls reflectance, the cases were analyzed considering the lighting metrics UDI and sDA300. Results demonstrate that the daylighting is adequate on the floors near the top of the building and weakens towards the base of it. In Macapá, São Paulo and Chile, the sDA values reach 100 % on the top floor, but only 3 % on the first floor. It was also observed that materials with high diffuse reflectance on the shaft is more efficient in improving the daylighting performance than increasing its geometry. This research presents early-design guidance to inform architects and policymakers when considering the exploitation of daylight by the use of the lightwell.

Keywords: Lightwell, daylighting, wall reflectance, built environment, parametric simulations.

1. Introduction

The lightwell, a shaft designed to admit daylight through the core of a building, is recognized as an important resource for transmitting lighting to the interior rooms positioned at lower levels [1]. Natural light not only benefits people's comfort and health [2] but can also contribute to the reduction in energy demands [3]. In Brazil, for instance, the lightwell geometry is often dimensioned following general guidelines, without accounting for architectural and climatic variables that may influence the lighting availability of the spaces connected to it. Thus, when design solutions that can influence the lighting conditions, such as adequate openings dimensions, are neglected by normative and building codes, it may result in environments without adequate daylight [4]. As a result, a poorly designed lightwell can lead to excessive natural light on the upper floors and insufficient natural light on the lower floors [3]. The amount of daylighting reaching the deeper floors depends mainly on the geometry of the lightwell and the reflectance of the internal surfaces. Lighter surfaces tend to better distribute light in the deepest portion of the building, while the amount of light received on upper floors is indifferent of wall's reflectance, since a considerable amount of light received comes directly from the sun [5]. White coloured surfaces can reach values above 80 % of reflectance, while coloured or grey surfaces can have a reflectance of 50 % [6]. Joudi et al. [7] pointed out that highly reflective surfaces can generate greater heating of the internal environment when they reflect direct sunlight. However, it is necessary to consider that inside the lightwells this reflection will depend on the solar altitude. In conditions where the sun's trajectory is lower, direct sunlight reaches only the upper floors, resulting in a significant reduction of daylight on the lower floors of the shaft [4], which tend to be cooler than the top [8]. Bugeat et al. [5] indicated that increasing the reflectance of surfaces to up to 85 % does not promote visual and thermal discomfort in the environment.

Some studies have measured the loss of illuminance in the lower rooms served by lightwells in residential buildings. In the city of Tehran, the average annual illuminance was 88 % lower on the first floor compared to the upper floor in interior rooms connected to a 4 m diameter lightwell in a 7-story building [8]. In Barcelona [5], this reduction reached 90 % in a building with 12 m high lightwell of 3 m diameter. Additionally, it was found that increasing the wall reflectance in 10 % was sufficient to double the illuminance on the first floor. Freewan et al. [9] identified that for buildings with three floors, lightwells with a geometry of 1 × 1 m or 2 × 2 m do not provide sufficient illumi-

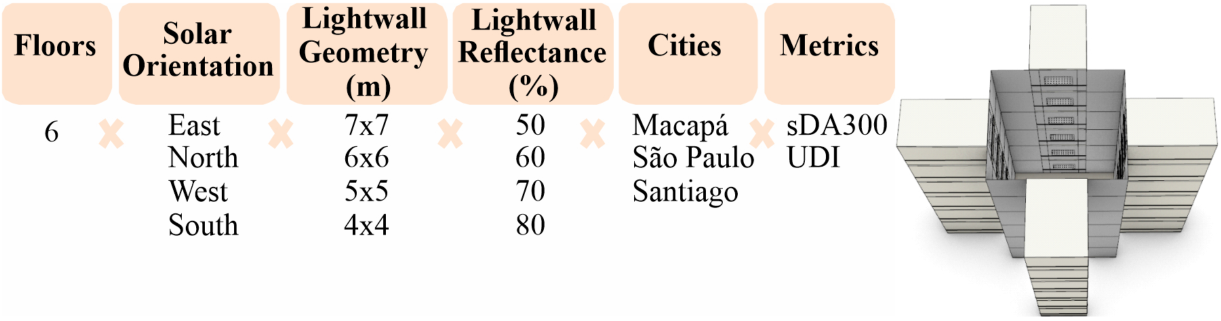

FIGURE 1. Simulated model settings.

