Daylighting Performance Simulation: Prediction Accuracy / Processing Speed Trade-off

Abstract

In the daylighting performance simulation of façade systems, a trade-off is often required between processing speed and prediction accuracy. This is particularly relevant at design onset, where plausible simulation outcomes are essential to drive decisions between several alternative façade configurations. To help address this trade-off, this paper presents a sensitivity analysis evaluating the influence of key input parameter settings, namely ambient bounces and grid size, on the convergence of performance outcomes and on simulation run times. The results provide statistical evidence that, although lower precision settings mostly accelerate calculations, they decrease the accuracy of prediction estimates, particularly for complex façades. Conversely, the relative increased accuracy resulting from higher precision simulations might reach a point where differences have a negligible practical impact. The paper concludes with a range of recommendations to support the early-stage selection of parameter settings and contributes to more robust simulation outcomes towards reducing the gap between simulated and measured data.

Keywords: Daylighting; Glare; Ambient Bounces; Grid Size; Prediction accuracy; Processing speed; Sensitivity Analysis

1 INTRODUCTION

Several simulation tools are available to support designers in dynamically modelling the daylight performance in buildings [1]. Although most software tools offer standardised or simplified choices for input parameters, no consistent framework or guideline has yet been documented in the literature to define the simulation settings that are appropriate to the geometry of the model and the granularity of prediction outcomes demanded by different stages of design [2, 3]. The trade-off between simulation results accuracy and the required processing time is especially relevant at design onset and for inexperienced users, when daylight distribution and glare probability have to be modelled for several alternative façade solutions or many spaces need to be calculated simultaneously [4, 5]. Although demands for higher accuracy and reliability inflate simulation run times and require additional processing power, this, however, is subject to a law of diminishing returns where the effectiveness of longer-time simulations needs to be weighed against incremental improvement in prediction accuracy [6].

1.1 Simulation Accuracy

Obtaining reliable simulation outputs can require high precision settings that may entail substantial computational power and increased processing time, especially for complex models. However, although higher precision can contribute to the robustness of results, at the early design stage, the relative incremental accuracy in calculation outcomes might reach a point where variations of input parameter values no longer have practical relevance [6]. Conversely, using lower precision settings, for example to decrease processing times, could affect the robustness and reliability of simulation results [7]. As such, the effects of inappropriate input settings at early stages of design may appear later in the design process when simulations are scaled up in resolution, potentially entailing significant discrepancies between simulated and measured data [6]. Inaccurate estimates of daylight potential through the façade could affect energy predictions in terms of supplementary artificial lighting needed and alter the calculation of its impacts on solar and internal heat gains [8].

1.2 Processing Time

Recently, significant attention has been given to defining simulation techniques that can produce plausible outcomes while reducing computational time [9]. For example, Wagdy proposed an algorithm that utilizes the maximum number of available CPU cores to accelerate daylighting modelling through running multiple simulations concurrently [10]. Similarly, Jones developed ‘Accelerated’; a GPU-accelerated version of RADIANCE that speeds up image-based simulations through GPU technology for parallel multiple-bounce irradiance catching [5]. Sullivan and Donn proposed a method based on small samples of random days (15 and 10 days/month) to generate faster light simulations that are statistically comparable to full-time period analyses [11].

1.3 Objectives

To support the development of the mentioned advanced simulation techniques, and contribute to address the **trade-off between prediction accuracy and processing time** – particularly at early design stages when more opportunities exist to improve performance – this paper proposes a parametric approach to statistically test the sensitivity of daylighting performance simulation to the selection of some fundamental simulation settings. The study presents the results of a sensitivity analysis conducted on a side-lit office under two climates. In so doing, we sought to quantify the impact of changes to key input settings – namely, the number of ambient bounces and the size of the analysis grid – on **outputs accuracy** and on **processing time**. The findings are discussed in the context of the challenges that should be addressed to fill the gap between simulated and measured building performance. A range of recommendations is finally provided that offers guidance to designers to help them produce reasonably robust simulation predictions at the early design stage.

2 Simulation Parameters

Among different algorithms, the raytracing technique is commonly used for daylighting simulations [12, 13]. Based on this technique, RADIANCE [14, 15] is a software tool that has been widely validated by the building performance simulation community [16, 17]. Within RADIANCE, the setting of some input parameters can strongly affect the simulation accuracy and influence its processing time [5]. Among these, the number of ray reflections can be controlled by setting the **ambient bounces** (-ab), that is the maximum number of diffuse bounces computed by the indirect calculation [6]. Recommendations for the number of ambient bounces to be used in daylighting and glare simulations vary considerably in the literature [7, 18-22]. Other parameters such as the ambient accuracy (-aa) or the ambient resolution (-ar) can also affect simulation accuracy and speed, but their potential biases can be managed by proper modelling techniques such as preventing light leakages from the model. Conversely, further settings (e.g., ambient divisions (-ad), ambient super-samples (-as), number of specular samples (-ss), minimum ray weight (-lw)) have been found not to lead to sizeable differences in visual discomfort and daylighting predictions, and to have relatively little effect on processing times [6, 23].

Additional settings that require definition before running a simulation include the **grid size** used to divide up the analysis plane and the **sky model** under which the calculation is run (e.g., CIE Clear Sky, Perez all-weather Sky). With respect to the latter, several studies have already explored the differences in prediction accuracy produced with various sky types, suggesting that measurement-based sky models such as the Perez Sky are able to match real-life conditions with more reasonable accuracy [7, 24].

Due to a lack of consistent evidence found in the literature, and based on their documented influence on the convergence of simulation results and on processing times [5], among the mentioned input parameters, this study focuses specifically on the number of ambient bounces (-ab) and grid size. The relevance of analysing these two input parameters is also due to their importance in the calculation of the metrics required for green building certification, such as Spatial Daylight Autonomy (sDA) and the Annual Sunlight Exposure (ASE) [25, 26] that are featured, among others, in the LEED v4.1 Daylight credit [27].

2.1 Ambient Bounces

The calculation of indirect light is heavily dependent on the number of light reflections on the model surfaces before a ray is discarded. Within *RADIANCE*, this value is expressed as 'ambient bounces' (-ab) and it has a strong influence on the robustness of daylighting and glare predictions [6, 7, 18, 28]. When the -ab value equals 0, only the direct sun/sky contribution is considered. At 1 –ab (-ab1), the sky and sun patch become potential sources of indirect illumination. From -ab2, there is the possibility to calculate indirect illumination for surfaces that have no direct line of sight to the sun, the sky patch or other light sources [7]. In practice, the number of ambient bounces should be high enough so that no important ray paths are discarded before reaching a source [6], although higher -ab values inflate simulation run times and require additional processing power.

Different values can be found in the literature regarding the 'recommended' number of ambient bounces to be used in building simulation. For daylight analysis in conventional workspaces, settings up to -ab8 have been reported [6, 7, 9, 15, 29]. For glare predictions, values up to -ab7 have been utilised, although calculating the interreflections due to such a high number of ambient bounces could be extremely time-consuming. For glare analysis at positions close to the façade, lower -ab values (-ab1) have been deemed reasonable [30]. The choice of -ab value is particularly relevant in the case of façades that have geometrically complex or light re-directing components [31].

2.2 Grid Size

Daylighting evaluations are based mainly on measurements taken on the horizontal plane where paper-based visual tasks are normally performed [32]. The spacing between light sensors on the horizontal grid is generally required to be no larger than 0.60x0.60m at a height of 0.8m. The Illuminating Engineering Society of North America describes this spacing as being 'small enough' to capture all work areas, whilst being relatively faster to calculate when compared to smaller grid sizes that have a denser arrangement of light sensors [25]. This is adopted in certification tools such as LEED [27]. Logically, the larger the grid size, the less precise the model will be in describing daylight penetration into the space. For this reason, the EFA guidance suggests that a denser grid (e.g., 0.25x0.25m) might be more suitable for Climate-Based Daylight Modelling (CBDM) analysis [33].

No evidence can be found in the literature suggesting that a certain grid size results in a similar level of accuracy for both simple and complex façade systems. Rather, a different number of light sensors on the grid may be required when design solutions featuring complex geometries or small perforations need to be evaluated. In such cases, it can be posited that large grids may not capture the full variations of daylight distribution on the simulation analysis surface, and only provide prevailing light estimates across the space. However, the higher granularity in illuminance estimations provided by denser grids needs to be traded-off with the additional processing times.

3 METHOD

Daylighting quantity and quality have been measured in terms of daylight illuminance level and discomfort glare probability respectively (hereafter simply called daylighting and glare). A shoe-box model was used to study the impact of different parameter settings in point-in-time, annual daylighting and glare simulation. It also used to identify variations in prediction outcomes along with differences in run times. To offer insights applicable to a range of different conditions, the analyses were performed under two different sky conditions: the dominantly sunny sky of Cairo, Egypt (30^{o}N, 31^{o}E), and the mostly cloudy sky of Birmingham, UK (52^{o}N, 2^{o}W). The annual sunshine duration of the former reaches 3348 hours [34], compared with 1395 hours for the latter [35].

