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PREDICTING REALITY WITHIN THE VIRTUAL: EXPERIMENTAL VALIDATION OF DAYLIGHT SIMULATION TOOLS FOR ARCHITECTURAL SPACES IN THE TROPICS

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Abstract

This study aims to develop a validation method to identify the predictive capacity of two daylight calculation engines applied to real-life scenarios within the Tropics. The main objective is to determine the accuracy of the calculations generated by simulation tools in correspondence to measured illuminance values, defining which conditions would render the best results. To achieve this, a field survey with photometric measurements of an indoor working space under tropical sky conditions was compared with simulation results of two software tools: VELUX Daylight Visualizer and DIVA for Rhino. The results were validated using dynamic daylight metrics and statistical analysis. Overall, the results showed a consistent overestimation of the simulated Daylight Autonomy (DA) values in the range of 9% to 36% in the afternoon hours. Useful Daylight Illuminance (UDI) values presented less deviation ranging from 7% to 9%, under- and overestimating the measured illuminance values. However, in the afternoon hours, the deviation for the UDI was as high as for the DA values. Therefore, this study concludes that direct light beam incidence can be a determining factor for program selection and sky model configuration when conducting daylight simulations in the tropical belt. Furthermore, the results of this study contribute to identifying lighting and visual discomfort problems and allow informed decisions for software tool selection, as well as adequate simulation parameters to be applied under tropical sky conditions.

Keywords: Building simulation, Daylight performance, Light analysis, Retrofitting, Tool validation, Tropical climate.

1. Introduction

Evidence suggests that energy simulation programs are among the most important tools in predicting the performance of the built environment. By using design simulations, architects can begin to understand the effects of their design on energy use and become better at the practice of high-performance architecture [1]. The last decades have seen numerous advances in numerically analysing the overall performance of daylit spaces. These advances include a trend away from static and towards dynamic climate-based daylight simulations [2]. This is important since lighting simulation increasingly replaces traditional verification techniques [3]. However, it is necessary to analyse whether simulated results are accurate enough to represent daylight realistically.

This study aimed to develop a validation method to identify the predictive capacity of two daylight calculation engines applied to real-life scenarios within the Tropics. The main objective is to determine the accuracy of the calculations generated by simulation tools in correspondence to measured illuminance values and define which configuration would render the best results. To achieve this, a field survey with photometric measurements of an indoor working space under tropical sky conditions was done, comparing the results with digital simulations of natural light performed with two software tools: VELUX Daylight Visualizer [4], which approaches static daylight simulations and DIVA for Rhino, that simulates with a dynamic climate-based file. Climate-Based Daylight Modelling (CBDM) predicts various luminous quantities using solar and sky conditions derived from meteorological datasets. It, therefore, depends upon both locale and orientation, in addition to building configuration and composition [5].

A systematic literature review was conducted, focussing on daylight concepts, illuminance measurement methods, lighting simulation software and validation studies. More than thirty research studies were analysed, and almost half (43%) related to simulation tools. Most studies compared the performance between two or more simulation programs (14%). More research is needed to validate computational results with data obtained from real-life scenarios (7%). Only two studies were carried out in tropical regions. However, in this case, only daylight calculation engines were considered. A summary of the literature review is shown in Table 1.

Table 1. Literature review summary by topic [6].

	Number of studies	Publication date range
Illuminance measurement	2	1992-2005
Lighting simulation software	12	2006-2020
Validation studies comparing two or more simulation software	4	2009-2017
Validation studies comparing measured and simulated daylight	3	2001-2016
Studies performed in Tropical regions	2	2002-2011
Concepts and theoretical framework	7	2006-2013

Most advanced simulation programs have a similar internal component scheme. According to the research conducted by Bhavani and Khan [7], the following components are identified: sky, room and light process model. A sky model is a mathematical equation that describes the variation in luminance across the hemispherical sky vault. The simplest possible model describes a sky of uniform luminance [8]. In the Tropics, it is necessary to define sky distributions under a range of scenarios, from a clear sky to a cloudy sky and overcast conditions. Tropical countries are regions with non-seasonal climates marked by high rainfall periods. Thus, cloud coverage and sunshine are highly variable and must be tested according to hypothetical situations to obtain precise results.