nance levels on the internal rooms, requiring a shaft of at least 3 × 3 m to provide adequate illuminance throughout the year. However, those studies did not consider the relationship between wall reflectance and shaft geometry. In addition, they focused on the analysis of cities in the northern hemisphere, making it necessary to also consider the use of such solution in the southern latitudes. Thus, this study aims to indicate the adequate architectural solutions to improve the daylighting performance of buildings with lightwells at three different southern latitudes. For this, different lightwell geometry, wall reflectance and solar orientations were compared through the use of parametric computational simulations.

2. METHODS

Building models were tested through the combination of Rhinoceros (Version 6.11.18348.17061), GrassHopper (Version 2019.01.00) and ClimateStudio (Version 1.5.7955.28487) software. A base model of a lightwell building was created using Grasshopper software. It has six floors, and the shaft has a square geometry of 4 m and 17.1 m height. For the external wall and floor surfaces, a 50 % reflectance was fixed, which is equivalent to a coloured wall [6]. On each floor, four rooms with a dimension of 2 × 4.5 × 2.85 m (W × L × H) were positioned connected to the lightwell under the main solar orientations. Each room has an aperture to the lightwell with a window/wall ratio of 22 %. The diffuse reflectance of the rooms' surfaces was fixed at 80 % for ceiling and wall, and 50 % for flooring. In each room, 551 sensors were placed at a height of 0.75 m from the floor, a distance of 0.15 m from the walls and spaced 0.15 m between them.

Illuminances in each room were calculated using dynamic sky models based on three latitudes: Macapá, Brazil (0° 2′ N, 51° 3′ W), São Paulo, Brazil (23° 32′ S, 46° 38′ W) and Santiago, Chile (33° 26′ S, 70° 40′ W). Alternative 5 m, 6 m and 7 m square lightwell models were also considered. For each case, five reflectance indices (50 %, 60 %, 70 %, 80 %) were simulated (Figure 1). Room configurations remained unchanged in the alternative models.

The metrics used to evaluate the lighting performance were: sDA (Spatial Daylight Autonomy) and UDI (Useful Daylight Illuminance). The sDA (sDA300.50 %) defines the percentage of the floor that receives at least 300 lux for at least 50 % of the busy hours – between 8 a.m. and 6 p.m.; and above 75 %, it is considered satisfactory [10]. The UDI determines the percentage of the floor area that receives natural light in the range of 300 to 2000 lux. Below this range, the light is considered insufficient to carry out work activities, and above this range, the light is considered excessively blinding [11]. The data obtained through the UDI identifies whether the adjustment of architectural variables would promote an increase in uncomfortable natural lighting, especially at the top floors. Thus, the combined use of metrics enables a more accurate analysis of the daylighting availability at the length of the building. Results are presented and discussed in the following item. It presents the findings of the base models under different latitudes (Macapá, São Paulo and Santiago). The results of daylight under different shaft geometries and reflectance are presented with a focus on the city of Mapacá due to the similarity of the cases performances among the different latitudes. Finally, it indicates the models with adequate natural lighting among the cases tested. This may help the early-stage design of lightwells.

3. RESULTS AND DISCUSSION

3.1. BASE MODEL UNDER DIFFERENT LATITUDES

Results demonstrated that the daylighting entering the rooms in all latitudes tested is adequate on the floors near the top of the building and weakens towards the base of it. As seen in Figure 2, in Macapá, the sDA values are reduced from 100 % to 48 % from the 6th to the 5th floor, reaching 10 % on the 4th floor. On the first floor, the floor area percentage that receives at least 300 lux for at least 50 % of the busy hours is as low as 3 %. It is important to note that those values were similar for the other latitudes, indicating that for a lightwell with 4 m depth and 50 % of reflectance, only the top floor would reach adequate natural lighting. UDI values were also significantly reduced from the 6th to the 1st floor. In Macapá, they ranged from 77 % to 3 %; in São Paulo, this variation was from 73 % to 3 %; and in Santiago, from 81 % to 3 %. Thus, the performance of adequate daylighting

