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An empirical validation of daylighting tools: Assessing radiance parameters and simulation settings in Ladybug and Honeybee against field measurements

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ABSTRACT

Most of the new studies in Radiance rely on industry-accepted values for setting Radiance parameters. Although Radiance is validated against the analytical test cases of CIE 171:2006, there is no scientific basis for these settings. Therefore, the aim of this study is to assess the effect of Radiance parameters and model-related components on the accuracy of simulation results in Radiance by comparing field measurements and simulation results. This study uses a point by point illuminance comparison of simulation results and field measurements under an overcast sky with measured illuminance in HoneybeePlus version 0.0.04 which uses Radiance version 5.1. The accuracy is rechecked with three other measured illuminance levels at different times under the same sky. Furthermore, this study assesses the effect of simulation parameters and model settings on the accuracy of simulation results. Results show that the recommended Radiance settings for having accurate results are accurate enough with a bias below 15%. Setting ambient bounces to more than 8 and disabling interpolation by setting ambient accuracy to 0 does not significantly affect the simulation results. By disabling interpolation, Monte Carlo ray tracing provides accurate results for simple geometries. Moreover, ± 0.1 difference in reflectance factors has a significant effect on the accuracy of results. This study makes a scientific basis for setting Radiance parameters and measuring reflectance factors in future studies. The outcome of this paper creates a validated model for future studies on shaders, light shelves, and related designable components that rely on daylight in general.

1. Introduction

1.1. The current problem

Radiance is validated against the analytical test cases of CIE 171:2006 which are the standard test cases for validating daylighting tools before their release (International Commission on Illumination (CIE), 2006; Reinhart and Walkenhorst, 2001). Although Radiance has passed the test cases successfully, the effect of its parameters and model-related components such as reflectance factors (RF) on simulation results is not investigated. As a result, many studies rely on previous studies for setting these settings or they just use industry-accepted values that are widely taught in universities (Mardaljevic, 2014). Some researchers do not consider these two approaches scientific enough and increase or decrease the values for achieving the maximum accuracy of results. For instance, a previous study set the ambient accuracy in its simulations to 5 (Monteoliva et al., 2020) while another study set this value to 10 and 30 for achieving the maximum accuracy (Yao et al., 2020). Such examples are abundant and it has remained unclear whether increasing or decreasing these values results in more accurate results.

1.2. Radiance and its calculations

Radiance compiles geometries in a scene into an “octree” which is the data structure for the ray tracing process. Radiance achieves accurate results in a reasonable time by implementing a hybrid approach of deterministic ray tracing and Monte Carlo method. Accordingly, the lighting simulation engine takes a measurement point and traces the ray of light back to the source of the light. This process is known as the backward raytracing. There are three main sources for the calculations, including the diffuse indirect component, the specular indirect component, and the direct component (Ward, 1994).

The direct component comprises the light which is emitted directly

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from a light source or flawlessly specular transfers from other surfaces. After listing emitters based on their potential contribution for minimizing the required rays for calculations, Radiance uses Monte Carlo sampling along with adaptive subdivision for accurate penumbra calculation. The specular indirect component encompasses reflected or transmitted light from other surfaces directionally. The diffuse indirect component includes light that arrives at a surface and is reflected or transmitted with no directional preference. Although this component requires examining many directions for accurate results, Radiance uses the diffuse indirect calculation along with gradient information of each Monte Carlo evaluation for improved interpolations (R. Chadwell, 1997). Therefore, simulation results in Radiance slightly differ after each run since Radiance implements the hybrid calculation method. It is important to determine the difference in results for accurate interpretation and validation in the next steps.

1.3. Radiance and its parameters

Many different factors such as the difference in sky models, climate conditions (Bhandari et al., 2012; Brembilla and Mardaljevic, 2019), the bias in simulation methods and settings (Brembilla et al., 2019, 2018), and other factors such as behavioral factors and occupants' behavior (Yan et al., 2015) affect predicted daylighting in buildings. Simulation-related biases can significantly influence the outcome and prediction of simulated daylighting and energy demand in the early stages of the design process or renovation projects. Various components of buildings along with simulation settings contribute to the calculation process. These components are mainly reflectance factors of surfaces (Brembilla et al., 2018), sky models (CIE, 2004; Perez et al., 1993), simulation settings (McNeil and Lee, 2013), and occupancy schedules (Wagner et al., 2018). In addition to the impact of occupancy schedules on the energy demand of the buildings (Yan et al., 2015), occupancy schedules are of significant importance to new dynamic metrics of daylighting such as Useful Daylight Illuminance (UDI) (Nabil and Mardaljevic, 2006). On the other hand, both artificial lighting and energy demand of the building depend on daylight. Various technological and behavioral studies tried to maximize the use of daylight in buildings efficiently (Grobman et al., 2017). Although many of these studies provide state-of-the-art technology, they usually do not have the means to validate their annual results in practice and rely on simulation programs. Daylight calculations in these programs are highly dependent on sky models for static indices such as Daylight Factor (DF) and weather conditions for dynamic indices such as Annual Sun Exposure (ASE) or Daylight Autonomy (DA) (Hensen and Lamberts, 2012). Furthermore, reflection factors for calculating reflections from internal and external surfaces, and simulation settings for engine-based calculations such as ambient accuracy or ambient bounces have a significant impact on the accuracy of simulations (Reinhart and Walkenhorst, 2001). Simulations for research projects without either validation or calibration may deviate significantly from the reality (Judkoff et al., 2008). In addition, there is no firm scientific basis and evidence for Radiance parameters.

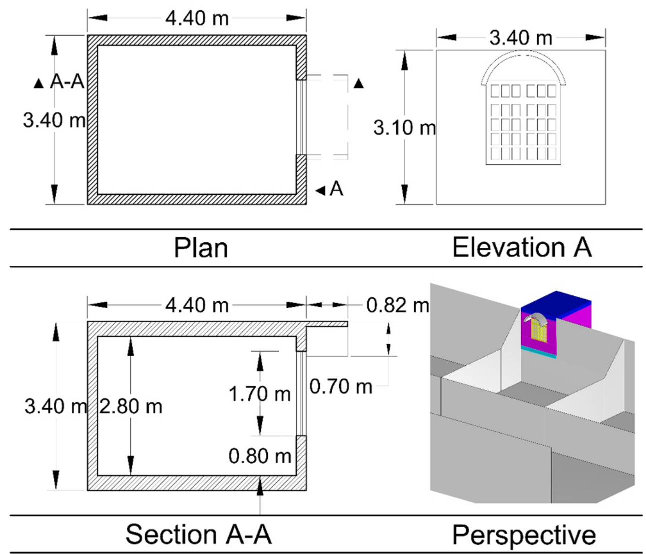

Fig. 2. The interior dimensions of the studied room.

Therefore, the aim of this study is to validate HoneybeePlus (Honeybee +) version 0.0.04 and Ladybug-Honeybee version 0.0.68–0.0.65, which both use Radiance version 5.1 as their daylight calculation engine, against field measurements for evaluating the internal consistency of Radiance and the effect of Radiance parameters and reflectance factors on the accuracy of simulation results under an

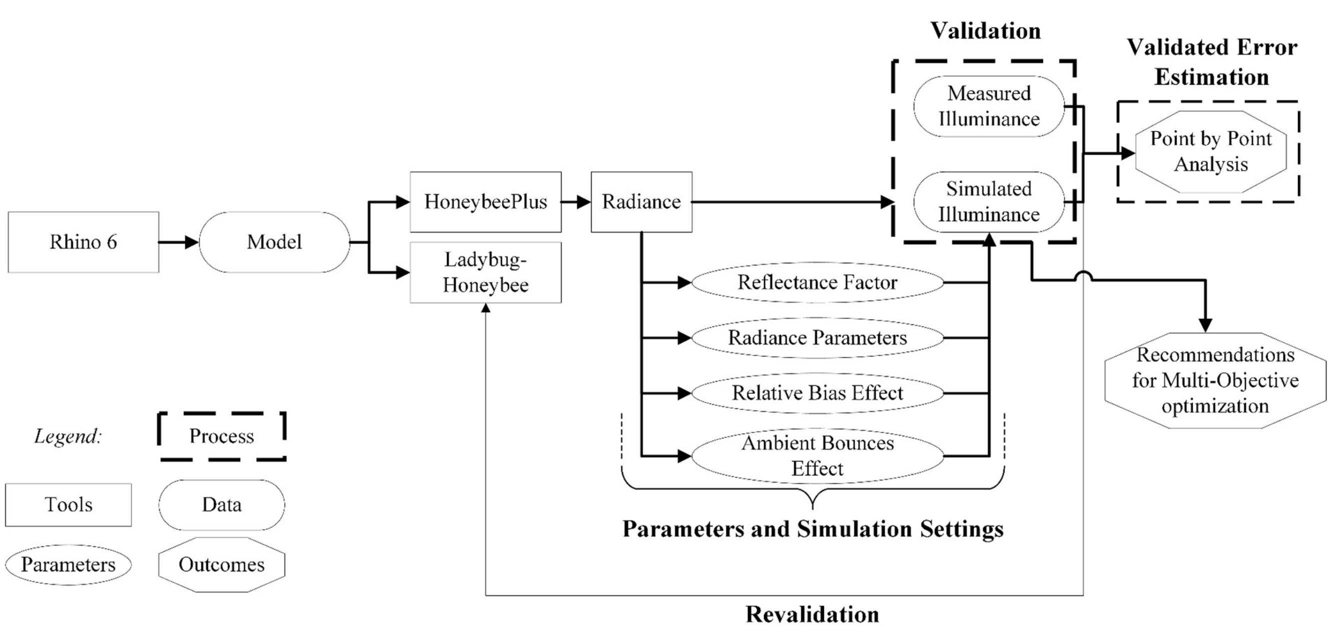

Fig. 1. Research method in brief.

Table 1
Reflectance factor.

