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Comparison between Radiance Daylight Simulation Software Results and Measured on-Site Data

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Abstract

The paper focuses on comparing the popular daylight simulation software results against the measured on-site data; it investigates software accuracy and its limitations when used to calculate the daylight illuminance in clear sky conditions. The objective of the study is to examine the existence of any discrepancy and identify any systematic trend between actual and predicted results. Petrodar and NTC, both high-rise office buildings in Khartoum, were selected as case studies for the validation purposes. The study concluded that the diffuse daylight was simulated more accurately than the direct component. The variation between the measured values and simulated ones occurs at the points facing direct sunlight, and mostly when the sun comes at a low angle, this variation reached twice the measured in four cases. The study highlights the need for more refinement of the software when simulating direct component of daylight in clear sky conditions.

المستخلص

يركز هذا البحث على التحقق من صحة النتائج المستخرجة بواسطة برنامج Radiance والتي تتعلق بحساب كمية الإضاءة الطبيعية داخل المباني، فالدراسة تقوم بتحري مدى دقة تلك النتائج ومعرفة القيود التي تواجه المستخدم للبرنامج عند حساب الإضاءة الطبيعية. والغرض من هذه الدراسة هو معرفة العلاقة بين القيم المقاسة في الموقع مقابل النتائج المتوقعة من البرنامج, والتحقق كان عن طريق إجراء مقارنة بينهما, وقد تم اختيار برجي بترودار والهيئة القومية للاتصالات كعينة دراسة. وخلصت النتائج إلى أن الإضاءة الطبيعية المتشتته يتم توقعها بدقة اكبر من ضوء الشمس المباشر، و الاختلاف بين القيم المقاسة والقيم المتوقعة من البرنامج يحدث في النقاط التي تواجه ضوء الشمس المباشر ويزيد مقدار الاختلاف عندما تكون الشمس في زاوية منخفضة، وقد يصل الاختلاف إلى ضعف القيمة المقاسة في أربعة حالات. الدراسة سلطت الضوء إن برنامج Radiance يحتاج لمزيد من التدقيق عند حساب ضوء الشمس المباشر في حالة السماء الصافية.

Keywords: Validation, daylight simulation software, Radiance, clear sky conditions, Khartoum, Sudan.

1. Introduction

Daylight design in hot arid climates is quite challenging. Designing openings is particularly difficult; as it should provide not only light and ventilation, but also keep unwanted solar gain to the minimum. This is more critical in office buildings, where energy consumption is typically quite high. Artificial lighting accounts for more than 40% from its total electricity consumption, consequently daylighting is recognised as a key strategy to achieve energy efficiency [1].

Architects introduce daylight into buildings to enhance the visual indoor quality, ensure healthy comfortable environments and improve occupants' productivity [1-2]. Due to the importance of daylighting in building design, an increasing number of simulation software were developed to predict and simulate interior illuminance. Radiance is considered as the best illuminance distribution tool for use at the design stage [1]. In a web-based survey of 185 designers, engineers and researchers from 27 countries on the use of daylight simulation during building design, the participants named a total of 42 different daylight simulation programs they routinely used. Over 50% of programs selected were for tools that use the Radiance simulation engine [3].

Radiance development started in 1984 at the Lawrence Berkeley Laboratory, Berkeley, USA [4]. It uses a backward ray-tracing technique, which creates a three-dimensional photo-realistic representation of a space, allowing glare and visual comfort studies. Illuminance values and daylight factors can be obtained as well [5].

Although Radiance is praised for its accurate simulation of indoor illuminance, many studies emerged comparing actual to measured values. None of them, however, was under sky conditions similar to that of Khartoum. The aim of this paper is to examine the congruency between Radiance's actual and predicted results. In case of significant discrepancy, it will identify when and why Radiance results are different.

2. Historical Background

2.1 Radiance Previous Validation Work

Galasiu and Atif [5] carried out a validation of three daylight simulations: Superlite, Superlink and Radiance. The study was carried out in a three-storey enclosed atrium space located in Ottawa, Canada, in both summer and winter conditions. The accuracy of the programs in simulating interior daylight levels was evaluated based on comparisons between the predicted and on-site measured illuminance. Radiance results showed that diffuse daylight was simulated more accurately than the direct component. There is a good agreement between predicted outputs and actual measurements under diffuse daylight for both summer and winter clear and overcast sky.

Another similar validation study was conducted in the Asian Civilisation Museum in Singapore. The study concluded that Radiance can be used to predict the internal illuminance with high degrees of accuracy under overcast sky conditions [6-7].

A third study by Jarvis and Mike [8] investigated the accuracy of Radiance results as well the balance between computer calculation time and Radiance rendering settings. The main result was that Radiance predictions of the internal lighting distribution under idealised sky distributions are highly dependent on rendering parameters. A high degree of correlation between predictions and measured results was obtained. The previous study, however, investigated the overall illuminance distribution agreement without examining the instantaneous discrepancy between measured and simulated illuminance [8].

A fourth similar study [9] was carried out in the humid continental climate of Seoul, Korea. The study compared Radiance results to those of ten photometers inside a scaled model. The results showed relative error between Radiance predicted results and the measurements on the scale model. As a result, the authors introduced a correction factor [9]. Their study is considered the first recent study to use results from a single case of predictions and monitored data to find a trend between Radiance software predicted results and the Luxmeter measurements. However, their correction factor is not suitable for use in Khartoum's clear sky conditions.

2.2 Radiance Sky Model

The source of daylight is the sun, while the scattering of sunlight in the atmosphere by air, water vapour, dust, and so on gives the sky the appearance of a self-luminous source of light. So both sun and the sunlight scattered in the sky are treated as a light source. The sky has the same shape and position but the brightness pattern of the sky can be difficult to characterise, so it was necessary to devise ideal sky brightness patterns known as sky models [10].

Radiance uses gensky"*sub-program that generates Radiance's scene description for the Commission Internationale de l´Eclairage (CIE) standard sky distribution at the given month, day and time* [11]" to generate a description of the sky, it uses the CIE standard sky model in three forms, the first one by specific date (month-day-time). The second one by giving the solar angles explicitly, the altitude measured in degrees above the horizon and the azimuth is measured in degrees west of South. The third form prints the default option values [11].

Moreover, Radiance uses a definition of sky that is more complex than that of other programs, adding the effect of turbidity in the distribution of luminance of the sky [12].

2.3 Radiance's Validation Acceptable Magnitude of Error

When performing a validation study, it is important to establish the acceptable magnitude of error. Daylighting studies rarely report a target accuracy, but a typical expected simulation error may be extrapolated from multiple studies [13]. The study was done by Ng et al [7] in Radiance validation reports errors of up to 20% at individual sensors, while it is unknown whether this error stems from measurement or simulation. A study in Freiburg, Germany, validated simulation results of annual indoor illuminance distribution for two office buildings. It used six different Radiance-based simulation methods and found Root Mean Square Errors (RMSEs) in illumination ranging from 16% to 63% [14].

