Sensitivity Analysis for Energy Modelling based on Daylight Simulations

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Abstract: Simulation techniques for modelling the lighting and energy performance of buildings are becoming widely available. Previous research by the authors found the outcomes of lighting simulation to be substantively influenced by individual settings of various model parameters (e.g., ambient reflections and grid size), particularly for complex façades. This study postulates that this influence is also reflected on predicted energy consumptions since daylight availability affects the artificial lighting needed to meet illuminance targets and the heat transferred from the façade. To test this hypothesis, a sensitivity analysis was performed investigating the influence of various daylight simulation settings on predicted energy loads. The sensitivity analysis was based on annual simulations using a shoebox model with simple and complex façade configurations under Cairo and Nottingham climates. Daylight simulations were conducted using RADIANCE while energy analysis was run through EnergyPlus. The results were statistically analysed for annual cooling, heating, lighting and total energy loads. The analysis showed that fast-low precision daylight simulation settings of ambient reflections overestimated lighting and cooling energy loads, and underestimated heating requirements. The differences were statistically and practically significant particularly in terms of lighting loads. The results were largely dependent on climatic conditions, and the differences consistently increased in case of complex façade systems. The findings from this study are discussed in the context of the challenges that façade designers need to tackle when using simulation tools at early design stage towards obtaining plausible performance outcomes.

Keywords: Daylight, Energy, Simulation, Sensitivity, RADIANCE

Introduction

The utilization of daylight in buildings can significantly affect anticipated energy requirements in different ways. Daylight in buildings has a direct impact on reducing lighting energy demands as it replaces the artificial lighting needed to meet indoor illuminance targets (Reinhart, 2014);(Reinhart, 2004);(Wienold, 2011), particularly when using lighting control systems that constantly take into account the natural daylight coming from windows (e.g. dimming light control systems) (Reinhart, 2004);(Wienold, 2007). However, a balance must be found between maximizing daylight potential, its associated solar loads and heat transfers across the façade, and the heating and cooling demands of the building (Johnson, 1984). Furthermore, the presence of daylight has also an indirect influence on the heating and cooling energy used to offset the radiative thermal output from artificial lights.

Several simulation tools are available to support designers to dynamically model daylight availability through windows, these using a range of performance metrics (Reinhart, 2012). However, there is not yet a consistent framework that defines the input parameters, methodologies and procedures on which a simulation should be based at different design stages (Reinhart, 2011), this potentially affecting the reliability of outcomes (Jones, 2017);(Ibarra, 2009). This is particularly evident when simulating complex façade systems, whereas advanced calculations could often require significant computational time and processing power (Reinhart, 2011). In such cases, using fast, low-precision simulation settings might still produce plausible results even if compared against high-precision settings demanding longer simulation times (Mardaljevic, 2000);(Jones, 2017). Considering the direct/indirect influences of daylight on energy demands, the uncertainty in daylight simulations expected from the settings utilised may therefore be reflected in predicted energy loads. Yet, at early design stages, the additional time and resources required by a more advanced calculation might not lead to substantial improvement in performance outcomes to drive decision making (Jones, 2017).

In response, following the presentation of some fundamental daylight simulation settings - i.e., indirect light reflection and light sensors of RADIANCE-based daylight simulation that could affect the outcomes of daylight estimates – this paper presents the findings of a sensitivity analysis investigating the influence of different simulation settings on the robustness of energy predictions, while considering issues of calculation time and power.

Daylight Simulation Settings

Ambient bounces

Among different simulation algorithms, the raytracing (Ward, 1988a);(Ward, 1988b) technique is commonly used to estimate daylighting. The calculations are heavily dependent on the number of reflections, or light bounces, onto the various model surfaces before a ray is discarded (Reinhart, 2012). Based on the raytracing method, the RADIANCE tool was developed (Ward, 1998, Ward, 1994) and validated (Ng, 2001);(Reinhart, 2001);(Ibarra, 2011);(Reinhart and Andersen, 2006). Within RADIANCE, the setting perhaps most influential to the level of detail of daylight predictions is the number of ambient bounces (-ab) (Reinhart, 2012);(Mardaljevic, 2000);(Jones, 2017). This setting represents the maximum number of diffuse bounces computed by the indirect calculation (Ward, 1997). When -ab value equals 0, only the direct sun/sky contribution is considered. At 1 ambient bounce, the sky and sun patch become potential sources of indirect illumination. At 2 ambient bounces, there is a potential to calculate indirect illumination for surfaces that have no direct line of sight to either the sky or the sun patch (Mardaljevic, 2000). In essence, the number of ambient bounces should be high enough so that no important ray paths terminate before reaching a source, although higher -ab causes simulation running times to inflate significantly. This, however, is subject to the law of diminishing returns where, in some cases, longer-time simulations may not be worth the incremental improvement in prediction accuracy (Jones, 2017).

