Optimized indoor daylight for tropical dense urban environments

Iluminação natural interna otimizada em ambientes urbanos tropicais adensados

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Abstract

Studies using metrics related to dynamic sky conditions for indoor daylight performance assessment in urban environment are rare in tropical latitudes. This study applied one of these metrics, the spatial Daylight Autonomy (sDA $_{300,50\%}$ ≥75%, IES LM 83-12) for Cuiabá (15ºS, 56ºW, Brazil), a savanna climate city with a high frequency of partly cloudy skies. Parametric simulations were used to investigate the availability of daylight in dense urban areas. So daylight conditions inside a reference room with varied depths located within a continuous urban canyon were simulated with Radiance/Daysim in Grasshopper/Honeybee. Dimensions of the street and heights of front buildings (obstructions) are also varied in order to observe the relation between the sky angle and the sDA, for the four main cardinal directions. The results of regression analysis for this case study showed that among all evaluated parameters, room depth tended to be the most relevant for the optimization of indoor daylight. Finally, limitations of this approach and opportunities for further investigations were discussed.

Keywords: Daylight. Illuminance. Computer simulation. Spatial Daylight Autonomy.

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Resumo

Estudos que utilizam métricas baseadas em céu dinâmico para abordagem de desempenho de iluminação natural em recintos são raros em cidades de latitudes tropicais. Este estudo aplicou a métrica Autonomia Espacial de Luz Natural (sDA $_{300,50\%}$ ≥75%, IES LM 83-12) para Cuiabá (15ºS, 56ºW, Brasil), uma cidade de savana com predominância de céus parcialmente nublados. Simulações paramétricas foram utilizadas para investigar a disponibilidade de iluminação natural em contexto urbano adensado. As condições de iluminação natural dentro de um recinto de profundidade variada localizado em um cânion urbano foram simuladas com Radiance/Daysim no Grasshopper/Honeybee. Dimensões da via e de altura dos edifícios frontais foram variadas com o objetivo de observar a relação entre o ângulo de céu e o sDA para as quarto orientações solares principais. Os resultados deste estudo de caso mostraram que a profundidade do recinto tende a ser o parâmetro mais relevante entre os analisados para a otimização de iluminação natural interna. Finalmente, as limitações dessa abordagem e oportunidades de futuras pesquisas foram discutidas.

Palavras-chave: Iluminação natural. Iluminância. Simulação computacional. Autonomia Espacial de Luz Natural.

Introduction

Artificial lighting accounts for about 20% of building electricity consumption worldwide, and the forecasted total electricity savings potential in building lighting by 2030 could be equivalent to all the electricity consumed in Africa in 2013 (INTERNATIONAL..., 2016).

Concurrently, in tropical locations the daylight is capable to ensure freedom from artificial light during a significant part of the day (DIAS *et al.,* 2009). Brazil being mainly one of them, is the focus of this paper.

Daylighting has potential in saving energy and decreasing maintenance costs. Apart from that, it promotes health, productivity, and well-being. Despite of its importance, researches dedicated to daylight assessment in dense urban spaces, are relatively recent. Internationally, examples of this kind of study can be found in the publications by Tsangrassoulis *et al.* (1999) for estimating illuminances in urban canyons, by Ng (2001) for daylight design in high-density urban residential buildings using a metric for overcast sky, and by Reinhart and LoVerso (2010) about a design sequence for diffuse daylight based on design "rules of thumb".

A larger review on urban daylighting was conducted by Nasrollahi and Shokri (2016), who addressed scientific publications between the years of 1993 and 2015. The authors addressed concepts of daylighting, sky types, solar movement, and effective architectural parameters in an urban context. They shortlisted fifty papers that were considered to bring relevant knowledge to the field within this period. Among other conclusions, they recorded that:

(a) increasing the street width increases the incident quantity of radiation inside an urban canyon, while the energy consumption in a building decreases;

(b) increasing solar reflectance of exterior surfaces increases the incident daylight indoor, while the demand of energy for artificial light reduces;

(c) exterior shading devices provide visual comfort, while decrease the energy consumption of a building; and

(d) the surfaces of an urban canyon can receive uneven radiation due to solar orientation.

However, part of those conclusions are generic, and need to be analyzed in detail according to local and climate conditions, in addition to other determined aspects that make the urban analysis quite complex.

These complexities are due to the fact that daylight availability indoor is affected by the interaction of the following:

(a) the source (sky and sun);

(b) the receptor (indoor characteristics); and

(c) the mediator (characteristics of external items such as surrounding buildings, vegetation, architectural components).

The potential use of the available daylight indoor is also determined by the agent (occupant) itself.

In studies of daylight optimization, it is considered that the first three aspects must be investigated considering pre-defined demands under a metric, which allows the comparison of daylight performance between different spaces. There are several indexes [metrics] for daylight assessment indoor, as presented by Carlucci *et al.* (2015) – and most of them are based on illuminance levels, commonly addressed as the range of quantity of light required for the execution of an activity.

The definition of appropriate illuminance levels for human needs, as well as the most suitable metric for daylight assessment, evolves as result of novelties in the research.

Regarding illuminance levels, for instance, the Brazilian standard NBR 5413 (ABNT, 1992) provided a basic guideline for selecting illuminance levels according to the visual task executed indoor: i.e., 150lux as the average for deposits and areas not-used for continuous work, 300lux for tasks with a limited visual requirement, and 750lux for offices (ABNT, 1992). Later, the Brazilian standard NBR ISO/CIE 8995-1 (ABNT, 2013) proposed different values for indoor illuminances. According to it schools, offices, and rooms for medical regular attendance must provide values between 300-750lux, departmental stores from between 300-500lux and multi-use rooms for entertainment activities, a minimum of 300lux. Mardaljevic *et al.* (2011) highlighted that levels above 300lux are frequently perceived by occupants in offices as desirable up to a certain limit, and it is less probable that the light will be switched-on beyond 300lux.