To test a varied range of parameter settings, the sensitivity analysis was conducted using the graphical algorithm editor *Grasshopper* (V.0.9.0076) [36] linked to the daylight simulation engine *RADIANCE* through *DIVA* (V.4.0) [29]. *DIVA*, a plugin for *Rhinoceros* (V. 5.0) [37], allows users to carry out daylighting and glare simulations through the *DAYSIM* analysis tool [16]. To compare processing times, all simulations were run using the same laptop equipped with an Intel Core i7-6500U 2.5 GHz processor, with 8 GB RAM and *NVIDIA* GeForce 920MX. The CPU's performance was entirely dedicated to the simulations with no other applications running in the background.

3.1 Model Properties

Figure 1 presents the shoebox model (reference office) used for this study. The office is 3.6 x 8.2m by 2.8m high and is furnished with six workstations. No internal blinds were considered. Material properties were mostly based on Reinhart's reference office [38], although some values were edited based on the objectives of the current analysis. The reflectance of the interior ceiling, walls and floor are 80%, 50% and 20% respectively. The glazing system consists of a double clear pane with T_{vis}=80%. For glare analysis, Cam1 and Cam2 represent the view positions of two subjects at a head height of 1.20m [39], sitting 1.20m from the window and facing their computer screens. These positions were chosen since the sun could be in the direct field of view of the observers, and therefore glare is more likely to occur. No external obstructions were included in the model.

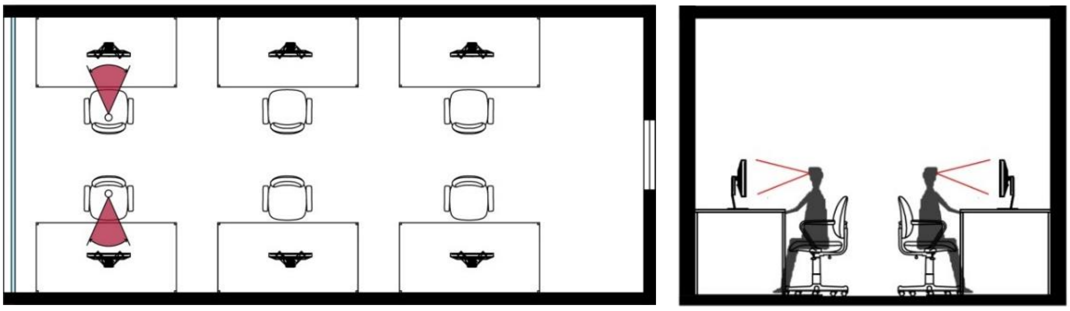


Figure 1. Reference office and view positions

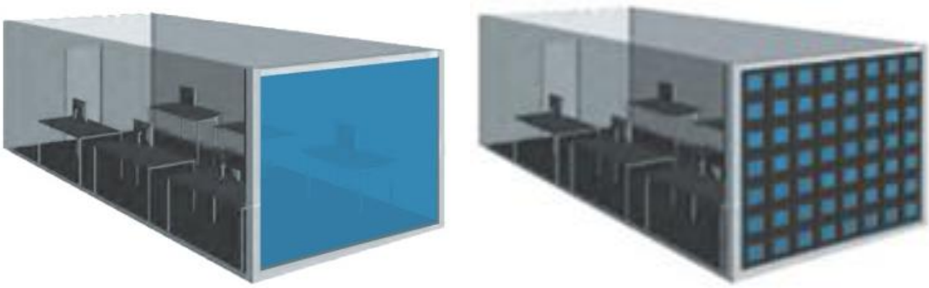


Figure 2. Simple (left) and complex (right) facade configurations

Since daylight simulations depend on the interaction of light rays with envelope components, two different façade designs with different geometrical configurations and complexity were used. This allowed a wider exploration and comparison of simulation outcomes and run times due to the variation of parameter settings. The choice of designs was based on previous comparative daylight studies that used shaded and unshaded windows for the same model [40]. The first configuration consisted of a simple fully-glazed façade (**Figure 2-left**). The second included a complex egg-crate shading system (**Figure 2-right**), mounted on an external frame of 0.10m width and featuring rectangular panels with dimensions of 0.25x0.20m and a thickness of 0.10m.

South and West orientations of the external façade were considered in the simulations. This selection was made to study, respectively, performance in the middle of the day and in the afternoon, which correspond to typical peak-load working hours.

3.2 Parameters Settings

3.2.1 Ambient Bounces

For daylight illuminance level simulation, RADIANCE guidance suggests keeping the number of ambient bounces to at least -ab2 for a reasonably accurate simulation, increasing to -ab8 for ultimate accuracy [28, 41]. However, previous studies evaluating simulation techniques for CBDM [9] and visual discomfort predictions [6] have demonstrated that, in general, most ray paths extinguish after 5 bounces and that increasing the number of bounces has little effect on results. Moreover, performed preliminary simulations during the design of the present study methodology showed that value of ambient bounces higher than -ab 6, in case of the reference office, has not led to significant changes in daylighting performance for both types of façade systems. Therefore, on the basis of the literature, the preliminary simulations, and also congruent with the settings used in previous analyses for the same reference office [42] and in other similar research [43], this sensitivity analysis selected to vary ambient bounces from a lower precision value of -ab2, through a medium setting of -ab4, and up to a higher precision value of -ab6.

For discomfort glare analysis, based on previous studies [30], the calculation settings started from a *lower* value of -ab1 in order to include not only direct light from the sun but also diffused illumination from the sky or reflections from the solar screen. Ambient bounces were then increased to -ab2 and -ab3 to investigate differences in glare predictions and prediction speed. Jones and Reinhart's study, which compared daylighting and glare modelling with measurements taken in physical spaces, suggested that at 3 ambient bounces RADIANCE simulations converge to contrast ratio values close to those computed via HDR photographs [44]. Therefore, examining ambient bounces above -ab3 was not considered necessary since the tested view positions were close to the facade. Other RADIANCE parameters (-ad, -as, -ar, -aa) were set based on recommendations from the literature [6, 7, 14, 23, 29] and are presented in **Table 1**.

Table 1. RADIANCE parameters used for daylighting and glare simulations

Radiance parameters	Ambient Bounces -ab	Ambient Division -ad	Ambient Sampling -as	Ambient Resolution -ar	Ambient Accuracy -aa
Daylighting simulation	2 – 4 – 6	1024	256	256	0.1
Glare simulation	1 – 2 – 3	2048	1024	256	0.2

3.2.2 Gride Size

Although current standards and rating tools – likely to be used as a reference at the early design stage – demand a maximum grid size of 0.60x0.60m [27], other studies suggest denser grids [9], especially when there is a large variation in sun penetration patterns due to internal or external obstructions. On these bases, this sensitivity analysis set the grid size from a *minimum* value of 0.20x0.20m between sensor nodes, through a distance of 0.40m and, finally, to 0.60x0.60m.

3.2.3 Sky Type

The simulation workflow used in this study included point-in-time and annual calculations. The point-in-time analysis was performed under both the **CIE Clear sky** [45] and the **Perez all-weather sky** [46]. These models were selected since they are the most common sky types available in many simulation tools, and they allowed testing under different sky luminance divisions. The data were sourced from the EnergyPlus IWEC weather files for Birmingham (UK) and Cairo (Egypt) [47]. Consistent with the literature [48], the annual analysis was based on the Daylight Coefficient approach proposed by Reinhart and Herkel [49], which considers 148 light sources for diffuse calculation and 63 for direct solar positions.

3.3 Performance Indicators

The metrics used to compare simulation outcomes due to the variation of parameter settings are described in many standards and rating systems, such as LEED [27], WELL [50], and EN17037 [51]. **Point-in-time daylighting** analysis used values of indoor illuminance on the floor area based on three thresholds of useful daylight illuminance **(UDI)** [52, 53]:

- Low illuminance (<300lux): insufficient daylighting
- Medium illuminance (300≤illuminance<3000lux): sufficient daylighting
- High illuminance (≥3000lux): excessive daylighting

Annual daylight analysis used the spatial daylight autonomy **(sDA)** and annual sunlight exposure **(ASE)**, which are commonly featured in standards and rating tools [27]. The sDA provides the percentage of sensors (or analysis area) achieving a target daylight illuminance level (typically 300 lux) for at least 50% of the occupancy schedule. The ASE is the percentage of analysis area exceeding a direct sunlight illuminance level higher than 1000 lux for more than 250 hours per year [25].

The **daylight glare probability** (DGP) was selected as the indicator for discomfort glare analysis [54, 55]. DGP classifies the probability of glare under four categories:

- Imperceptible: DGP≤0.35
- Perceptible: 0.35<DGP≤0.40
- Disturbing: 0.40<DGP≤0.45
- Intolerable: DGP>0.45

Although this metric was not originally developed to predict glare from complex façades, the DGP was selected among other indices (Daylight Glare Index; New Daylight Glare Index; Visual Comfort Probability; etc.) since it has been found to be the most robust metric to model glare occurrence for side-lit spaces under daylight conditions [56]. The DGP has been used extensively in simulation studies evaluating complex and scattering façades [40, 57, 58], and it is embedded in various daylight simulation software [42] and in standards such as EN 17037 [51].