Reinhart and Walkenhorst [15] also validated the dynamic Radiance-based daylight simulation method DAYSIM, and found errors under 20% and

RMSE under 32%. The previous percentages of errors have been considered as acceptable maximums compared to Reinhart and Breton [16] who found higher errors in 15 out of 80 data points in their study.

Using advanced modelling and measurement techniques, Reinhart and Anderson [17] reduced the error to 9% and RMSE of 19%. However, they allowed 20% error in daylight simulation results used in energy calculations. This was also deemed acceptable by McNeil and Eleanor [18]. From the above discussion, a threshold of 20% Mean Bias Error (MBE) and 32% RMSE in illuminance simulations appears to be typical in daylight studies. Accordingly, a similar error range will be deemed acceptable in this study.

3. Methodology

A well-established methodology for validating daylight simulation programs is to examine the illuminance difference between measured on-field data and computer simulation [1-2]. Accordingly, this study follows the same methodology using two case studies of real buildings. Existing buildings offer an important reference point for the evaluation; it gives the opportunity to measure the actual lighting conditions inside the building for comparison with the daylighting predicted by Radiance.

The two case studies are both high-rise office buildings in Khartoum; Petrodar HQ (15 floors) and the National Telecommunications Tower NTC (25 floors).

3.1 Case Study A

Petrodar Headquarter tower was selected as the first study case. The tower is a 15-storey building and was the first to be completed in (Al-Sunut) the new Khartoum CBD (central business district) in the Nile confluence area. The site is at a latitude of 15.65°, a longitude of 32.15° and an altitude of 383 m [19]. The tower’s façade is a combination of curtain walls and aluminium cladding. The reflectance of walls and ceilings inside the tower has been estimated to be between 57-65%; walls are painted with light grey colour; with white colour gypsum board ceiling. Partitions are solid MDF (medium density fiberboard) with aluminium frame having an off-white colour, floors are finished with porcelain tiles having a reflection of 80% [20].

The measurements were taken on the 11th floor to minimise the obstruction and reflectance effects. Fig. 1 shows a typical floor plan. The tower's main occupancy occurs between 8:00 to 16:00 hours.

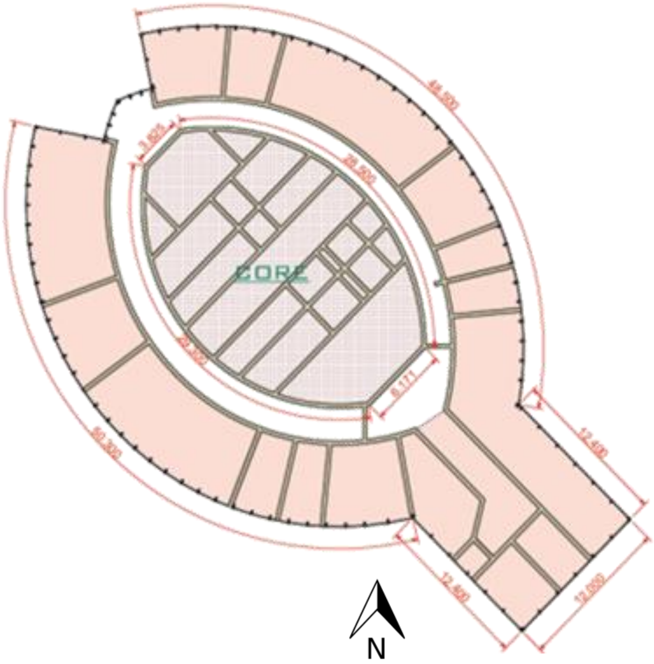

Fig. 1: Petrodar tower typical floor plan

The illuminance level was measured at five locations inside the building; these points were selected on the floor perimeter facing all cardinal directions. Fig. 2 shows the locations of the test-points on each floor.

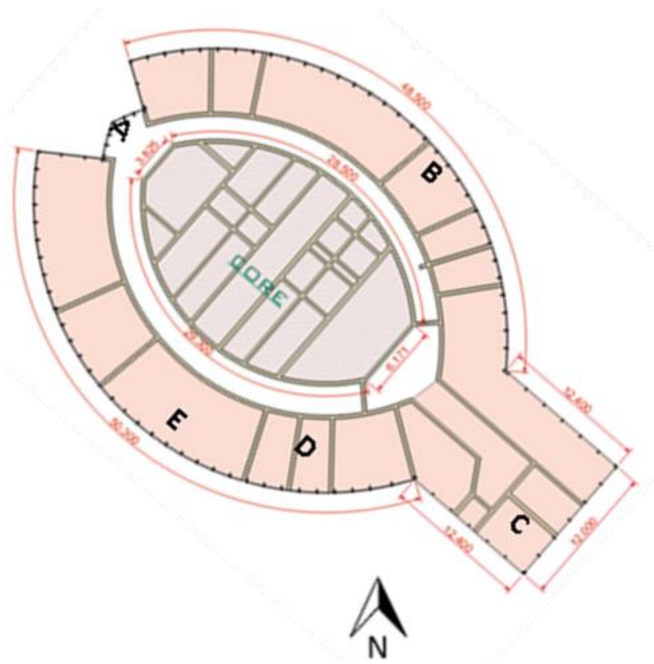

Fig. 2: Test point locations at 11th floor

The measurements were taken in two days during the autumn season on 9th of April 2015, both software simulation results and the Luxmeter readings were taken at 8:00 and 14:00, the field work included measurements of horizontal indoor and outdoor illuminance.

The lighting source was taken as daylight obtained from indirect and direct sunlight source. The artificial lights were switched off.

3.2 Case Study B

NTC HQ was selected as the second case study, it is a 25-storey office building located in Burri, Nile Street. The site is at a latitude of 15.6°, a longitude of 32.58° and an altitude of 383 m [19]. The tower's façade is a combination of curtain walls and aluminium cladding at the North East (NE) and South East façades (SE), and transparent photovoltaic cells (PV) at the South West (SW) façade.

Two types of PV cells are distributed throughout the SW façade, transparent panels are at the vision height 2.7m above the floor level, and opaque panels cover the rest of each floor's height.

The reflectance of walls and ceilings inside the tower was estimated at 70 - 80%. The walls are off-while colour white the ceiling was a combination of 60x60 aluminium tiles and white gypsum board. The floors are finished in marble tiles with a reflection of 80% [20].