Surface	Reflectance factor		
	Standard	Measured	Investigated
Ceiling	0.8	0.72	Varies (± 0.1 and ± 0.2)
Wall	0.5	0.57	Varies (± 0.1 and ± 0.2)
Floor	0.2	0.24	Varies (± 0.1 and ± 0.2)

overcast sky with certain illuminance level. The outcome of this research creates a scientific foundation for setting Radiance parameters and model-related components in future studies. Furthermore, this study provides a validated simulation model in Radiance as a database for future studies. Subsequently, this study provides a validated foundation with measured error for examining newer technologies as well as the effects of building components such as light shelves in buildings, especially for multi-objective optimizations.

2. Methods

In this study, point by point analysis is carried out for validating Radiance version 5.1 (hereafter Radiance) in HoneybeePlus version 0.0.04 and Ladybug-Honeybee version 0.0.68–0.0.65 (Mostapha Sadeghipour Roudsari, 2020) against field measurements. Point by point analysis is used for comparing available illuminance levels on the work plane at the height of 76 cm from the ground (DiLaura et al., 2011). Furthermore, this paper investigates the relative bias of Radiance, the effect of Radiance parameters on the accuracy of results, the effect of ambient bounces (-ab) on simulation results, and the effect of reflectance factors on simulation results. Moreover, this study recommends the optimized settings for multi-objective optimization in Radiance and investigates the related Radiance parameters. The term relative bias is used only for the internal consistency of the research instrument (Section 3.1). Fig. 1 shows the research method and outcomes briefly. It should be mentioned that some graphs in the study have linear representation for easier interpretation but the relation between illuminance levels is not necessarily linear.

2.1. Point by point analysis

This study uses point by point analyses for comparing illuminance levels on the work plane (analysis grid) between the simulation results and the field data. For this purpose, the studied tool reports illuminance levels in lux (lx) for validation against field measurements. To achieve this comparison, grid-based analysis under a sky with certain illuminance is used for simulations that calculate illuminance for a single moment in time based on the sky illuminance (Kjell, 2014). Sky model plays a vital role in daylight calculations. In this regard, this study uses CIE overcast sky based on available horizontal illuminance (CIE, 2004). Furthermore, Radiance is the calculation engine for illuminance levels in HoneybeePlus and Ladybug-Honeybee. Therefore, it is essential to report the Radiance version. Engine versions are mentioned in Section 2.2.

Table 3
Recommended values for the best practice.

Parameter	Values for Section 3.1	Values for other sections
-ab	24	Varies
-aa	0.1	Varies
-ar	128	Varies
-ad	4096	Varies
-as	1024	Varies

2.1.1. Illuminance measurements

The method of validation against field data was explained in Section 2.1. In this subsection, general considerations regarding the comparison are discussed. As explained earlier, this study adopted the IESNA method for measuring the daylight inside the building. Equation (1) shows the general formula for the average illuminance in interior spaces. Accordingly, Equation (2) shows the formula for calculating the average illuminance in the studied room in this study. *P* represents the reading on the measurement points in lux while *ΣnPi* shows the total number of measurement points (35 points in this study).

Equation (1): Average Illuminance

$$E_{avg} = P_i/\Sigma n_{Pi} \tag{1}$$

Equation (2): Average Illuminance in this study

$$E_{avg} = (P_1 + P_2 + \ldots + P_{35})/35 \tag{2}$$

2.2. Simulation program

As mentioned earlier, this study uses HoneybeePlus version 0.0.04 mainly (Mostapha Sadeghipour Roudsari, 2020) for conducting grid-based analyses. Radiance is the calculation engine for lighting in this program and Honeybee and Ladybug are more of interfaces that facilitate conducting simulations. It is clear that validating HoneybeePlus also validates Ladybug-Honeybee version 0.0.68–0.0.65 since both versions of Ladybug and Honeybee rely on the same version of Radiance (version 5.1). In general, simulation programs work as an interface for modeling buildings, rooms, etc. but they use Radiance (illuminance calculator) and DAYSIM (annual illuminance calculator) for simulating daylighting. The model drawings are done in Rhino version 6.

2.3. Field data collection

This study adopted general guidelines of the Illuminating Engineering Society of North America (IESNA) on measuring luminance in indoor environments for measuring illuminance in the studied room

Table 2
Simulation parameters.

Parameter	Abbreviation in radiance	Definition	Consideration
Ambient bounces	-ab	is the maximum number of diffuse bounces computed by the indirect calculation.	Higher values provide better accuracy
Ambient accuracy	-aa	is the maximum error (expressed as a fraction) permitted in the indirect irradiance interpolation.	lower values give the best accuracy
Ambient resolution	-ar	sets the distance between ambient calculations by determining the maximum density of ambient values used in interpolation.	Higher values provide better accuracy
Ambient divisions	-ad	sets the number of initial sampling rays sent from each ambient point into the hemisphere to determine the indirect incident light.	Higher values provide better accuracy
Ambient super-samples	-as	The number of extra rays that will be used to sample areas in the divided hemisphere that appear to have high variance.	Higher values provide better accuracy (it is normally set to one half or one-quarter of Ambient divisions)

(DiLaura et al., 2011). For maximum accuracy and based on this approach, the room was divided into 35 equal rectangles, and illuminance was measured at the center of each rectangle with one-hour intervals from noon to 4 PM, except 1 PM, on November 19, 2019. This study used Milwaukee MW700 Standard Portable Lux Meter, which its accuracy is ± 6% of reading/ ± 1 digit according to the manufacturer (Milwaukee Electric Tool Corporation, n.d.), to measure the illuminance. According to IESNA, the surface of the measuring instrument should be position horizontally and 76 cm above the floor (DiLaura et al., 2011).

2.4. Simulation model and studied room

Fig. 2 shows the physical characteristics of the studied room and the context of the model.

The window in the building was single-glazing with clear glass and a thickness of 4 mm. This window provides 0.88 visible transmittances out of 1 which was used in the simulations to evaluate the models. Table 1 shows the industry-accepted standard reflectance factors (European Committee for Standardization, 2011) along with the measured ones. The measured factors are used for investigating the effect of Radiance parameters on the simulation results but the effect of reflectance factors is studied in Section 3.4 separately. This study used a previously researched method for measuring the reflectance factors on-site (Brembilla et al., 2016). Accordingly, a lux meter was used perpendicular to surfaces, once toward and once against the surface, for measuring the reflectance factor on site. Although ASTM E1331 – 15 (2019), Standard Test Method for Reflectance Factor, is the standardized method for measuring reflectance factor (ASTM International, 2019), the mentioned in-situ method is comparatively accurate (Brembilla et al., 2016). Reflectance factors for the simulations are mentioned in each figure throughout the study. Measured values are used in sections that the reflectance factors are not mentioned. The reflectance factor for the overhang of the window was 0.3. The overall reflectance factor for the environment was set to 0.2.

2.5. Simulation settings

Simulation settings are the most important part of simulations in daylighting. Setting parameters for variables such as ambient bounces

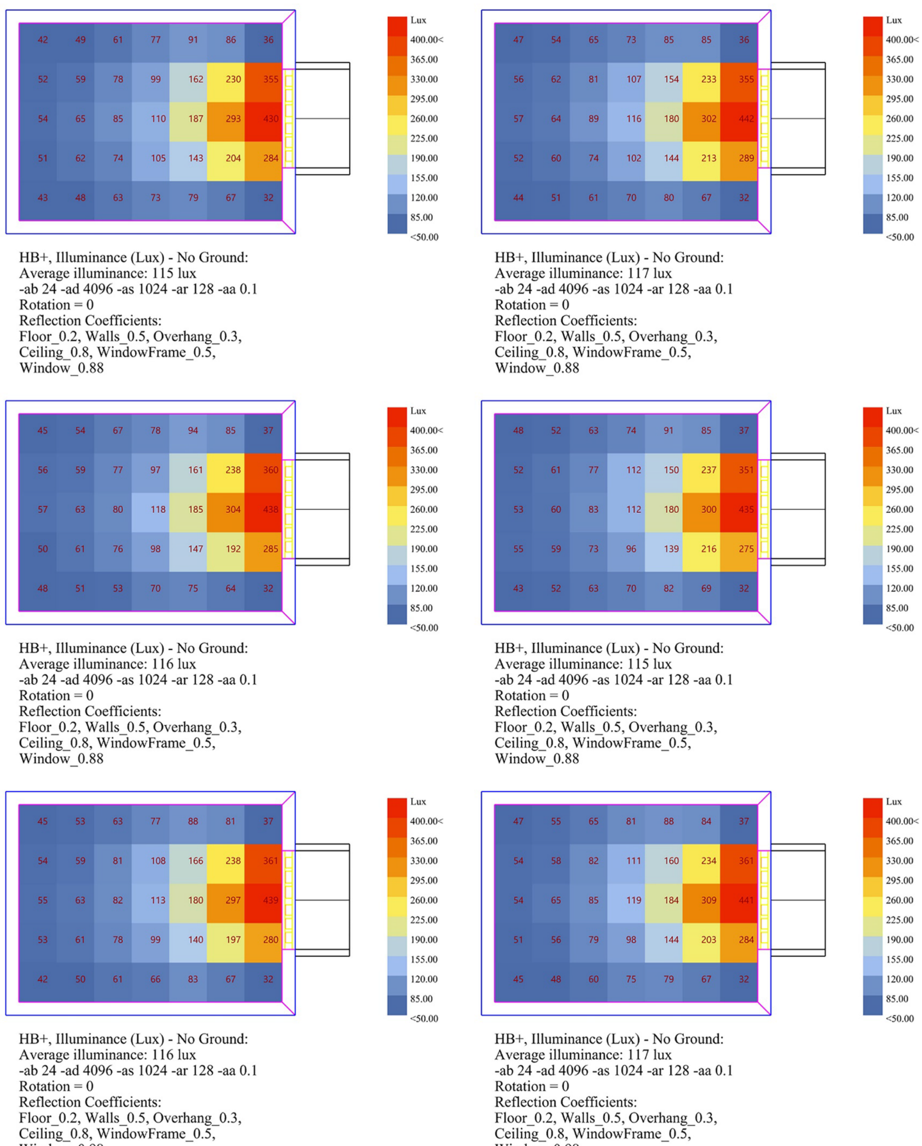

Fig. 3. Assessing relative bias in results.