3.4 Simulation Workflow

This study adopted a simulation logic based on the parametric workflow proposed by Wagdy to compute a large number of variations of parameter settings, simulation conditions, and model properties in a closed-loop process without switching between modelling and simulation software [59]. For the point-in-time daylight analysis, 2592 cases were generated using a parametric variation of ambient bounces (-ab2, -ab4, -ab6); analysis grid (0.20x0.20m, 0.40x0.40m, 0.60x0.60m); sky condition (CIE, Perez); orientation (south, west); day of the year (21st June/September/December); time of day (8am, 10am, 12am, 2pm, 4pm, 6pm); façade design (simple, complex); location (Cairo, Birmingham). For annual daylight analyses, the simulations used the same variations of ambient bounces, analysis grid, and orientations for the two façade designs under the two sky conditions, giving a total of 72 cases.

For daylight glare probability analysis, the point-in-time analysis included 1728 cases using parametric variations of ambient bounces (-ab1, -ab2, -ab3); view position (Cam1, Cam2); sky model (CIE, Perez); orientation (south, west); day of the year (21st June/September/December); time of day (8am, 10am, 12am, 2pm, 4pm, 6pm); façade design (simple, complex); location (Cairo, Birmingham). For annual DGP analysis, DIVA assessed 48 cases for the two view positions using the same variations of ambient bounces, orientations, façades, and locations.

3.5 Statistical Analysis

Statistical analysis was performed to compare simulation results against each other, revealing their 'sensitivity' to input parameter settings and quantifying the difference or convergence in predictions. A multiple regression analysis with linear fits examined the relationships between results under varying values of parameter settings. The root-mean-square error (RMSE) was calculated to compute the difference between predictions expressed in the same unit of measure of the dependent variable. The Cohen's d effect size, a standardised measure of the mean differences between two groups of data, was used to estimate the magnitude of the differences detected and interpret their practical relevance [60]. The interpretations of the outcomes for the coefficient of determination r^2 (representing a measure of how well outcomes are replicated) and for the effect size (Cohen's d) were based on benchmarks from the literature as follows [61]:

- Negligible: $r^2<0.04$ $d<0.41$
- Small: $0.04\leq r^2<0.25$ $0.41 \leq d<1.15$
- Moderate: $0.25\leq r^2<0.64$ $1.15 \leq d<2.70$
- Strong: $r^2\geq 0.64$ $d\geq 2.70$

The simulation running time was measured in order to examine the relative influence of each variation of parameter settings on processing speed.

4 RESULTS

4.1 *Daylighting Results*

4.1.1 Ambient Bounces

The variations of daylight illuminance predictions due to different values of ambient bounces were evaluated for point-in-time and annual analysis. For each -ab value, all other simulation conditions were varied giving 216 cases for point-in-time, and 6 cases for annual simulations.

For point-in-time analysis, **Figure 3** presents an example of the results for the simple façade in Cairo (south orientation, noon, winter solstice). **Figure 3-left** shows a comparison between -ab2 and -ab6. The graph shows a tendency for -ab2 to predict lower percentages of the illuminated area that fall within the medium and high illuminance bins compared to -ab6. The medium and high illuminance data points are consistently above the diagonal null hypothesis line representing no difference in simulation outcomes based on the variation of -ab. The opposite can be said for low illuminances. This is also confirmed by the comparison of the illuminance data maps for -ab2 and -ab6 that are shown in **Figure 3-right**.

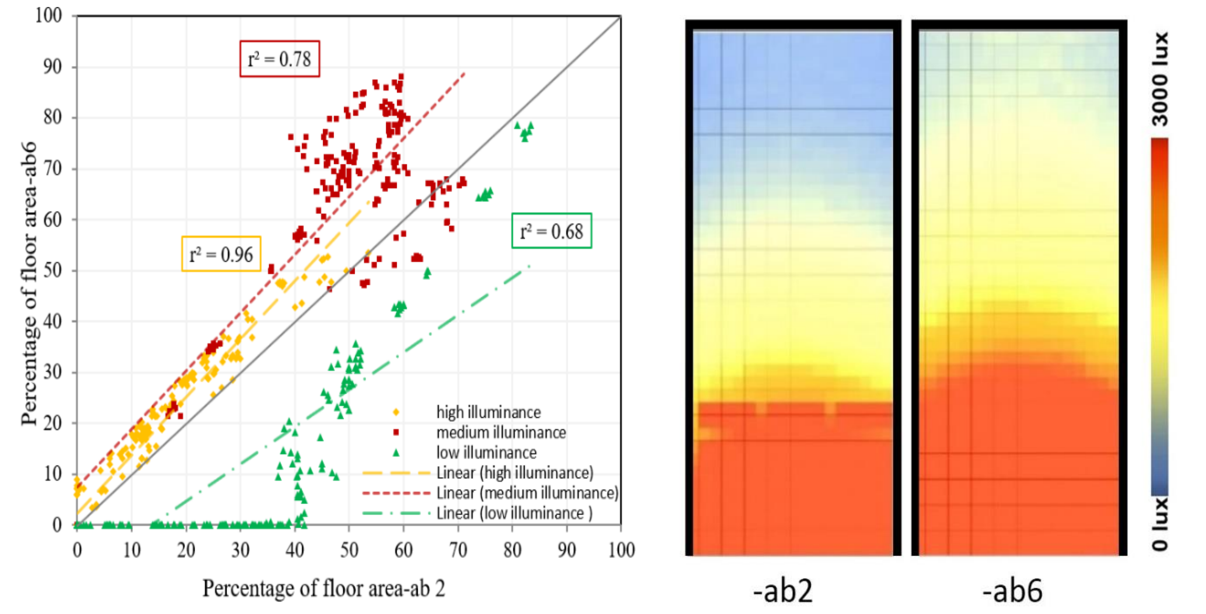


Figure 3. Point-in-time daylight analysis (left) and illuminance distribution (right): simple façade, south, noon, winter solstice, Cairo

Table 2 shows the inferential data of the point-in-time pair-wise comparisons. For both locations, the effect sizes are consistently positive for low UDI and negative for medium UDI, confirming the visual inspection of **Figure 3** where these data points were, respectively, below and above the diagonal line. Effect sizes for high UDI thresholds are null or negative. Practically relevant differences (d≥0.41) were detected for low and medium UDI when comparing simulations performed with low values of ambient bounces (-ab2) against medium (-ab4) and high (-ab6) precision settings, particularly for the simple façade. These comparisons are also characterised by the highest RMSE values and the lowest r^2 coefficients. Conversely, **negligible differences (d<0.41) were detected when comparing -ab4 and -ab6.** For both locations and façade systems, the comparisons returned strong correlations ($r^2 \geq 0.98$) and low RMSEs, ranging between 0 and 3.4% of the floor area.

Table 2. Point-in-time daylighting analysis: comparisons between ambient bounces

Location	Ambient Bounces	Illuminance Bins	Simple Façade			Complex Façade		
			r^2	RMSE (m^2)	Cohen's d	r^2	RMSE (m^2)	Cohen's d
Cairo	-ab2 vs.-ab4	Low	0.74	19.97	**0.76**	0.96	8.92	0.23
		Medium	0.82	16.43	**-0.57**	0.92	8.92	**-0.47**
		High	0.96	4.99	-0.27	1.00	0.00	0.00
	-ab2 vs.-ab6	Low	0.68	22.06	**0.85**	0.96	10.09	0.26
		Medium	0.78	18.31	**-0.63**	0.91	10.09	**-0.52**
		High	0.96	5.49	-0.29	1.00	0.00	0.00
	-ab4 vs.-ab6	Low	0.98	3.43	0.09	0.99	1.78	0.03
		Medium	0.98	3.36	-0.05	0.99	1.78	-0.06
		High	0.99	0.75	-0.03	1.00	0.00	0.00
Birmingham	-ab2 vs.-ab4	Low	0.81	17.68	**0.56**	0.98	7.06	0.14
		Medium	0.90	14.77	**-0.47**	0.94	7.03	-0.34
		High	0.98	3.65	-0.13	0.99	0.21	-0.01
	-ab2 vs.-ab6	Low	0.78	19.28	**0.62**	0.97	8.17	0.17
		Medium	0.88	16.16	**-0.50**	0.93	8.13	-0.39
		High	0.98	4.03	-0.15	0.99	3.94	-0.01
	-ab4 vs.-ab6	Low	0.99	2.74	0.06	0.99	1.59	0.03
		Medium	0.99	2.65	-0.04	0.99	1.59	-0.05
		High	0.99	0.59	-0.01	0.99	0.16	0.00

Bold values have practically relevant effect sizes.

