VALIDATION OF VELUX DAYLIGHT VISUALIZER 2 AGAINST CIE 171:2006 TEST CASES

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ABSTRACT

Velux Daylight Visualizer 2 is a software tool dedicated to daylighting design and analysis. It is intended to simulate daylight transport in buildings and to aid professionals by predicting and documenting daylight levels and appearance of a space prior to realization of the building design. The critical question is whether Velux Daylight Visualizer 2 produces trustable simulations the user can be confident in. A key point to answer this question is to assess the software capability to simulate the light transport in a physically correct way. In this paper, we assess the accuracy of Velux Daylight Visualizer 2 against CIE 171:2006 test cases. Like many simulation softwares, several settings (tuned by the final user) rule the accuracy of the simulation and impact the rendering time. We propose an iterative workflow aimed at identifying a range of simulation settings which achieve accurate predictions, and calibrating the simulation settings in regards to accuracy and rendering time. This workflow needs less simulations to perform than simulating each test case for each setting, while remaining robust. We illustrate the proposed workflow by identying low, medium, and high values of the settings of Daylight Visualizer 2.

KEYWORDS

Physical accuracy assessment, Daylighting, CIE test cases, Setting identification.

INTRODUCTION

Light transport simulation is a key tool for professionals (architects, designers, research departments) to study light levels (both artificial and natural) and appearance of a building prior to its realization. Light simulation softwares try to solve the global illumination problem formalized in the rendering equation (Kajiya, 1986); in the last decades, various algorithms were proposed to simulate the physical behaviour of light (Pharr et al., 2004). Radiance (Ward, 1994) is one of the most famous software implementing such algorithms. Several simulation softwares for building design are based on Radiance, like Daylight 1-2-3 (Reinhart, 2007) which is aimed at studying both daylighting and energy performances in buildings.

For its part, Velux Daylight Visualizer 2 is a new simulation tool specifically dedicated to daylighting design and analysis. Like any light transport software, the critical question is whether Velux Daylight Visualizer 2 produces accurate and trustable simulations. In other words, is the software able to simulate the light transport in a physically correct way ? The answer to this question is crucial for the user, and should be considered as a chief criterion for choosing a simulation software (Donn et al., 2007).

In this paper, we assess the accuracy of Velux Daylight Visualizer 2 against CIE 171:2006 test cases (Test Cases to Assess the Accuracy of Lighting Computer Programs) (CIE, 2006). The test methodology is based on the comparison of simulation results to analytical reference, for different aspects of the light propagation. Other aspects of building simulation, like heat transfer, can be assessed through other standards, for instance IEA BESTEST (IEA, 2008).

Internally, various light transport algorithms are involved. The settings of each algorithm impact the simulation accuracy and rendering time. The final user can set a single parameter that rules the global rendering quality, and that is mapped to internal settings.

Rather than performing the test cases for a single value of the global rendering quality parameter, we propose an iterative workflow aimed at identifying a range of simulation settings which achieve accurate predictions, and calibrating the simulation settings in regards to accuracy and rendering time. More precisely, the proposed workflow is aimed at identifying low, medium, and high values of the global rendering quality parameter. The low value optimizes the rendering time while ensuring an acceptable accuracy (i.e. the maximal error observed for any of the test cases will be under a threshold); the high value ensures in addition that the average error observed for all the test cases will be under a second threshold; the medium value leads to a compromise between accuracy and rendering time.

The paper is organized as follows. In the next section, Velux Daylight Visualizer 2 is presented. Details about the mapping between the global rendering quality parameter and the internal settings are given. The following section explains how the CIE test cases are used and presents the proposed workflow. An example of implementation is detailed in the last section: the workflow is applied for several maximum and average tolerated errors, and results of identification are given.