Table 4
Detailed values of six consecutive runs.

Row	Point	1st Run(Lux)	2nd Run(Lux)	3rd Run(Lux)	4th Run(Lux)	5th Run(Lux)	6th Run(Lux)	Min(Lux)	Max(Lux)	Difference(%)
1st Row	1	32	32	32	32	32	32	32	32	0
	2	284	289	285	275	280	284	275	289	5
	3	430	442	438	435	439	441	430	442	3
	4	355	355	360	351	361	361	351	361	3
	5	36	36	37	37	37	37	36	37	3
2nd Row	1	67	67	64	69	67	67	64	69	8
	2	204	213	192	216	197	203	192	216	13
	3	293	302	304	300	297	309	293	309	5
	4	230	233	238	237	238	234	230	238	3
	5	86	85	85	85	81	84	81	86	6
3rd Row	1	79	80	75	82	83	79	75	83	11
	2	143	144	147	139	140	144	139	147	6
	3	187	180	185	180	180	184	180	187	4
	4	162	154	161	150	166	160	150	166	11
	5	91	85	94	91	88	88	85	94	11
4th Row	1	73	70	70	70	66	75	66	75	14
	2	105	102	98	96	99	98	96	105	9
	3	110	116	118	112	113	119	110	119	8
	4	99	107	97	112	108	111	97	112	15
	5	77	73	78	74	77	81	73	81	11
5th Row	1	63	61	53	63	61	60	53	63	***19***
	2	74	74	76	73	78	79	73	79	8
	3	85	89	80	83	82	85	80	89	11
	4	78	81	77	77	81	82	77	82	6
	5	61	65	67	63	63	65	61	67	10
6th Row	1	48	51	51	52	50	48	48	52	8
	2	62	60	61	59	61	56	56	62	11
	3	65	64	63	60	63	65	60	65	8
	4	59	62	59	61	59	58	58	62	7
	5	49	54	54	52	53	55	49	55	12
7th Row	1	43	44	48	43	42	45	42	48	14
	2	51	52	50	55	53	51	50	55	10
	3	54	57	57	53	55	54	53	57	8
	4	52	56	56	52	54	54	52	56	8
	5	42	47	45	48	45	47	42	48	14
Average		115	117	116	115	116	117	115	117	2

can significantly affect simulation results since it can control the number of reflections of light (bounces) in a room. Although there are so many different parameters in Radiance for controlling the outcome, the five parameters of Ambient bounces (-ab), Ambient Accuracy (-aa), Ambien Resolution (-ar), Ambient Divisions (-ad), and Ambient Supersamples (-as) are the most important parameters that have a direct effect on simulation results and accuracy (Lawrence Berkeley National Laboratory, 2020). In addition to the aforementioned parameters, there are other parameters in Radiance but are not investigated since they have no or little effect on simulation results, and some tools, such as DesignBuilder v. 6.1, do not include them in their user interfaces. In this study, Ladybug-Honeybee has all the five parameters included in their user interface and other noneffective parameters on results such as source jitter (-sj). This study follows the general recommendations for noneffective parameters but investigates the main parameters of -ab, -aa, -ar, -ad, and -as thoroughly (Lawrence Berkeley National Laboratory, 2020). The same applies to the CBDM (Climate-based Daylight Modeling) metrics. Table 2 shows the simulation parameters and their definition along with their effects on simulation results.

The values for parameters are not described in this section since they vary during the study. The parameters are investigated in Section 3.2 thoroughly. Table 3 shows the values that were used only in Section 3.1 for measuring the relative bias of the tool based on the highest values available on the website of Radiance (Chadwell, 2011).

3. Results

3.1. The difference in radiance calculations (relative bias)

As described earlier simulation results in Radiance slightly differ after each run since Radiance implements the hybrid calculation method. It is important to determine the difference in results for accurate interpretation and validation in the next steps. In this section, this study repeated the simulation six times with the same settings for the room only to measure the difference between results. Fig. 3 shows the analysis grid along with the simulation parameters, the average illuminances, and reflectance factors.

Accordingly, the relative bias in each run ranges from 0% to 19% difference in illuminance levels. The bias is higher in areas that receive more light from the source (emitters) as shown in Fig. 3. The maximum difference in percentage was observed in point 21 (Table 4) while the maximum difference in illuminance value was observed in point 7 (Fig. 4). The average difference in illuminance levels for all points was 9% while the difference in average illuminance level of the room was 2%. This shows that Radiance is accurate in estimating the overall illuminance level on the analysis grid but there might be an average bias of 9% in point by point analysis. It is noteworthy to mention that changes in illuminance levels do not follow a pattern; Fig. 3 shows that illuminance levels do not necessarily increase in all measurement points if the illuminance level increases in a specific measurement point. This creates the foundation for accurate average values.

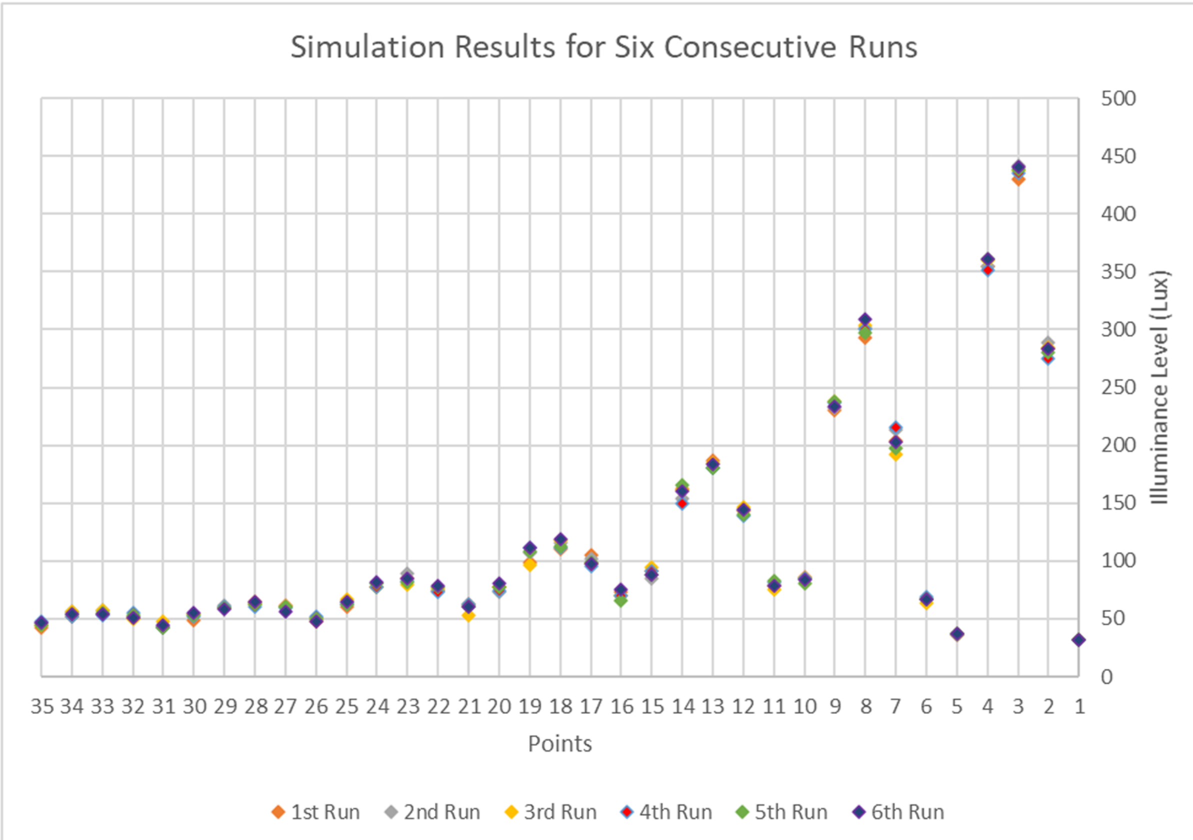

Fig. 4. Simulation results for six consecutive runs.

Table 5
Recommended radiance parameters and the studied parameter setting by this study.

Parameter	ps	pt	pj	dj	ds	dt	dc	dr	dp	sj	st	ab	aa	ar	ad	as	lr	lw
Minimum	16	1	0	0	0	1	0	0	32	0	1	0	0.5	8	0	0	0	0.05
Fast	8	0.15	0.6	0	0.5	0.5	0.25	1	64	0.3	0.85	0	0.2	32	32	32	4	0.01
Accurate	4	0.05	0.9	0.7	0.15	0.05	0.5	3	512	0.7	0.15	2	0.15	128	512	256	8	0.002
Maximum I	1	0	1	1	0.02	0	1	6	0	1	0	8	0.1	256	4096	1024	16	0
Maximum II	1	0	1	1	0.02	0	1	6	0	1	0	8	0.05	512	4096	1024	16	0
Maximum III	1	0	1	1	0.02	0	1	6	0	1	0	8	0.01	1024	4096	1024	16	0
Maximum IIII	1	0	1	1	0.02	0	1	6	0	1	0	8	0	0	4096	1024	16	0
Maximum-ab 10 I	1	0	1	1	0.02	0	1	6	0	1	0	10	0.1	256	4096	1024	16	0
Maximum-ab 10 II	1	0	1	1	0.02	0	1	6	0	1	0	10	0.05	512	4096	1024	16	0
Maximum-ab 10 III	1	0	1	1	0.02	0	1	6	0	1	0	10	0.01	1024	4096	1024	16	0
Maximum-ab 10 IIII	1	0	1	1	0.02	0	1	6	0	1	0	10	0	0	4096	1024	16	0

3.2. Assessing radiance parameters

In this section, the results of simulations with different Radiance parameters are compared to each other for assessing the effect of the parameters on the simulation results. Then, the simulation results are compared to the field measurements. This study followed the general recommendation of the Radiance website for setting its parameters that includes Minimum, Fast, Accurate, and Maximum (Maximum IIII) settings (Table 5). Furthermore, this study developed its own parameter settings which are named “Maximum -ab 10 I - IIII” and “Maximum I - III” in Table 5. Please note that setting -aa parameter to 0 turns the interpolation off technically and might be a misinterpretation that some researchers may come up with. In other words, values closer to 0, 0.01 for instance, offer more accurate results. Therefore, this study used interpolation (-aa parameter) with different values including 0.05 and 0.01 along with ambient bounces (-ab) set to 10. In addition to the recommended parameters of Maximum IIII by Radiance, this study investigated simulation results with -aa set to 0.1, 0.05, and 0 (no interpolation) with -ab 8. Ambien resolution (-ar) provides softer renderings in Radiance and therefore, it is following the same logic of increasing values.