For annual daylight analysis, **Figure 4** shows an example of estimated sDA varying the number of ambient bounces for the simple façade, south orientation, in both locations. **Table 3** provides the inferential data from all comparisons. It shows that, when comparing -ab2 with -ab4 and -ab6, consistently negative effect sizes were detected with strong and moderate

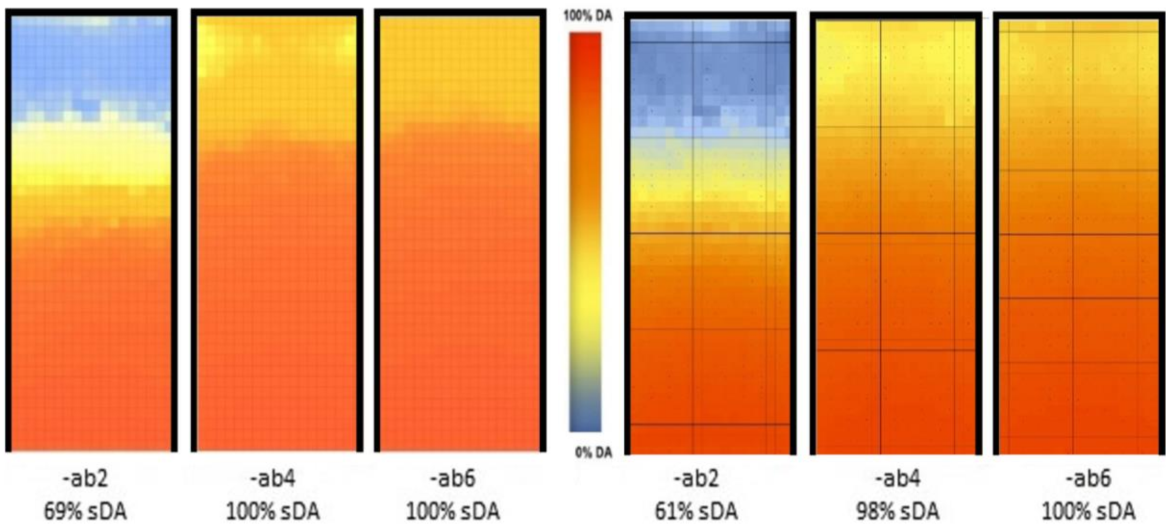


Figure 4. Annual daylighting analysis (sDA): simple façade, south, Cairo (left) and Birmingham (right)

magnitudes. The differences detected are also supported by considerable values of RMSE. When **comparing -ab4 and -ab6, the analysis detected strong correlations** and low errors for each façade system and location, although some practically relevant differences were found for the solar screen in Cairo (d=-0.43).

Table 3. Annual daylighting analysis: comparisons between ambient bounces

Location	**Ambient Bounces**	**Simple Façade**			**Complex Façade**		
		r^2	RMSE (sDA%)	Cohen's d	r^2	RMSE (sDA%)	Cohen's d
Cairo	-ab2 vs.-ab4	NE	32.84	**-14.78**	0.66	9.82	**-2.91**
	-ab2 vs.-ab6	NE	32.84	**-14.78**	0.57	10.94	**-3.36**
	-ab4 vs.-ab6	1.00	0.00	0.00	0.88	1.40	**-0.43**
Birmingham	-ab2 vs.-ab4	0.95	29.49	**-2.58**	0.89	7.39	**-0.90**
	-ab2 vs.-ab6	0.96	32.50	**-3.09**	0.93	8.31	**-1.24**
	-ab4 vs.-ab6	0.99	3.60	-0.24	0.98	2.24	-0.18

NE= Not Estimable
Bold values have practically relevant effect sizes.

4.1.2 Grid Size

Comparing daylighting estimates due to changing the size of the grid also included point-in-time and annual calculations. For each grid size, all other settings were varied, giving 216 cases for point-in-time and 6 for annual analysis.

For point-in-time analysis, **Figure 5-left** shows an example for the complex façade in Birmingham at noon on the winter solstice, comparing the UDI obtained using 0.60x0.60m and 0.20x0.20m grid sizes. For the same comparison, **Figure 5-right** provides illuminance distributions maps. **Table 4** provides the inferential data of all point-in-time simulations. For most comparisons, strong associations were detected in the data (particularly for the simple

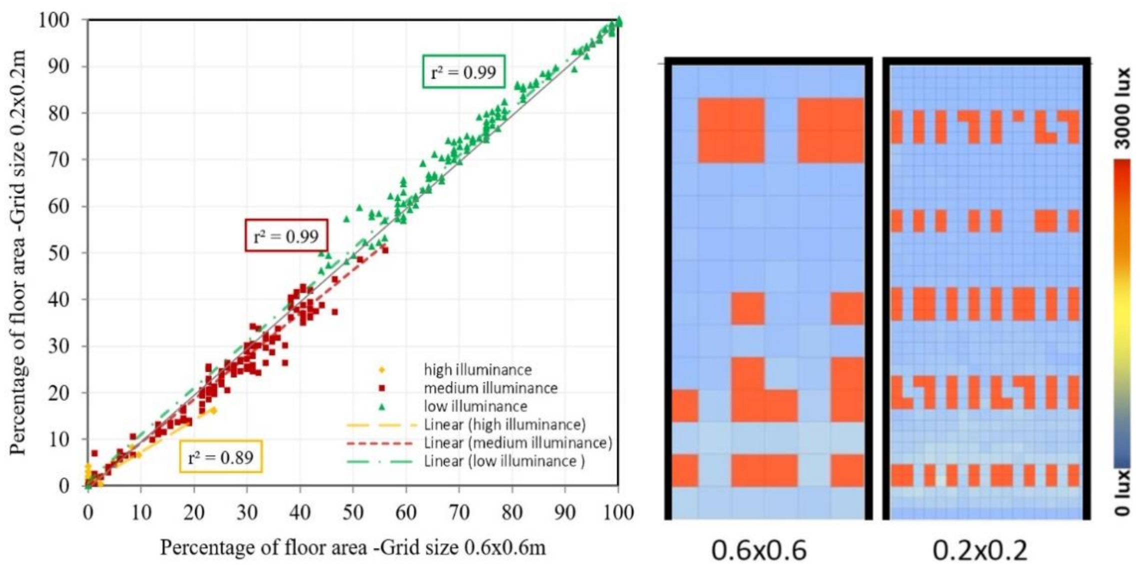


Figure 5. Point-in-time daylighting analysis (left) and illuminance colour maps (right): complex façade, south, noon, winter solstice, Birmingham

façade), with low RMSE values (0.71-2.78 m^2) and negligible effect sizes. This supports the visual inspection of **Figure 5-left**, where all data points were clustered around the null hypothesis line. **These results suggest that varying the size of the grid has a negligible impact on point-in-time daylighting estimates**. Nevertheless, when looking at the maps of **Figure 5-right**, it is evident that the patches of higher illuminance transmitted from the solar screen were captured differently by the smaller grid size. Although the analysis did not lead to detect practically relevant differences in overall percentage of floor area falling within a certain illuminance bin, changes in distribution and size of light patches might be relevant when focusing on specific points of interest.

Table 4. Point-in-time daylighting analysis: comparisons between grid sizes

Location	**Ambient Bounces**	**Illuminance Bins**	**Simple Façade**			**Complex Façade**		
			r^2	RMSE (m^2)	Cohen's d	r^2	RMSE (m^2)	Cohen's d
Cairo	0.60x0.60	Low	0.99	1.17	0.00	0.99	1.84	-0.02
	vs.	Medium	0.99	1.68	0.01	0.97	2.85	0.03
	0.40x0.40	High	0.99	1.37	-0.01	0.22	2.36	0.00
	0.60x0.60	Low	0.99	1.40	-0.01	0.99	1.96	-0.02
	vs.	Medium	0.99	2.04	0.01	0.98	2.66	0.06
	0.20x0.20	High	0.99	1.45	0.00	0.98	1.90	-0.05
	0.40x0.40	Low	0.99	1.22	-0.01	0.99	1.51	-0.01
	vs.	Medium	0.99	1.44	0.00	0.99	1.82	0.02
	0.20x0.20	High	0.99	0.71	0.00	0.78	1.00	-0.04
Birmingham	0.60x0.60	Low	0.99	1.15	0.00	0.99	2.07	-0.02
	vs.	Medium	0.99	1.84	-0.02	0.98	2.78	0.06
	0.40x0.40	High	0.99	1.41	0.01	0.74	2.19	-0.09
	0.60x0.60	Low	0.99	1.21	0.00	0.99	2.17	-0.02
	vs.	Medium	0.99	1.81	-0.02	0.98	2.39	0.07
	0.20x0.20	High	0.99	1.34	0.01	0.89	1.68	-0.01
	0.40x0.40	Low	0.99	0.91	0.00	0.99	1.36	-0.01
	vs.	Medium	0.99	1.50	0.00	0.99	1.59	0.00
	0.20x0.20	High	0.99	1.25	0.01	0.94	1.16	0.09

For annual daylight analysis, **Table 5** shows the inferential data for the comparisons between grid sizes when calculating sDA and ASE. For ASE, the results are expressed in terms of RMSE and effect size since only 2 cases were compared for each façade type and location. **For sDA, strong associations in the data were detected for all comparisons**, with RMSE values ranging between 0.16% and 2.37% and consistently negligible effect sizes. **For ASE, practically relevant differences were detected for the complex façade, particularly in Cairo**, when comparing different grid sizes. These comparisons corresponded to RMSEs between 3.58% and 9.36% of ASE.