The most important climatic modifiers for Costa Rica are the trade winds, the seasonal migration of the Intertropical Convergence Zone (ITCZ), the episodes of cyclones in the Caribbean, and the effect of cold fronts from the north. All these phenomena contribute to modulating cloudiness and precipitation and, consequently, the number of sunshine hours available in each region and time of the year [9]. This situation is difficult to simulate and marks a gap between daylight simulations in tropical latitudes and other locations with more stable sky conditions.

A study that highlighted the problem of discrepancy between simulation and reality analysed the applicability of daylighting simulation in existing buildings. They compared the horizontal illuminance measured at selected points within an atrium building located in Ottawa and simulated the same space [10]. Their main objective was to verify the accuracy of the Adeline program in predicting the horizontal illuminance of the interior according to daylight exposure. In this case, the on-site measurements were done in June and December to address both summer and winter conditions. The authors emphasised the importance of indicating the visible transmittance and reflectivity of all the surfaces in the digital model.

In a more advanced study, LBNL's RADIANCE program was used, which provides a Light Reflectance Values (LRV) database for each material and grants flexibility for measured data input [11]. In the case of tropical regions, this is relevant, specifically having a history of Global horizontal irradiance (GHI), which allows for determining the sky condition on point-in-time simulations. Dynamic simulations can be done by applying the Perez sky luminance model, which simulates indoor illuminances under sky conditions calculated with specific GHI input data. The study recommended simulations with various sky conditions when no input data is available. It was found that the illuminance distribution patterns in both the on-site measured values and the digital prediction were correctly simulated; however, some points were overestimated.

Another study using RADIANCE looked specifically at tropical sky conditions with an experimental approach, comparing simulated and measured illuminance [12]. The authors argued that tropical sky conditions fundamentally differ from established standard sky conditions and therefore need specific parameter settings. This was confirmed in an experimental test room in tropical Malaysia using illuminance meters for indoor and outdoor measurements while recording the sky conditions with a Fisheye camera on an hourly basis. The results showed a mean difference between the measured and simulated values of 25.5% for the relative ratios and 76% for the absolute ratio of Daylight Factors and Daylight Ratios. The study concluded by validating RADIANCE for furnished and unfurnished rooms under tropical sky conditions.

The comparison between measured and simulated daylighting in the reviewed studies demonstrated that, for any particular sky condition, the computer model has the potential to predict daylighting behaviour in an indoor space accurately, given precisely modelled geometry, detailed material properties, specific climatic parameters and the exact sky conditions. Nevertheless, more validation studies can benefit further research about the precision of the tools on the market and establishing the parameter settings that would render the most accurate results under tropical sky conditions.

2. Methods

The following section outlines the different methods used to conduct this study. In the first part, the context and conditions of the experimental room used are described, followed in the second part by details of the field measurements. The third part describes the procedures and settings for the performed daylighting simulations.

2.1. Description of the Case Study

The study was conducted in the Tropical Architecture Laboratory (LAT) at the University of Costa Rica (UCR). Located in eastern San Jose, at a latitude of 9°56'N and a longitude of 84°3'W, the space has access to natural light on two façades through glazed surfaces: Northeast and Southeast. It is located on the third level of the building, with a floor-to-ceiling height of 3.60 meters.