Results illustrate that the Minimum setting does not provide any result while Fast setting provides completely biased results. Setting parameters to accurate simulation provides proportionally accurate results but its average illuminance differs almost 34% from field measurements and the results of Maximum as well as “Maximum -ab 10” settings. The simulation results for both Maximum and “Maximum -ab 10” variations were almost similar with slight changes to the grid and

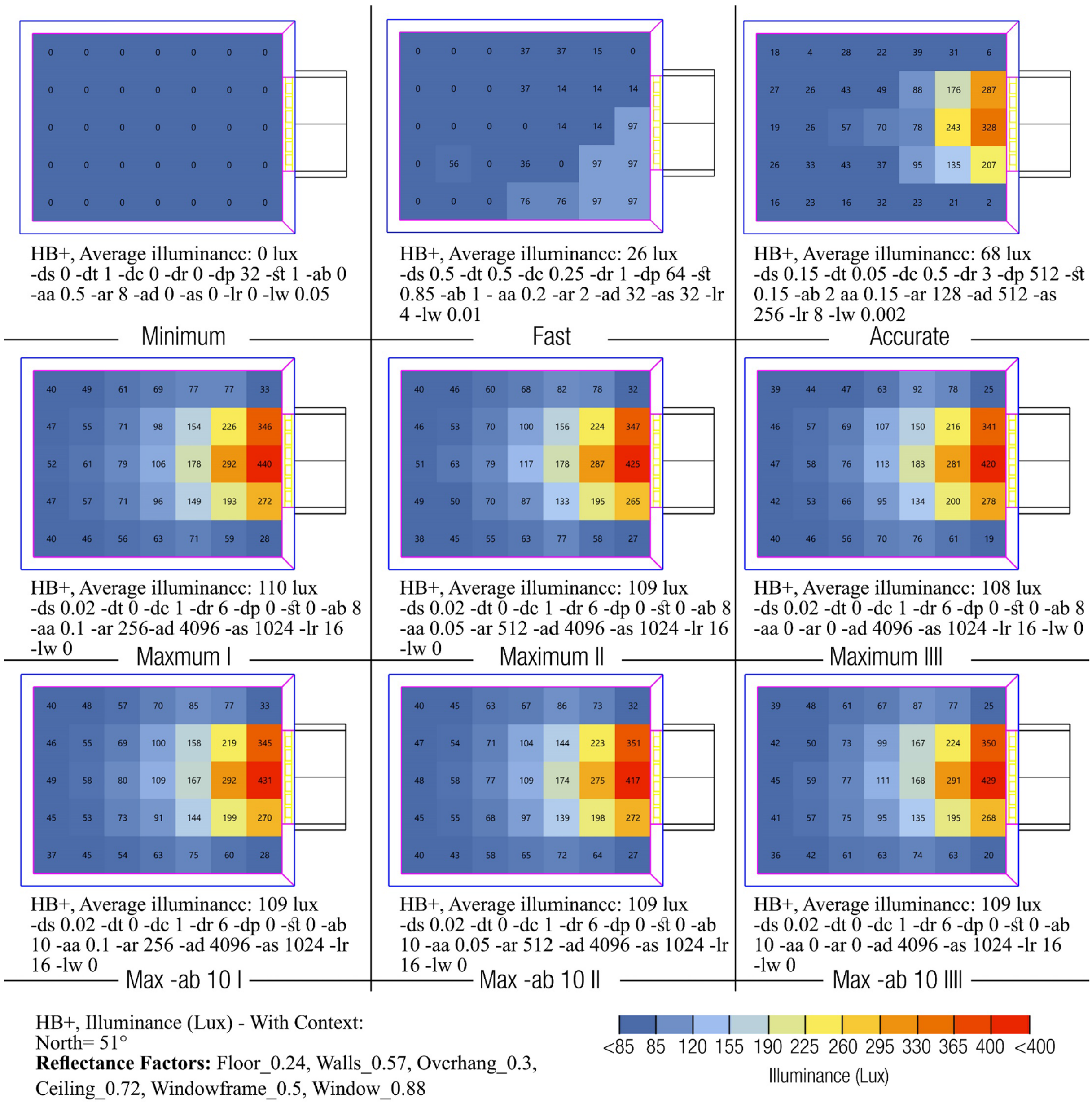

Fig. 5. Simulation results on the analysis grid based on different Radiance parameters.

Table 6
Calculation time and availability of results.

Setting	Calculation time	Results
Minimum	7 ms	Available
Fast	17 ms	Available
Accurate	789 ms	Available
Maximum I	2.7 min	Available
Maximum II	14.9 min	Available
Maximum III	Aborted	Aborted
Maximum IIII	6.4 s	Available
Maximum -ab 10 I	2.8 min	Available
Maximum -ab 10 II	14.5 min	Available
Maximum -ab 10 III	Aborted	Aborted
Maximum -ab 10 IIII	7.6 s	Available

averages (Fig. 5). The term "Rotation = 51 degrees" in Fig. 5 implies that the north sign is 51 degrees toward the west. However, going from Maximum to "Maximum -ab 10" along with their increased variations imposed significant power usage on the system and increased the calculation time. For instance, increasing -aa and -ar from 0 to 0.05 and 512 increased the calculation time by approximately 140 times. The complete list of calculation times is presented in Table 6.

According to Table 6, Maximum III and Maximum -ab 10 III were both aborted since they could not provide results after 3 h of calculations. This makes the settings impractical since such settings won't be useful for large scale projects or complex projects that may have light shelves or other similar complex components. Besides, they won't be practical for multi-objective optimizations.

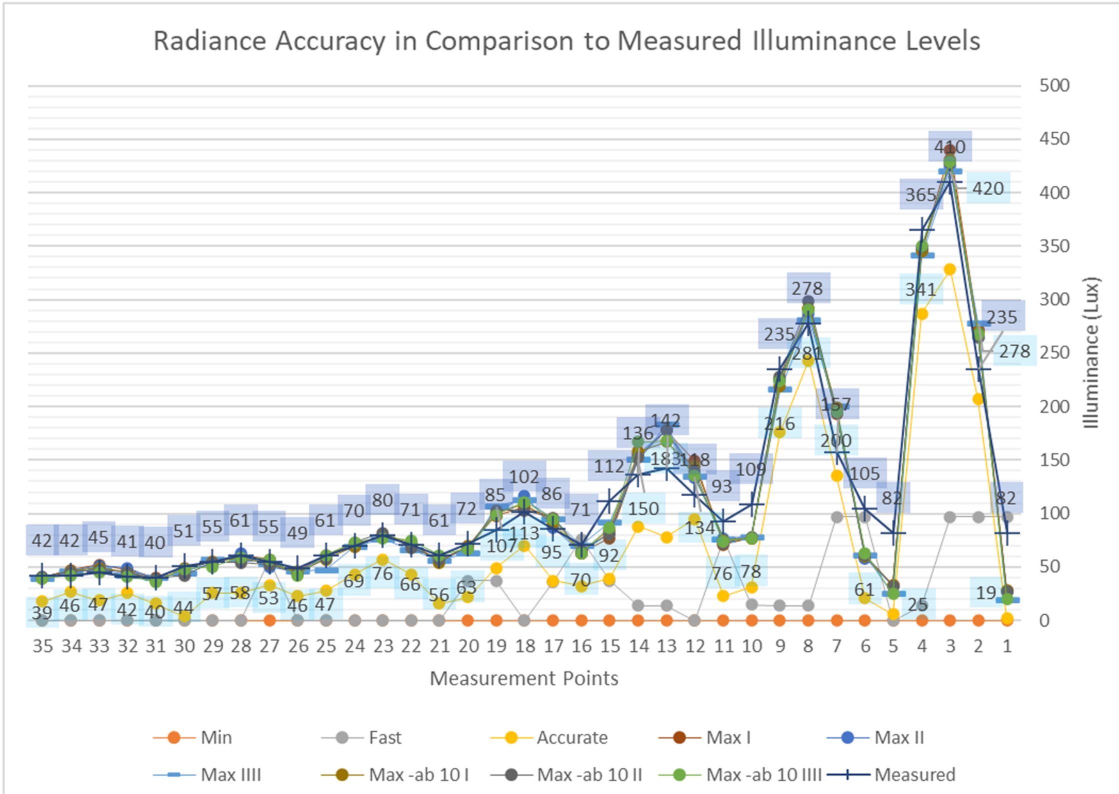

Fig. 6. Measured illuminance and simulated illuminance levels.

Table 7
Detailed illuminance levels on the measurement points.