Table 5. Annual daylighting analysis: comparisons between grid sizes

Location	**Grid Size**	**Metric**	**Simple Façade**			**Complex Façade**		
			r^2	RMSE (%)	Cohen's d	r^2	RMSE (%)	Cohen's d
Cairo	0.60x0.60 vs.	sDA	0.99	0.81	0.02	0.98	1.73	0.00
	0.40x0.40	ASE	-	1.65	0.10	-	9.36	**3.24**
	0.60x0.60 vs.	sDA	0.99	0.84	0.01	0.97	1.79	0.29
	0.20x0.20	ASE	-	1.05	-0.08	-	5.53	**1.83**
	0.40x0.40vs.	sDA	1.00	0.16	0.00	0.98	2.34	0.25

	0.20x0.20	ASE	-	1.06	-0.21	-	3.85	**-1.17**
Birmingham	0.60x0.60 vs.	sDA	0.99	1.53	0.00	0.96	1.69	0.03
	0.40x0.40	ASE	-	1.68	0.06	-	3.46	**-0.69**
	0.60x0.60 vs.	sDA	0.99	1.09	-0.01	0.96	2.19	0.06
	0.20x0.20	ASE	-	1.18	0.07	-	1.55	-0.38
	0.40x0.40 vs.	sDA	0.99	0.57	-0.01	0.95	2.37	0.02
	0.20x0.20	ASE	-	0.92	0.02	-	1.92	0.35

Bold values have practically relevant effect sizes.

4.1.3 Processing Time

Table 6 shows the individual processing times required for point-in-time and annual daylighting simulation using different combinations of parameter settings. The annual analysis only refers to the calculation of sDA. As expected, a longer processing time was required when a higher number of ambient bounces or a smaller grid size was used. **Table 7** provides a quantification of the relative inflation in the processing time that results from using higher precision settings, normalising the calculated inflation against the time required to accomplish the simulation using the lowest precision settings (i.e., -ab2 and 0.60x0.60m).

Table 6. Processing time for daylighting analysis (in seconds)

Analysis	**Façade Type**	**Simple Façade**			**Complex Façade**		
	Grid size / -ab	0.60x0.60m	0.40x0.40m	0.20x0.20m	0.60x0.60m	0.40x0.40m	0.20x0.20m
Point-in-Time	-ab2	6	8	11	13	15	25
	-ab4	42	44	53	75	84	102
	-ab6	48	54	60	90	102	122
Annual	-ab2	75	94	151	124	157	227
	-ab4	264	314	462	525	614	835
	-ab6	376	444	693	612	697	1030

Table 7. Processing time inflation for daylighting analysis

Analysis	**Façade Type**	**Simple Façade**			**Complex Façade**		
	Grid size / -ab	0.60x0.60m	0.40x0.40m	0.20x0.20m	0.60x0.60m	0.40x0.40m	0.20x0.20m
Point-in-Time	-ab2	**0%**	33%	83%	**0%**	15%	92%
	-ab4	600%	633%	783%	477%	546%	685%
	-ab6	700%	800%	900%	592%	685%	838%
Annual	-ab2	**0%**	25%	101%	**0%**	27%	83%
	-ab4	252%	319%	516%	323%	395%	573%
	-ab6	401%	492%	824%	394%	462%	731%

The highest precision settings (i.e., -ab6, 0.20x0.20m) resulted in 731% - 900% inflation in the processing times of the different cases. The results demonstrate that the processing time is more sensitive towards changing the ambient bounces number than reducing the grid size. **Table 7** shows that increasing the ambient bounces precision from -ab2 to -ab6 inflates the simulation run time at least 394%, and up to 817% when using a 0.20x0.20m grid to predict a point-in-time daylighting for a simple façade. Whereas, decreasing the grid size from 0.60x0.60 to 0.20x0.20m inflates the simulation run time at least 83%, and up to 423% when using -ab6 to predict a point-in-time daylighting for a simple façade.

The impact of raising the ambient bounces precision from -ab2 to -ab4 is so much bigger than the extra increase to -ab6, as shown in **Figures 6**. The first increase produces an average inflation time of 354%, whilst the second increase produces an average of 104%.

Reducing the grid size has less impact on the simulation run time. Reducing the size to 0.40x0.40m inflates the processing time by 18% on average (from 5% to 33%), whilst additional reduction of size to 0.20x0.20m has average inflation of 47% (from 13% to 77%), as shown in **Figures 7**.

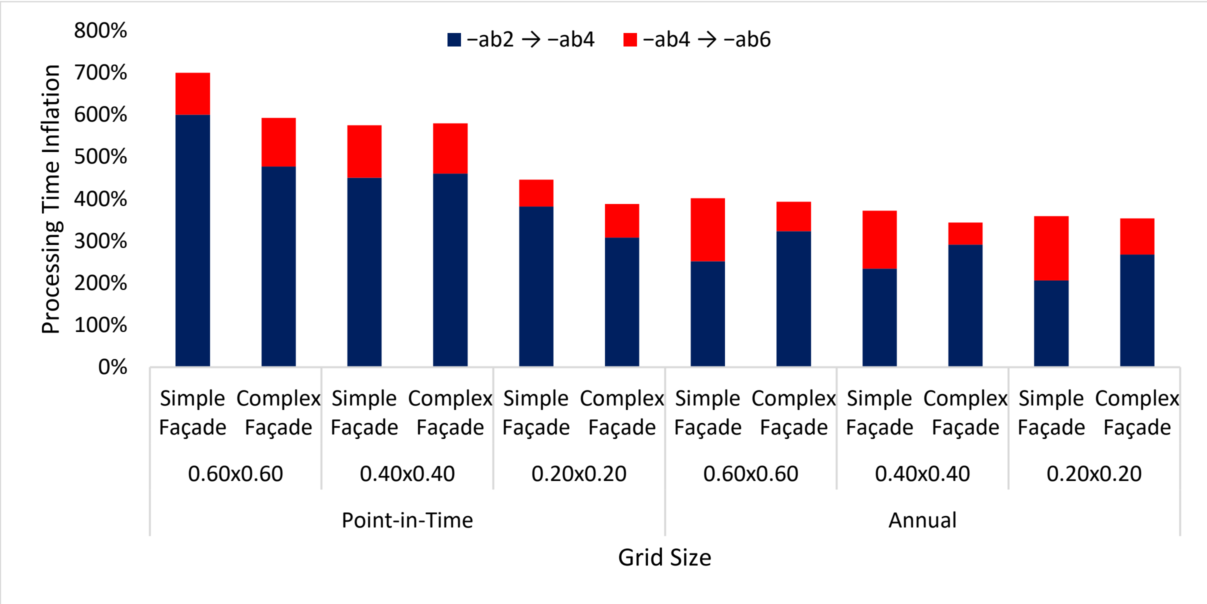


Figure 6. Daylighting analysis: Processing time inflation in response to the increase of ambient bounces

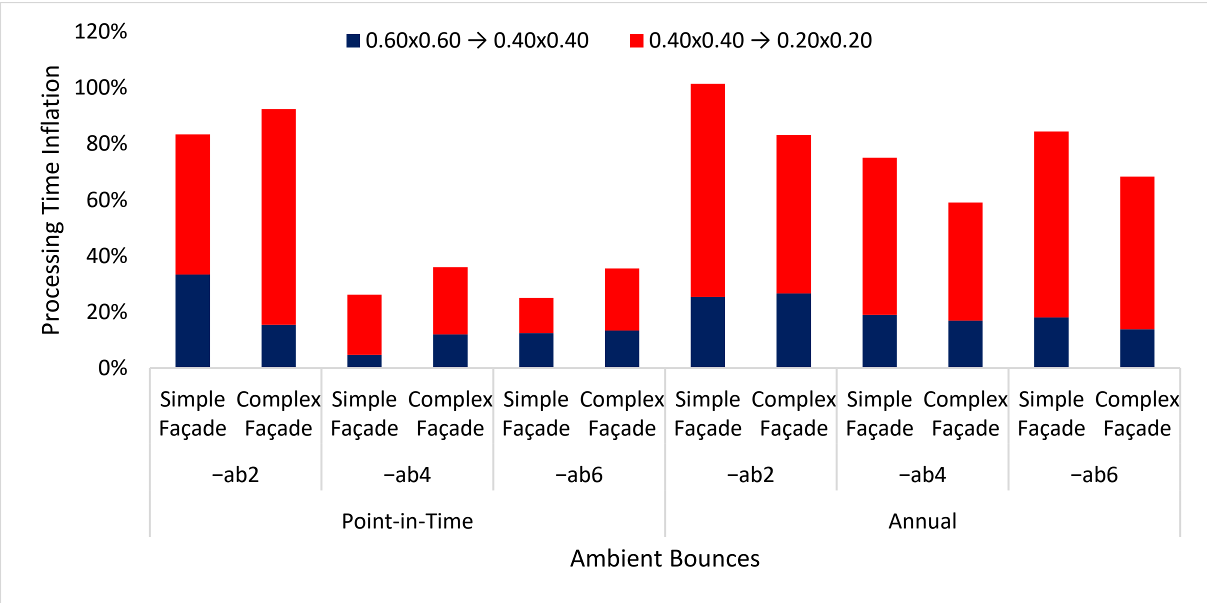


Figure 7. Daylighting analysis: Processing time inflation in response to the gride size reduction