Recent development combines the use of computer simulation for analyzing dynamic skies considering variations of sun positions and sky conditions within a period of time (usually one year). Spatial Daylight Autonomy (sDA), endorsed by the Illuminating Engineering Society of North America, IESNA (ILLUMINATING..., 2012) is one of the recent metrics proposed. The sDA reports the floor area indoor (%) that exceeds two

thresholds (Lighting Measurement IES LM 83-12 (ILLUMINATING..., 2012)):

(a) the minimum daylight illuminance level (lux) to be achieved; and

(b) a fraction of the occupied hours per year (%).

The sDA threshold is 300lux and 50% of the occupancy time from 8am-6pm considering adjustment for longitude and daylight savings time. The performance result of an analysis area can then be classified as "nominally acceptable" (sDA≥55%) or "preferred" (sDA≥75%). These limits of sDA(300,50%) were established based on the investigation of occupant preferences in open plan offices, meeting rooms, classrooms, public lobbies and public spaces in libraries between latitudes 37ºN-48ºN in U.S.A.; and it is considered that they could be extended for areas with similar visual tasks (ILLUMINATING..., 2012). The IES LM 83-12 is adopted since October/2016 by the building rating system Leadership in Energy and Environmental Design (LEEDv4), one of the Green Building certifications that is applied in Brazil (GREEN..., 2014).

In this context, the sDA metric was chosen for this study to conduct a quantitative assessment of daylight availability in a dense urban location under predominantly partly cloudy skies.

This predominantly partly cloudy sky is typical in Savanna climate, in its duality between dry (sunny) season and a wet (rainy) season. Several cities above 500.000 inhabitants will tend to appear by 2030 in Savannas within the tropics (Figure 1). It is expected that due to higher solar altitudes in lower latitudes there might be different outcomes in the spatial distribution of indoor daylighting, affecting sDA when compared to other luminous sky conditions.

Therefore, such assessment is decisive to avoid unsatisfactory daylight conditions and hence, excessive energy consumption of indoor lighting, for these forecasted dense urban areas.

Background: data and software for daylight assessment

Climatic-based metrics for daylight assessment in an enclosed system (a room or open space) rely on atmospheric data which may be measured or calculated based on models.
The International Building Performance Simulation Association- IBPSA (INTERNATIONAL..., 2016) reports that daylight data for building simulation purposes is a field for improvements. Illuminance data is usually calculated from irradiance values. Additionally, the Association points out that information of cloud cover, which are used for daylighting and sky temperature calculations, should be used carefully, since these reports are not standards worldwide.

Figure 1 - **World map with cities> 500.000 inhabitants, forecast for 2030; Savanna climate in blue colour (Köppen-Geiger "Aw" classification)**
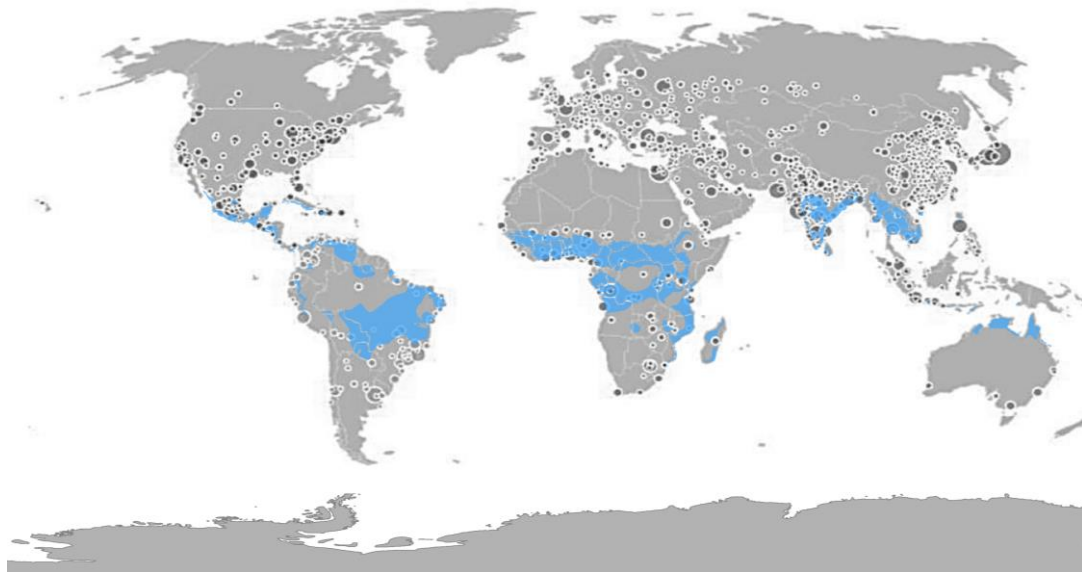
Source: adapted from Kottek *et al.* (2006) and United Nations (2014).

To fulfil the lack of daylighting measurement stations with long-term data, models such as the one proposed by Perez *et al.* (1990) are used. These authors proposed models to predict direct, global and diffuse illuminance; diffuse irradiance or illuminance received by a tilted surface; sky zenith luminance and sky luminance angular distribution, representing different sky conditions, from clear to overcast sky. The models were developed considering data from high latitudes collected in 10 cities in U.S.A. and 3 in Europe, under conditions which ranged from "high altitude desert to temperate maritime, including humid continental, subtropical and highly polluted environments".

One of the most common weather data sets for characterizing a local climate is the Typical Meteorological Year (TMY). A TMY for computer simulation is composed of 12 months of hourly data (8,760 hours); each month is selected from different years, considering it closest proximity to a statistical weighted long-term distribution of solar radiation, dry-bulb temperature, dew point, and wind velocity: a more complete methodology than that used in the Test Reference Year (TRY) (CRAWLEY, 1998). TMY is available for more than 5000 locations worldwide under different formats such as the Solar and Wind Energy Resource Assessment (SWERA), the Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE), ASHRAE's International Weather for Energy Calculations 2.0 (IWEC2), the Chinese Standard Year Weather Data (CSWD), and the Typical Meteorological Year 3 (TMY3) (INTERNATIONAL..., 2016). Weather files built over the Brazilian Instituto Nacional de Meteorologia (INMET) data also use the TMY methodology (RORIZ, 2012). The TMY files may be converted to different formats which are readable by building/urban simulation packages, i.e. "epw". Recent versions of weather files for computer simulation based in the TMY adopt the model by Perez *et al.* (1990) (U.S…., 1995).