SOFTWARE PRESENTATION AND SETTINGS

Velux Daylight Visualizer 2 is intended to aid professionals by predicting and documenting daylight levels and appearance of a space prior to realization of the building design. The software permit generation of 3D models in which roof and facade windows are freely inserted. Other settings include the location and orientation of the models, the date and time of the simulation, as well as the sky type (from clear to overcast). All the features of the building, windows, furniture, orientation and sky conditions can be edited also. In addition to photorealistic rendering, the simulation output includes luminance, illuminance and daylight factor maps. Figure 1 illustrates the Visualizer interface. Figure 2 presents an example of a render obtained with Velux Daylight Visualizer 2 and Figure 3 presents a false colour luminance map.
Internally, various light transport algorithms are involved: photon mapping (Jensen, 2001), bidirectional path tracing, irradiance caching. The

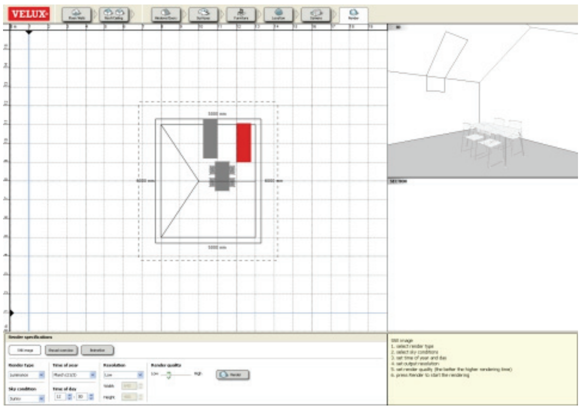

Figure 1: Illustration of Velux Daylight Visualizer 2 interface

Figure 2: Example of a photo-realistic render

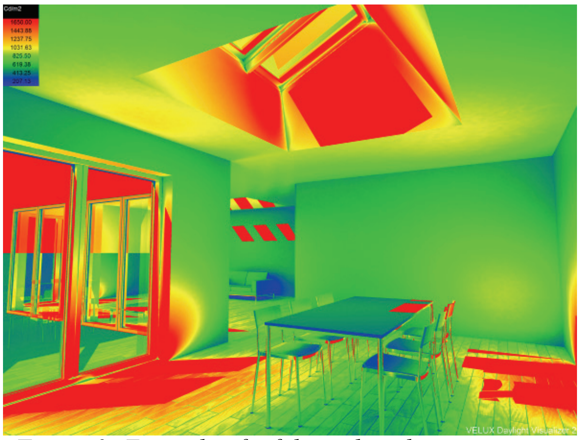

Figure 3: Example of a false colour luminance map

settings of each algorithm impact the simulation accuracy and rendering time. The final user can set a single parameter that rules the global simulation quality, and that is mapped to internal settings. Six settings are used internally to parameter the light transport algorithms used:

- *ambient:* indicates whether indirect illumination is simulated,
- *trace level:* is the number of bounces of all types of lighting,
- *ambient trace level*: is the number of bounces of ambient (indirect) lighting,
- *ambient precision:* relates to the image based sampling used,
- *ambient complexity:* describes the lighting complexity. It influences the number of samples used. Higher values equals higher precision,
- *ambient feature size:* relates to the image interpolation quality.

Since the goal of the study is to assess the accuracy of the software in terms of physical correctness, and not with respect to the image quality, the *ambient feature size* setting will be set to 0 in the experiments. The global rendering quality value (RQ) can be set by the user between 0 and 10 and is mapped to internal settings as follows:

- *ambient* = on
- *trace level* = 4
- *ambient trace level* = 8
- *ambient precision* = RQ x 0.2 + 0.5
- *ambient complexity* = RQ + 1
- *ambient feature size* = 0

PROPOSED WORKFLOW

CIE test cases

In 2006, the CIE proposed a benchmarking entitled CIE 171:2006 Test Cases (Test Cases to Assess the Accuracy of Lightning Computer Program) (CIE, 2006). The test methodology is based on the comparison of simulation results to analytical reference, for different aspects of the light

propagation. This methodology has been used to assess the accuracy of several simulation sofwares, including Radiance (Geisler-Moroder et al., 2008). An example of a test case will be given in the next section for readers not familiar with the CIE standard. In our study, since Velux Daylight Visualiser 2 is dedicated to the simulation of natural lighting, we took into account only the test cases corresponding to situations where natural lighting is involved. In the remainder of the paper, these test cases will be denoted according to the test case numbers in the original CIE document. Thus, the test cases involved are: *5.4 – 5.5 – 5.6 – 5.7 – 5.9 – 5.10 – 5.11 – 5.12*
Each selected test case is dedicated to a particular aspect of the natural light propagation. More precisely:

- *5.4:* Luminous flux conservation,
- *5.5:* Directional transmittance of clear glass,
- *5.6:* Light reflection over diffuse surfaces,
- *5.7:* Diffuse reflection with internal obstructions,
- *5.9:* Sky component for a roof unglazed opening for CIE sky types 1-15,
- *5.10:* Sky component under a roof glazed opening for CIE sky types 1-15,
- *5.11:* Sky component and external reflected component for a façade unglazed opening for CIE sky types 1-15,
- *5.12:* Sky component and external reflected component for a façade glazed opening for CIE sky types 1-15.

Objective of the workflow

11 settings are available to the final user, and are the ones corresponding to the global rendering quality setting in range [0 ; 10]. For instance, RQ5 is the global quality setting mapped to the following internal settings:

- *ambient* = on
- *trace leve* = 4
- *ambient trace level* = 8
- *ambient precision* = 1.5
- *ambient complexity* = 6
- *ambient feature size* = 0

The objective is to identify 3 settings out of these 11 settings: low, medium, and high, as detailed in the introduction. In addition to simulation accuracy, the rendering quality (RQ) impact the simulation time, which includes the following tasks:

- parsing,
- setup,
- light transport simulation,
- image rendering.

The simulation time analysis is useful to assess whether it is realistic and reasonable to perform simulations with a particular rendering quality.

Proposed workflow

In order to identify the low, medium and high global rendering quality values, the simplest approach would be to perform all the test cases for all the rendering qualities, and determine the relevant settings afterwards. Though robust, this approach is time consuming since it requires to perform a large number of simulations. Instead, we propose an iterative workflow aimed at performing a fewer number of simulations while guarantying a robust identification. In order to describe the workflow further, some quantities need to be defined:

- SET is the full set of test cases available,
- SUB is a subset of test cases taken out of SET, that can be reduced to a single test case, or include all the test cases (in this event SUB = SET),
- RQ is a global setting value,
- For a test case $_i$, $(E_i)[RQ]$ is the error (in %) of the simulation result with respect to the analytical reference, for the rendering quality RQ,
- $(E_{max})_{acceptable}$ is the maximum error (in %) acceptable for a test case in SET,
- <E>[RQ] is the average error (in %) of the simulation result of all the test cases in SET with respect to the analytical reference, for the rendering quality RQ,
- $\langle E\rangle_{acceptable}$ is the maximum average error (in %) acceptable for the full set of test cases,
- <ST>[RQ] is the average simulation time of all the test cases in SET.

Formally, the objective of the workflow is to identify 3 rendering quality values RQ_{low}, RQ_{medium} and RQ_{high} such as:

$\forall_i \in$ SET:

$$(E_i)[RQ_{low}] < (E_{max})_{acceptable},$$
$$(E_i)[RQ_{medium}] < (E_{max})_{acceptable},$$
$$(E_i)[RQ_{high}] < (E_{max})_{acceptable},$$

and:

$$\langle E\rangle[RQ_{high}] < \langle E\rangle[RQ_{medium}] < \langle E\rangle[RQ_{low}],$$
$$\langle E\rangle[RQ_{high}] < \langle E\rangle_{acceptable},$$

and:

$$\langle ST\rangle[RQ_{low}] < \langle ST\rangle[RQ_{medium}] < \langle ST\rangle[RQ_{high}]$$
$\langle ST\rangle[RQ_{low}]$ is minimal.

The underlying assumption in this workflow is that the average error <E>[RQ] decreases when RQ increases, and the average simulation time <ST>[RQ] increases when RQ increases.

The proposed workflow is based on the two following principles:
- implement an iterative dichotomous approach with respect to the successive tested RQ values,
- identify the low, medium and high RQ values for a subset of test cases SUB, and then check that the identified RQ values hold for the remaining tests (i.e. for SET).