Points(Lux)	Min	Fast	Accurate	Max I	Max II	Max IIII	Max-ab 10 I	Max-ab 10 II	Max-ab 10 IIII	Measured
1	0	97	2	28	27	19	28	27	20	82
2	0	97	207	272	265	278	270	265	268	235
3	0	97	328	440	425	420	431	428	429	410
4	0	14	287	346	347	341	345	349	350	365
5	0	0	6	33	32	25	33	32	25	82
6	0	97	21	59	58	61	60	61	63	105
7	0	97	135	193	195	200	199	195	195	157
8	0	14	243	292	287	281	292	299	291	278
9	0	14	176	226	224	216	219	228	224	235
10	0	15	31	77	78	78	77	78	77	109
11	0	76	23	71	77	76	75	72	74	93
12	0	0	95	149	133	134	144	139	135	118
13	0	14	78	178	178	183	167	178	168	142
14	0	14	88	154	156	150	158	152	167	136
15	0	37	39	77	82	92	85	81	87	112
16	0	76	32	63	63	70	63	65	63	71
17	0	36	37	96	87	95	91	96	95	86
18	0	0	70	106	117	113	109	103	111	102
19	0	37	49	98	100	107	100	103	99	85
20	0	37	22	69	68	63	70	68	67	72
21	0	0	16	56	55	56	54	57	61	61
22	0	0	43	71	70	66	73	68	75	71
23	0	0	57	79	79	76	80	82	77	80
24	0	0	43	71	70	69	69	73	73	70
25	0	0	28	61	60	47	57	58	61	61
26	0	0	23	46	45	46	45	44	42	49
27	0	56	33	57	50	53	53	52	57	55
28	0	0	26	61	63	58	58	54	59	61
29	0	0	26	55	53	57	55	54	50	55
30	0	0	4	49	46	44	48	42	48	51
31	0	0	16	40	38	40	37	39	36	40
32	0	0	26	47	49	42	45	45	41	41
33	0	0	19	52	51	47	49	47	45	45
34	0	0	27	47	46	46	46	45	42	42
35	0	0	18	40	40	39	40	41	39	42
Average	**0**	**26**	**68**	**110**	**109**	**108**	**109**	**109**	**109**	**111**

Table 8
Error in simulation results.

Points	Measured (Lux)	Error (%)					
		Max I	Max II	Max IIII	Max -ab 10 I	Max -ab 10 II	Max -ab 10 IIII
1	82	66	67	77	66	67	76
2	235	16	13	18	15	13	14
3	410	7	4	2	5	4	5
4	365	5	5	7	5	4	4
5	82	60	61	70	60	61	70
6	105	44	45	42	43	42	40
7	157	23	24	27	27	24	24
8	278	5	3	1	5	8	5
9	235	4	5	8	7	3	5
10	109	29	28	28	29	28	29
11	93	24	17	18	19	23	20
12	118	26	13	14	22	18	14
13	142	25	25	29	18	25	18
14	136	13	15	10	16	12	23
15	112	31	27	18	24	28	22
16	71	11	11	1	11	8	11
17	86	12	1	10	6	12	10
18	102	4	15	11	7	1	9
19	85	15	18	26	18	21	16
20	72	4	6	13	3	6	7
21	61	8	10	8	11	7	0
22	71	0	1	7	3	4	6
23	80	1	1	5	0	3	4
24	70	1	0	1	1	4	4
25	61	0	2	23	7	5	0
26	49	6	8	6	8	10	14
27	55	4	9	4	4	5	4
28	61	0	3	5	5	11	3
29	55	0	4	4	0	2	9
30	51	4	10	14	6	18	6
31	40	0	5	0	8	3	10
32	41	15	20	2	10	10	0
33	45	16	13	4	9	4	0
34	42	12	10	10	10	7	0
35	42	5	5	7	5	2	7
Average	**–**	**14**	**14**	**15**	**14**	**14**	**14**

3.3. Validation of radiance against field measurements

At this stage of research, comparing the results in Section 3.2 with the field measurements can confirm the validity of the software and defines its possible error. Fig. 6 compares the simulation results to the measured illuminance levels in the room. Accordingly, Minimum and Fast settings fail to represent real-world conditions. Similarly, Accurate setting simulated illuminance with a significant difference. On the other hand, simulations with both Maximum and "Maximum -ab 10" variations resulted in almost precise results. Accordingly, this study proceeds with these two settings. Consequently, the maximum difference happens at the corners of the first row (Points 1 and 5) for these two settings. In terms of illuminance, the second major difference occurs in the corners of the second row (points 6 and 10). In the third and fourth rows, there are visible differences in the middle points while the corners have more accurate results. In general, although the Maximum setting shows better performance in the middle points, the "Maximum -ab 10" setting has a slightly improved performance in the corners. In general, according to Fig. 6 and Table 7, one can argue that since the "Maximum -ab 10" overestimated the illuminance levels, it will have improved performance in the corners but its overall average illuminance level is closer to the measured illuminance levels (error = less than 3%).

An explanation for this issue would be the effect of ambient bounces (-ab) since this parameter controls the number of bounces from surfaces. Therefore, the effect of -ab is investigated in the simulation tool in Section 3.3.1 aside from the effect of reflectance factors that will be investigated in 3.4 for model validation. For now, the present study confirms and recommends using the Maximum IIII setting for Radiance parameters since it results in highly accurate results with an error of almost 3% for the average illuminance.

According to Table 8, the error in illuminance simulation is significant in the corners but it is reduced for the middle points. The average error for illuminance levels ranges from 14%to 15% for the current study. This error range is acceptable and can be used for analyses.

3.3.1. Assessing the ambient bounces (-ab) and ambient accuracy (-aa) effect

As shown in the previous section, the accuracy of results for the Maximum IIII setting is reasonable. Therefore, the ambient bounces (-ab) effect is studied in this section to assess illuminance levels in the corners and the overall accuracy of the results. Therefore, the -ab parameter in Maximum IIII setting is changed from 2 to 12, 16, and 24 while other parameters remain the same. The last variation with -ab 24 is also assessed with -aa 0.1. According to Fig. 7, -ab 2 is the worst simulated illuminance although its proportional values are correct. Next, -ab 3 and -ab 4 are the appropriate parameters but still have major discrepancies. On the other hand, -ab 5 matches the measured values more accurately than the previous parameters but there are some discrepancies at some points in the corners. The analyses show -ab 6 is the first best match for simulated illuminance levels. Simulated results from -ab 7 to 12, 16, and 24 remain almost the same and improves slightly but yet there is the relative bias of the tool. The simulated results are best improved by using -ab 24 and -aa 0.1 although there are still significant discrepancies in the corners.

These results show that increasing -ab and -aa parameters do not improve the results significantly. Therefore, maintaining reasonable values for Radiance parameters can significantly contribute to the calculation times. The present study confirms the use of Maximum IIII settings which do not use interpolations.

3.3.2. Assessing radiance parameters for multi-objective optimizations

Multi-objective optimization, which is normally carried out in Grasshopper (a Rhino-based component) by using Ladybug-Honeybee, consumes a lot of power. Subsequently, calculation time plays an important role in such studies since a simple multi-objective optimization study can take from several hours to several days for simple to slightly complex projects and several weeks for complex projects. Calculation time depends on many different factors such as the number of variables, engine settings, etc. The aim here is to utilize Radiance parameters for future use in multi-objective optimization based on daylighting metrics such as the DF as a static metric and Useful Daylight Illuminance (UDI) as a dynamic metric.

According to the results in Section 3.3.1, -ab 6 is the first best match for analysis results and the Maximum IIII setting, with -ab 8 and no interpolation (-aa 0), is the best match for precise simulations. Although the overall performance is better for -ab 8 setting (Fig. 8), Table 9 shows that the average error for illuminance levels in all three parameters is almost 15%.

3.4. Reflectance factor and its effect on illuminance

In this section, the effect of reflectance parameters on simulation results is investigated. For this purpose, the model is simulated based on eight variants of reflectance factor values that are presented in

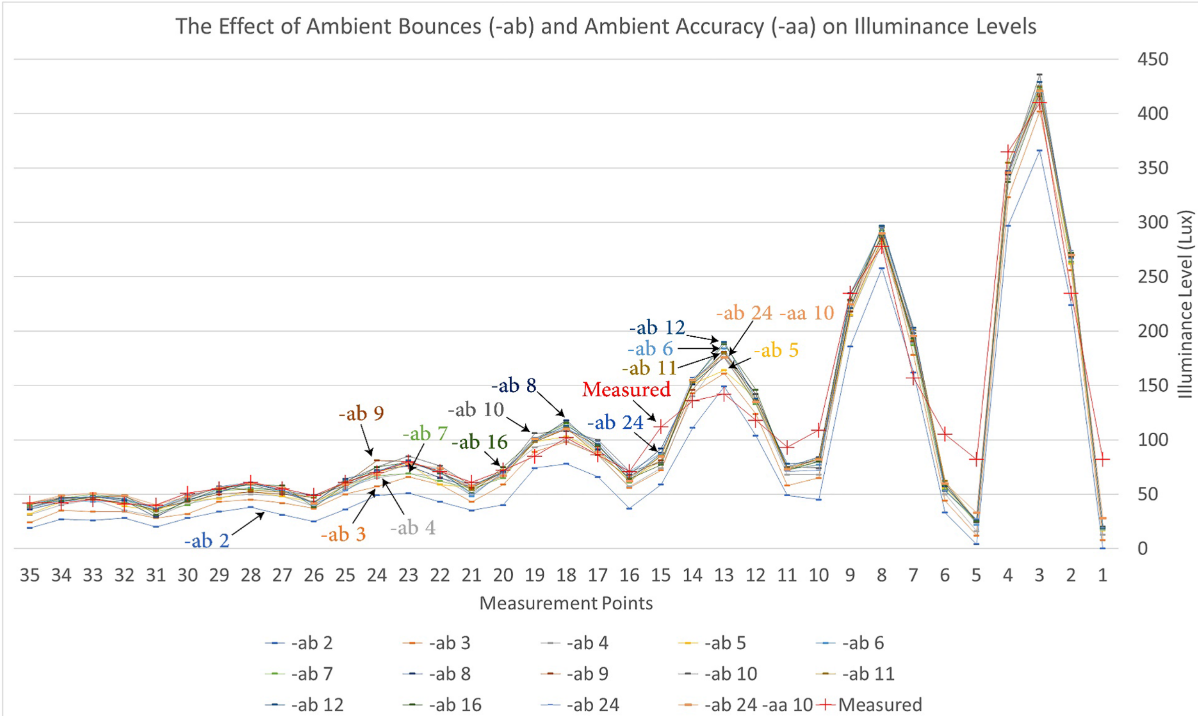

Fig. 7. The effect of ambient bounces (-ab) and Ambient Accuracy (-aa) on simulated illuminance levels.