Concerning software for daylight simulations. Bhavani and Khan (2011) described the features of some of them: Radiance, Relux, ADELINE, DIALux, Light scope, Inspirer, Rayfront, 3D studio MAX, Superlite, Lumen Micro, Specter, ESP vision, Light works and DAYSIM. In Brazil, Troplux and Apolux are avaible varieties.

Daysim/Radiance is one of the most used software for indoor analysis. Radiance was developed in the Lawrence Berkeley National Laboratory in the 1980`s. It calculates luminance required for visualization using backward ray-tracing, a technique in which the light is traced from the observer to the source(s), and it calculates illuminances for a selected type of sky. Daysim uses the algorithms of Radiance as a foundation to calculate illuminance and luminance profiles from a weather file (REINHART, 2006), becoming known as Daysim/Radiance. Daysim/Radiance incorporates a model based in Perez *et al.* (1990) for internal calculations of dynamic skies.

Recent parametric studies use Rhinoceros to conduct the simulations: i.e., Wagdy *et al.* (2015). Rhinoceros is a software for three-dimensional computer graphics and computer-aided design (CAD) which can incorporate a graphical algorithm editor called Grasshopper. The Ladybug Analysis Tools in turn connects Grasshopper to various simulation engines such as EnergyPlus, Radiance, and Daysim for building energy, comfort, daylighting and lighting simulations[1].

Urban daylight in the tropics

In the tropics, Assis and Valadares (1995) proposed a mathematic model to be incorporated by urban legislation of the city of Belo Horizonte (19°55'S, Brazil, partially Savanna climate), in order to favor daylight and insolation. More than 20 years ago, they defined thresholds similar to the concept of sDA, except for the spatial percentage of indoor floor area. The research adopted 150lux in the work plane of residences; 80% time of the year from 8am to 4pm; under different values of external horizontal illuminances found in literature (the higher value being of 26.4klux), as the premise. Subsequently, the authors demarcated the minimum sky angle for the area. The sky angle was determined between the vertical plane containing the window and the top of the opposite building, with a vertex located on the top of the window sill of a defined space on the ground floor. Thus, a minimum sky angle of 27°30` was defined for preserving daylight in the residential urban areas. The authors recommended that 150lux should not be adopted in mixed land use designating at least 300lux for offices and commercial activities and therefore new sky angles should be determined in those cases.

Indeed, urban planning in rapidly growing cities face the challenge to promote the concept of buildings prepared for flexibility over time, and to shelter mixed activities simultaneously. Henceforth, minimum illuminance levels based on the demands of a unique typology with lower requirement levels, such as the residential one,

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[1]<http://www.food4rhino.com/app/ladybug-analysis-tools>. Accessed: 16/Feb/2017.

could not be adopted as a reference for the entire urban design.

More recently, Laranja *et al.* (2012) evaluated the effect of solar orientation on the indoor daylight availability of a room located in the coastal city of Vitoria (20°17'S, Brazil, Savanna climate). They used the software Troplux for an annual simulation of three CIE skies (with a daily schedule of 13 hours from 6am-6pm). The output was the average global illuminance based on a dynamic metric assessment that computed indoor values between 100-2000 lux. The room was modelled with dimensions of 2.60x3.85x2.60m (width x depth x height, m), and internal reflectances of 20/50/85 % (floor, walls, ceiling, %). One window on the façade, was defined with clear glass, sill height of 1.10m, and dimension of 1/8th of the area of the room floor according to local laws, resulting in a total area of 1.25 m². The room was located in the 4th floor of a building on a 20m wide street. Three front buildings were modelled with different heights (37.6 m; 37.6 m and 29m), different distances from the sidewalk, and different spaces between them. The window was simulated facing to four different solar orientations (N, S, E, W). The results for this case study showed small differences of indoor daylight under the expected homogeneous output from CIE sky type 3 (overcast). Under the CIE sky type 7 (partially cloudy) and type 12 (clear), the window oriented to North resulted in the highest illuminance percentage, to South the lowest, while to East and West presented similar percentages. The reasons for the choice of the obstructions configured in the study were not described in the paper, neither references of external reflectances.

Scalco and Pereira (2016) proposed a method to analyze the impact of buildings in static daylight performance of a neighborhood in Brazil. Different urban configurations with the same built area were compared. The software Apolux was used, assuming partially cloudy sky. The results indicated that a higher percentage of adverse impacts occurred in regular, homogeneous building configurations with 5 floors and building footprint of 75% of the gross area of the plot. Comparatively, better results were observed in taller buildings with low building footprint. Considering the outdoor reflection by obstructions, evaluation of different type of skies, and use of dynamic simulation, were some of the suggestions for future studies.

Furthermore, Paule and Kaempf (2016) assessed the daylight performance of rooms in the urban context of Bogotá (4°37'N, Colombia). They compared the results provided by two software: one specialized for the room scale (DIAL), and the other for urban scale (CitySIM). They established a threshold, as per the number of annual hours during which the indoor illuminance exceeds 300lux for two points located inside each room. This study demonstrated that there were discrepancies in the results of the points located far from the façade, probably due to indoor reflectances. Indirectly, the study evidenced that the tool used for urban assessment needed improvements for quantifying indoor reflectances. The authors suggested to create a link between the two software for complementing the capabilities of both.

CitySIM was used before by Martins *et al.* (2013) in a study on the impact of urban form on the energy demand of buildings in the city of Maceió (9° 39′ S), computing the demand for indoor artificial lighting and climatization. In this case, the authors identified that total built density, verticality, compactness, and the mean prospectus (ratio of the canyon height to canyon width, H/W) had a major impact on quantitative daylight.