4.2 Discomfort Glare Results

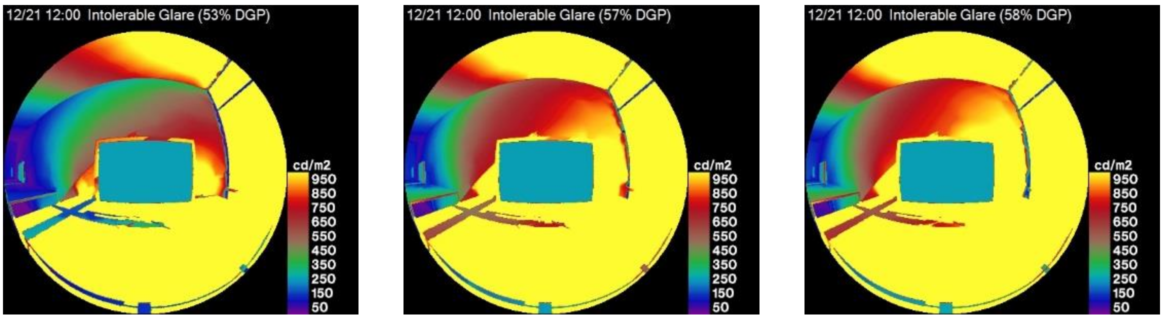
4.2.1 Ambient Bounces

Daylight glare probability was calculated using different values of ambient bounces. For each value, all other simulation parameters were varied, giving 144 cases for point-in-time analysis. For annual analysis, 4 cases were considered, generating 14600 hourly DGP estimates for each façade type under each sky condition.

Table 8 shows the inferential data for the point-in-time comparisons between DGP results. The analysis detected strong correlations between DGP values across all comparisons ($r^2 \geq 0.92$) and effect sizes of consistently negligible magnitude. The RMSE values ranged between 0.00 and 0.02 for most comparisons, although they were higher (between 0.05 and 0.07) for the simple façade in Cairo. **Figure 7** shows an example of this latter case, at noon on the winter solstice.

Table 8. Point-in-time glare analysis: comparisons between ambient bounces

Location	**Ambient Bounces**	**Simple Façade**			**Complex Façade**		
		r^2	RMSE (DGP)	Cohen's d	r^2	RMSE (DGP)	Cohen's d
Cairo	-ab1 vs.-ab2	0.92	0.07	-0.07	0.99	0.00	-0.01
	-ab1 vs.-ab3	0.96	0.06	-0.08	0.98	0.02	-0.01
	-ab2 vs.-ab3	0.97	0.05	0.00	0.98	0.02	0.00
Birmingham	-ab1 vs.-ab2	0.99	0.02	-0.05	0.99	0.00	-0.01
	-ab1 vs.-ab3	0.99	0.02	-0.06	0.99	0.01	-0.01
	-ab2 vs.-ab3	0.99	0.01	-0.01	0.99	0.01	0.00



-ab1: DGP 0.53 *-ab2: DGP 0.57* *-ab3: DGP 0.58*

Figure 3. Point-in-time glare analysis (Cam 1): simple façade, south, noon, winter solstice, Cairo

For the annual analysis, **Figure 9** provides examples of the comparisons for the simple façade in Birmingham. For the same case, **Figure 10** shows annual DGP profiles throughout the year. All inferential data are provided in **Table 9**.

Visual inspection of **Figure 9-left** suggests that a low value of ambient bounces (-ab1) might lead to lower hourly DGP estimates compared to -ab3 (plots are consistently above the null hypothesis line). This is supported by **Figure 9** since, especially in the middle part of the year, -ab1 predicted imperceptible glare (DGP<0.35), while perceptible (0.35>DGP>0.40) and disturbing (0.40>DGP>0.45) glare were returned by -ab3. The inferential data confirms that practically relevant negative effect sizes were detected for most comparisons between -ab1 and -ab3, with RMSE values ranging from 0.07 to 0.09 (it should be considered that the cut-off values for the four DGP glare categories – imperceptible, perceptible, disturbing, intolerable – have absolute differences of only 0.05 points between each other). When comparing -ab1 and -ab2, effect sizes of substantive magnitudes were only detected for the complex façade in Cairo, however for all other cases RMSE values consistently ranged between 0.05 and 0.07. Conversely, the results obtained with -ab2 and -ab3 revealed strong associations, lower errors, and negligible magnitude of differences, this being evident also from **Figure 9-right**.

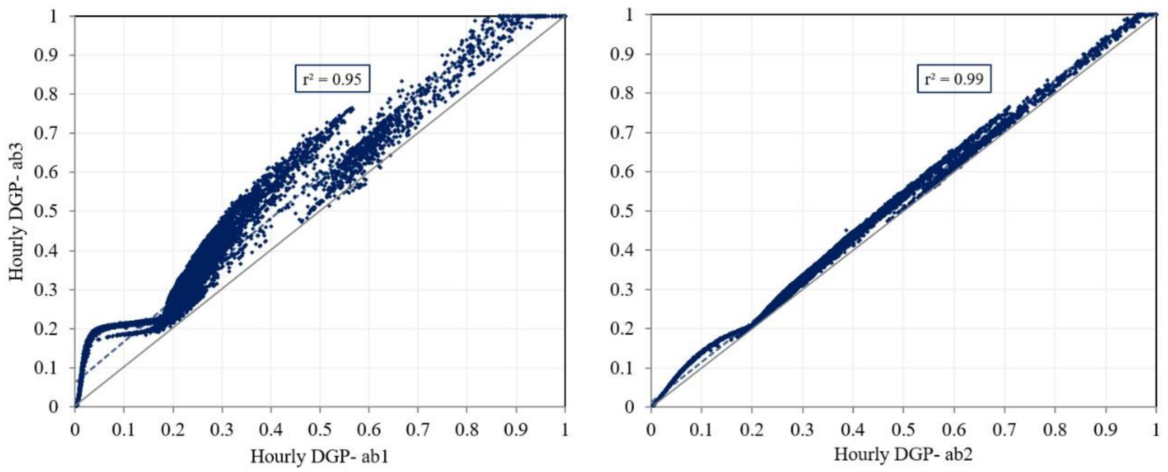


Figure 9. Annual glare analysis (cam1): simple façade, south, Birmingham

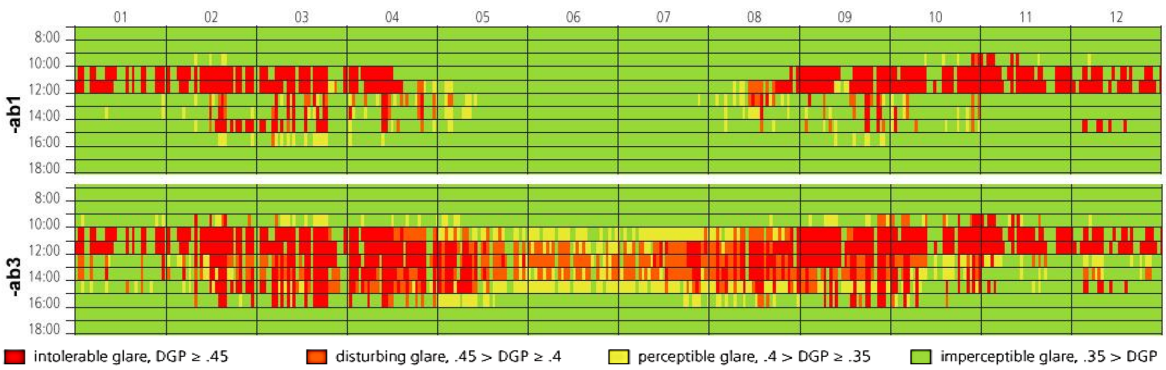


Figure 10. Annual glare map (Cam1): simple façade, south, Birmingham

4.2.2 Processing Time

Table 10 shows the simulation run times that each -ab value is required for point-in-time and annual DGP calculation. Consistent with daylighting simulations, the run time increased with a higher number of ambient bounces. For point-in-time analysis, based on façade type, using

-ab3 instead of -ab1 inflated the processing time by 824% and 550% for simple and complex façade respectively. For annual calculations, decreasing the number of ambient bounces did not have a relevant effect on run times, resulting in a maximum reduction of up to 5% (**Figure 11)**.

Table 9. Annual glare analysis: comparisons between ambient bounces

Location	Ambient Bounces	Simple Façade			Complex Façade		
		r^2	RMSE (DGP)	Cohen's d	r^2	RMSE (DGP)	Cohen's d
Cairo	-ab1 vs.-ab2	0.97	0.07	-0.29	0.89	0.06	**-0.45**
	-ab1 vs.-ab3	0.95	0.09	**-0.42**	0.82	0.09	**-0.65**
	-ab2 vs.-ab3	0.99	0.03	-0.12	0.98	0.03	-0.19
Birmingham	-ab1 vs.-ab2	0.96	0.07	-0.29	0.91	0.05	-0.28
	-ab1 vs.-ab3	0.95	0.09	-0.39	0.84	0.07	**-0.42**
	-ab2 vs.-ab3	0.99	0.02	-0.11	0.98	0.02	-0.14

Bold values have practically relevant effect sizes.