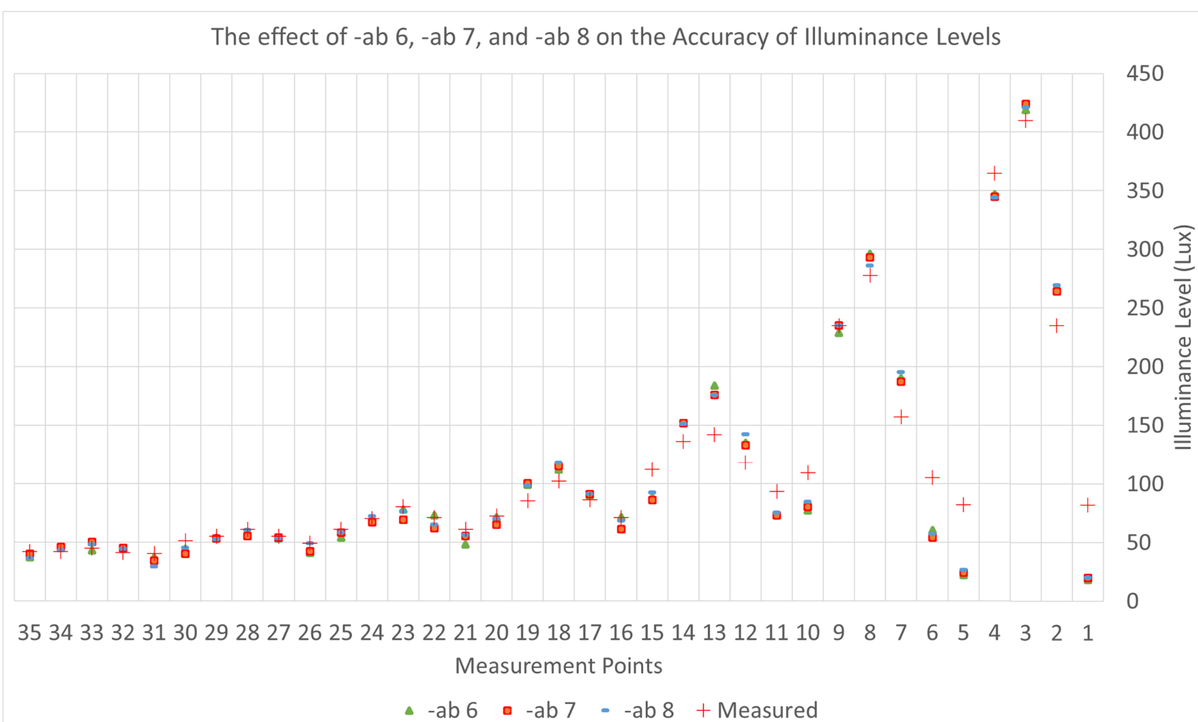

Fig. 8. Simulated illuminance levels for different parameters.

Table 10. The visible transmittance of windows and the reflectance factors of the overhang and window frame have remained the same during the analyses.

As shown in Fig. 9, there is no significant difference between the simulation results that used the standard reflectance factor and the measured ones. On the other hand, the difference between +0.1 and +0.2 reflectance factors (RFs) is higher than the difference between −0.1 and −0.2. Both higher and lower investigated RFs are not as accurate as of the measured RFs and the industry-accepted standard RFs. They resulted in overestimated and underestimated illuminance levels in the model.

Table 11 shows that both measured and standard RFs provide the

Table 9
Estimated error in simulation results for multi-objective optimization.

Points	Illuminance level (Lux)			Measured	Error in results (%)		
	-ab 6	-ab 7	-ab 8		-ab 6	-ab 7	-ab 8
1	18	20	20	82	78	76	76
2	267	264	269	235	14	12	14
3	419	424	421	410	2	3	3
4	347	345	344	365	5	5	6
5	22	24	26	82	73	71	68
6	60	54	57	105	43	49	46
7	190	187	195	157	21	19	24
8	296	293	286	278	6	5	3
9	229	235	235	235	3	0	0
10	77	80	84	109	29	27	23
11	73	73	75	93	22	22	19
12	135	133	142	118	14	13	20
13	184	176	176	142	30	24	24
14	152	152	151	136	12	12	11
15	88	86	92	112	21	23	18
16	71	61	68	71	0	14	4
17	90	91	91	86	5	6	6
18	112	115	118	102	10	13	16
19	99	100	98	85	16	18	15
20	71	65	70	72	1	10	3
21	48	55	56	61	21	10	8
22	73	62	65	71	3	13	8
23	78	69	76	80	3	14	5
24	68	67	72	70	3	4	3
25	54	58	58	61	11	5	5
26	41	42	49	49	16	14	0
27	53	54	53	55	4	2	4
28	56	55	60	61	8	10	2
29	54	53	52	55	2	4	5
30	44	40	45	51	14	22	12
31	37	34	29	40	8	15	28
32	44	45	44	41	7	10	7
33	43	50	48	45	4	11	7
34	45	46	43	42	7	10	2
35	37	40	36	42	12	5	14
Average	–	–	–	–	15	16	15
CalculationTime	4.6 s	5.4 s	6 s		4.6 s	5.4 s	6 s

most accurate average illuminance levels. The results of +0.1 RFs and +0.2 are 11.71% and 27.02% percent higher than the measured illuminance levels respectively. Similarly, the simulation results of −0.1 and −0.2 RFs are 8.1% and 12.61% lower than the measured illuminance levels. Furthermore, increasing or decreasing RFs did not help to improve the estimated illuminance levels in Radiance. As a result, there are still significant discrepancies in the corners. Fig. 10 shows the grid analyses for the results.

3.5. Test-retesting simulations for different hours with different illuminance levels

Fig. 11 shows the difference between simulated and measured illuminance levels at noon and 2–4 PM. Accordingly, the illuminance at the three middle points is generally overestimated while they are underestimated at the corners. This is in accordance with the previous results but the error is different for each point.

The error increases as the illuminance levels on the horizontal plane decrease. According to this study, illuminance levels below 3900 lx have a significant effect on the error of simulations. This is especially true for middle points rather than the corners (Table 12). The differences in the error of average illuminance levels for 11 k, 5 k, 3.9 k, and 3.5 k skies are 0%, 13%, 16%, and 53% respectively. Similarly, the overall errors for the points are 15%, 23%, 26%, and 62% respectively.

3.5.1. The effect of activating interpolations (-aa ≠ 0)

As we described earlier setting -aa to 0 disables the interpolation. This study showed that the effect for simple geometries is nominal and

Table 10
Reflectance factors for analyses.

Surface	Reflectance factor					
	Measured	Standard	Measured + 0.1	Measured + 0.2	Measured – 0.1	Measured – 0.2
Floor	0.24	0.2	0.34	0.44	0.14	0.04
Wall	0.57	0.5	0.67	0.77	0.47	0.37
Ceiling	0.72	0.8	0.82	0.92	0.62	0.52

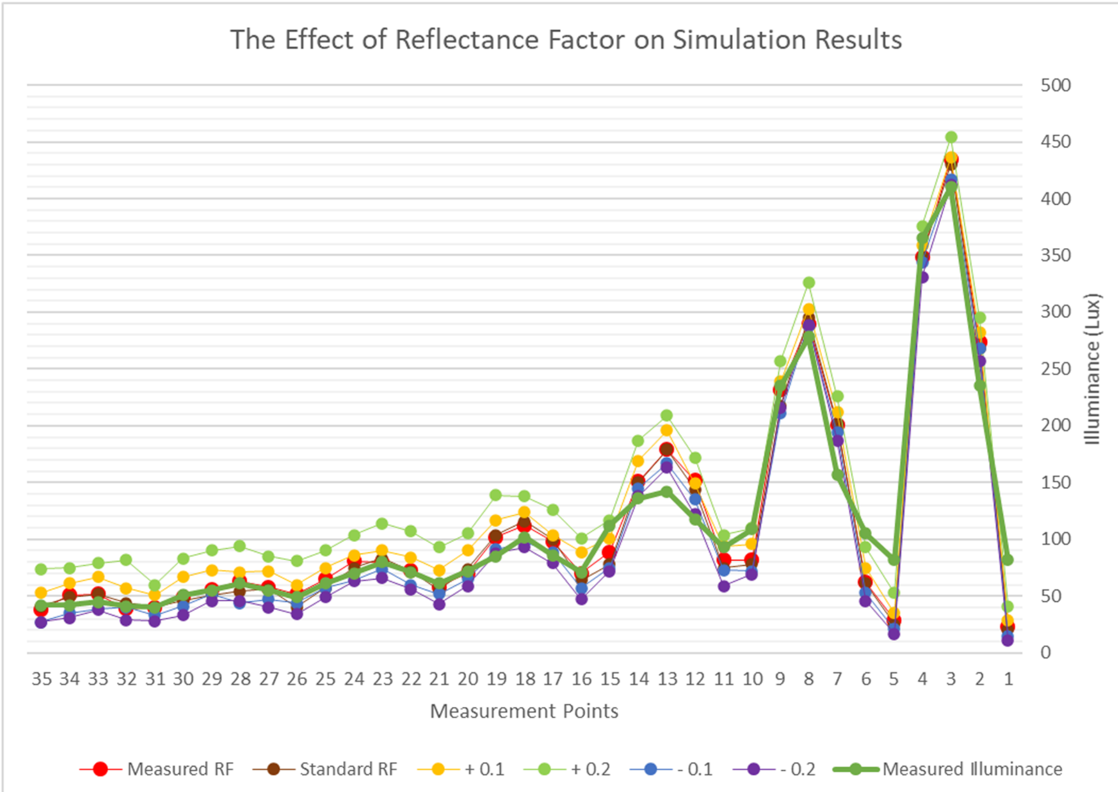

Fig. 9. The effect of Reflectance Factor on Simulation Results.