Formally, let $[RQ_{min}\ ;\ RQ_{max}]$ denote the range of possible RQ values. The workflow is as follows:

$RQ_d \leftarrow (RQ_{min} + RQ_{max}) / 2$

While (RQ_{low}, RQ_{medium} and RQ_{high} not identified)
    and (($RQ_d \neq RQ_{min}$) and ($RQ_d \neq RQ_{max}$))

    While (candidate RQ_{low}, RQ_{medium} and
        RQ_{high} not identified)

        Perform the test cases in SUB for the rendering quality RQ_d.

        If $(E_i)[RQ_d]$ ($i \in$ SUB) < $(E_{max})_{acceptable}$
            $[RQ_{min}\ ;\ RQ_{max}] \leftarrow$
            $[RQ_{min}\ ;\ (RQ_{min} + RQ_{max}) / 2]$
        else
            $[RQ_{min}\ ;\ RQ_{max}] \leftarrow$
            $[(RQ_{min} + RQ_{max}) / 2\ ;\ RQ_{max}]$
        endIf

        $RQ_d \leftarrow (RQ_{min} + RQ_{max}) / 2$

        Identify candidate RQ_{low}, RQ_{medium}
        RQ_{high} if possible

    endWhile

    If the candidate identified RQ do not hold for all the test cases in SET, i.e. $\exists_i$ in SET such as $(E_i)[RQ_d] \geq (E_{max})_{acceptable}$ or $\langle E\rangle[RQ_{high}] \geq \langle E\rangle_{acceptable,}$ include the problematic tests in the initial subset SUB, and reinitialize $[RQ_{min}\ ;\ RQ_{max}]$

endWhile

This process does not guaranty the number of simulations to perform will be lower than the simplest approach (full assessment process) but at worst, it will be equal; experiments show it is lower in practice (see next section).

IMPLEMENTATION AND RESULTS

For illustration purpose and readers not familiar with CIE 171:2006 test cases, we first present test case 5.4. Then, we show how the proposed workflow is implemented for various couples $\{(E_{max})_{acceptable}\ ;\ \langle E\rangle_{acceptable}\}$.

CIE test case illustration: test case 5.4

Test case 5.4 is presented below. We also give the results obtained for RQ5. The other test cases used in this paper are detailed in (CIE, 2006).

Objective. The objective of test case 5.4 is to assess the luminous flux conservation between the light source and the internal surfaces of a space. An error in this conservation is equivalent to source of error in the calculated illuminance in a given scenario.
For daylighting simulations, the flux conservation should be verified between the incident luminous flux (in lumens) at an opening surface and the total direct flux reaching the different internal surfaces.

Test case description. The luminous flux arriving at an opening surface depends on the sky model used by the software to be tested and can vary from one program to another. However, the flux conservation remains valid. A sequence of geometries is defined, and can be used to verify whether this conservation is achieved for roof openings and for wall openings, and if it is affected by the size of the openings.The geometry is a square room of dimensions 4m x 4m x 3m, with either a roof or a side opening at the centre of the roof or the wall. The roof opening sizes are 1m x 1m, 2m x 2m, 3m x 3m or 4m x 4m (full opening) with a thickness of 200 mm. The wall opening sizes are 2m x 1m, 3m x 2m or 4m x 3m (full opening) with a thickness of 200 mm. The lighting simulation should be carried out with black interior surfaces (0% reflectance) to avoid the inter-reflection errors, and with no exterior ground reflections in the case of wall openings (0% external ground reflectance).

Analytical solution. In theory, in the case of a room with one opening (unglazed) and with black internal surfaces of 0% reflectance, the total direct luminous flux reaching the interior different surfaces ϕ_i, should be equal to the flux arriving at the opening surface ϕ_o: $\phi_i = \phi_o$.If $R_S = \phi_i / \phi_o$ for the simulation results, the relation $100 \times (R_S - 1)$ can be used to calculate the error in percentage due to the reduction or increase in the transmitted flux.

Assessment results. Table 1 presents test case 5.4 assessment results for a roof opening of 1 m x 1 m, for rendering quality RQ5. The results obtained with the other variants and the other rendering qualities are presented in table 4.