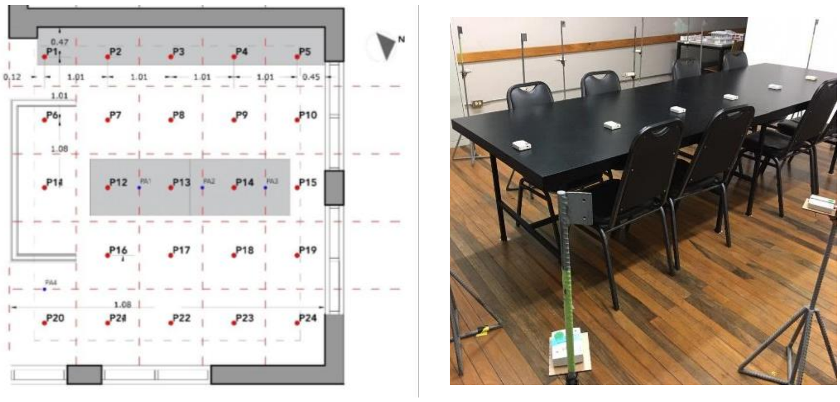
The location was chosen for the following reasons: the existing furniture has a black low-reflective material that reduces secondary reflections, the room has a regular shape, the blinds could be uninstalled to perform the measurements, and public access was limited on weekends. These features allowed to focus on analysing elements affecting the light distribution directly and exclude other indirect factors. GHI data from the weather station on the University campus, at a 1.2 km distance from the monitored space, was used to determine the sky condition during the measurement days.

2.2. Field Measurements

Monitoring of the daylight performance at the laboratory space was conducted in December 2019, during rainy season conditions. This period was selected to meet extreme sun angles from the south (winter solstice). The density of test points was defined according to Brazilian Technical Standard NBR15215-4, called "Natural lighting - Part 4: Experimental verification of internal lighting conditions in buildings" [13]. More test points were included to increase the resemblance with the digital grids, as shown in Fig. 1(a).

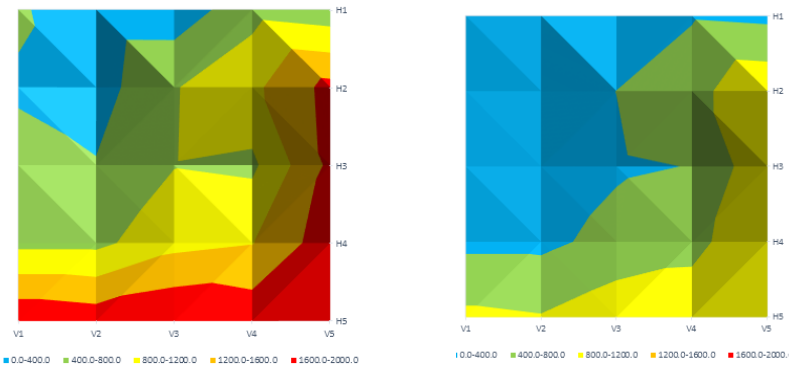
For the measurement of the indoor relative light levels, Hobo U12-012 data loggers with a range of 0 - 32,300 lumens/m^2, and an accuracy of ± 2.5% of the absolute reading, were used. The work plane where the measurement devices were placed was set at 0.8m above the floor level. Measured parameters included horizontal indoor illuminance at each point. To raise the reliability of average values, each data logger was set to save information every 10 minutes. A total of 580 measurements per point were recorded. Subsequently, a method was developed to plot the photometric curves with gathered data and compare them with the digital simulation results. In addition, hourly averages of illuminance per point (E), average illuminance of the entire space (E_m), as well as static daylight autonomy

(*DA*$_{400lx}$) were generated. The photometric patterns were used to compare results and determine whether the digital simulation corresponds to the on-site measured daylight conditions. A false colour scale with blue for the darkest areas and red for the brightest was applied (shown in Fig. 2) for comparison with the results from the daylighting simulation programs.



(a) Floorplan. **(b) Photo of LAT.**

Fig. 1. Point grid (a) used for illuminance measurements in the LAT (b).