Recommendations for the number of ambient bounces for daylight simulation vary considerably in the literature, mostly suggesting -ab values between 2 and 7 (Mardaljevic, 2000, Jones, 2017, Solemma, 2014, Tindale, 2005, Mardaljevic, 1995, Ward, 1997). However, it should be noticed that the reliability of daylight simulations may require some trial and error for -ab settings, even for experienced users, since using a certain setting for a simple scene may not be adequate for complex scene calculations.

To explore this, a previous study by the authors examined the influence of individual RADIANCE -ab settings on daylight estimates for simple and complex façade systems (Abdelwahab et al., 2017). The analysis showed that using low ambient bounce values (e.g. -ab2) decreased simulation time but could underestimate daylight predictions, the differences detected being statistically and practically significant when compared to higher settings (e.g. -ab4, -ab6). Instead, using higher settings, such as -ab4, produced results that had small or negligible errors compared to those obtained under higher precision setting (i.e. -ab6), yet using shorter simulation times. These results were consistent for simple and complex façade systems, although the magnitude of differences revealed some climate dependency.

Light sensors

Quantitative daylight evaluations are mainly based on measurements taken on the horizontal plane where paper-based visual tasks are performed (Tregenza and Mardaljevic, 2018). According to (USGBC, 2013);(IESNAI, 2012), the spacing between light sensors on the horizontal simulation grid is required to be no more than 0.6x0.6m, at a height of 0.8m from the floor (USGBC, 2013);(IESNAI, 2012);(Reinhart, 2006). According to (IESNAI, 2012), the 0.6x0.6m grid was specified as it is 'small enough' to adequately capture all possible work areas, whilst being comparatively quicker to calculate when compared to smaller grid sizes. Additionally, the larger the grid, the less accurate the model will be in describing sunlight penetration into the space (IESNAI, 2012).

There is, however, no evidence in the literature suggesting that a simulation based on a smaller grid might not lead to more robust results. This could be expected, for example, when simulating modern façade systems featured with solar screen and complex geometries or small perforations. In such cases, in fact, it can be postulated that a 0.6x0.6m grid might not be sufficiently spaced to capture the variations of daylight distribution on the simulation grid surface and only return the prevailing light estimates across each light sensor. This was tested by the authors in a previous study (Abdelwahab et al., 2017) that sought to explore the impact of smaller grid sizes on daylight predictions. Here, the estimated differences for illuminance were consistently negligible across all cases of simple and complex facades for point-in-time and annual basis daylight simulations. However, when using a smaller analysis grid, predictions for complex façade systems showed some differences in direct ray calculations (using the Annual Sunlight Exposure, ASE, metric as a performance indicator).

In essence, the results of previous studies show that varying simulation settings of RADIANCE parameters may lead to substantial differences in daylight estimates. On these bases, this study was design to investigate the influence of these settings on energy modelling, in terms of heat transfer from the façade, complementary artificial lighting needed to meet illuminance targets, and the radiative heat from artificial light.

Methodology

The sensitivity analysis was based on annual daylight and energy simulations performed using a reference office space (Reinhart, 2013);(Reinhart, 2014). The analysis was carried out under the hot climate of Cairo, Egypt, and the temperate conditions of Nottingham, UK. Daylight calculations were performed using the graphical algorithm editor Grasshopper (V.0.9.0076) linked to the daylight simulation engine RADIANCE through the DIVA V.4 tool (Solemma, 2014). The Archsim Energy Modelling plugin for Grasshopper (Dogan, 2016) took the hourly lighting schedule profiles imported from DIVA and was interfaced with EnergyPlus (V.8.2.7) (Crawley, 2004);(Crawley, 1998) where all energy simulations were run.

The following sections provide details of the optical and thermal properties of model components, the simulation engines and workflow, and the statistical analysis performed.