Outside the tropical region, Reinhart (2014) exposed the relation of daylight and the depth of a space according to design guides from the USA, UK and Germany. As a rule of thumb, the depth of a daylit area of a sidelit space in these documents lies between 1 to 2.5 times the dimension of the window head height. The author used computer simulation to examine this rule of thumb. One of the models was a reference office room (3.6 x 8.2 x 2.8m, WWR of 45%), positioned inside an urban canyon of uniform height. This model was rotated in four cardinal directions and simulated using annual weather files of three cities (latitudes>33°N). A linear decrease of the daylit area as a consequence of the increase of the front obstruction was observed.

Later, Saratsis (2015) proposed a simulation-based framework for urban zoning rules from daylight. The method was applied for different urban typologies considering the city of New York (40°43'N, U.S.A.). Focusing on the maximum daylight performance potential of a neighborhood, buildings were modelled with a window-to-wall ratio of 100%, glazing with a visible transmittance of 50%, and blinds with 50% cut-off value in case of illuminances crossing 20.000lux. Blocks were simulated using a tool named Urban Daylight, pursuing the sDA(300/55%).

Likewise, Wagdy *et al.* (2015) investigated the optimum window-to-wall-ratio (WWR) for dwellings of informal settlements in Cairo (30°3'N, Egypt, hot desert climate). They assessed sDA(300/55%) of a south-oriented room of dimensions 4.0x6.0x3.0 (wxdxh, m) and reflectances 20/50/80 (floor, walls, ceiling, %), under different H/W ratio (streets varying from 4-8m wide, front buildings heighted up to nine floors)

using Rhinoceros/Daysim. Among other results, they concluded that daylight reflected from the ground had a lower impact in overall indoor daylight.

It is important to point out that the typology of a continuous urban canyon is being intensively used in researches of daylight in the urban environment (NASROLLAHI; SHOKRI, 2016), probably because it can represent complex repeated urban patterns in a simplified way (STRØMANN-ANDERSEN; SATTRUP, 2011).

It is also remarkable that different researches adopted a 3m wide room for daylight analysis (CABÚS, 2005; REINHART, 2014; ALBUQUERQUE; AMORIM, 2012). For instance, the dimension of a test room of 3.0x9.0x2.7m (wxdxh) was implemented for software validation (AIZLEWOOD et al., 1996[2] apud CABÚS, 2005). Studies of Radiance were developed using the "typical [dimension] of a deep-plan office module" of 3.0x9.0x2.7m (wxdxh) with a single window of 2.6m width and 1.5m height (MARDALJEVIC, 1999).

The dimension of 3m wide represents somehow a worst case in the urban scene, where wider rooms might be commonly found. In fact, in narrow rooms the view of the sky at points distanced farther from the façade is decreased in comparison to wider rooms of same WWR. Thus, the sDA results would be even better in other typologies with potentially wider rooms, like residences.

After this brief review of researches in urban daylight assessment, the following session presents the main purpose of this study.

Objective

The main goal of this paper was to quantify and understand the influence of parameters related to urban planning strategies on indoor daylight in predominant partly cloudy sky in the tropical region, using a dynamic metric named sDA. Furthermore, the study aimed to identify the conditions within an urban context that are sufficient for providing a minimum daylight illuminance level to a reference room to allow the execution of indoor daily multi-purpose activities with less dependence on artificial lighting under these sky conditions. Additionally, the relevance of outdoor reflectance in obstructed sites were discussed.

Method

A parametric computer simulation of a reference room in the city of Cuiabá was executed using Grasshopper for Rhinoceros, with Radiance/Daysim interfaced by Honeybee (v.0.0.59) and Ladybug (v.0.0.62, jan-28-2016). The room intended to represent a "worst case" scenario: located in the ground floor of a building, in a dense urban context. The parametric parameters were building depth (related to the depth of the reference room), solar orientation of facades, height of front obstructions, and street width. The pursued outputs were sDA(300,50%) $\geq$ 75%.

Selected case-study: Cuiabá and its weather files

Cuiabá (15°35'S, 56°05'O, Brazil) is an intercontinental tropical city with a Savanna climate with ca. 863.509 inhabitants, located at an altitude of 151.34m. The reasons for selecting Cuiabá as a case study were its considerable sky variations throughout the year; its low latitude; the availability of a reliable weather file; and the intention of the municipality in increasing its density.

As stated by Alves et al. (2013), the sky cover condition in the urban area of Cuiabá is influenced by diverse factors, such as cloudiness and atmospheric combustion products. Another phenomenon is a typical characteristic of the central-western Brazilian territory: outbreaks of fire in the surrounding native vegetation. Therefore, during the dry season, when sky should ideally be clear, the particles diffused by this burning biomass, reduce the incident solar radiation. The authors observed the effect of this type of incident in Cuiabá and reported that in 2005 the project Solar and Wind Energy Resource Assessment (SWERA), which mapped solar energy resources in the country using a model of radiative transfer.

Lamberts et al. (2015) statistically compared weather files for Cuiabá. The authors analysed two available files, INMET and SWERA, in terms of temperature and solar radiation, both prepared in the TMY (Typical Meteorological Year) format. SWERA project initiated in 2001 with the focus on making reliable data of solar radiation and wind available. The INMET file results of data measured in official meteorological stations between 2000 and 2010. One of the most remarkable results of this study by Lamberts et al. (2015) is that the differences of horizontal diffuse radiation between both the files are considerable. The report did not

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[2]AIZLEWOOD, M. et al. The Development of a Reference Data Set for Lighting Computer Programs. **CIBSE - National Lighting Conference**. Bath - UK: CIBSE, 1996.

present any imprecision of both files, neither suggested that one file should be preferred rather than the other. However, they informed that before the analysis it was necessary to fulfil many existing data gaps in the INMET file, without detailing the extension of this problem. In light of this information, for the purposes of this study, the SWERA weather file was chosen for the simulations (named BRA_Cuiaba-Marechal.Ron.833620_SWERA). It is important to point out that in the TMY category the files ideally result of long term measurement data: a minimum of 30 years is recommended (U.S...., 1995). None of these files seem in compliance with this recommendation.