Proposed worklow: example of implementation

We illustrate below how the proposed workflow can be implemented for the validation of Velux Daylight Visualizer 2. Comparisons with the simple full assessment approach will be carried out, in terms of robustness (identification of low, middle and high RQ values) and number of simulations actually performed.

Test case 5.4 **Rendering quality RQ5**

Internal setting	Value
ambient	on
trace level	4
ambient trace level	8
ambient precision	1.5
ambient complexity	6
ambient feature size	0

Φi / Φo for a roof opening of 1 m x 1 m

Opening type / Luminaire type	Φi / Φo Analytical	Rs = Φi / Φo Simulation	error (%) 100(Rs - 1)
Roof 1 m x 1 m	1	0.993	-0.77

Error (%) **0.77**

Table 1: Test case 5.4 assessment result for a roof opening of 1 m x 1 m

Full assessment process as ground truth. The full assessment process (i.e. simulating each test case for each rendering quality) is used as ground truth. Table 4 presents the error observed and table 5 the simulation time for each test case, and each rendering quality. The simulations have been performed using a bi-Xeon 2.4 GHz computer. It should be noticed test cases 5.9 to 5.12 are performed for each available sky type, i.e. 15 sky types (CIE sky type 1 to 15). Thus, the number of required simulations is 11 x (6 + 1 + 3 + 1 + 15 x (2 + 2 + 2 + 2)) = 1441.

Tables 4 and 5 allows to identify directly the low, medium and high settings for different couples $\{(E_{max})_{acceptable}$; $<E>_{acceptable}\}$. Examples of sets $\{(E_{max})_{acceptable}$; $<E>_{acceptable}$; RQ_{low} ; RQ_{medium} ; $RQ_{high}\}$ are:

{6 % ; 1.5 % ; RQ3 ; RQ4 ; RQ6},

{10 % ; 3 % ; RQ2 ; RQ3 ; RQ4},

{20 % ; 5 % ; RQ1 ; RQ2 ; RQ3}.

Workflow implementation and illustration

We illustrate below how the proposed workflow is implemented for various couples $\{(E_{max})_{acceptable}$; $<E>_{acceptable}\}$. The successive RQ tested are listed, as well as the test case subset involved in the simulation. For instance, RQ5(SUB) means the simulation is performed for the test case subset SUB for the rendering quality 5; RQ2(SET) means the simulation is performed for all the test cases for the rendering quality 2. The reader can follow and check the process from tables 4 and 5.

The test case subset SUB used in the simulation is the set ***{test case 5.4 ; test case 5.5 ; test case 5.6}***.

A simulation is indicated in *italic* if the maximum error observed is under the maximum tolerated error, i.e.:

$(E_i)[RQ_d]$ ($_{i} \in$ SUB) $< (E_{max})_{acceptable}$

A simulation is indicated in ***italic bold*** if, in addition, the average error observed for the full set of test cases is under the average tolerated error, i.e.: $<E>[RQ_d] \;<\; <E>_{acceptable}$

$\{(E_{max})_{acceptable} = 6$ % ; $<E>_{acceptable} = 1.5$ %}

The successive simulations performed in the iterative workflow are as follows:

RQ5(SUB)→RQ2(SUB)→*RQ3(SUB)*→*RQ4(SUB)*→*RQ3(SET)*→*RQ4(SET)*→*RQ5(SET)*→*RQ7(SUB)*→*RQ6(SUB)*→***RQ6(SET)***

The identified settings are {RQ3 ; RQ4 ; RQ6}.

The total number of simulations performed is:

4 x (6 + 1 + 3 + 1 + 15 x (2 + 2 + 2 + 2)) + 2 x (6 + 1 + 3) = 544, i.e. 37.75 % of the number of simulations required in the full assessment process. The identified settings from the full assessment process are the same.

$\{(E_{max})_{acceptable} = 10$ % ; $<E>_{acceptable} = 3$ %}

The successive simulations performed in the iterative workflow are as follows:

RQ5(SUB)→*RQ2(SUB)*→RQ1(SUB)→*RQ3(SUB)*→*RQ4(SUB)*→***RQ2(SET)***→***RQ3(SET)***→***RQ4(SET)***

The identified settings are {RQ2 ; RQ3 ; RQ4}.