(a) Illuminance results at 12 p.m. **(b) Illuminance results at 3 p.m.**

Fig. 2. Samples of dynamic graphs generated in Excel, showing a plot of calculated daylight illuminance based on measurements.

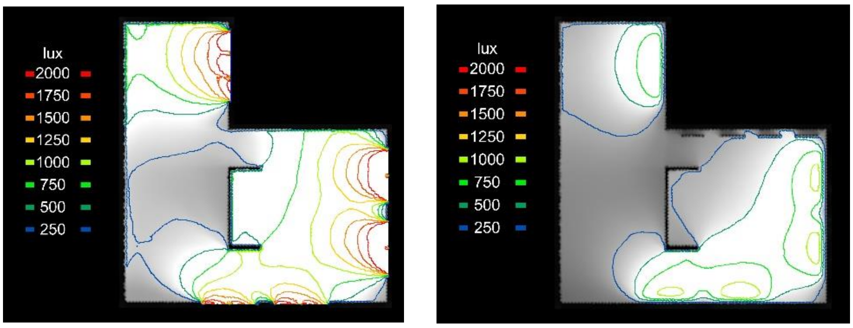
2.3. Computer Daylight Simulations

The evaluation was performed with two daylight simulation programs with different characteristics: VELUX Daylight Visualizer and DIVA for Rhino. The type of simulation performed by VELUX is static, which means that generating results requires the specific position of the sun (azimuth and solar altitude according to the location, day and time of the analysis). On the contrary, DIVA performs static and dynamic simulations, which implies the creation of a weather file containing average data of multiple parameters: temperature, humidity, radiation, and wind, among others.

Once the boundary conditions of the simulation were defined, a three-dimensional model of the site was prepared, including all the information necessary to determine the lighting performance: the shapes of the enclosure surfaces, the location of the furniture, material emissivity and colours of all surfaces, with their respective LRV and the orientation of the building. Together these parameters constitute the digital twin of the space. However, due to the different format requirements of the simulation engines, two models were made, one for each program.

The simulations were carried out during the month of November to allow the comparison with the field survey matching period. Three different hours were chosen to analyse the behaviour during the entire day (9 a.m., 12 p.m., and 3 p.m.), mainly because of the east orientation of the openings and expected light variability.

Tests were performed with three different sky conditions: clear sky, partly cloudy sky and overcast sky. Illuminance and luminance were calculated, keeping the same colour scale for all simulations, as this allows a correct comparison. Sample result images (see Fig. 3) were used during the validation process to determine which sky conditions resembled the measurements of the day more realistically. San Jose is a city with highly variable cloudiness, typical to the tropical region; therefore, different sky conditions can exist on the same day, which must be considered.



(a) Illuminance at December 9 a.m., clear sky.

(b) Illuminance at December 3 p.m., cloudy sky.

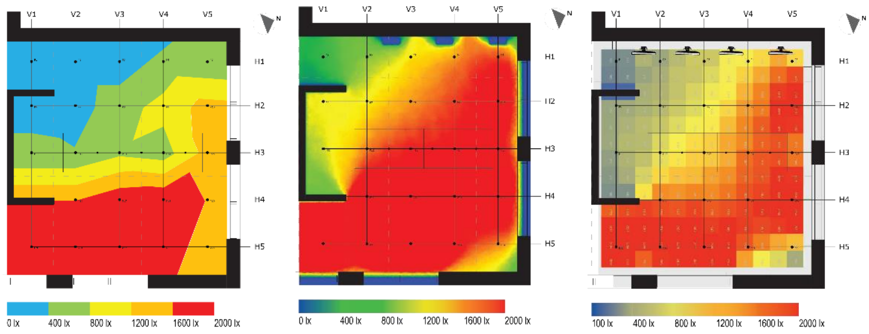
Fig. 3. Plotted simulation results of lighting levels generated in VELUX DAYLIGHT VISUALIZER on a scale from 300 lx to 2000 lx.