For a better understanding of the overall data and annual sky conditions in this selected SWERA file, it was analysed using the software ClimateConsultant v6. The generated outputs presented an annual average mean of sky cover around 57%, varying between 29% and 80%. The monthly lowest sky cover average is 30% in the dry season, and the maximum of 81% in the wet season. Considering the annual illumination based on daylit hours, the global horizontal average ranges between 10-92klux (mean of 49klux), while the direct normal average ranges from 9-59klux (mean of 32klux) (Figure 2, column "A").

## Selected input and output parameters

A hypothetical continuous urban canyon was built in a virtual environment (Figure 3), assuming that it could be the worst case in terms of poor daylight compared to a non-continuous canyon.

Therein, a multi-purpose empty room on the ground floor is modelled. The room was defined as a commercial/ office/ multi-purpose room, since in mixed urban blocks those activities are located commonly in the levels of pedestrians, while residences are located on the upper floors. The dimensions where chosen based on a literature review: 3.0x2.7m (width x height), both kept constant during the entire experiment. Particularly, the dimensions of the side of the canyon that contains the room were also kept constant.

Clear glazing, typical in the local real-estate market, was located 1m above the floor with 1.8m height. Dirt depreciation factor of window was neglected and visible transmittance was of 0.88. The resulting window-to-wall ratio was approximately 60%, measured from inside and without frames. This exaggerated WWR of 60% is not usual, neither recommended due to thermal issues. However, it was intended to represent the maximum effective available indoor daylight. If the desired levels of sDA are barely achieved, the conditions in reality might be worse because of lower WWR values, dirt depreciation due to pollution, presence of additional obstructions such as trees, etc.

For this study, four factors (urban parameters) were varied on four levels, resulting in a total of $4^4 = 256$ combinations. Factors acknowledged from previous researches as the ones playing important role in indoor daylight performances, were selected for these parametric simulations. The range values of these parameters were chosen partially based on literature and partially from the analysis of characteristics of dense cities in tropical regions.

Figure 2 - **Example of graphic generated for the analysis of the weather data (city of Cuiabá): Hourly illumination (only daylit hours), Direct normal and Global Horizontal (klux) in the year**
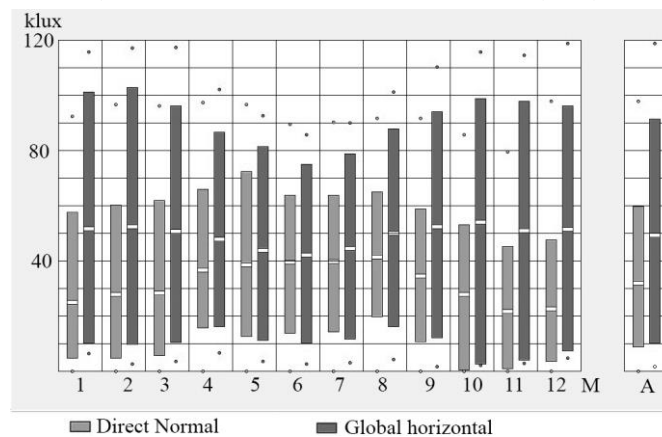
Note: M = Month (i.e., 1=January); and A: Annual.
Source: adapted from ClimateConsultant.

Figure 3 - **Simplified perspective of the model used in the parametric simulation (Sketch Up)**
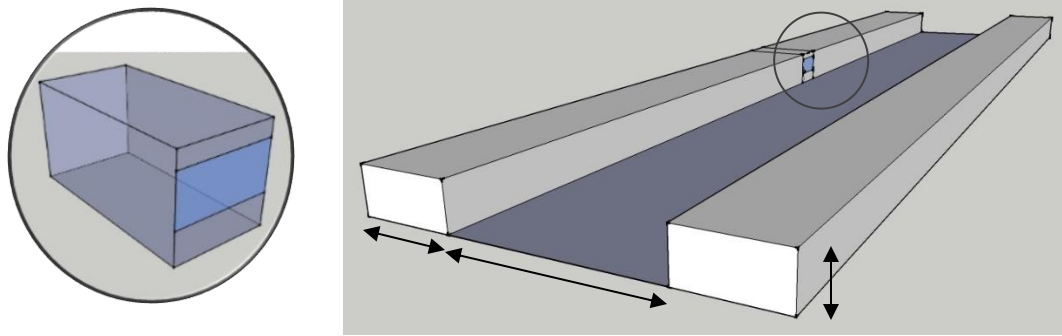
Note: Left: the reference room. Above: The continuous urban canyon containing the reference room. Double arrows indicate the variable dimensions of street width, front obstruction height, and room depth.

Additionally, these ranges were selected based on a preliminary simulation in which one value was changed at each run, to pre-evaluate their potential influence on the results and on the time-demand of pilot simulations. Then, accordingly, several combinations were chosen due to restrictions of computer time-processing.

Table 1 illustrates the alterations demarcated on the depth of the reference room (6, 7, 8, 9m), solar orientation of room facade (N, S, E, W), height of buildings determining front obstruction (12, 24, 48, 72m – respectively of 4, 8, 16, 24 floors), and street width (5,10,15, 20m). The heights of front obstructions were chosen to represent different vertically dense buildings. The minimum depth of the reference room exploited the rule of two times the height of the window head to optimize daylight potential. Street width varied from 5m, representing a pedestrian passage or the measure of one car lane with one sidewalk, in which shadowing effect is significant, up to 20m.

Table 2 describes relevant input parameters for the simulation. The mentioned reference IES LM 83-12 (ILLUMINATING…, 2012) was adopted as the main guide in the choice of some of them.

Regarding the reflectance of façades, important parameter of this investigation, Givoni (2016) suggests for tropical regions a percentage of 40% considering mold and lack of maintenance, despite the recommendation for higher percentages in these regions for thermal benefits. This percentage was adopted, although the LM83-12 recommended a value of 30%, when the outdoor reflectance is unknown.