Model parameters

A model of a reference office, with size 3.6 x 8.2m and height of 2.8m, was created. The optical and thermal properties of materials were based mainly on Reinhart's model (Reinhart, 2013), although some materials were edited in order to exclude factors that could have affected the comparison of energy performance (Table 1). Heat flows through the internal partitions, ceiling and floor were assumed to be adiabatic. No external obstructions were considered.

Table 1 Optical and thermal properties of the reference office

Component	Properties
Glazing	Glazing Double Pane Clear: T visible= 80 %; SHGC= 72%; U-value= 2.71W/m^{2}K.
Interior walls	Lambertian diffuser with a 50% reflectance 0.15 m brick (Y=5.38 W/m^{2}K), Adiabatic surface
Exterior wall	35% reflectance 0.15 m brick, U-value= 2.33W/m^{2}K.
Ceiling	Lambertian diffuser with 80% reflectance 0.2m concrete (Y=6.00 W/m^{2}K), Adiabatic surface (office not under a roof)
Floor	Lambertian diffuser with 20% reflectance 0.2m concrete (Y=6.00 W/m^{2}K), Adiabatic surface
External ground	Lambertian diffuser with 20% reflectance

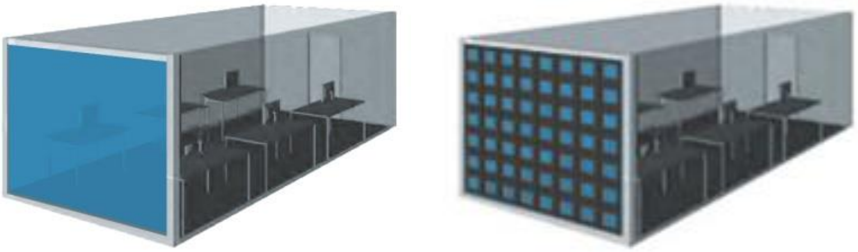


Figure 1 Simple (left) and complex (right) facade configurations

Since daylight simulation is heavily dependent on the interaction of light rays generated at the source with façade objects, two façade designs with varying levels of complexity were investigated for this study. The first featured a fully-glazed façade (Figure 1- left). The second, a complex façade with a 'solar screen' based on an egg-crate shading system (Figure 1- right), consisted of rectangular panels with dimensions of 0.45m x 0.40m with a 0.1m frame. The enclosed space featured six workstations in two rows facing the internal walls. An 8am-6pm occupancy schedule was assumed, representing a normally occupied office. Daylight saving time was considered for Nottingham but not for Cairo.

The reference office was assumed to be heated and cooled by a HVAC system during its normal hours of occupation. According to the recommended comfort criteria for general office spaces in the CIBSE Guide A (CIBSE, 2015), the set point temperatures for the Nottingham climate were 21°C for heating and 25°C for cooling. In accordance with the literature for Cairo, the set points were 22°C for heating and 26°C for cooling (Sherif et al., 2014). For both locations, the infiltration rate was assumed to be 0.5 ach^{-1}.

Four out of the six workstations were assumed to be constantly occupied (Reinhart, 2013), resulting in a peak occupancy of 0.13 person/m^2. The total internal appliance load was set at 8 W/m^2, this corresponding to an Energy Star rated LCD monitor and a laptop for each occupant present (Reinhart, 2013);(ENERGYSTAR, 2007). The installed peak lighting power density was set at 11.38 W/m^2 assuming that four 28W TL5 recessed down lights were installed on each workstation row.

Artificial lighting was linked to a dimming unit (Bierman, 2003);(Roisin, 2008). When daylit levels fell below the target illuminance level of 300 lux, artificial lighting was switched on. This would increase the active use of daylight compared to a manual light control

(Reinhart, 2004);(Wienold, 2007), leading therefore to maximizing daylighting from window, so the variations in energy loads following daylight estimates obtained with different settings could be tackled. For the same purpose, no internal blinds were assumed. Three light sensors were installed at each workstation row at distances of 1.2m, 3.6 and 6.0m from the window.

Simulation settings and workflow

The study varied the -ab calculation settings from -ab2, the minimum setting for calculating indirect light for surfaces with no direct line of sight to light sources, through - ab4 and -ab6, see Figure 2. It was assumed that the smallest pattern of light projection from complex façade systems (e.g. egg-crate, perforated shading, etc.) could be captured by a grid size of 0.2x0.2m. Hence, the size of the analysis grid varied from 0.2x0.2m (738 light sensors across floor area) to the 0.6x0.6m (84 light sensors)- the maximum size recommended by the IES for light calculations- via 0.4x0.4m (180 light sensors), see Figure 3. All variables were examined for the south and west facade orientations giving 18 cases in total for each façade type (i.e. simple and complex) under each climate (i.e. Cairo and Nottingham).