The measurements were taken on the 17th floor based on the same criterion in case study A. Fig.s 3 and 4 show the typical floor plan and a section of the building. The tower's main occupancy occurs between 8:00 to 16:00 hours.

The illuminance level was measured at five locations inside the building; these points' locations were selected on the floor perimeter facing all cardinal directions. Fig. 5 shows the locations of the test-points on each floor. The measurements were taken during three days in winter season on 3rd, 13th and 20th of March 2016, both software simulation results and the Luxmeter readings were taken at 8:00, 12:00 and 16:00. The fieldwork included measurements of horizontal indoor and outdoor illuminance. The lighting source was taken as daylight obtained from indirect and direct sunlight source. The artificial lights were switched off.

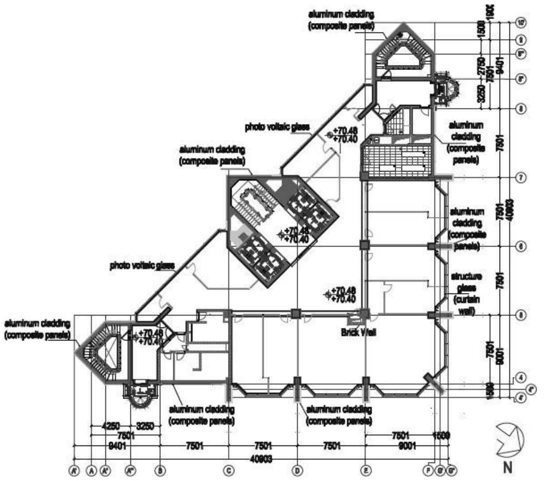

Fig.3: NTC typical floor plan

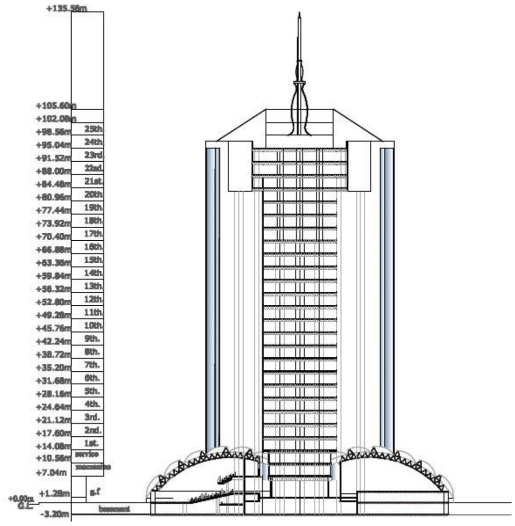

Fig.4: Section of NTC building

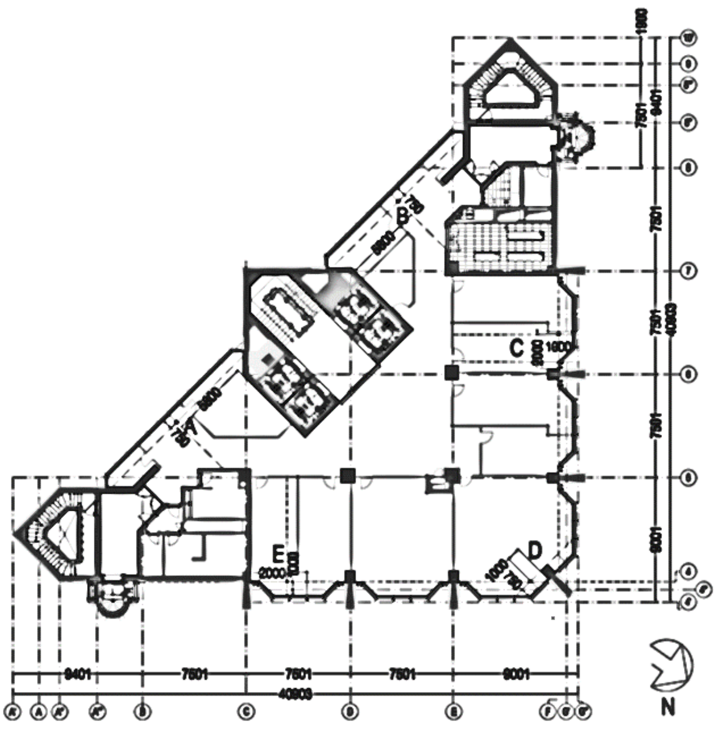

Fig. 5: Test points location at the 17th floor

The Luxmeter used for this study is model Mavolux5032B which measures brightness in lux, fc or cd/m², with sensitivity and accuracy in accordance with DIN 5032-7, IEC 13032-1 and CIE 69. The device was placed at 1.3 m above the finished floor level to avoid the obstruction effect of office furniture.

Meteonorm software, a comprehensive meteorological reference, was used to create Khartoum's weather file. Meteonorm compiles data from 8325 weather stations including Khartoum [21].

The accuracy level was evaluated based on comparisons between the Radiance's predicted results and the site measurement.

4. Results and Discussion

The validation work included two tasks: on site monitoring and computer simulation.

4.1 On-site Monitoring

4.1.1 Case Study A

The on-site measurements of indoor illuminance were carried out at five locations inside the building. They were taken on 9th of April 2015, both software simulation and the Luxmeter readings were taken at 8:00, 14:00. Moreover, the fieldwork included measurements of horizontal indoor and outdoor illuminance. Fig. 6 shows the annual sun path diagram marking the sun's position during the testing hours.

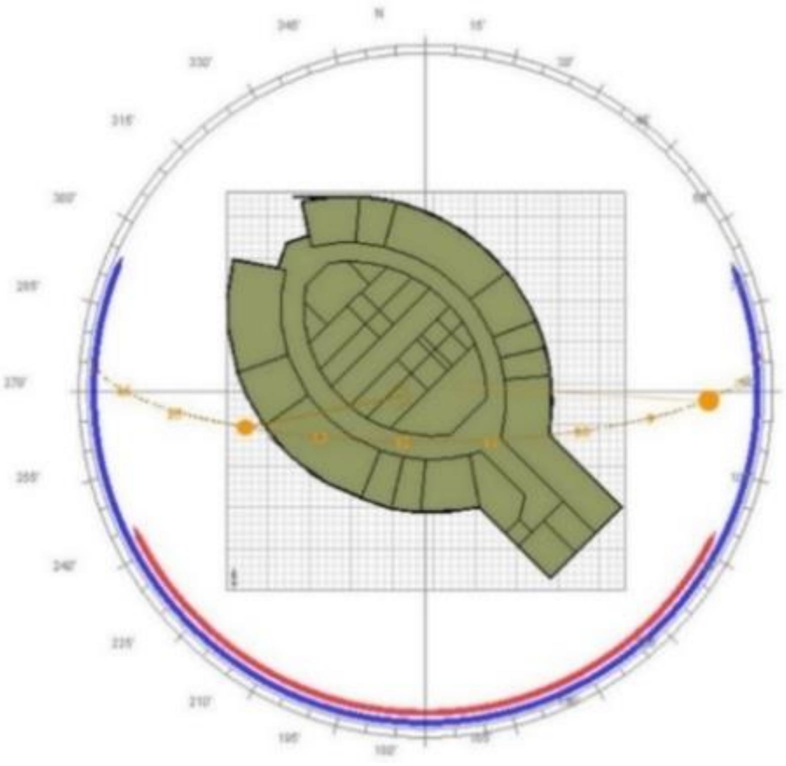

Fig. 6: Annual sun path showing the sun's position during the testing hours for case study A