Table 11
Simulations results of different reflectance factors.

Points	Measured RF	Standard RF	+ 0.1	+ 0.2	− 0.1	− 0.2	Measured illuminance
1	23	20	29	41	15	11	82
2	274	268	282	295	268	257	235
3	435	430	436	454	417	412	410
4	349	349	359	376	344	331	365
5	29	25	35	53	21	17	82
6	62	61	75	93	53	46	105
7	201	202	212	226	194	187	157
8	290	295	303	326	288	289	278
9	232	218	239	257	211	216	235
10	82	78	96	110	72	69	109
11	82	75	94	104	73	59	93
12	152	144	149	172	135	122	118
13	179	179	196	209	167	163	142
14	151	150	169	187	145	138	136
15	89	78	101	117	75	72	112
16	70	64	89	101	57	47	71
17	98	100	104	126	89	79	86
18	112	116	124	138	97	93	102
19	102	104	117	139	91	88	85
20	70	74	90	105	65	59	72
21	58	55	73	93	52	43	61
22	73	72	84	107	60	56	71
23	80	83	90	114	74	66	80
24	81	75	86	104	64	63	70
25	65	57	75	90	57	49	61
26	52	40	60	81	44	34	49
27	58	56	72	85	47	40	55
28	63	54	71	94	44	46	61
29	56	51	73	90	52	46	55
30	49	46	67	83	41	33	51
31	40	40	51	60	33	28	40
32	39	44	57	82	40	29	41
33	52	52	67	79	39	38	45
34	51	49	61	75	35	31	42
35	38	41	53	74	27	27	42
Average	112	110	124	141	102	97	111

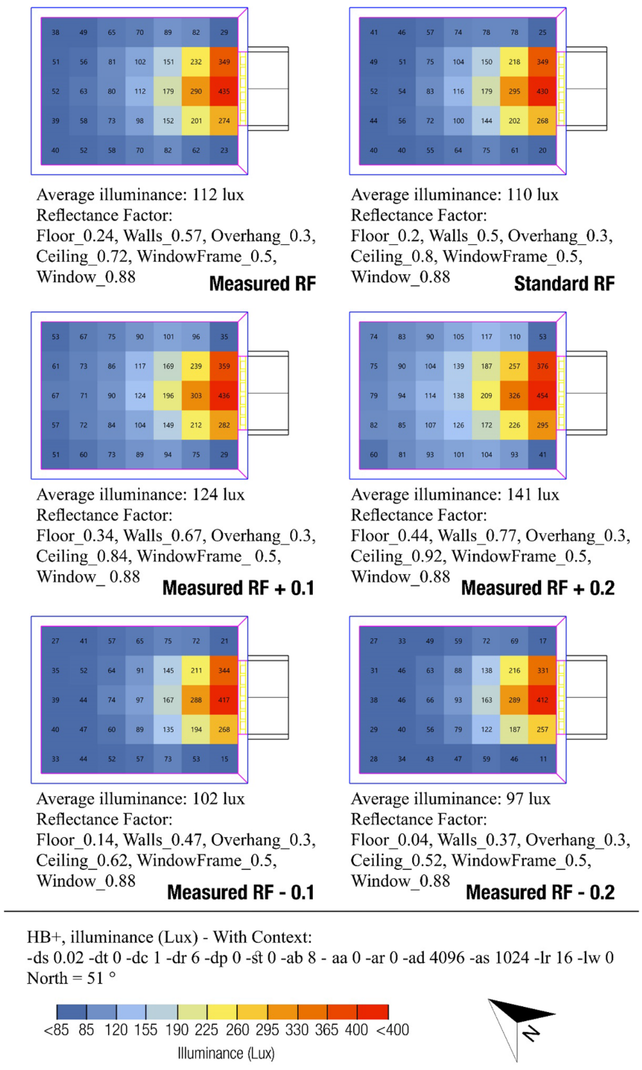

Fig. 10. Grid-based analyses for difference reflectance factors.

thus setting -aa to 0 does not affect the results significantly. At this point, we assess the impact of -aa on simulation results for skies below 3900 lx. Fig. 12 shows enabling interpolation by setting -aa to 0.1 does not have an effect on the accuracy of the results in comparison to the simulation result with -aa set to zero.

4. Discussion

4.1. Relative bias and radiance parameters for accurate results

The simulation results showed that Radiance, as a research instrument, is consistent in simulated illuminance levels. This was illustrated by repeating simulations with the same parameters in Section 3.1. Previous works on Radiance on its official website suggest that increasing -ab from 3 to 5 does not have a significant effect on predicting the Daylight Factor (DF) as a metric that relies on the CIE overcast sky (Mardaljevic, 2014). However, the present study shows that Maximum IIII setting with -ab 6 is the first best setting for accurate analysis and Maximum IIII setting with -ab 8 and no interpolation (-aa 0) is the most accurate setting, without imposing extra power usage on the calculation engine, for precise simulations. Any further increase in Radiance parameters only increases power usage and calculation time without having any significant effect on the accuracy of results. This is of significant importance since current studies try to increase the parameters for achieving more accurate results. However, the findings of the present study show such actions do not increase the accuracy of results. For instance, -ab 5, -ad 2048, -as 512, -aa 0.08, and -ar 512 were used in a previous study (Monteoliva et al., 2020) and -as 1024, -ar 64, -ad 4096, -aa 0.0, and -ab 10 (as well as -ab 30) were used in another (Yao et al., 2020). The results of the first study may not be as accurate as it could be with -ab 6 or -ab 8 and the other study just increased the power usage and calculation time significantly without improving the accuracy of results. Similar studies in recent years have been done based on precedents that were not based on scientific suggestions for setting the Radiance parameters for calculations. For instance, a multi-objective optimization study used -ab 5 with -aa set to 0.1 (Zhang et al., 2017). The present study shows that the aforementioned setting is not as accurate as it could be with -ab 8 and imposed only power usage on the system and increased the calculation time by setting -aa to 0.1. Such instances have been numerous in recent years (Mainini et al., 2019; Manni et al., 2020, 2018; Marzouk et al., 2020; Vlachokostas and Madamopoulos, 2017). Therefore, the current research creates a foundation based on scientific analyses for setting the Radiance parameters in future studies (Table 13). Moreover, this study determined the corresponding error of each setting in Radiance. Furthermore, with an overall error of 15%, simulation results that are generated by using the Maximum IIII setting are reliable and precise. As a result, this paper suggests the settings in Table 13 for the Radiance parameters.

4.2. Reflectance factors and accuracy of results

Although this study relied on a previous study that used an in-situ approach for measuring reflectance factors (Brembilla et al., 2016), it did not investigate the accuracy of this in-situ approach under different illuminance levels. However, the in-situ approach for measuring reflectance factors resulted in accurate simulation results in this study. Although a range for reflectance factors of different surfaces are generally recommended by different standards (European Committee for Standardization, 2011), the present study shows slight changes in reflectance factors have a significant effect on results. For instance, the recommended range for the reflectance factor of walls ranges from 0.3 to 0.8 (European Committee for Standardization, 2011). By investigating the effect of reflectance factors on simulation results, it was shown that a 0.1 increase or decrease in values affects the simulation results significantly. Therefore, this study suggests acquiring information about reflectance factors from manufacturers. In the absence of such information, in-situ measurements of reflectance factors under an overcast sky with an illuminance level of 11,000 lx are accurate enough for carrying out simulations based on the findings of this study.

4.3. CIE test case and radiance calculations

4.3.1. CIE test case

Although Radiance has passed the CIE 171:2006 test cases (International Commission on Illumination (CIE), 2006; Reinhart and Walkenhorst, 2001), this study shows the tool is not accurate in calculating illuminance levels in immediate corners next to the windows (points 1 and 5 in this study). However, the simulations for the subsequent side points such as points 6 and 10 or 11 and 15 improved as they distanced from the immediate corners. This might be due to the CIE test case that places the measurement points in the middle of the room (International Commission on Illumination (CIE), 2006). Although this is an important issue to be addressed, the widespread metrics such as Useful Daylight Illuminance (UDI) rely on the average

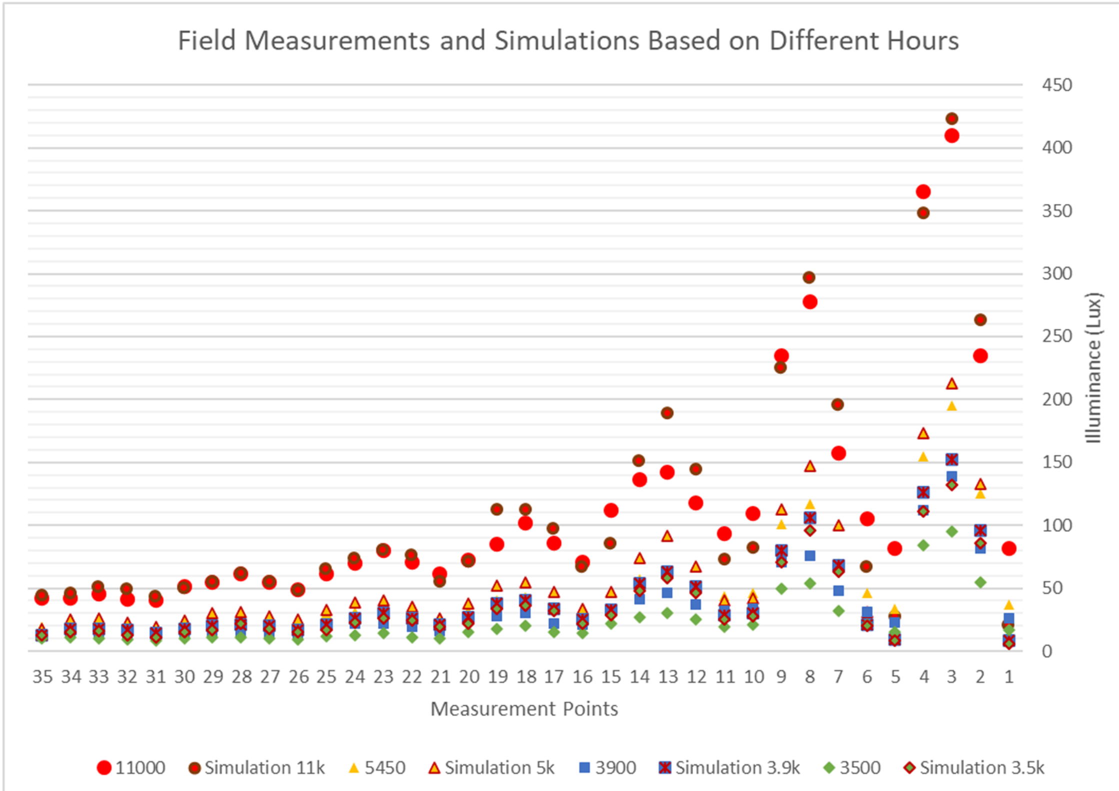

Fig. 11. Field measurements and simulation results based on illuminance levels at different hours.

illuminance level of a room. Radiance, as shown in this study, is accurate in predicting overall average illuminance levels by using the Maximum IIII settings. Although revising or introducing a new test case in this regard is not deemed necessary for current static and dynamic metrics such as Daylight Factor (DF) or UDI, the present research suggest introducing a new test case that includes corners by placing test points (measurements points) through the space uniformly.