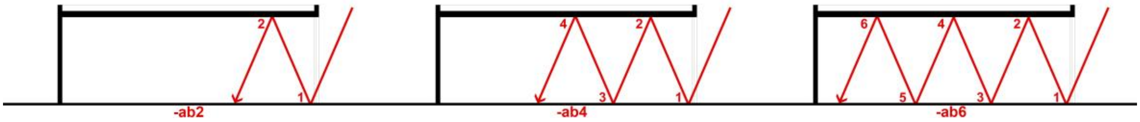
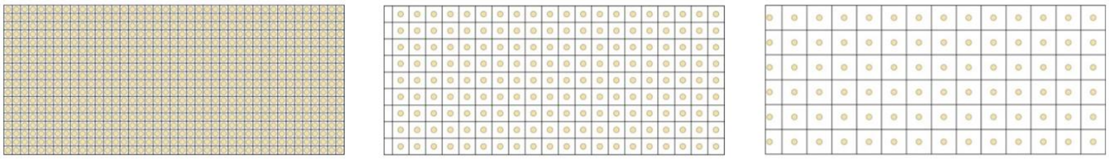


Figure 2 RADIANCE parameters (ambient bounces) used in the sensitivity analysis.



0.2x0.2m

0.4x0.4m

0.6x0.6m

Figure 3 Light sensors of 0.2X0.2, 0.4X0.4 and 0.6X0.6m grid for daylight analysis.

At a first stage, DIVA was used to pre-calculate daylight and hourly artificial lighting schedules. These calculations were produced for each time step in a year for each value of ambient bounces and grid size. At a second stage, Archsim integrated light schedules into the thermal zone in order to calculate energy loads. This workflow was followed for each façade type and location. The study analysed energy loads arising from artificial lighting, heating, cooling and the sum of all these, 'total energy load', expressed in kWh/m^2/annum.

Statistical analysis

A multiple regression with linear fits was used to analyse the data. This allowed to examine the correlation between energy loads obtained under different simulation settings for each of the cases studied. The root-mean square error (RMSE) was calculated to rigorously examine the differences detected between comparisons. The Cohen's d coefficient was used as an estimation of the effect size, a standardised measure of the difference between groups of data with varying simulation parameters. The interpretation of the outcomes for the linear fits (r^2) and for the effect size (d) was based on published benchmarks (Ferguson, 2009), where: $r^2<0.04$= negligible; $0.04\leq r^2<0.25$=small; $0.25\leq r^2<0.64$= moderate; $r^2\geq 0.64$= large and $d<0.41$= negligible; $0.41\leq d<1.15$=small; $1.15\leq d<2.70$= moderate; $d\geq 2.70$=large.

Results and Discussion

Under the Cairo climate and during occupancy hours, no heating energy loads arose for the specified set points. This generally complies with other studies in the literature conducted under hot clear sky climates with no or almost negligible heating requirements (Sherif, 2012); (Sherif et al., 2014);(Singh et al., 2016). Conversely, for the Nottingham case, no cooling loads arose from the simulations.

In general, lighting loads increased when applying the solar screen under both climates due to the complex façade reducing the illuminance levels reaching the working plane. The average of lighting loads under Cairo increased by almost 7 times when applying the solar screen, whereas the average loads increased by 3 times under Nottingham (see Figure 4 for the simple façade and Figure 5 for the complex façade). As expected, the complex façade system significantly reduced the cooling loads under the Cairo climate compared to the case with the fully glazed façade. In fact, the complex facade blocked direct sunlight, provided shading and reduced heat transfer through the facade. This caused the average cooling loads to reduce almost by half. These results agree with the findings from a previous study (Sherif et al., 2010), showing that external solar screens are effective in reducing cooling demands. Conversely, the solar screen caused an increment in the average heating loads by almost a third compared to the fully glazed façade under the Nottingham climate.

Ambient bounces (-ab)

Figure 4 and Figure 5 show the results of energy simulations based on lighting calculations using different values of ambient bounces under both climates.