4.1.2 Case Study B

The on-site measurements of indoor illuminance were carried out at five locations inside the building. They were taken on three days 3rd, 13th and the 20th of March 2016, both software simulation and the Luxmeter readings were taken at 8:00, 12:00 and 16:00. Similar to case study A, the fieldwork included measurements of horizontal indoor and outdoor illuminance. Fig. 7 shows the annual sun path diagram marking the sun's position during the testing hours. The measurements were taken at 1.3 m above the finished floor level to avoid the obstruction effect of office furniture. Measurements represent the indoor illuminance using the Lux units.

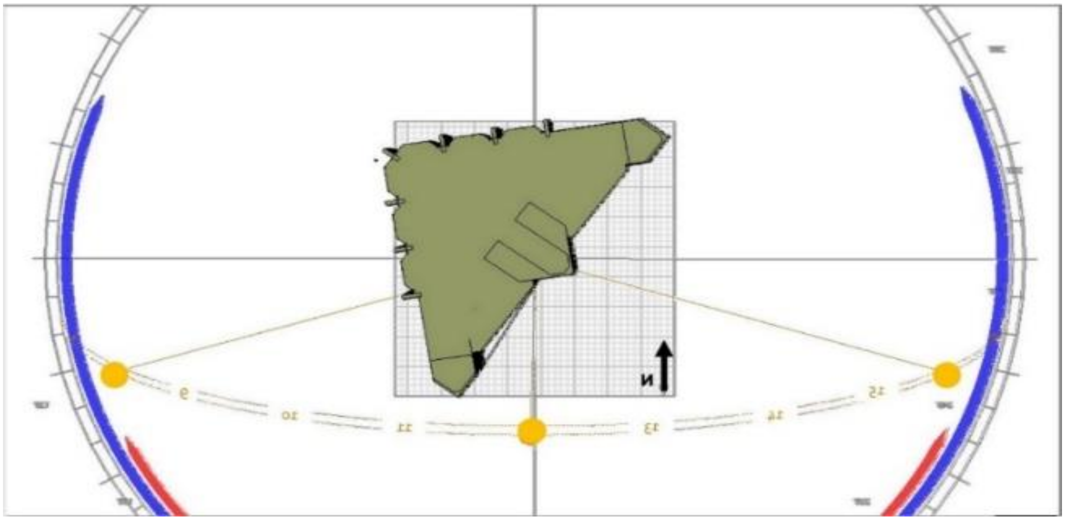

Fig. 7: Annual sun path shows the sun's position during the testing hours at case study B

Table 2, 3 and 4 represent the on-site measurements taken on 3rd, 13th and the 20th of March 2016 at 8:00, 12:00 and 16:00, at five locations on the 17th floor of NTC tower.

Table 2: Measured indoor illuminance for case study B in Lux on March 3rd, 2016

Hours	**Locations**				
	A	**B**	**C**	**D**	**E**
08:00	126	170	340	7,020	9,400
12:00	333	245	712	1,650	1,420
16:00	3,100	3,400	413	502	480

Table 3: Measured indoor illuminance case study B in Lux on March 13th, 2016

Hours	Locations				
	A	B	C	D	E
08:00	130	101	540	2,900	1,800
12:00	570	319	640	1,650	1,300
16:00	3,180	2,600	710	710	565

Table 4: Measured indoor illuminance case study B in Lux on March 20th, 2016

Hours	Locations				
	A	B	C	D	E
08:00	099	082	552	3,350	5,400
12:00	231	256	812	1,320	369
16:00	3,700	3,880	300	508	601

4.2 Computer Simulation

4.2.1 Input and Run Characteristics of the Software

The input file was a 3D Studio file originally generated in ArchiCAD 18 allowing all the geometric complexity of Petrodar and NTC tower to be accurately modelled, edited by Ecotect modelling to suit the program's nature as shown in Fig. 7. The building materials properties were well addressed in Ecotect [20]. The image generated by Radiance is an illuminance image, it shows the amount of light falling on each surface. It is a purely analytical image showing Lux levels. The lighting analysis is presented as surface and point analysis which calculates and stores levels at specific points in the model, and then reads back as grid point values. The sky condition that has been used in the simulations is a sunny sky using the CIE clear sky model to generate a localised sun and clear blue sky to represent a best-case summer design condition.

4.2.2 Simulated Results

I. Case Study A

a) 9th of April 2015 Simulated Results

Table 5 represents Radiance model simulated results for each of the five points at the same times of actual measurements. The illuminance ranged from 1,137 Lux to 12,003 Lux at 8:00, while it ranged from 1,430 - 12,304 Lux at 14:00.

Table 5: Simulated indoor illuminance for case study A in Lux on April 9th, 2015

Hours	Locations				
	A	B	C	D	E
08:00	1,140	12,003	4,216	1,137	1,331
12:00	1,584	1,542	1,430	7,004	12,304
16:00	1,140	12,003	4,216	1,137	1,331

Fig. 8 and Fig. 9 illustrate the grid analysis showing the illuminance levels at the selected floor at 8:00 and 14:00.