Reinhart (2014) recommends an outdoor ground reflectance of 20% for simulation purposes. This percentage was applied in the model.

As main output, an sDA(300,50%) ≥ 75% was established as the minimum desirable conditions for indoor daylight over a work plane height of 0.8m in this room in the first floor. The value of 300lux based on the IES LM 83-12 (ILLUMINATING…, 2012) was adopted overall as an in indicator of potential energy savings with indoor lighting. In the future, this threshold and approach could be reviewed based on far-reaching surveys of occupant preferences and behavior, as well as on advanced qualitative metrics related to human comfort and health.

It is important to highlight that the sDA is recommended to be evaluated together with the Annual Sunlight Exposure (ASE), a metric that evaluates the risk of excessive daylight that potentially could cause visual discomfort. Visual comfort is not addressed in this work, and ASE is not considered – as acompensation, the "preferred" level (sDA≥75%) is pursuit. Notwithstanding, "nominally acceptable" results (sDA≥55%) are also discussed.

Method for data treatment and analysis

From the outputs, quality control methods were carried out aiming to verify the existence of outliers and the overall coherence of outputs before proceeding to the analysis, to:

(a) prevent unreliable results generated from software bugs, computer failure, and data treatment based on personal experience or (lack of) attention; and

(b) allow the reproduction of the experiment through methods accepted by the international community. Multiple regression analysis was undertaken to verify the correlation between the parameters and sDA percentages.

The search for outliers considered a Modified Thompson Tau=1.954 obtained from a student's t value based on α = 0.05, population of 256 and df = n-2.

Table 1 - **Variation in input parameters of the 3-D model for the simulation**

Parameter	Variation	(1st)	(2nd)	(3rd)	(4th)
Depth of the reference room (m)	(1st)	6	7	8	9
Height of front obstruction (m)	(2nd)	12	24	48	72
Street width (m)	(3rd)	5	10	15	20
Orientation of façade (º)	(4th)	0	90	180	270
Total number of combinations= $4^4 = 256$					

Table 2 - **Input parameters for the simulation**

Parameter	Value	Parameter	Value
Ambient bounces	6	Occupancy (local time)	8am to 6pm
Ambient division	4096	Illuminance Threshold (lux)	≥ 300
Quality	2 (High)	Period of occupancy (%)	≥ 50
Ambient sampling	4096	Indoor floor area – pursued sDA (%)	≥ 75
Ambient accuracy	0.1	Reflectance of indoor floor (%)	20
Ambient resolution	128	Reflectance of indoor walls (%)	50
Specularity of materials	0	Reflectance of indoor ceiling (%)	70
Roughness of materials	0	Outdoor ground reflectance (%)	20

Then, a regression analysis was carried out in an attempt to create a model to predict the value of sDA from the known values of the variables which were defined within the selected urban design parameters, considering the studied conditions. The hypotheses were established as follows:

H0: M1 = 0 (Null hypothesis: slope is zero, meaning no correlation); and

H1: M1 ≠ 0 (Alternative hypothesis: slope is different from zero in the population).

A multiple regression analysis was conducted in Excel, considering a significance level of 5%, and it generated one equation representing the behavior of the model. The regression of each parameter separately was performed to support the analysis; nonetheless, they were not detailed here. Overall results were analysed and discussed in the following session.

Results and discussion

The sDA results obtained from variations in the urban model using Grasshopper Daysim/Radiance are presented below. No outliers were found among the outputs; therefore, no datum resulting from the simulation was excluded from the analysis.

Figure 4 presents graphics of sDa values resulting from variations in three factors: height of front obstruction (m), street distance (m), and room depth (m), for the North orientation. The "y" axis (dependent variable) presents the results of sDA(%) for each variation, meaning the percentage of floor area of the room which exceeded 300lux during 50% of the occupied hours of the year (8am-18pm).

The dashed lines highlight the minimum values of sDA required by LM 83-12 as "preferred" (75%, which is the desired condition defined for this research). The "x" axis (independent variable) presents the heights of the buildings that compound the front obstruction: from 12m (buildings with 4 floors) to 72m (24 floors). The results in this graphic are grouped by color: tones of blue represent street width of 5m, orange 10m, green 15m, and red 20m. Each tone represents a depth of the room.

The main results of the statistical analysis for each parameter are summarized in the Table 3.

The multiple regression analysis generated the Equation 1:

$$sDA = 130.2 - 11.17*r + 1.45*s - 0.19*h + 0.038*o$$
$$\text{Eq. 1}$$

Where "r", "s", "h" and "o" represent respectively the room depth, street width, height of obstruction and facade orientation of the room.

Considering the general Equation 1 it is possible to infer that an increase in street width influenced positively in the sDA. Additionally, an increase in the height of front obstruction and in the room depth depreciates the sDA levels. Based on the p-values<5%, there is a strong evidence that the slope was not zero in the population; therefore, the null hypothesis was rejected and it is possible to affirm that there was a correlation between the four parameters and the variation in sDA (95% confident). These results match the ones by previous studies conducted in other cities, and therefore they indicate consistency in the simulation.