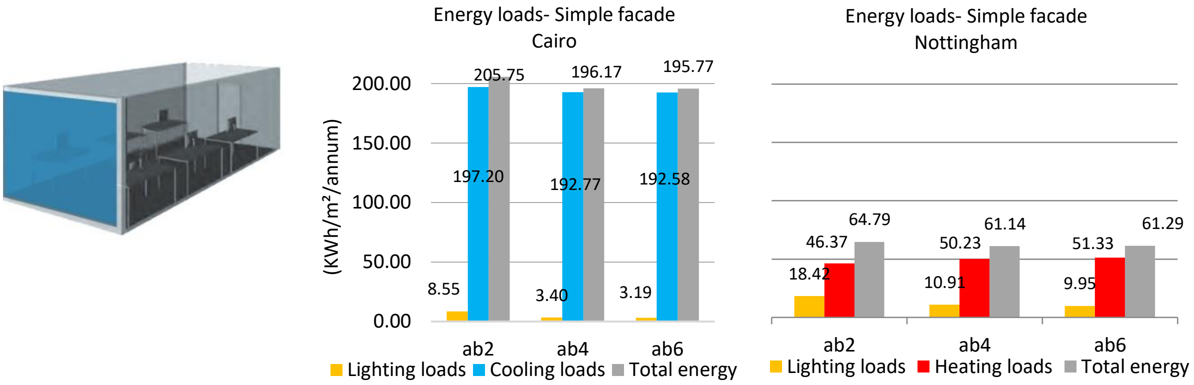


Figure 4 Energy loads for simple façade (fully glazed) under Cairo (left) and Nottingham (right)

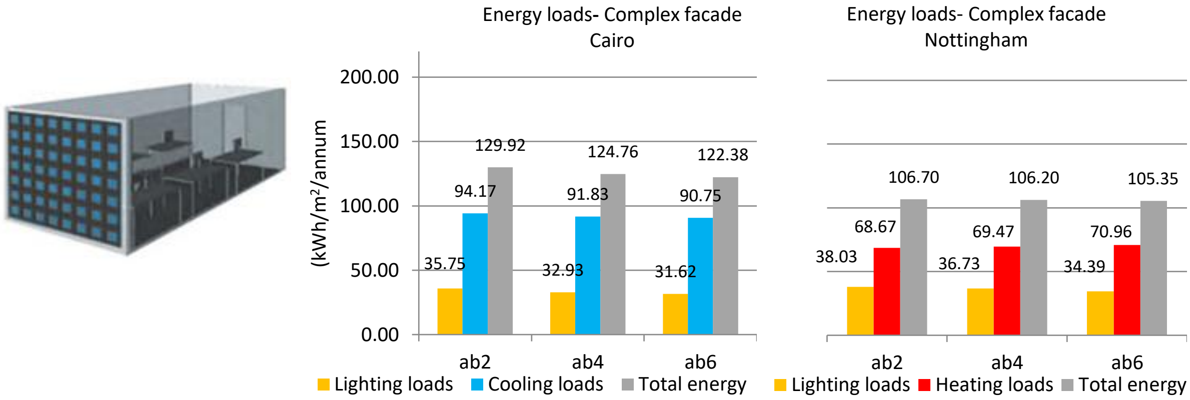


Figure 5 Energy loads for complex façade (solar screen) under Cairo (left) and Nottingham (right)

The data generally show that using a higher precision setting of ambient bounces (i.e.-ab6) results in lower lighting loads predictions, for Cairo and Nottingham, in the case of both facade systems, although reductions are much less evident for the complex façade under either climate. A reduction in lighting loads could have been expected due to a higher estimation of daylight availability when more light reflections (-ab) are considered for indirect calculations. Thus, the illuminance target of 300lux could be mostly met across the floor area for a significant proportion of the day. The results also showed a slight reduction in cooling loads for both façade systems estimated under Cairo based on lighting calculations with high ambient bounces (-ab6) compared to low ambient bounces (-ab2). On the other hand, an increase in estimated heating loads could be detected for Nottingham for both the simple and complex façade. As noted before, higher precision settings lead to increased daylight in the space. By proxy, artificial lighting is switched on less often, therefore reducing potential gains from this source, as already evidenced in the literature (Bourgeois et al., 2006).