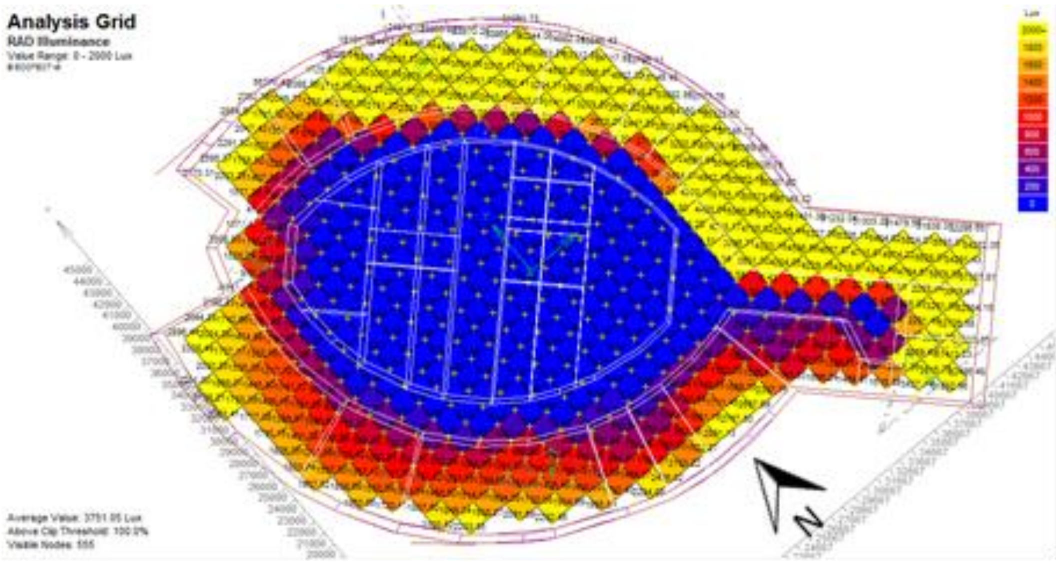

Fig. 8: Indoor illuminance grid analysis - April 9th, 2015 8:00

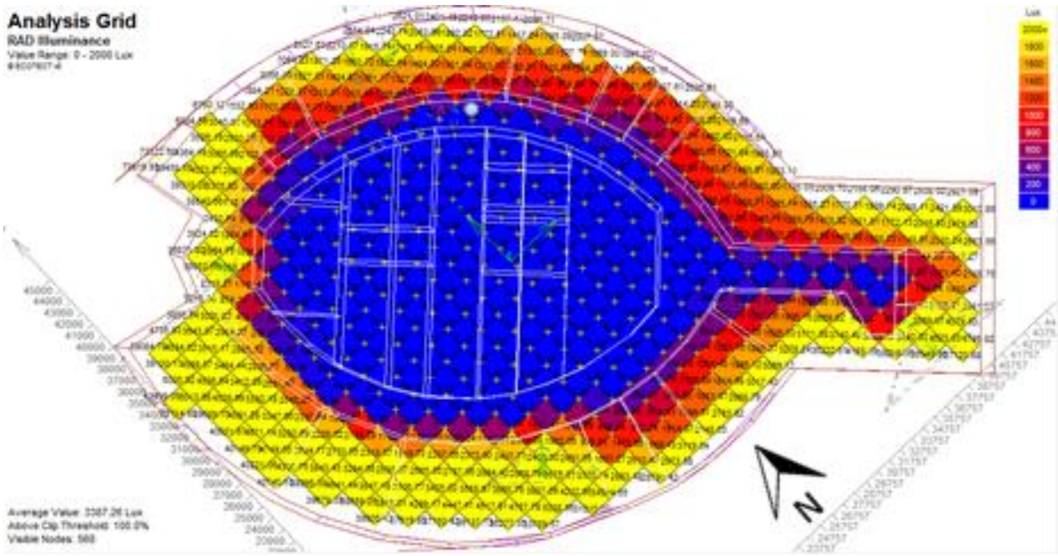

Fig. 9: Indoor illuminance grid analysis - April 9th, 2016 14:00

II. Case Study B

a) 3rd of March Simulated Results

Table 6 represents Radiance model simulated results for each of the five points at the same times of actual measurements. The illuminance ranged from 165 Lux on the SW point A to 9,000 Lux on the NE point D at 8:00. At 12:00 the simulated illuminance results range from 446-1,021 Lux, while it ranged from 451 Lux at the eastern point E to 3,829 Lux at the SW point A at 16:00.

Table 6: Simulated indoor illuminance for case study B in Lux on March 3rd, 2016

Hours	Locations				
	A	B	C	D	E
08:00	165	200	495	9,000	8,414
12:00	446	465	702	1,021	905
16:00	3,171	3,829	458	539	451

Fig. 10, 11 and 12 illustrate the grid analysis showing the illuminance levels at the selected floor at 8:00, 12:00 and 16:00.

b) 13th of March Simulated Results

Table 7 represents Radiance model simulated results for each of the five points at the same times of actual measurements. The illuminance ranged from 140 - 2,128 Lux at 8:00, and it range from 405 to 1,046 at 12:00, while it ranged from 458 Lux at the northern point C to 3,130 Lux at the SW point A at 16:00.

Fig. 13, 14 and 15 illustrate the grid analysis showing the illuminance levels at the selected floor at 8:00, 12:00 and 16:00.

Table 7: Simulated indoor illuminance for case study B in Lux on March 13th, 2016

Hours	Locations				
	A	B	C	D	E
08:00	140	153	484	1,467	2,128
12:00	405	448	741	1,046	926
16:00	3,130	2,465	458	546	473