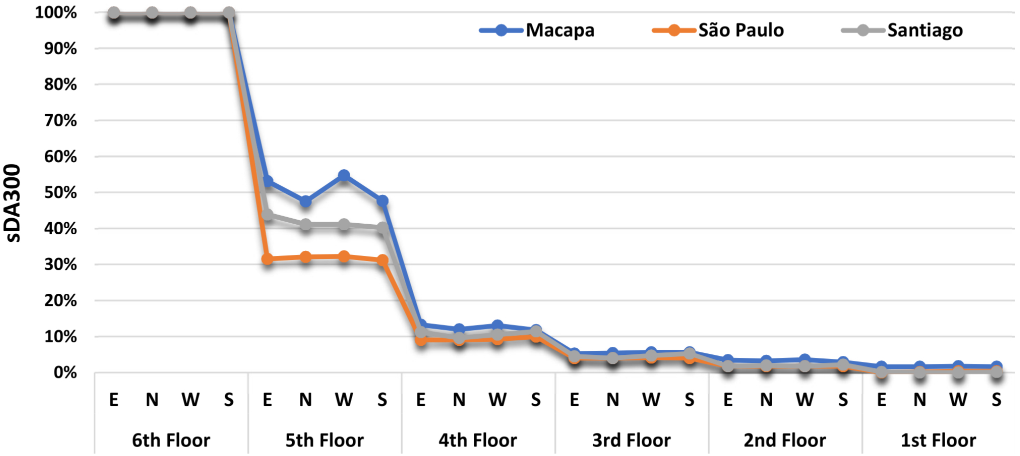

Figure 2. sDA values for the base model at different latitudes.

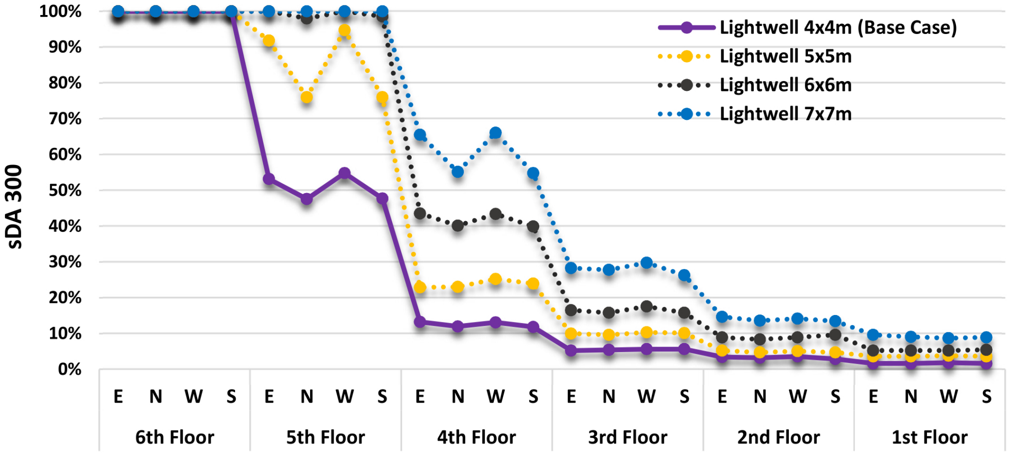

Figure 3. sDA values in the Macapa's model at different lightwell geometries.

was similar in the cities analysed. In all cases, the 6th floor receives more than 2000 lux on at least 20 % of the floor during the year. This dazzling lighting remains on the 5th and 4th floors, although to a lesser extent. However, it is important to highlight that high daylight values occur near the windows, which reduces its uncomfortable effect within the environment. It is also interesting to note that the daylight availability is similar on the faces tested. This can be due to the fact that the illuminance corresponds to an average value throughout the year.