A statistical analysis of the data was performed to establish the influence on energy loads of varying the -ab settings of daylighting calculation. For each comparison under different values of -ab, the analysis considered 6 cases (2 orientations x 3 grid sizes) for both façade types (simple, complex) under Cairo and Nottingham climates. Table 2 shows the estimated r^2, RMSE and Cohen's d coefficients for each comparison between energy simulation results. The highest value of -ab was taken as a benchmark for each comparison.

Table 2 Annual energy analysis: Comparisons between different ambient bounces

Climate	Ambient bounces	Energy loads	Simple façade (Fully glazed)			Complex façade (Solar screen)		
			r^2	RMSE $[kWh/m^2/a]$	Cohen's d	r^2	RMSE $[kWh/m^2/ a]$	Cohen's d
Cairo	-ab2 vs. -ab4	Lighting loads	0.12	5.21	9.02	0.63	3.49	1.39
		Heating loads	-	-	-	-	-	-
		Cooling loads	0.99	4.47	0.65	0.48	2.92	1.45
		Total loads	0.99	9.68	1.49	0.57	6.41	1.41
	-ab2 vs. -ab6	Lighting loads	0.28	5.43	9.14	0.56	4.71	2.07
		Heating loads	-	-	-	-	-	-
		Cooling loads	0.99	4.66	0.68	0.98	3.86	2.16
		Total loads	0.99	10.09	1.54	0.80	8.56	2.11
	-ab4 vs. -ab6	Lighting loads	0.39	0.26	1.21	0.91	1.34	2.26
		Heating loads	-	-	-	-	-	-
		Cooling loads	0.99	0.22	0.03	0.52	1.13	2.71
		Total loads	0.99	0.48	0.06	0.88	2.46	2.48
Nottingham	-ab2 vs. -ab4	Lighting loads	0.98	7.65	3.81	0.85	1.69	0.74
		Heating loads	0.99	4.01	-0.51	0.86	1.03	-0.72
		Cooling loads	-	-	-	-	-	-
		Total loads	0.99	3.68	0.39	0.84	0.65	0.78
	-ab2 vs. -ab6	Lighting loads	0.94	8.61	4.36	0.93	3.81	2.15
		Heating loads	0.99	5.15	-0.65	0.93	2.38	-2.11
		Cooling loads	-	-	-	-	-	-
		Total loads	0.99	3.66	0.38	0.89	1.43	2.20
	-ab4 vs. -ab6	Lighting loads	0.96	0.98	0.99	0.80	2.39	2.15
		Heating loads	0.99	1.36	-0.13	0.78	1.52	-2.04
		Cooling loads	-	-	-	-	-	-
		Total loads	0.99	0.89	-0.02	0.83	0.87	2.37

$r^2<0.04$= negligible; $0.04\leq r^2<0.25$=small; $0.25\leq r^2<0.64$= moderate; $r^2\geq0.64$= large
$0.41\leq d<1.15$=small; $1.15\leq d<2.70$= moderate; $d\geq2.70$=large

Lighting loads

In the case of simple façade configuration, the inferential data from Table 2 shows that using -ab2 tends to increase the estimation of lighting loads. This is revealed by the weak correlation against its equivalents of -ab4 and -ab6 specifically under Cairo (r^2<0.28), although the correlations are stronger under the Nottingham climate. The estimated errors from -ab2 were considerably high relative to the actual lighting loads obtained under both climates (RMSE values around 5 kWh/m^2/annum under Cairo and 8 kWh/m^2/annum under Nottingham). The differences between lighting loads corresponded to large effect sizes (Cohen's d≥2.70) under both climates. Using -ab4 led to a stronger correlation with the results obtained with -ab6 in terms of estimated lighting loads. The analysis generally showed negligible errors (RMSE <1 kWh/m^2/annum) under both climates. This suggests that using low -ab for lighting calculations might lead to an overestimation of lighting loads, while -ab4 can produce predictions similar to -ab6 but with shorter calculation times. However, it should be noticed that the analysis detected some differences that have moderate and small magnitude of effect under both Cairo and Nottingham, hence inferences should be treated with caution.