The total number of simulations performed is:

3 x (6 + 1 + 3 + 1 + 15 x (2 + 2 + 2 + 2)) + 2 x (6 + 1 + 3) = 413, i.e. 28.66 % of the number of simulations required in the full assessment process. The identified settings from the full assessment process are the same.

$\{(E_{max})_{acceptable} = 20\ \%\ ;\ \langle E\rangle_{acceptable} = 5\ \%\}$

The successive simulations performed in the iterative workflow are as follows:

RQ5(SUB)→*RQ2(SUB)*→*RQ1(SUB)*→RQ0(SUB) →*RQ3(SUB)*→***RQ1(SET)***→***RQ2(SET)***→ ***RQ3(SET)***

The identified settings are {RQ1 ; RQ2 ; RQ3}. The total number of simulations performed is:

3 x (6 + 1 + 3 + 1 + 15 x (2 + 2 + 2 + 2)) + 2 x (6 + 1 + 3) = 413, i.e. 28.66 % of the number of simulations required in the full assessment process. The identified settings from the full assessment process are the same.

$\{(E_{max})_{acceptable} = 2\ \%\ ;\ \langle E\rangle_{acceptable} = 2\ \%\}$

We study now a case where no setting can be identified, if we refer to table 4. Indeed, no RQ value lead to a maximum error below 2 %.

In this case, the successive simulations performed through the iterative process are as follows:

RQ5(SUB)→*RQ7(SUB)*→*RQ8(SUB)*→ *RQ9(SUB)*→RQ7(SET)→RQ8(SET) →RQ9(SET)→*RQ10(SUB)*→ RQ10(SET)

No settings are identified.

The total number of simulations performed is:

4 x (6 + 1 + 3 + 1 + 15 x (2 + 2 + 2 + 2)) + 1 x (6 + 1 + 3) = 534 = 37.05 % of the number of simulations required in the full assessment process.

$\{(E_{max})_{acceptable} = 5\ \%\ ;\ \langle E\rangle_{acceptable} = 2\ \%\}$

We study another case where no setting can be identified, since no RQ value lead to a maximum error below 5 % (see table 4). The successive simulations performed in the iterative process are as follows:

RQ5(SUB)→RQ2(SUB)→*RQ3(SUB)*→ *RQ4(SUB)*→RQ3(SET)→RQ4(SET)→ RQ5(SET)→*RQ7(SUB)*→*RQ6(SUB)*→ *RQ8(SUB)*→RQ6(SET)→RQ7(SET)→ RQ8(SET)→*RQ9(SUB)*→*RQ10(SUB)*→ RQ9(SET)→RQ10(SET)

No settings are identified.

The total number of simulations performed is: 8 x (6 + 1 + 3 + 1 + 15 x (2 + 2 + 2 + 2)) + 1 x (6 + 1 + 3) = 1058 = 73.42 % of the number of simulations required in the full assessment process. This case is not favorable to the iterative workflow and many RQ values must be successively tested: indeed the pre-identified settings from the test case subset SUB are not suitable when tested for the full set of test cases SET. Nevertheless, the number of simulations performed remains lower than the total number of simulations required in the full assessment process.

Result overview

Table 2 gathers the results obtained. The average number of simulations required to identify the low, medium and high settings is, on average, 58.89 % lower than the number of simulations required in the full assessment process. The identification is robust, if we refer to table 4.

$\{(E_{max})_{aceptable}$; $\langle E\rangle_{aceptable}\}$	{2 % ; 2 %}	{5 % ; 2 %}	{6 % ; 1.5 %}	{10 % ; 3 %}	{20 % ; 5 %}
Low setting	none	none	RQ3	RQ2	RQ1
Medium setting	none	none	RQ4	RQ3	RQ2
High setting	none	none	RQ6	RQ4	RQ3
# simulations	534	1058	403	413	413
% simulations	37.05 %	73.42 %	37.75 %	28.66 %	28.66 %

Table 2: Identified settings and number of simulations required for various maximum tolerated errors.