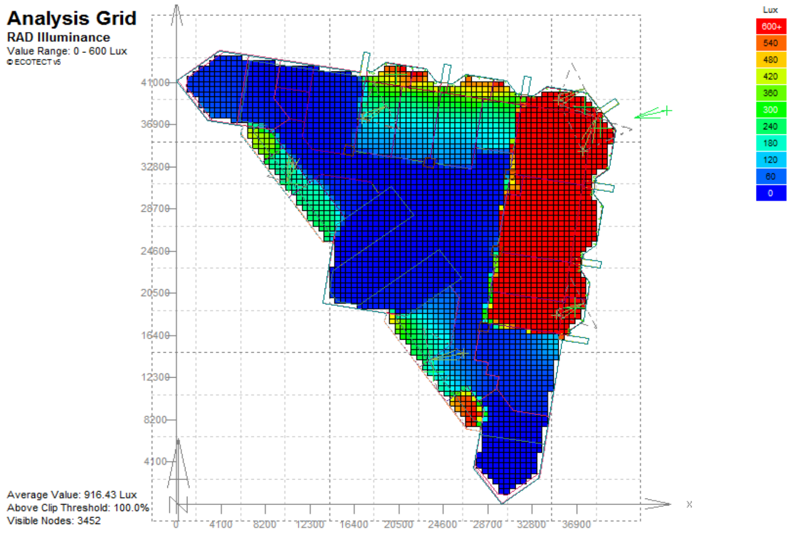

Fig. 10: Indoor illuminance grid analysis - March 3rd, 2016 8:00

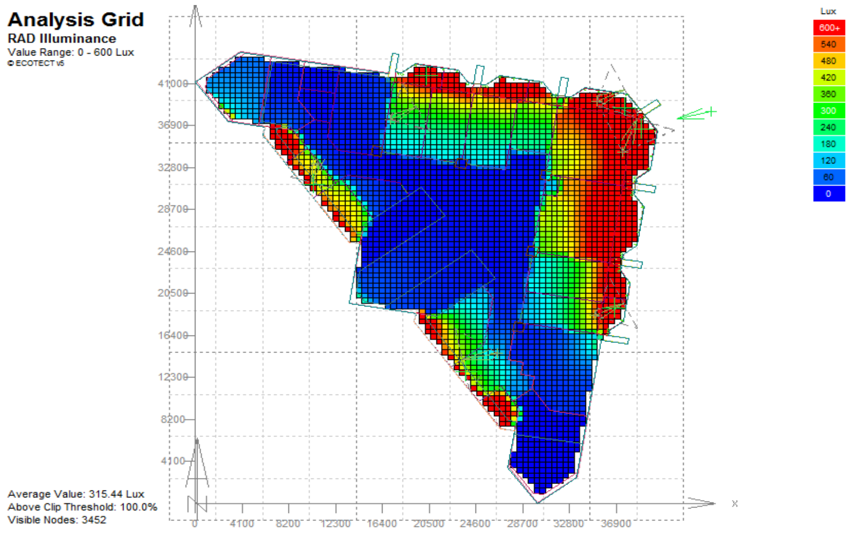

Fig. 11: Indoor illuminance grid analysis– March 3rd, 2016 12:00

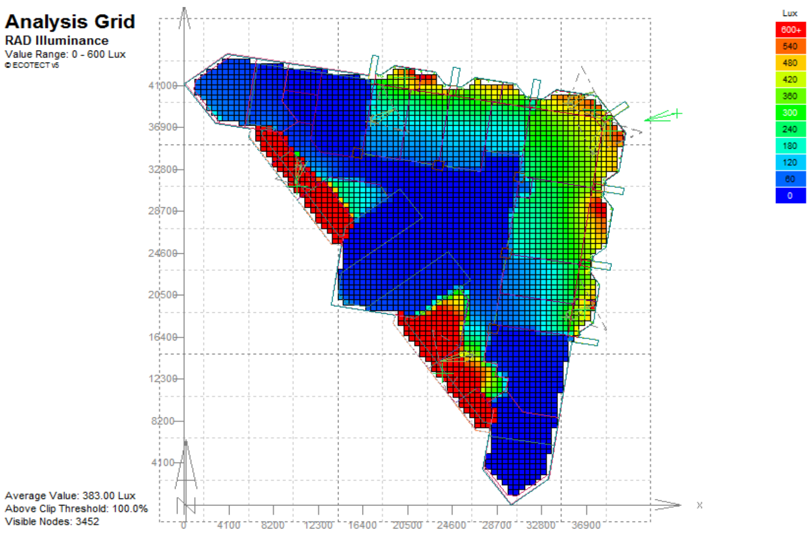

Fig. 12: Indoor illuminance grid analysis– March 3rd, 2016 16:00

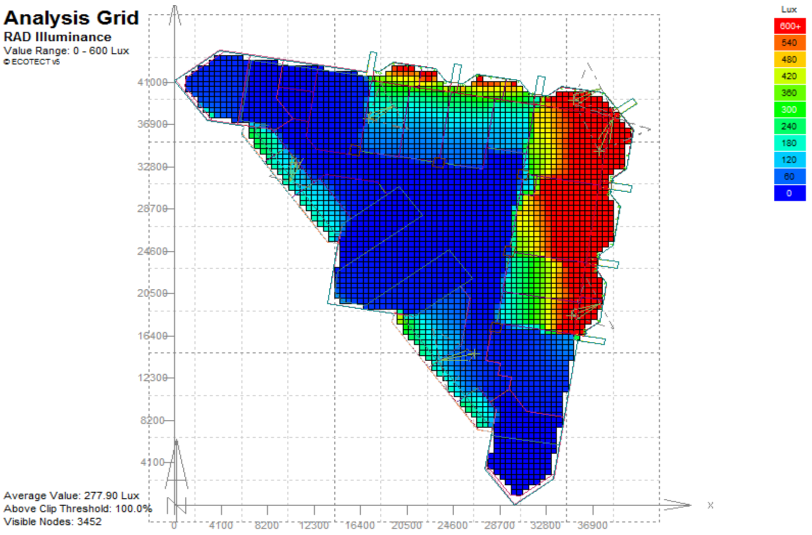

Fig. 13: Indoor illuminance grid analysis– March 13th, 2016 8:00

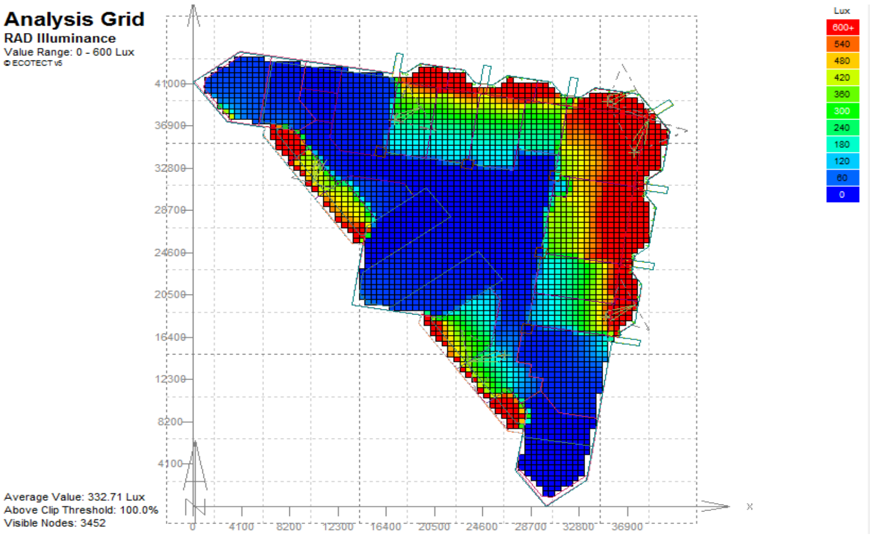

Fig. 14: Indoor illuminance grid analysis – March 13th, 2016 12:00

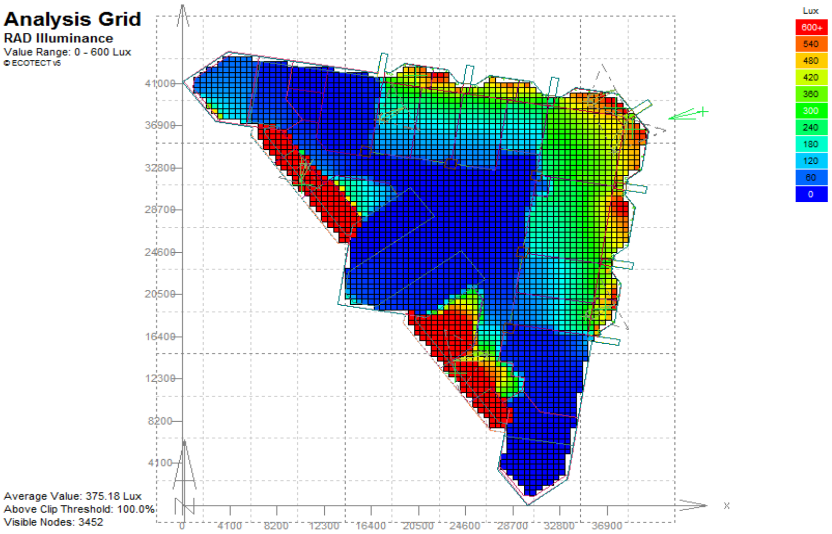

Fig. 15: Indoor illuminance grid analysis - March 13th, 2016 16:00

c) 20th of March Simulated Results

Table 8 represents Radiance model simulated results for each of the five points at the same times of actual measurements. The illuminance ranged from 169 Lux on the SW point A to 9,174 Lux on the NE point D at 8:00. At 12:00 the simulated illuminance results range from 395-1,099 Lux, while it ranged from 450 Lux the northern point C to 3,768 Lux at the SW point B at 16:00.

Table 8: Simulated indoor illuminance for case study B in Lux on March 20th, 2016

Hours	Locations				
	A	**B**	**C**	**D**	**E**
08:00	169	210	581	3,489	9,174
12:00	395	456	785	1,099	995
16:00	3,101	3,768	450	595	473

Fig. 16, 17 and 18 illustrate the grid analysis showing the illuminance levels at the selected floor at 8:00, 12:00 and 16:00.