For complex façade systems, using low -ab settings (-ab2) generally resulted in lower errors in lighting loads compared to the fully glazed façade. When comparing -ab2 to -ab4 and -ab6, the differences detected corresponded to errors of 1.69-3.81 kWh/m^2/annum for Nottingham, and 3.49-4.71 kWh/m^2/annum for Cairo. The estimated effect sizes were practically relevant for most comparisons under both climates. This indicates that using low ambient bounces for complex façades can also lead to an overestimation of lighting loads, although the errors are generally lower than the simple façade. Instead, using higher value of ambient bounces (i.e. -ab4) led to strong association between lighting loads when compared to -ab6 with marginally low RMSEs under both climates (RMSE≤2.4 kWh/m^2/annum). Therefore, this shows that -ab4 can result in reasonable predictions of lighting energy for complex facades compared to -ab6, although again some differences with moderate effect sizes were detected.

In general, these results show that the using low -ab settings of indirect light calculation can potentially lead to an increase in the estimation of lighting loads with practically relevant errors compared to higher precision settings.

Heating loads

In the case of the simple façade, comparing heating loads data obtained under -ab2 with results using -ab4 and -ab6 for Nottingham showed strong associations (r^2=0.99), although RMSE returned relevant errors relative to the actual heating loads (4.01-5.15 kWh/m^2/annum). This leads to postulate an underestimation of heating loads with differences generally of small magnitude. Instead, using -ab4 against -ab6 resulted in a strong correlation with marginally low errors and negligible magnitude of differences. This leads to conclude that, also in this case, using -ab4 for lighting calculations can be acceptable when predicting heating requirements for simple facades at early design stage.

In the case of the complex façade, strong associations (r^2≥0.86) were detected when comparing heating loads obtained with both -ab2 and -ab4 to the results using -ab6, with RMSE values relatively low compared to actual heating loads (1.03 to 2.38 kWh/m^2/annum). However, differences with small and moderate effect size were detected for these comparisons. These results suggest that heating energy can be underestimated based on lighting predictions obtained with low ambient bounces (i.e. -ab2) compared to higher precision settings (-ab6). It is important to note that estimating heating loads based on light calculation with -ab4 provided results similar to -ab6 in the case of simple façade. However, for complex facades, a difference of moderate effect size between -ab4 and -ab6 was detected, showing that choosing between these -ab values might affect heating predictions.

Cooling loads

For the fully glazed façade, the analysis detected a strong correlation ($r^2 \geq 0.99$) between cooling loads for all comparisons under Cairo climate. The estimated RMSEs were generally negligible relative to the actual cooling loads (≤4.66 kWh/m^2/annum), although differences associated to effects sizes of small magnitude using -ab2 were detected. Conversely, the comparisons between -ab4 and -ab6 resulted in negligible differences. Correlations were weaker in the case of the complex façade. For this façade type, the analysis detected differences with moderate or higher magnitude of effects for all comparisons.

These results show that using low settings of ambient bounces (-ab2) for light calculations can also affect cooling requirements. Instead, a choice of higher ambient bounces (-ab4 and – ab6) lead to similar results for simple facades, but it may significantly impact the estimation of cooling loads for the complex façade system.

Total energy loads

In the case of the simple facade, comparing total energy loads based on lighting calculations with low ambient bounces (-ab2) led to strong association with the results obtained under other simulation settings ($r^2 \geq 0.99$). The estimated RMSEs are relatively low (about 4 kWh/m^2/annum) for Nottingham, but are higher under the Cairo climate (RMSE 10 kWh/m^2/annum) leading to some differences with moderate magnitude of effect. This might suggest that-ab2 could be more suitable depending on specific climates conditions. On the other hand, using higher ambient bounces (i.e. -ab4) led to an overall strong correlation in total energy loads compared to -ab6 with a negligible magnitude of differences and low errors (RMSE<1 kWh/m^2/annum) under both climates.

Results of total energy loads for the complex façade system are mostly similar to the simple façade configuration, although the estimated differences are generally higher with moderate effect sizes ($1.15 \leq d < 2.70$) for most comparisons under both climates.

In summary, the results of the sensitivity analysis show that increasing the value of ambient bounces used for lighting calculations can affect differently the estimation of final lighting, heating and cooling loads. More specifically, the findings suggest that using a low value of ambient bounces, i.e. -ab2, may substantively affect the outcomes of the energy simulation especially in terms of lighting loads estimation, while -ab4 generally results in final energy loads that are similar to those obtained with higher precision settings (i.e. -ab6). However, it should be noted that using -ab4 may not always lead to predictions consistent to -ab6, since some differences of practically relevant effect size were observed for the case of the complex façade. Also, even if these outcomes should be validated under different climates and weather files, the differences detected seem to be location dependent. In fact, the estimated differences were higher for Cairo compared to the equivalents for Nottingham.