Figure 4 - sDa (%) x height of front obstruction (m) in four different street distances (m), room depths (m), and solar orientations (Continues…)
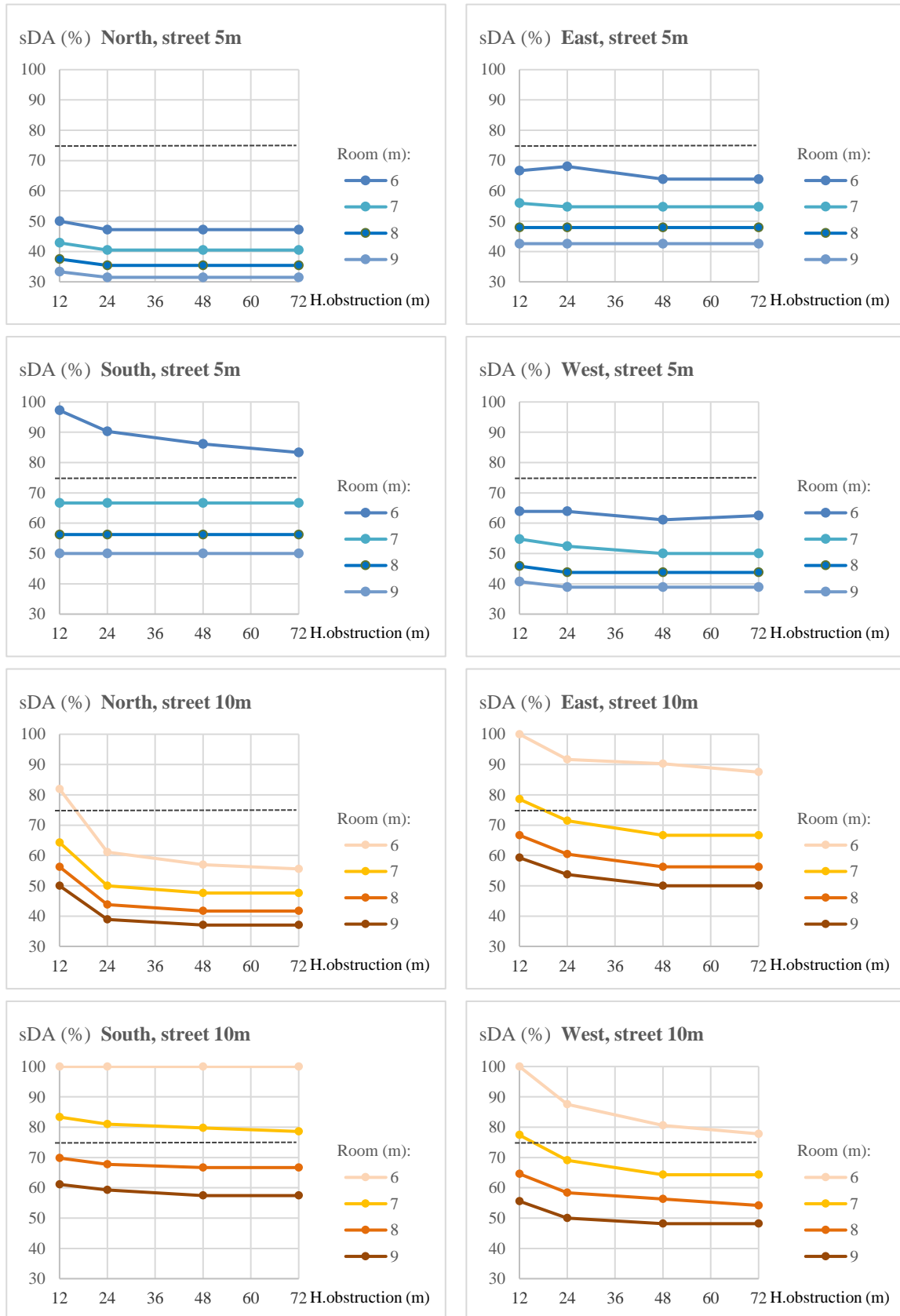
Figure 4 - sDa (%) x height of front obstruction (m) in four different street distances (m), room depths (m), and solar orientations (continuation)

The higher R-sq value of 43.5% (Table 3) indicates that the room depth had the stronger correlation to sDA among the four evaluated parameters, and in other words, that 43.5% of variation in sDA was explained by room depth. This higher R-sq value also indicates that it probably presented the higher level of influence on sDA; however, a complementary study using another statistical method is necessary to confirm this possibility. Combined, all parameters explained only 71.5% (R-sq=0.715) of the variation in sDA; this indicates that other parameters should be considered in future simulations, to achieve a better correlation (closer or above 90%). Considered the regression made separately only with the room depth, it is possible to affirm that each additional meter in the depth of the room decreased the value of sDA from 9.6% up to 12.7% (lower and upper values).

The orientation of the façade must be carefully interpreted: the unit was not normalized to match the others (m), and the negative sign in Equation 1 is meaningless; an additional analysis was made for this parameter. A regression considering only sDA and solar orientation results in a R-sq=0.04, which indicated lower impact of solar orientation on sDA in face of the other parameters.

Detailing the results as per orientation, for South a room of 6m depth provides sDA≥75% in all the cases; a 7m depth the same except for the narrow street (5m width); 8m depth only with maximum street width (20m) and minimum obstruction height (12m). Street width of 5m was not favorable for daylight: only rooms of 6m depth in South orientation exceeded the established value of sDA. For East, if the room is a 6m depth, the sDA≥75% in all cases, except with the street width of 5m; a 7m depth required street distances over 10m and front obstructions up to 48m; a room of 8m only achieved the preferred sDA if the street is 15m or wider, and the external obstruction is limited to 12m height.

West differs from East in two cases: 7m depth (with 48m of obstruction), and 8m depth (with 15m street width) were not sufficient. For North, an sDA≥75% was only achieved for room depths of 6m (if street width≥10m and front obstruction of 12m to 24m), or room depth of 7m (if street has 15m or 20m, and front obstruction only 12m height). A room of 9m depth did achieve results of sDA≥75% in any of the cases. Table 4 presents the average of sDA as per solar orientations: North was the orientation that presented lower sDA results, South and West presented very similar results of sDA, and South presented the higher sDA percentages.

The global results for solar orientation diverged from the ones obtained by Laranja *et al.* (2012). First, it is necessary to underline that the simulated characteristics were different in this study. Second, the last column of Table 4 presents the average of sDA considering only conditions more similar to the ones simulated by those authors: street width of 20m, room depth of 6m, obstructions of 24 and 48m. In this case, the major difference was related to North. The influence of the outdoor reflectance, the difference of height between the sides of the canyon, and solar path can explain the differences on the results: the hypothesis ist that front buildings acted as a "blocker" for direct sun light from the window oriented to North, while they acted as "reflectors" of light in the other orientations, producing better results of sDA. It is important to remember that the height of the reference room and adjacencies was kept constant, while the height of the front building increased. The result for North could be better if the side of the canyon where the room is located was also increased simultaneously. Further investigations should consider the simulation of different values of façade reflectance combined with a sensitivity analysis in order to understand the influence of this factor on indoor daylight performance.