To evaluate and validate the correlation between the two simulation methods and the site surveys, three different daylighting metrics were selected: average Illuminance (E_m), Useful Daylight Illuminance ($UDI_{400\text{-}2000lx}$) and Daylight Autonomy (DA_{400lx}). The applied method was not intended to compare identical values, but to analyse patterns of light distribution, considering the same room conditions, sky model, time of day and day of the year in each scenario analysis.

3. Results and Discussion

In Costa Rica, during the month of November, south-facing surfaces receive a greater incidence of solar radiation. This had to be considered, especially for the 9 a.m. scenario, since one of the facades of the LAT has openings facing southeast.

The following section discusses the results for the 9 a.m. scenario, with result plots shown in Fig. 4.



(a) E_m: 1688 lx. **(b) E_m: 1949 lx.** **(c) E_m: 1338 lx.**

Fig. 4. Comparison between Illuminance results at 9 a.m. with the partly cloudy sky: (a) Field measurements, (b) VELUX simulations, (c) DIVA simulations.

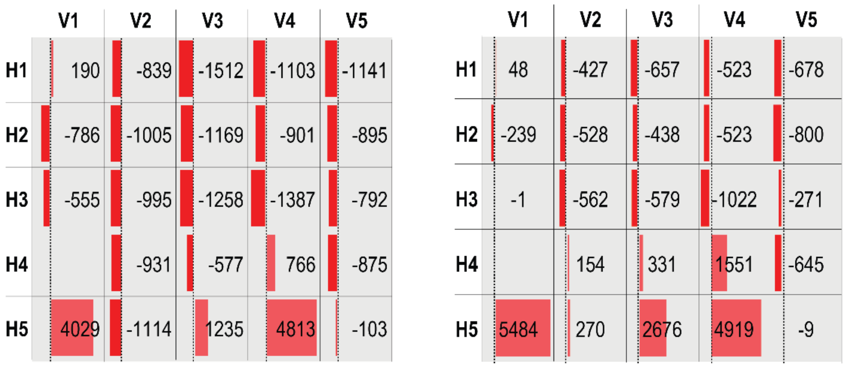
The plot in Fig. 4(a) shows that the percentage of UDI in the space is 60% at 9 a.m. Likewise, the E_m of the laboratory space is 1688 lx, a value within the accepted range. However, it can generate glare when it exceeds 2000 lx due to high contrast and non-uniformity. These values are recorded under a partly cloudy sky condition.

The results observed in plots Figs. 4(b) and (c) compare well with the measured values, showing a similar trend of excess illuminance near the southeast and northeast façades. Overall, the photometric pattern is very similar in all three cases. In the simulated results in VELUX, Fig. 4(b), 66% of the area was in the range of Useful Daylight Illuminance ($UDI_{400Lx\text{-}2000Lx}$), while in DIVA, Fig. 4(c), 68%. The minimum and maximum illuminance points, p1 and p22 (points adjacent to the southeast window), were nearly identical in both simulations. The E_m value in Fig. 4(b) is closer to the average. However, the results for Fig. 4(b) also show that 44% of the area has excess light, while in Fig. 4(c), it is only 20% of the area. Overall, the simulated results compare well to the measured values.

Accordingly, an average deviation value was calculated for all measurement points (Fig. 5) to determine which software provides closer results to reality. At 9 a.m., the most proximate result was simulated with DIVA, with an average value of $\sigma = 972$, while the one simulated with VELUX was $\sigma = 1207$. It is important to note the application of the Perez method to determine the type of sky in DIVA using the measured irradiation values provided by the meteorological weather station.

By midday, the simulation results obtained with VELUX were closer to the measured values, with an average deviation value of $\sigma = 320$, while those obtained with DIVA marked $\sigma = 496$. In both cases, the prediction of the light scenario is closer to the actual measured results than in the simulations at 9 a.m. In addition, the method for determining the sky type was not as conclusive in this case, a factor that might have influenced the results.