3.2. Daylight availability for different lightwell geometries

In Macapá, the enlargement in the lightwell geometry resulted in improvements in the daylighting performance. By increasing the shaft square from 4 m to 5 m, the 5th floor achieved the recommended sDA. As can be seen in Figure 3, in all solar orientations, this percentage rises from around 48 % to over 75 %, reaching 95 % on the west face. On the lower floors, although the sDA values have a considerable increase from the 4 m to the 5 m case, they remained with insufficient adequate natural lighting, reaching less than 25 % on the 4th floor and 4 % on the first floor.

In the 6 m geometry model, the 4th floor still has insufficient sDA values, with a maximum of 43 %, while the first floor does not exceed 5 %. In the largest lightwell case (7 m), the sDA reaches 66 % on the 4th floor and 10 % on the first floor. In all simulated geometries, the UDI and sDA values were similar at the top floors of the cases tested, indicating that these floors are well lit. Increasing the depth of the shaft improves lighting in the intermediate floors, but these improvements are not extended to floors near the first floor, which remain receiving little daylight.

3.3. Daylight availability under different shaft reflectance

Modifications in the reflectance index of the shaft walls resulted in an increase in the sDA and UDI values in the rooms. By increasing the reflectance from 50 % to 80 %, the 5th floor achieved ideal sDA values, jumping from 48 % to 93 %. In those cases, the UDI values have also increased, going from around 48 % to 65 %, indicating that daylighting is useful. On the 4th floor, daylighting improves with the increase in reflectance, but do not exceed 33 % of sDA. On the first floor,

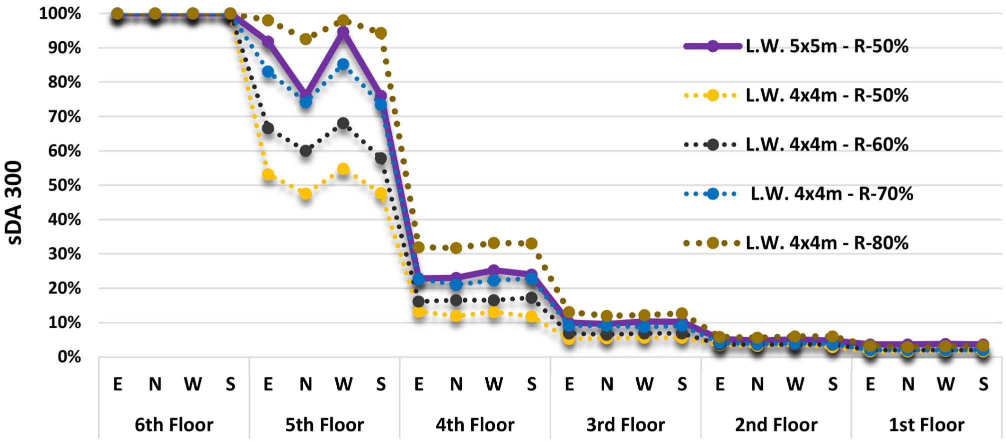

Figure 4. sDA values in the Macapa's models at different lightwell reflectance.

sDA and UDI double, but still do not reach significant values, remaining at 8 % and 3 %, respectively.

Figure 4 shows the sDA values for the case with 4 m lightwell under different reflectance applied in the shaft. Analysing all cases, it was observed that the narrower well (4 m) is the one that benefits the most from the increasing in the reflectance levels. This can be due to the intensity on the reflections rays within the shaft. It can be seen that for the 4 m lightwell case with 80 % of reflectance, the 5th floor showed sDA values similar to those on the top floor. On the 4th floor, these values drop, reaching about 30 %.

Thus, it can be said that increasing the reflectance of the shaft walls proved to be an efficient alternative in improving daylighting performance. In the model with 4 m geometry and 80 % reflectance, the daylight availability is higher than in the 5 m model with 50 % reflectance.