4.3.2. Radiance results

Aside from the immediate corners, another major difference in measured and simulated illuminance levels occur in the middle of the room in the third row. The assumption of the present paper is that the difference is similar to the error that occurs in illuminance levels below 3900 lx. Different factors are related to this issue such as the used sky in Radiance (Reinhart and Walkenhorst, 2001). This study was not able to find previous research in this regard but the early validations of Radiance show similar proportional patterns in errors to the current findings (Reinhart and Herkel, 2000). The issue still exists although Radiance has improved significantly over time. At the moment, Radiance is capable of predicting the overall average illuminance levels of rooms precisely.

5. Conclusion

Due to the lack of sufficient scientific data on setting parameters for the maximum accuracy of simulation results in Radiance, this study aimed at validating Radiance version 5.1, which works based on Monte Carlo ray tracing and interpolation, in HoneybeePlus version 0.0.04 and Ladybug-Honeybee version 0.0.68–0.0.65 against field measurements under an overcast sky with certain illuminance level. Accordingly, the results show that the accuracy of Radiance significantly relies on its settings. By evaluating the effects of various parameters, this study showed that disabling interpolation, by setting -aa to 0, in simulation models with simple geometry does not affect the accuracy of results but imposes significant power usage on the system and increases the calculation time. Therefore, this issue won't have an adverse effect in simulations that require a significant amount of time such as multi-objective optimizations. On the other hand, reflectance factors can significantly affect simulation results. This study suggests acquiring reflectance factors from manufacturers and in the absence of such information, in-situ measurements under a sky with 11,000 lx of illuminance can be accurate for simulations. However, such measurements should be carried out with excessive caution.

This study shows that Radiance can achieve precise overall averages although its predictions for immediate corners and middle areas, where illuminance levels go beyond the efficient light penetration depth, are not as accurate as other points. This requires fundamental improvements in Radiance. Despite these issues, Radiance is still the most powerful and the most accurate tool for predicting illuminance levels in buildings. This is especially true in the case of predicting overall averages in buildings. Furthermore, current daylighting metrics rely on the average illuminance levels in buildings rather than point by point illuminance levels. Therefore, Radiance simulations that use Maximum IIII settings are accurate and their results, either as metrics or average, are reliable in the industry.

This study was based on grid analyses under an overcast sky with a certain illuminance level. Conducting a study on annual predictions is highly suggested since annual studies rely on the combination of Radiance and DAYSIM. For now, the present study confirms that Radiance is accurate in predicting illuminance levels and suggests optimum Radiance settings for maximum accuracy of simulations.

Table 12
Measured and simulated illuminance levels along with their errors.

Points	11,000	Simulation 11 k	Error	5450	Simulation 5 k	Error	3900	Simulation 3.9 k	Error	3500	Simulation 3.5 k	Error
	Lux		%	Lux		%	Lux		%	Lux		%
1	82	21	***74***	37	10	***73***	26	8	***69***	17	6	***65***
2	235	263	***12***	125	133	***6***	82	96	***17***	55	86	***56***
3	410	423	***3***	195	213	***9***	139	152	***9***	95	132	***39***
4	365	348	***5***	155	173	***12***	112	126	***13***	84	111	***32***
5	82	27	***67***	34	14	***59***	23	9	***61***	15	8	***47***
6	105	67	***36***	46	31	***33***	31	21	***32***	21	20	***5***
7	157	196	***25***	70	100	***43***	48	68	***42***	32	63	***97***
8	278	297	***7***	117	147	***26***	76	106	***39***	54	96	***78***
9	235	225	***4***	101	113	***12***	71	80	***13***	50	71	***42***
10	109	82	***25***	46	42	***9***	34	30	***12***	21	28	***33***
11	93	73	***22***	44	40	***9***	32	29	***9***	19	25	***32***
12	118	144	***22***	52	67	***29***	37	51	***38***	25	46	***84***
13	142	189	***33***	63	92	***46***	46	63	***37***	30	58	***93***
14	136	151	***11***	57	74	***30***	41	54	***32***	27	48	***78***
15	112	85	***24***	47	47	***0***	33	33	***0***	22	29	***32***
16	71	67	***6***	28	34	***21***	21	25	***19***	14	22	***57***
17	86	97	***13***	35	47	***34***	22	34	***55***	15	32	***113***
18	102	112	***10***	43	55	***28***	30	40	***33***	20	36	***80***
19	85	112	***32***	40	52	***30***	28	38	***36***	18	34	***89***
20	72	71	***1***	32	38	***19***	25	27	***8***	15	22	***47***
21	61	55	***10***	24	26	***8***	16	21	***31***	10	19	***90***
22	71	76	***7***	28	35	***25***	19	26	***37***	11	24	***118***
23	80	80	***0***	33	40	***21***	22	30	***36***	14	26	***86***
24	70	74	***6***	31	39	***26***	22	26	***18***	13	23	***77***
25	61	65	***7***	30	33	***10***	22	21	***5***	12	17	***42***
26	49	48	***2***	21	25	***19***	14	17	***21***	9	15	***67***
27	55	55	***0***	23	28	***22***	15	20	***33***	10	18	***80***
28	61	62	***2***	25	31	***24***	16	21	***31***	11	22	***100***
29	55	55	***0***	25	30	***20***	16	20	***25***	11	17	***55***
30	51	50	***2***	23	24	***4***	15	18	***20***	10	15	***50***
31	40	43	***8***	19	19	***0***	13	14	***8***	8	11	***38***
32	41	49	***20***	19	23	***21***	14	17	***21***	9	13	***44***
33	45	51	***13***	20	26	***30***	15	18	***20***	10	16	***60***
34	42	46	***10***	17	25	***47***	14	18	***29***	11	15	***36***
35	42	44	***5***	19	18	***5***	13	13	***0***	10	13	***30***
Average	111	112	0	49	56	13	34	40	16	23	35	53
Average Error	–	–	15	–	–	23	–	–	26	–	–	62

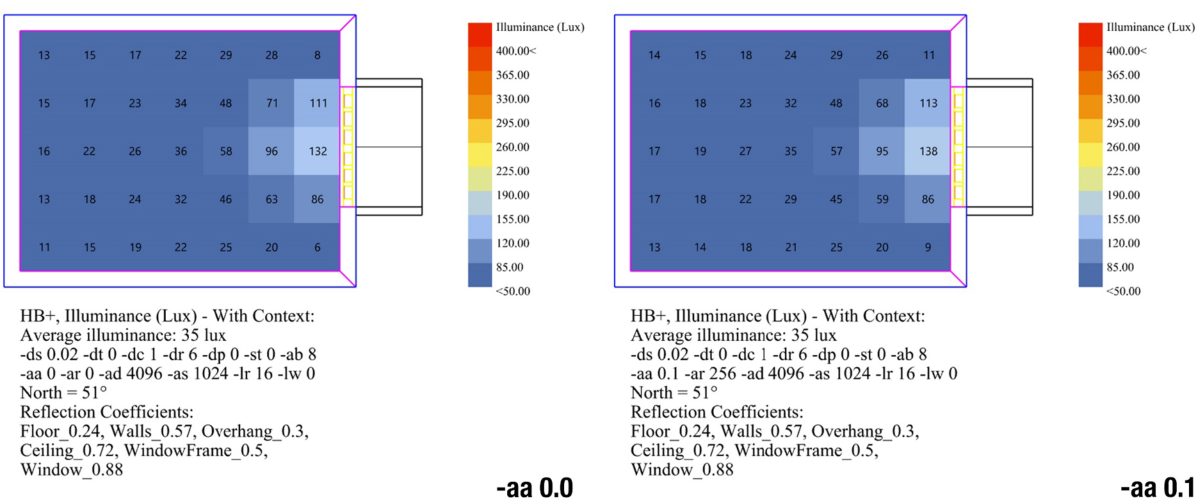

Fig. 12. The effect of enabling and disabling Monte Carlo ray tracing on the simulation results for skies with illuminance level below 39,000 lx.

Table 13
Suggested parameters for radiance.

Parameter	ps	pt	pj	dj	ds	dt	dc	dr	dp	sj	st	ab	aa	ar	ad	as	lr	lw
Maximum IIII (Best)	1	0	1	1	0.02	0	1	6	0	1	0	8	0	0	4096	1024	16	0
Maximum IIII – (Average)	"	"	"	"	"	"	"	"	"	"	"	7	"	"	"	"	"	"
Maximum IIII (Acceptable)	"	"	"	"	"	"	"	"	"	"	"	6	"	"	"	"	"	"

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.solener.2020.07.054.

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