4.2 Comparison between Measured and Simulated Data

Comparison graphs are the most common techniques used to visualise the difference between simulated and actual data. The scattered diagram has been used to plot the difference between the two variables. The x-axis denotes the measured values, while the Y-axis denotes simulated values.

As it is illustrated in Fig. 19, there is an overall agreement in illuminance levels distribution between the measured and the simulated indoor illuminance.

The points under diffuse light showed a very good agreement between measured values and simulated results at all times, while the points under direct sunlight showed a good correlation with small values and had a notable instantaneous discrepancy at higher values. This is clear at Reading location D, 8:00 on the 3rd of March, and reading location E 8:00 on the 20th of March.

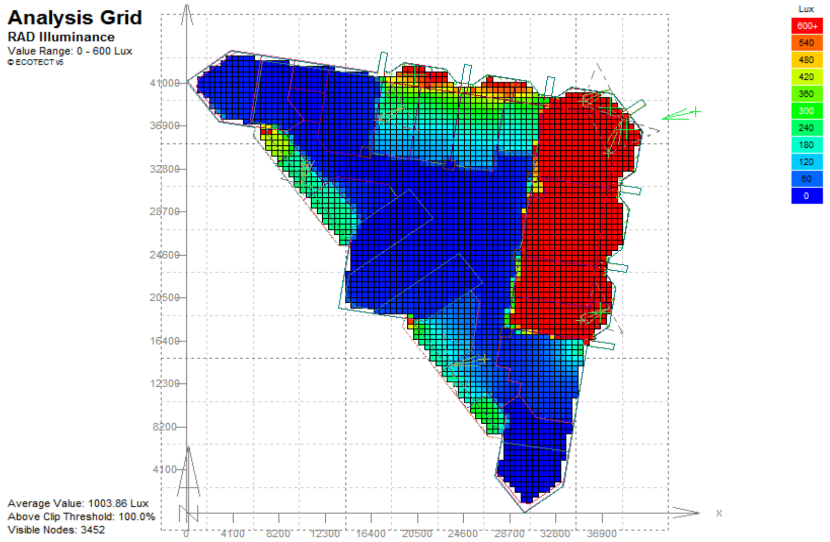

Fig. 16: Indoor illuminance grid analysis– March 20th, 2016 8:00

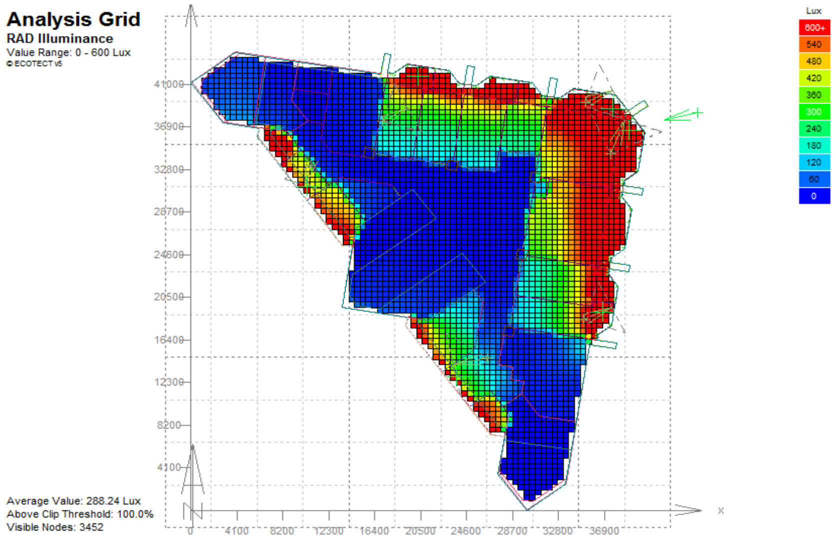

Fig. 17: Indoor illuminance grid analysis– March 20th, 2016 12:00

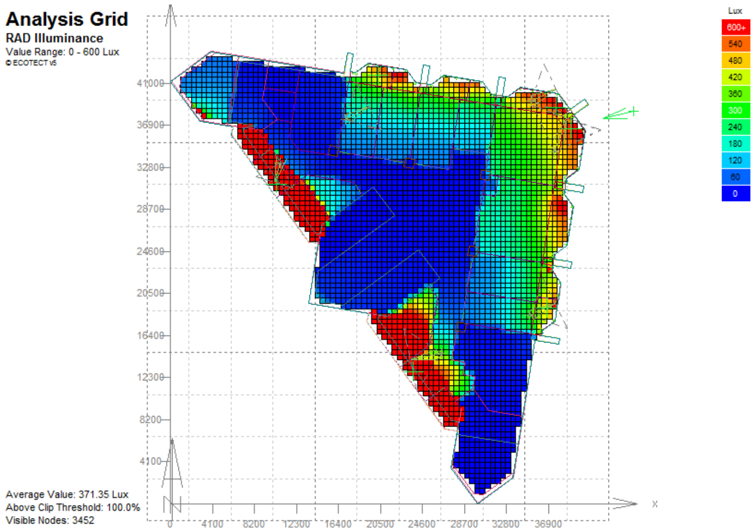

Fig. 18: Indoor illuminance grid analysis– March 20th, 2016 16:00

This reveals that points receiving diffuse light tend to be simulated more accurately, while simulated values for the ones under direct light tend to show significant discrepancy.