However, it is important to note that increasing wall reflection does not vary natural lighting penetration on the floors at the top of the building. In these rooms, the main source of light comes directly from the sun, so reflection contributes little. However, as UDI values remains similar in the cases tested, this suggests that there is no increase in lighting above 2000 lux, which would result in uncomfortable lighting.

3.4. Best case scenario for each latitude

The case that presents the best results is the lightwell with 7 × 7 m geometry and 80 % reflectance (Table 1). In the Macapá model, the sDA values reach 100 % from the upper floor up to the 4th floor and drops to 68 % on the 3rd and 29 % on the first floor. Half of the building achieved a satisfactory level of daylight, with sDA300 index above 75 % (Figure 5). However, they are located on the top three floors, which demonstrates that the improvements lose efficiency as the lightwell gets deeper. The best scenario for the ground floor has a sDA of 29 %, which is 14.5 times more than the base model with 4 × 4 m geometry and 50 % reflectance. The improvements in daylighting performance are due to the better light capture by increasing the geometry of the well, and then to the better distribution of light to the bottom of the building due to the increase in reflectance. Thus, the potential effect of the combination of architectural variables to improve the performance of daylight is evident.

From the analysis of the UDI (Table 1) in the 7 m model, it was observed it reached 78 % and 78 % on the upper floor and 21 % and 38 % on the first floor of the cases with 50 and 80 % of reflectivity, respectively. Thus, increasing the reflectivity enhances the UDI values at the bottom of the building, although it remained similar at the top of it. Thus, it is possible to conclude that the use of highly reflective surfaces does not contribute to excessive daylighting in the lightwell, reducing the risk of glare and may lowering the heat gains into the building.

At the latitudes corresponding to the cities of São Paulo and Santiago, the results are comparable to those of Macapá, due to the similarity in the performance of daylight in the lightwell.

4. Conclusion

This study aimed to indicate the adequate architectural solutions to improve daylighting performance in buildings with lightwells at three different southern latitudes. For this, different lightwell geometry, wall reflectance and solar orientations were compared. Results indicated that using materials with a high diffuse reflectance index to cover the walls of the lightwell is the more efficient solution for improving the daylighting performance of the rooms connected to it that increasing the shaft geometry. It is important to highlight however the potential effect of the combination of architectural variables to improve the performance of daylight.

In a narrow well (with 4 m side), a diffuse reflectance index above 80 % results in sDA300 values similar to the values of a wider lightwell, such as 6 and 7 m. This indicates that modifying the material that covers the well wall can contribute to improve the daylighting