The last lighting scenario corresponds to 3 p.m. in the afternoon. When calculating the average deviation for this scenario, the VELUX simulation was the most accurate, with an average value of $\sigma = 340$. At the same time, the DIVA results had an average deviation of $\sigma = 381$. However, the scenario of measured and simulated illuminance during the afternoon showed the most accurate matching results obtained within this study. The difference between both simulated scenarios and the measured value was neglectable.



(a) S1: Simulation with Velux. **(b) S2: Simulation with DIVA.**

Fig. 5. Point-to-point average deviation results at 9 a.m.

Taken together, these results suggest an overall close agreement between measured and simulated results. However, a consistent overestimation of the simulated Daylight Autonomy ($DA_{400\text{-}2000lx}$) values in the range of 9% to up to 36% were observed in the afternoon hours. Useful Daylight Illuminance values (UDI_{400lx}) presented less deviation ranging from 7% to 9%, with some scenarios under- and others overestimating the illuminance compared to the measured values. During afternoon hours, the deviation for the UDI was as high as for the DA values. Therefore, when it comes to cases with more direct light beam incidence, this can be a determining factor for program selection and sky model configuration.

4. Conclusions

The use of daylighting as a primary source of illumination for human activities requires planning during the early stages of design, as its variability over time can affect design decisions and must necessarily be considered. Therefore, learning and implementing new methods to evaluate lighting behaviour within architectural spaces is necessary. Energy and daylighting simulations allow designers to identify undesirable scenarios and propose solutions before building in a faster way and even with multiple variations. However, it is important to validate the results of a simulation program to know its benefits and limitations, as well as the margin of error of its predictions.

The results of this study showed that computer models have the potential to accurately predict daylighting behaviour of architectural spaces in a tropical environment if relevant input data such as exact geometry, detailed construction information with material properties and description of the correct sky model, either from radiation data or sky images, are available. However, it is noteworthy that this study was limited by spatial and temporal constraints, analysing only one space layout for two weeks. Nonetheless, the developed validation method is considered applicable also for analysing other daylight simulation tools which designers commonly use along the global tropical regions.

Notwithstanding these limitations, it can be concluded that the obtained illuminance values are within the ranges observed in the on-site measurements. It is, therefore, possible to design with daylighting patterns, trends and behaviours obtained from both simulation tools. However, it is worth mentioning that the illuminance values obtained have a more significant deviation in the morning hours. In this case, the program that provided a closer data match with the measured results was DIVA. When analysing the results obtained during the afternoon hours at 12 p.m. and 3 p.m., VELUX results were closer to the measured values. Likewise, the maximum, minimum and average illuminance values remained within the same range observed under partially cloudy sky conditions. In general terms, this might suggest that if daylight analyses in the Tropics are performed under clear skies, the deviation from the average may increase since there is a greater probability of receiving direct light incidence.

In the context of the energy crisis and climate change, understanding energy performance and consumption from the early design stages is essential. The procedure used in this study was considered an appropriate validation technique. The method allows to determine the quality of daylight and whether it is necessary to implement a complementary energy efficient artificial lighting system. Future research should consider expanding the list of software to obtain a more comprehensive overview of the predictive accuracy of daylight simulations.

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Nomenclatures

E	Hourly averages of illuminance per point
E_m	Average Illuminance of the entire space
GHI	Global Horizontal Irradiance
DA_{400lx}	Static Daylight Autonomy at 400 lx
$UDI_{400\text{-}2000lx}$	Useful Daylight Illuminance between 400 and 200 lx

Greek Symbols

σ	Average Deviation

Abbreviations

CBDM	Climate-Based Daylight Modelling
DA	Daylight Autonomy
ITCZ	Intertropical Convergence Zone
LAT	Tropical Architecture Laboratory

LRV	Light Reflectance Value
UCR	University of Costa Rica
UDI	Useful Daylight Illuminance

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