Table 3 indicates the relative simulation time corresponding to the identified RQ (1 corresponds to 4.19 s using a bi-Xeon 2.4 GHz computer). These times are reasonable for using the software for building design and analysis.

	RQ1	RQ2	RQ3	RQ4	RQ6
Relative simulation time	1	1.89	3.02	4.47	8.19

Table 3: Relative simulation time corresponding to the identified RQ.

CONCLUSION

In this paper, Velux Daylight Visualizer 2 physical accuracy was assessed against CIE 171:2006 test cases dedicated to natural lighting. The rendering quality and simulaiton time depends on a global setting (RQ) that is mapped to the software internal settings.

Test Case number	Test Case variant	RQ0	RQ1	RQ2	RQ3	RQ4	RQ5	RQ6	RQ7	RQ8	RQ9	RQ10
Test Case 5.4	Roof opening 1 m x 1 m	3.68	1.38	1.22	0.92	0.84	0.77	0.75	0.71	0.66	0.67	0.69
	Roof opening 2 m x 2 m	0.75	0.14	0.29	0.05	0.09	0.05	0.05	0.03	0.01	0.02	0.03
	Roof opening 4 m x 4 m	0.21	0.25	0.02	0.17	0.14	0.16	0.14	0.14	0.17	0.16	0.15
	Wall opening 2 m x 1 m	1.88	0.32	0.07	0.21	0.32	0.39	0.42	0.45	0.44	0.76	0.46
	Wall opening 3 m x 2 m	1.49	0.84	0.62	0.62	0.53	0.49	0.48	0.45	0.47	0.46	0.46
	Wall opening 4 m x 3 m	0.10	0.14	0.33	0.27	0.33	0.34	0.37	0.38	0.36	0.38	0.39
Test Case 5.5	-	1.15	1.08	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07
Test Case 5.6	S_2 of 50 cm x 50 cm	32.38	11.66	6.64	3.57	2.35	2.87	2.09	1.93	0.99	1.29	1.39
	S_2 of 4 m x 4 m	0.96	0.70	0.45	0.45	0.44	0.39	0.38	0.39	0.37	0.36	0.36
	S_2 of 500 m x 500 m	3.88	3.07	2.42	2.36	2.10	2.11	1.91	1.99	1.98	1.87	1.87
Test Case 5.7	-	2.23	0.68	0.25	0.42	0.30	0.13	0.15	0.15	0.06	0.04	0.05
Test Case 5.9	Roof opening 1 m x 1 m	11.50	4.17	2.74	2.40	1.91	1.56	1.28	1.40	1.22	1.15	1.07
	Roof opening 4 m x 4 m	3.83	3.31	3.21	3.19	3.18	3.15	3.12	3.12	3.12	3.12	3.12
Test Case 5.10	Roof opening 1 m x 1 m	9.71	3.34	3.92	5.19	5.10	5.33	5.46	5.54	5.27	5.19	5.22
	Roof opening 4 m x 4 m	2.14	1.70	1.56	1.62	1.67	1.65	1.65	1.66	1.68	1.67	1.66
Test Case 5.11	Wall opening 2 m x 1 m	5.75	2.48	1.49	0.96	0.83	0.67	0.60	0.45	0.39	0.36	0.31
	Wall opening 4 m x 3 m	1.55	0.97	0.84	0.67	0.71	0.67	0.64	0.67	0.65	0.61	0.61
Test Case 5.12	Wall opening 2 m x 1 m	8.53	5.70	4.99	4.44	4.68	4.59	4.64	4.57	4.51	4.38	4.31
	Wall opening 4 m x 3 m	2.69	2.53	2.39	2.34	2.36	2.33	2.27	2.26	2.28	2.28	2.28
Minimum		**0.10**	**0.14**	**0.02**	**0.05**	**0.09**	**0.05**	**0.05**	**0.03**	**0.01**	**0.02**	**0.03**
Maximum		**32.38**	**11.66**	**6.64**	**5.19**	**5.10**	**5.33**	**5.46**	**5.54**	**5.27**	**5.19**	**5.22**
Average		**4.97**	**2.34**	**1.82**	**1.63**	**1.52**	**1.51**	**1.45**	**1.44**	**1.35**	**1.36**	**1.34**

Table 4: Full assessment process results.
Error (%) with respect to analytical reference for each test case and each rendering quality.