		Lightwell 4 × 4 m								Lightwell 7 × 7 m							
		R-50 %		R-60 %		R-70 %		R-80 %		R-50 %		R-60 %		R-70 %		R-80 %	
		sDA	UDI	sDA	UDI	sDA	UDI	sDA	UDI	sDA	UDI	sDA	UDI	sDA	UDI	sDA	UDI
6th Floor	E	100 %	74 %	100 %	74 %	100 %	74 %	100 %	74 %	100 %	74 %	100 %	74 %	100 %	74 %	100 %	74 %
	N	100 %	77 %	100 %	77 %	100 %	77 %	100 %	77 %	100 %	78 %	100 %	78 %	100 %	78 %	100 %	78 %
	W	100 %	76 %	100 %	77 %	100 %	77 %	100 %	77 %	100 %	78 %	100 %	78 %	100 %	78 %	100 %	78 %
	S	100 %	76 %	100 %	77 %	100 %	77 %	100 %	77 %	100 %	78 %	100 %	78 %	100 %	78 %	100 %	78 %
5th Floor	E	53 %	52 %	67 %	58 %	83 %	62 %	98 %	66 %	100 %	71 %	100 %	73 %	100 %	74 %	100 %	74 %
	N	48 %	48 %	60 %	55 %	74 %	60 %	93 %	65 %	100 %	71 %	100 %	73 %	100 %	75 %	100 %	76 %
	W	55 %	53 %	68 %	58 %	85 %	63 %	98 %	67 %	100 %	73 %	100 %	74 %	100 %	75 %	100 %	75 %
	S	48 %	49 %	58 %	55 %	74 %	60 %	94 %	65 %	100 %	71 %	100 %	73 %	100 %	75 %	100 %	76 %
4th Floor	E	13 %	21 %	16 %	27 %	23 %	32 %	32 %	39 %	66 %	56 %	84 %	62 %	97 %	66 %	100 %	69 %
	N	12 %	22 %	17 %	27 %	21 %	32 %	32 %	39 %	55 %	53 %	72 %	59 %	93 %	64 %	100 %	69 %
	W	13 %	22 %	17 %	27 %	22 %	32 %	33 %	39 %	66 %	57 %	87 %	63 %	99 %	66 %	100 %	70 %
	S	12 %	22 %	17 %	27 %	23 %	32 %	33 %	39 %	55 %	53 %	71 %	59 %	92 %	64 %	99 %	69 %
3rd Floor	E	5 %	10 %	7 %	12 %	9 %	16 %	13 %	21 %	28 %	38 %	40 %	45 %	52 %	52 %	68 %	59 %
	N	5 %	10 %	7 %	13 %	9 %	16 %	12 %	21 %	28 %	36 %	38 %	43 %	49 %	50 %	64 %	57 %
	W	6 %	10 %	7 %	12 %	9 %	16 %	12 %	21 %	30 %	39 %	40 %	46 %	52 %	52 %	68 %	59 %
	S	6 %	10 %	7 %	13 %	9 %	16 %	13 %	21 %	26 %	37 %	38 %	44 %	49 %	50 %	63 %	57 %
2nd Floor	E	3 %	5 %	4 %	6 %	4 %	8 %	6 %	11 %	15 %	26 %	20 %	33 %	30 %	38 %	41 %	46 %
	N	3 %	5 %	4 %	7 %	4 %	8 %	6 %	11 %	14 %	27 %	20 %	32 %	29 %	38 %	41 %	45 %
	W	4 %	5 %	4 %	6 %	4 %	8 %	6 %	11 %	14 %	26 %	19 %	32 %	30 %	39 %	43 %	46 %
	S	3 %	5 %	4 %	6 %	4 %	8 %	6 %	11 %	13 %	27 %	19 %	32 %	29 %	38 %	42 %	45 %
1st Floor	E	2 %	4 %	2 %	4 %	2 %	6 %	3 %	8 %	10 %	21 %	13 %	26 %	17 %	31 %	28 %	37 %
	N	2 %	4 %	2 %	4 %	2 %	6 %	3 %	7 %	9 %	22 %	12 %	26 %	18 %	31 %	27 %	37 %
	W	2 %	3 %	2 %	4 %	2 %	6 %	3 %	7 %	9 %	21 %	13 %	26 %	18 %	31 %	28 %	38 %
	S	2 %	3 %	2 %	5 %	2 %	5 %	3 %	7 %	9 %	22 %	12 %	26 %	18 %	31 %	29 %	37 %

TABLE 1. Comparison between the metrics values under different reflectance levels at Macapá city.