Grid size

The study compared the results of energy loads for each of the different grid sizes used in the lighting calculation, and for each façade type and location.

Table 3 Annual energy analysis: Comparisons between different grid sizes

Climate	Grid Sizes	Energy loads	Fully-glazed façade			Solar screen		
			r^2	RMSE [kWh/m^2/a]	Cohen's d	r^2	RMSE [kWh/m^2/a]	Cohen's d
Cairo	0.6x0.6 vs.0.4x0.4 m	Lighting loads	0.99	0.33	0.04	0.97	0.45	0.09
		Heating loads	-	-	-	-	-	-
		Cooling loads	0.99	0.27	0.01	0.99	0.28	0.09
		Total loads	0.99	0.60	0.02	0.98	0.68	0.09
	0.6x0.6 vs.0.2x0.2 m	Lighting loads	0.99	0.29	0.04	0.97	0.41	-0.04
		Heating loads	-	-	-	-	-	-
		Cooling loads	0.97	0.27	0.01	0.96	0.38	-0.04
		Total loads	0.98	0.56	0.02	0.97	0.79	-0.04
	0.4x0.4 vs.0.2x0.2 m	Lighting loads	0.99	0.23	0	0.93	0.69	-0.14
		Heating loads	-	-	-	-	-	-
		Cooling loads	0.97	0.20	0	0.94	0.54	-0.14
		Total loads	0.98	0.42	0	0.94	1.20	-0.14
Nottingham	0.6x0.6 vs.0.4x0.4 m	Lighting loads	0.99	0.33	-0.02	0.97	0.42	0.06
		Heating loads	0.99	1.02	0.07	0.97	0.24	-0.02
		Cooling loads	-	-	-	-	-	-
		Total loads	0.99	1.07	0.06	0.96	0.19	0.12
	0.6x0.6 vs.0.2x0.2 m	Lighting loads	0.99	0.35	-0.03	0.94	0.52	0.03
		Heating loads	0.99	1.02	0.08	0.93	0.34	-0.02
		Cooling loads	-	-	-	-	-	-
		Total loads	0.99	1.05	0.06	0.94	0.19	0.05
	0.4x0.4 vs.0.2x0.2 m	Lighting loads	0.99	0.26	-0.01	0.93	0.55	-0.03
		Heating loads	0.99	0.14	0.01	0.93	0.35	0
		Cooling loads	-	-	-	-	-	-
		Total loads	0.99	0.13	0	0.94	0.21	-0.07

$r^2<0.04$= negligible; $0.04\leq r^2<0.25$=small; $0.25\leq r^2<0.64$= moderate; $r^2\geq0.64$= large;
$0.41\leq d<1.15$=small; $1.15\leq d<2.70$= moderate; $d\geq2.70$=large

The results presented in Table 3 show strong associations across all comparisons between different grid sizes, although the correlations detected are slightly weaker in the case of the complex façade configuration. Most of the comparisons resulted in relatively low errors (RMSEs≤1 kWh/m²/annum) for lighting, heating, cooling and total energy loads under both simple and complex façade systems. The differences detected generally have a magnitude of negligible effect size. These results show that any differences in estimation that could possibly occur using smaller grid sizes in a direct/indirect light calculation through a simple or complex facade would have no practically relevant influence on energy predictions.

Conclusion

This study presented and discussed the results of a sensitivity analysis comparing performance outcomes in terms of lighting, heating and cooling loads obtained under different simulation settings and for different faced types and climates. The study showed that the consistency of energy predictions can be substantively affected by the input parameters chosen. In particular, the sensitivity analysis identified that the value of the ambient bounces setting, -ab, can significantly influence the calculations, leading to practically relevant errors in total estimated energy loads, particularly for lighting demands. The differences in energy outcomes are more evident in the case of complex façade systems and are dependent on prevailing climatic conditions. In this study, the variations in lighting power and the radiative thermal output due to varying the value of ambient bounces were found to affect cooling and heating loads. The correlation between artificial lighting and heating/cooling demands is coherent with the literature (Bourgeois et al., 2006).

The findings from this study are particularly relevant at early design stage when designers have to balance the robustness of data required to inform decision making against the simulation time and computational power necessary to run the analysis. Future work should investigate the impact of other simulation settings and assumptions including user-related actions on the reliability of performance outcomes of daylight and energy.

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