Table 3 - **Main outputs of ANOVA for each Regression Analysis considering the four simulated parameters**

Parameter	R-square	Coefficients	Lower 95%	Upper 95%
Room depth (m)	0.435957	-11.175	-12.7457	-9.60436
Street width (m)	0.184183	1.452722	1.074924	1.83052
Height of obstruction (m)	0.054537	-0.19177	-0.29043	-0.0931
Orientation (º)	0.040972	0.038065	0.015309	0.060822
Significance F < 0.05 in all four cases (significance level of 5%)				
P-value < 0.05 (Significance level) in all four cases				

Table 4 - Solar Orientation x sDA

Orientation	Average sDA (%)	
(º)	Global	Street>20m
North	52.83	79.8
West	65.67	100
East	68.45	100
South	75.59	100

As a general outcome for this case-study located in the South hemisphere with low latitude and partly cloudy sky, solar orientation had a minor impact on sDA when compared with the other simulated urban parameters. In a room, highly obstructed by surrounding buildings, the indirect light provided by reflectance of front buildings seemed to be more important. This result reinforces the importance of the choice of reflectances in daylight urban simulations, and in future studies this parameter should be investigated. Assuming that based on the reflectance factor, in general, the worst performance of North orientation was compensated by the better ones in South, West, and East. Regarding the worst result for North, future studies could incorporate variations in the height of the canyon which contains the reference room. Henceforth, complementary studies should focus on the effect of distances between front buildings with pavilion (non-continuous) typology. Considering the findings here and the ones by Scalco and Pereira (2016), the variation of building footprints is a recommended option for future studies. The conclusions by Martins *et al.* (2013) may be used as reference for exploiting these overall results in terms of built density, verticality, compactness, and H/W ratio.

Another outcome from the present study was that street widths should be defined higher than 10m, profusely from 15m - the results tended to be better, 20m obtained the optimum outputs. Room depth was found as the most relevant parameter for sDA in this Savannah. To favor minimum daylight levels, building depths that can provide room depths until 7m (better 6m) should be stimulated when there is only one lateral window providing illuminance.

The sky angle of 27°30` calculated by Assis and Valadares (1995) for daylight purposes in a similar climate and latitude may be beneficial for the sDA level in Cuiabá if, and only if, the room depths are restricted to 6m with a high WWR. In case of the worst orientation, an sDA preferred (sDA≥75%) was observed in a room depth of 6m combined to a sky angle of 34°; a minimum sky angle of 53° is required for a depth of 7m.

The overall results indicated that sDA(300,50%), meaning 300lux indoor during 50% of the occupied time of the year, was feasible to achieve under these simulated conditions, but not easily. A major debate on the implications of this limit must be carried out, and maybe the inferior limit of sDA≥55% could be considered a reference for urban design in this latitude.

When the percentage sDA≥55% was adopted, the compliance cases increased significantly in number even for the worst solar orientation. For North (Figure 4), the percentages obtained from the cases with street of 5m are all insufficient; however, almost all simulated conditions complied for front obstructions until 18m height (max.6 floors), and for room depth below 6m.

The general results of this study might be valid for a similar case of dense urban context under predominantly partly cloudy sky. However, additional studies are necessary to investigate to which extension.

Conclusion

This paper explored the quantitative comprehension of the relation between urban design based on increased density and daylight access to prevent unsatisfactory urban conditions and the excessive energy consumption for artificial lighting, in a Savanna.

An urban parametric simulation was developed for a low latitude city in Brazil (Cuiabá, 15°35'S, 56°05'O). The IES LM 83-12 (ILLUMINATING…, 2012) was adopted as a main guide for the simulation: based in this document, a Spatial Daylight Autonomy sDA(300,50%)≥75% was established as the minimum desirable condition for indoor daylight; visual comfort was not addressed. For a test reference room with variable depth located in a continuous urban canyon, solar orientation, height of dense front obstruction, and street width were varied.

For this city located in the South hemisphere and with predominantly partly cloudy sky, solar orientation had a minor impact on sDA when compared to other simulated urban parameters. For an optimized urban daylight design, considering the defined parameters here simulated, street widths > 20m, room depths < 6m; height of front obstruction

< 41m (13 floors) offers the optimum scenario. In case of a room depth of 6m, a sky angle>34° already provides the minimum conditions. Room depth was found as the most relevant parameter for sDA in this case. Taking into account the results as per orientations, it is estimated that the differences of height between the sides of the canyon combined to outdoor reflectance were very significant aspects to sDA levels. The general results of this study are probably valid for similar cases; however, additional investigations are needed to confirm this and to which extension.

As an overall comment regarding the results, regression analysis was useful for determining the behavior and potential correlation between parameters; however, a complementary statistical method could add information regarding the most important aspects. Further simulations of window to wall ratio (WWR) should cover percentages lower than the 60% adopted here, which are more appropriate for the tropics and more representative of the residential sector. The definition of the threshold of 300lux and 75% was based on the researches which supported the IES LM 83-12 (ILLUMINATING…, 2012) for latitudes above 37° and developed for determined occupant activities, since similar investigations on the preferences of occupants regarding daylight in the tropics where not found. The pertinent percentage defined as a threshold for sDA must be supplementary discussed and investigated, considering that it is the element from which results would support to shape the local urban design. Future research should also focus on variable reflectance, as well as other urban typologies. The comparison of results of sDA in different sky conditions, latitudes, indoor and outdoor configuration is also an opportunity for investigations.

Finally, even though daylight is fundamental for health, productivity, energy savings and livability of cities, there are still several gaps in studies dedicated to the effect of density. This paper aimed to fill a part of the gap regarding urban daylight design, but there still are several points missing that call for a collective effort in further investigations, especially within the tropics.

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