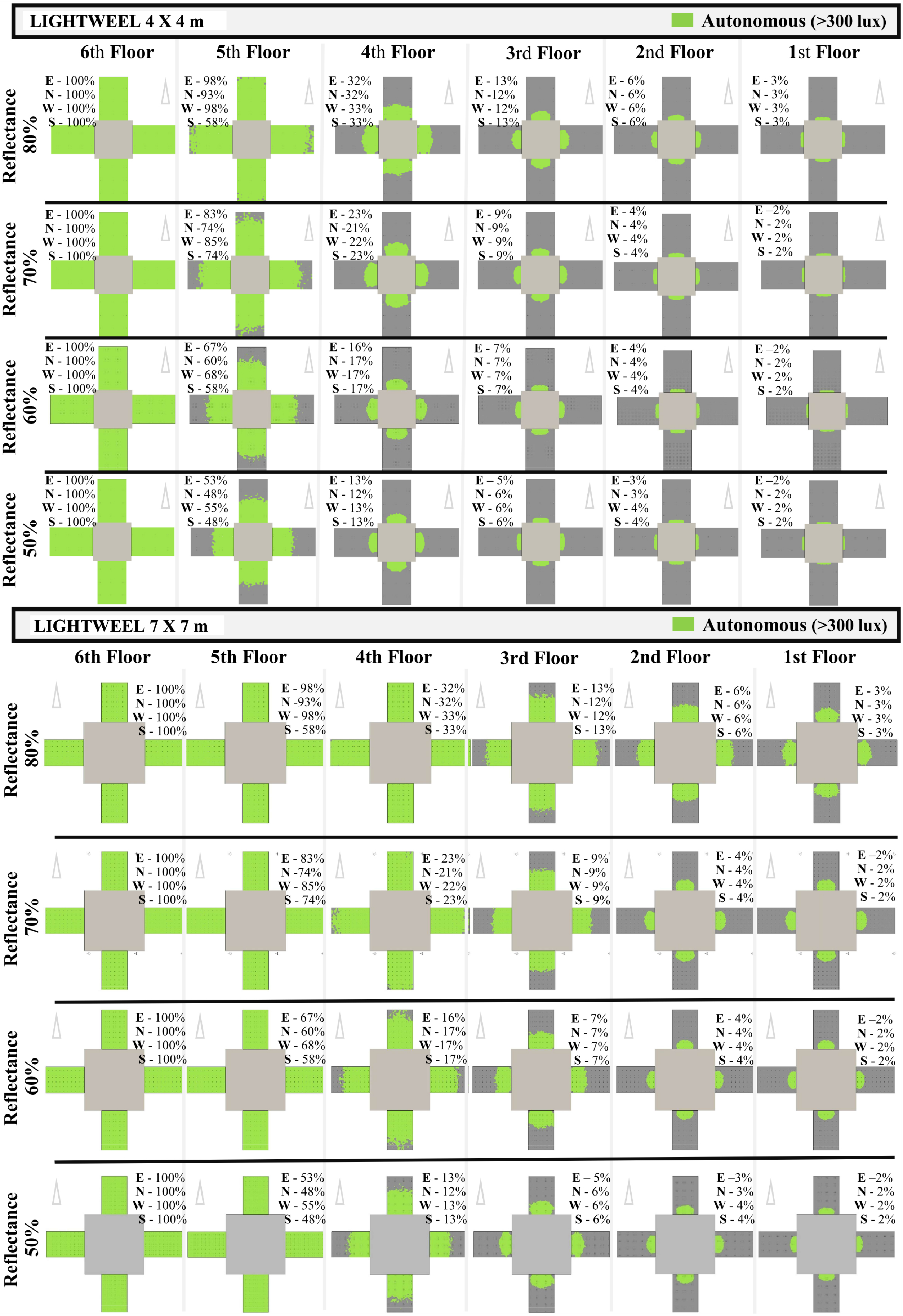

Figure 5. sDA values in the model at Macapá city.

performance in situations where it is not feasible to increase the shaft geometry. Despite this, the lightwell with 4 m geometry showed the best results with increased illuminance, especially on the fifth floor. It is also important to note that there were no substantial differences in results among the cities studied or among the cardinal orientations.

The use of highly reflective surfaces does not contribute to excessive daylighting in the lightwell. On the 7 m model with 80 % and 50 % reflectance, the UDI remains at 78 %. This indicates that most of the illuminance is below 2000 lux. Thus, it reduces the risk of glare and heating of the building.

Not consider the reflections of furniture in the light distribution inside the rooms is one of the limitations of this research. It should also be considered that the dynamic simulations were made using annual climate data. It is possible that in a static simulation, with data referring to a certain time, the values in specific face or latitude may change. It is still necessary to evaluate the contribution of lighting to the heat gains into the interior spaces. This research can provide a better understanding of the functioning of the lightwell, so it is designed to ensure adequate daylighting performance in residential environments. It is suggested that future studies analyse the contribution of natural ventilation in the lightwell of the studied cases.

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