Table 10. Processing time for discomfort glare analysis (in seconds)

Analysis	Simple Façade			Complex Façade		
	-ab1	-ab2	-ab3	-ab1	-ab2	-ab3
Point-in-Time	17	93	157	36	132	234
Annual	3540	3566	3660	4805	4845	5065

5 DISCUSSION

The results obtained in this study provide substantive evidence that the setting of key lighting simulation input parameters have a practically relevant influence on the outcomes of daylighting and glare predictions and ultimately impact processing speed. The detected influence of the simulation run time is most important at the early design stage when several alternatives need to be investigated and compared. Meanwhile, the impact of prediction accuracy is most influential at the final stage when more precise results are required. The sensitivity analysis presented in this paper offers a statistically robust quantification of the

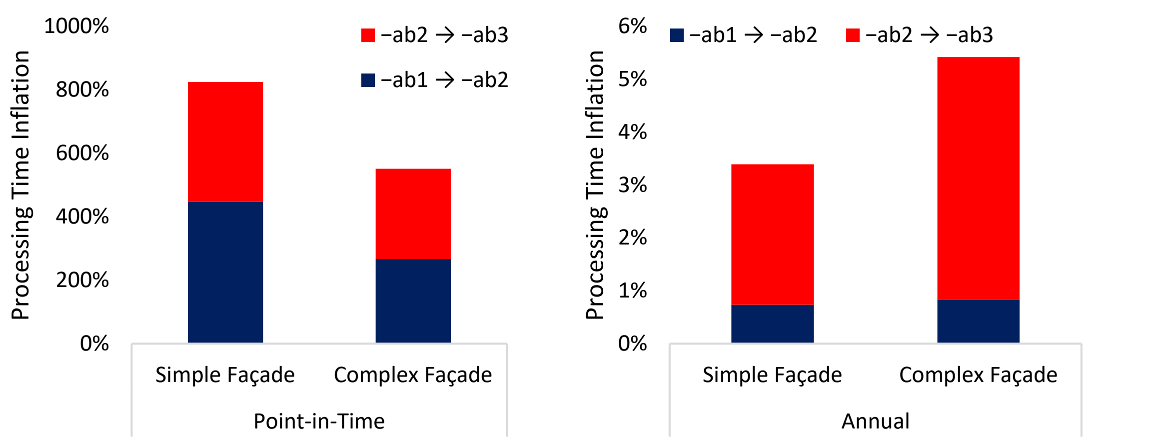


Figure 11. Glare analysis: Processing time inflation in response to the increase of ambient bounces

trade-offs that are necessary to consider between prediction accuracy and processing speed. They are measured against each other to provide practical guidance towards a robust implementation of the study findings.

5.1 Daylighting prediction

In general, daylighting calculations were found to be considerably more sensitive towards changing ambient bounces values than grid size, as discussed in the following sections.

5.1.1 Ambient Bounces

For point-in-time daylight calculations, the results of the sensitivity analysis revealed that using a low value of ambient bounces (-ab2) leads to a slight overestimation of the illuminated area falling within the low UDI and underestimation of the zone characterised by medium UDI. The estimation of the illuminated area with high UDI was not substantively affected by changes in -ab settings. The summarised results in **Figure 12** demonstrate that small or negligible improvements in the simulation precision can be obtained as a result of increasing the ambient value from two to four bounces; in return for a 310-600% increase in the processing time. Practically, no further improvement results from raising the number of bounces beyond -ab4. Nevertheless, if such accuracy is essential, it could increase the processing time from 64% to 125%, which looks acceptable for the examination of a limited number of alternatives or a final solution.

The annual calculations resulted in a substantive decrease in the estimated daylight autonomy of the space. The considerable improvement in the prediction accuracy, particularly under a clear sky, can be obtained as a result of increasing the ambient value from two to four bounces; in return for a 210-320% increase in the simulation run time. Differences in the predicted daylighting values were not practically relevant when the bounces further increased.

This is an important finding that practitioners need to consider when interpreting recommendations which suggest that a value of -ab2 might generally offer reasonably accurate predictions [41]. Although at early design stages inexperienced users may rely on ***low* -ab settings** to evaluate multiple spaces or design alternatives within a reasonable time, they should be cautious of the differences in the predictions' accuracy between point-in-time and annual estimates to avoid the effect of the low precision settings on the thresholds of performance predictions and the impact on final decision making.

Using ***medium* parameter settings** have the potential to produce estimates that have a negligible statistical difference with higher precision values for both point-in-time and annual values, yet require less computational resources. At the early design stage, this might question the effective advantage of using higher precision settings. In fact, if several solutions need to be compared, even a small difference in simulation speed may inflate considerably when considering the overall time required to assess multiple scenarios.

The designers should be aware that the use of **higher precision settings** (i.e., -ab6 and above) may not necessarily result in a substantive improvement in simulation accuracy [5]. As mentioned, studies have found that increasing the number of bounces above -ab5 might have little effect on final estimates [6, 9]. This was supported by our analysis. Balancing the appropriate precision settings with the characters of the model should be paramount when selecting the required accuracy level of any building performance simulation. The parsimonious approach presented in this paper intends to support end-users to make informed decisions in accordance with the computational resources available.

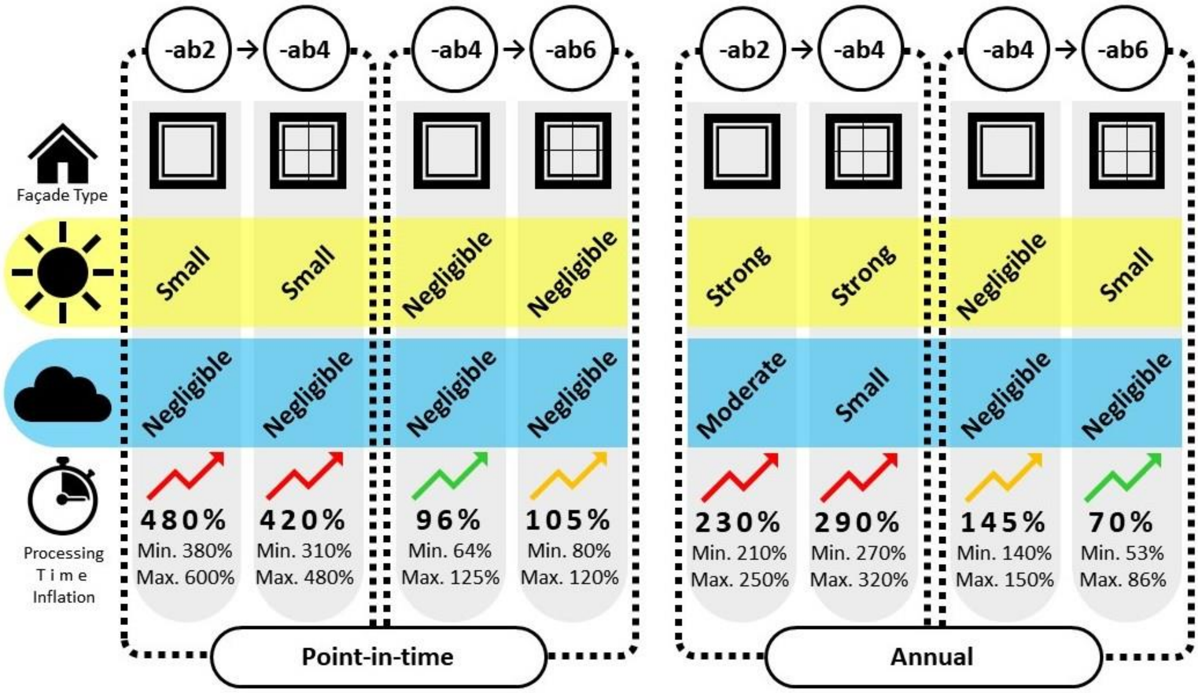


Figure 12. Summary of the ambient bounces effect on daylight prediction and processing time inflation

5.1.2 Grid Size

The calculations of point-in-time illuminance distribution and annual daylight autonomy across the illuminated area were not substantively influenced by the spacing between sensor nodes. However, in the presence of a complex façade, a denser grid is more likely to afford a more accurate prediction of light patches (i.e., ASE) on specific points of interest, specifically under sunny conditions. In such cases, the up-to-56% processing time inflation looks acceptable -if compared with that occurred due to changing the (-ab)- as summarized in **Figure 13**.