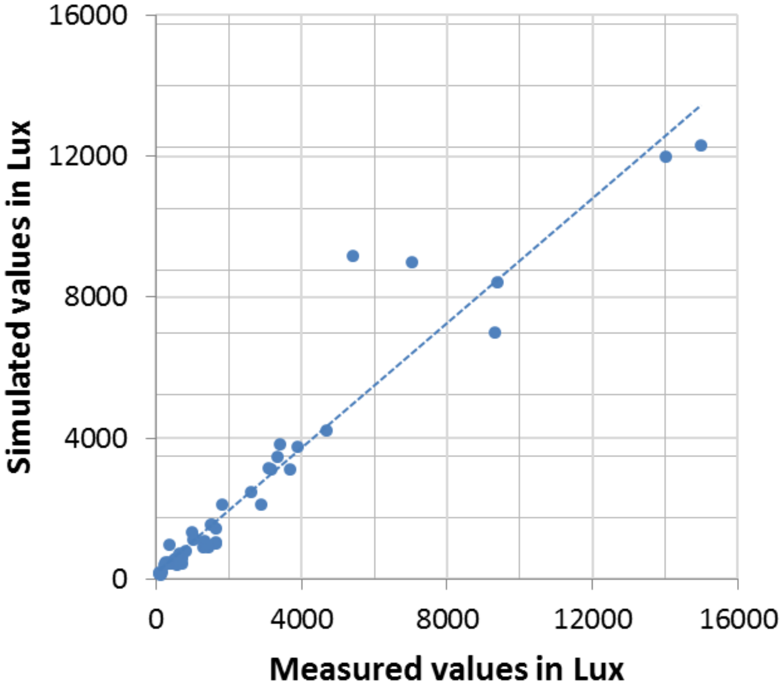

Fig. 19: Radiance simulated indoor horizontal illuminance at study case A and B

4.3 Comparison Using Bias Error Calculations

Previous researches established that the relatively low resolution of BSDF (bidirectional scattering distribution functions) combined with the presence of the sun makes variation between simulated results and actual measurements at the points receiving direct sunlight. It had a lower effect under diffuse lighting condition [18].

Reinhart and Walkenhorst [15] and Reinhart and Breton [16] stated that simulation considered reliable if the Mean Bias Error (MBE) is less than 20% and the Root Mean Squared Error (RMSE) is less than 32%. To calculate the percentage error, the difference between the simulated results and the measurements was divided by the measured illuminance [18].

Table 9 represent the calculations of the MBE and the RMSE for all days analysed for case study A. All the analysed points had the mean bias error below 20%, and all the points had root mean squared error (RMSE) less than 32%.

Table 9: The percentage of bias error at all days analysed for case study A

Tested points	**Relative errors percentage**			
	MBE		RMSE	
	08:00	14:00	08:00	14:00
A	3.21	1.07	5.55	1.85
B	-4.75	0.04	8.24	0.07
C	-3.43	-4.44	5.94	7.70
D	3.82	-8.23	6.62	14.25
E	11.94	-5.99	20.68	10.38

Table 10 analyses the same for case study B. The minus sign indicates that simulated value was underestimated. 69% of the analysed points had the mean bias error below 20%, and 56% of the points had root mean squared error (RMSE) less than 32%.

Table 10: The percentage of bias error at all days analysed for case study B

Tested points	**MBE %**									**RMSE %**								
	3 March			*13 March*			*20March*			*3 March*			*13 March*			*20 March*		
	08:00	12:00	16:00	08:00	12:00	16:00	08:00	12:00	16:00	08:00	12:00	16:00	08:00	12:00	16:00	08:00	12:00	16:00
A	31.48	11.21	-6.22	30.51	6.55	-6.06	40.07	16.16	-5.21	37.00	44.84	11.27	35.86	26.20	10.99	47.09	64.64	9.44
B	41.18	74.69	1.78	69.31	57.37	2.33	85.37	71.48	1.56	48.01	76.38	7.87	80.82	58.66	10.29	99.54	73.09	6.90
C	12.55	3.00	-4.60	7.90	3.33	-2.68	7.73	2.63	-6.33	28.42	8.52	41.48	17.89	9.47	24.13	17.50	7.47	57.10
D	3.26	-29.37	-2.66	7.89	-29.37	-1.88	6.83	-36.72	-2.62	20.13	31.48	21.77	48.74	31.48	15.39	42.19	39.35	21.51
E	11.05	-6.17	-17.29	57.70	-6.74	-14.69	19.23	-23.76	-13.81	24.04	36.30	19.28	125.56	39.65	16.38	41.85	39.68	15.40

5. Final Results

The results presented are directed towards analysing the degree of accuracy of Radiance in predicting daylight when applied to real building with complex geometry.

The distribution pattern of the simulated outdoor illuminance followed closely the pattern of the site-measured illuminance for all days analysed. Radiance shows high level of agreement between instantaneous measured and simulated illuminance for almost all points receiving diffuse light. However, at the points getting direct sunlight there is a good correlation at lower values and it gets weaker at higher values.

The magnitude of error analysis, done through MBE and RMSE for all points, confirms the fact that diffuse light is calculated more accurately than the direct component.

6. Conclusions

The aim of the research was to find a systematic pattern that describes the difference between actual daylight measurements and Radiance predictions.

This was achieved through examining real differences between actual measurement and simulation results. Choosing NTC and Petrodar towers in Khartoum as case studies offered an important reference point for the evaluation; it gave the opportunity to measure the actual lighting conditions inside the building for comparison with the daylighting predicted by Radiance.

The results revealed that diffuse daylight was simulated more accurately than the direct component. The variation between the measured values and simulated ones occur at the points facing the direct sunlight and mostly when the sun comes at low angle, the variation reached twice the measured values in four cases.

It has to be noted that this research has a time limitation; the experiments were conducted during one day in autumn season in Petrodar tower, and three days in winter at NTC tower when the sky was clear at the tested days. Moreover, the weather file for simulation was generated using Meteonorm. The study is a validation exercise not a research into the calculation algorithms of this software package, the results should be viewed with regard to these limitations.

It is recommended that future research should be done all year round covering all seasons to cover all cloud cover conditions. This could possibly highlight a systematic pattern in observed discrepancy. Moreover, the experiments could be conducted in 3-4 buildings to generate more data sets.

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