For the following settings: RQ3, RQ4, RQ5, RQ6, RQ7, RQ8, RQ9, RQ10, the maximal error with respect to the reference is below 5.54 % and the average error is below 1.63 %; thus, for all these settings, Velux Daylight Visualizer 2 can predict accurately daylight levels and appearance of a space lightened with natural light, prior to realization of the building design. The simulation times are reasonable for using the software for building design and analysis.

Moreover, an iterative workflow was proposed to exploit CIE 171:2006 test cases in order to identify low, medium, and high settings of the software. The proposed workflow allows to reduce the number of tests to perform, while maintaining results robust. Compared to a full assessment process, the number of tests performed is on average, 58.89 % lower in our experiments.

Future work will be concerned with the assessment of the rendered image quality from representative scenes the software can do, where various aspects of light transport are involved simultaneously.

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Test Case number	Test Case variant	RQ0	RQ1	RQ2	RQ3	RQ4	RQ5	RQ6	RQ7	RQ8	RQ9	RQ10
Test Case 5.4	Roof opening 1 m x 1 m	4.1	12.2	23.2	37.4	55.1	106.1	100.1	129.1	156.1	44.6	53.9
	Roof opening 2 m x 2 m	4.2	12.5	24.0	38.1	56.1	105.1	103.1	128.1	164.1	202.1	240.1
	Roof opening 4 m x 4 m	4.8	14.7	27.0	43.1	64.1	112.1	117.1	148.1	184.1	222.1	270.1
	Wall opening 2 m x 1 m	4.0	11.9	22.8	36.1	54.0	94.1	98.1	121.1	156.1	191.1	228.1
	Wall opening 3 m x 2 m	4.2	12.0	23.8	38.2	56.0	97.1	101.1	131.1	166.1	201.1	238.1
	Wall opening 4 m x 3 m	4.4	13.0	24.8	40.1	59.0	100.1	107.1	141.1	166.1	211.1	248.1
Test Case 5.5	-	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Test Case 5.6	S_2 of 50 cm x 50 cm	0.1	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.8	0.9	1.1
	S_2 of 4 m x 4 m	0.2	0.6	1.4	2.0	3.2	4.6	7.5	8.2	10.8	13.1	15.5
	S_2 of 500 m x 500 m	0.1	0.4	0.9	2.1	4.1	7.3	11.7	21.1	28.1	52.8	62.1
Test Case 5.7	-	0.1	0.2	0.3	0.4	0.6	0.8	1.3	1.4	1.7	2.0	2.5
Test Case 5.9	Roof opening 1 m x 1 m	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.5	0.6	0.7
	Roof opening 4 m x 4 m	0.1	0.1	0.2	0.2	0.2	0.3	0.4	0.5	0.5	0.6	0.8
Test Case 5.10	Roof opening 1 m x 1 m	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.8
	Roof opening 4 m x 4 m	0.1	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0
Test Case 5.11	Wall opening 2 m x 1 m	0.1	0.1	0.2	0.3	0.3	0.5	0.5	0.6	0.8	0.9	1.0
	Wall opening 4 m x 3 m	0.1	0.2	0.2	0.3	0.3	0.5	0.5	0.7	0.8	0.9	0.9
Test Case 5.12	Wall opening 2 m x 1 m	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.9	1.0	1.2
	Wall opening 4 m x 3 m	0.1	0.2	0.2	0.3	0.4	0.6	0.6	0.8	0.9	1.1	1.3
Minimum		0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.5	0.6	0.7
Maximum		4.8	14.7	27.0	43.1	64.1	112.1	117.1	148.1	184.1	222.1	270.1
Average		1.5	4.2	7.9	12.7	18.7	33.3	34.3	44.0	54.8	60.4	72.0

Table 5: Full assessment process results.
Simulation time (s) with respect to analytical reference for each test case and each rendering quality.

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