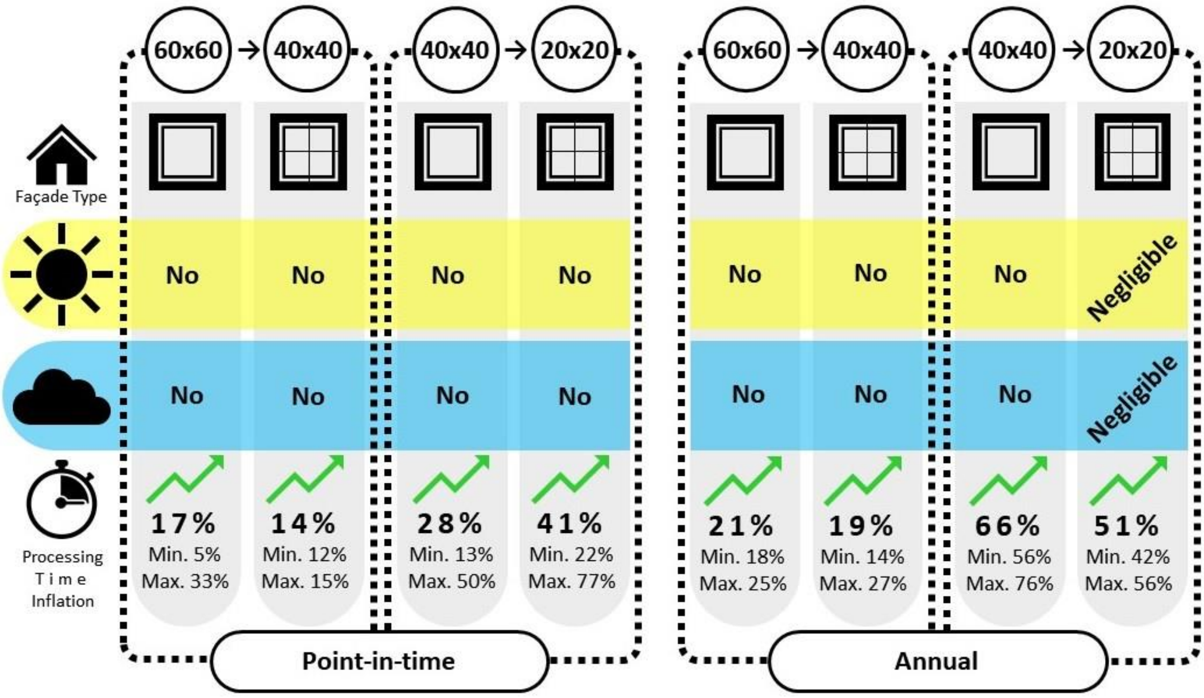


Figure 13. Summary of the grid size effect on daylight prediction and processing time inflation

The complexity of the façade can make the prediction more sensitive to the choice of parameter settings. If a larger grid (0.60x0.60m) can produce reasonable estimations while affording decreased processing times, with complex façades a denser grid (0.20x0.20m) is recommended for a more robust simulation of the light patches pattern over the year. This suggests that the distance between sensor points should be selected based on the characteristics of the model (simple vs. complex façade), the target of the analysis (point-in-time vs. annual) and the nature of the sky conditions (sunny vs. cloudy).

5.2 Glare Prediction

Figure 14 shows that the DGP estimates did not reveal substantive differences in effect sizes irrespective of the -ab value used. However, the analysis revealed that –for annual calculations of complex façades– a low value of ambient bounces (-ab1) led to slightly lower DGP estimates than higher precision settings.

Despite the negligible improvement in the DGP estimates, point-in-time calculations can be up to 9.3 times faster when using a low value of ambient bounces (e.g., -ab1 vs. -ab3). In the meantime, the processing time required by annual analysis was shown not to be sensitive to the -ab value chosen. Consequently, lower precision settings can be mostly adopted, particularly for point-in-time analysis, to accelerate the simulation run time. However, it should be considered that metrics such as DGP are characterised by very small absolute differences (0.05 points) in the cut-off values between consecutive ratings, hence increasing the possibility that lower precision parameters lead to an estimation falling in different glare categories.

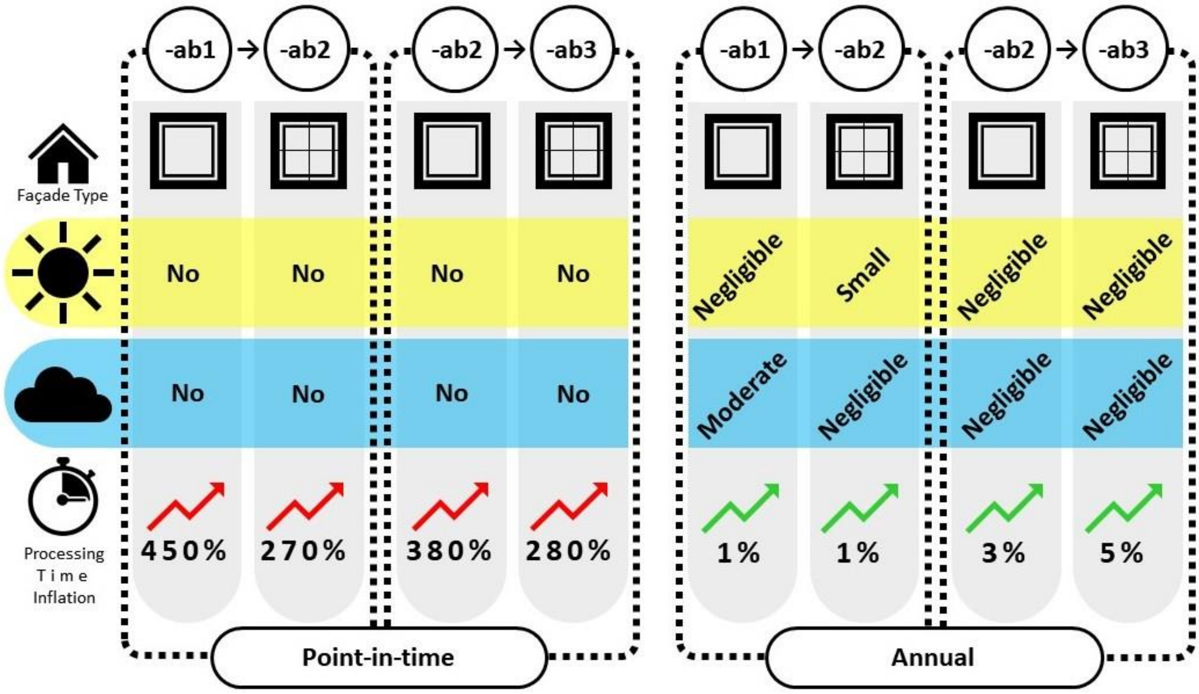


Figure 14. Summary of the ambient bounces effect on glare prediction and processing time inflation

6 LIMITATIONS AND FUTURE WORK

Before the results of this study can be generalised, some limitations should be acknowledged. The results presented relate to simulations solely based on a reference office tested under two sky conditions (i.e., sunny and cloudy skies) that apply to vast geographical regions. The validation of these results against real data was beyond the scope of this study. Nevertheless, the raytracing software utilised for the calculations, and the graphical algorithm editor and modelling tools employed, have been widely tested and validated by the building performance simulation community [9, 17].

The two tested façade types cover a wide range of building fenestrations alternatives. However, they cannot be fully representative of the entire building stock. Further research should extend the variety of study cases included in the sensitivity analysis in terms of façade types, climate and buildings' characteristics, occupants' behaviours, etc. [62].

This study has endeavoured to only make reasonable inferences supported by data on the relative differences detected in simulation outcomes. Moreover, although the metrics chosen are those most commonly found in software tools, they might only have partial applicability. For example, the index used for discomfort glare evaluation, DGP, was originally developed using test-rooms equipped with venetian blinds and vertical lamellas, which might bear different glare implications from the complex facade configuration used in this study [54]. The consistency of other metrics, such as ASE, has been found to be dependent on the simulation method adopted [9].

The authors would like to highlight that in the process of reporting the findings of this study and the preparation for further validation tests, DIVA software has been discontinued by the developer and replaced by ClimateStudio; an environmental performance analysis software [63]. It uses a different Radiance-based approach where the timing issue was addressed using what so-called 2-phase method. In this method, ambient interpolation settings are no longer used (-a, -as and -ar), whereas other parameters such as -ab and -ad still play an important role in producing an accurate outcome. Despite the remarkable acceleration in ClimateStudio simulations, yet the differences in computational time between -ab settings exist, suggesting further investigation in future work. Having that said, the authors argue that the discussed concept should be considered and the developed method can be applied to validate the potential of the recently released simulation software. A trade-off remains often necessary to balance the granularity of prediction accuracy and the computational speed, particularly for complex scenes and multiple alternatives.

7 CONCLUSION

To close the gap between predicted and measured building performance, simulation tools must provide practitioners with adequate information to drive their decisions along the design process. To this aim, a trade-off is often necessary between the granularity of accuracy and the computational resources required, particularly at early design stages when more opportunities exist to improve performance and many alternatives need to be examined. To support the characterisation of a parsimonious workflow for the early-stage daylighting and glare simulation of façade systems, this paper has offered a rigorous quantification of the sensitivity that the convergence of prediction outcomes and the inflation of processing times show towards some key input parameter settings. The analysis revealed that a simplified daylighting simulation can be up to 10 times faster than a calculation using higher precision settings.

In order to reduce the 'entry point' required to run daylighting analyses, front-end software developers are providing practitioners with standardised and simplified choices for simulation settings. However, insufficiently accurate predictions might have severe impacts on design development, so it is important to communicate to designers how different parameter settings, at various design stages, can affect the robustness of simulations and how appropriate selections can influence the processing power required. In response, this paper has presented a range of recommendations, that can be replicated and updated using the suggested concept and developed method, which might be helpful to resolve these trade-offs, whilst also offering a systematic method for statistical analysis based on simple indicators to allow a rigorous estimation of the consistency in convergence of building performance simulation outcomes.

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