Real world complexity in reflectance value measurement for climate-based daylight modelling

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REAL WORLD COMPLEXITY IN REFLECTANCE VALUE MEASUREMENT FOR CLIMATE-BASED DAYLIGHT MODELLING

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ABSTRACT
The magnitude and distribution of inter-reflected light is often the most important factor in any assessment of daylight illumination. This is so for the traditional Daylight Factor (DF) method as it is for metrics founded on climate-based daylight modelling (CBDM). A recent study of classroom spaces showed how wall reflectivity is a key determinant of the outcome of a climate-based daylight evaluation. Typically, when a real space is occupied, interior walls get partially covered by fixtures, furniture, posters, etc. Hence they can become very different from the initial design assumptions used for the computer modelling of daylight.

The work presented here examines the differences between assumed and real surface reflectance values, assessed on a case study by means of different methods, and the consequences that this may have for predicted measures of daylighting performance. This is of particular importance now that climate-based measures of daylighting performance are a mandatory requirement for the UK’s Priority Schools Building Programme (PSBP). One of the techniques used to determine real-world surface reflectance values is based on High Dynamic Range (HDR) photography; it allows for the measurement of luminance on a per-pixel basis and thus for the creation of interpolated reflectance maps of complex patterns. This new technique is applied for the first time on real spaces here and an initial assessment of its values and limits is presented.

The resulting reflectance values obtained from the measurements on the case study are invariably different than those typically assumed when carrying out daylight simulations. The impact this can have on the outcomes determined using daylight simulation is presented and discussed.

INTRODUCTION
Daylight simulation has progressed from a static evaluation (i.e. the Average Daylight Factor calculation) to a more dynamic-like, annual, climate-based type of modelling. Even though it may resemble the passage from static to dynamic thermal simulation, what is now known as climate-based daylight modelling (CBDM) is more of a series of “snapshots”, taken at hourly or sub-hourly steps, capturing the instantaneous luminous environment for specific space and sky conditions. Along with these advancements in simulation techniques, new approaches to the measurement of luminous quantities appeared, such as the use of High Dynamic Range (HDR) imaging to record luminance values (Inanici, 2006), opening new doors to field study applications, e.g. assessment of potential damages to artworks due to excessive daylight exposure in heritage buildings (Mardaljevic et al., 2015b). Meanwhile, research in other scientific fields revealed the importance of daylight for people’s health and well-being, as well as its role as an aid in increasing the productivity in work spaces (van Bommel and van den Beld, 2004).

Recognising the importance of good daylighting design in educational spaces, the UK Education Funding Agency (EFA) inserted in 2013 CBDM metrics as mandatory requirements for 261 schools in England and Wales. This marked the first time CBDM metrics were used in daylighting policy and took effect within the Priority Schools Building Programme (PSBP) (EFA, 2013). While the intent is widely perceived as commendable, the outcomes are still unknown as the first schools under the new PSBP daylight requirements have yet to be completed. To gain a complete understanding of the performance of such new buildings, and to draw a meaningful assessment of the method, a post-occupancy evaluation should be carried out after the spaces have been occupied and used for a certain amount of time. However, any post-occupancy evaluation presents several challenges, even when it is ‘limited’ to an assessment of the internal luminous conditions. Many building simulation tools are created for concept stage design, when the necessary level of detail is relatively low. For example, one window fixture that can often be found in classrooms and offices are venetian blinds. Although commonplace, these fixtures are in fact complex optical devices with highly variable light transmission properties. Even for a fixed configuration (i.e. without any user intervention) they are challenging to model using the most state-of-the-art daylighting simulation software (McNeil and Lee, 2013). When the vagaries of an occupants use of venetian blinds are considered, the uncertainty in any long-term simulated output (e.g. CBDM metrics) must be considerable.

Among the confounding factors that increase the complexity of daylighting analysis on built environments, the measurement and assignment of reflectance values were found to be directly influencing the final results,
whether they are expressed in terms of average Daylight Factor (DF) or annual CBDM metrics (Brembilla et al., 2015).

This paper lists some of the existing methodologies for measuring and assigning reflectance values in a daylighting analysis simulation and shows how annual results expressed with CBDM metrics change according to the chosen methodology. Particular emphasis is given to a new technique based on HDR captures, applied on real spaces for the first time by means of this work and still under development.

METHODOLOGY

The case study chosen for this work is one of four school classrooms used by the authors for a wider project on daylighting performance assessment in educational spaces (Drosou et al., 2015). This specific classroom is part of a building used mainly as a college and built in the 1960s. Two sides of the space have windows looking directly outside, oriented towards North-East and South-East. The walls and ceiling are painted in light colours, while the floor is carpeted with a pattern in dark blue shades. On the walls a number of fixtures, appliances and posters are hanged for teaching purposes; of particular relevance are violet pinboards, which partially cover the smartboard wall (Fig. 1) and large part of the opposite wall. Practically all pieces of furniture are movable and are very often rearranged in the room depending on the lesson’s needs. Even though at first glance the space looks fairly simple and representative of a traditional type of classroom, assigning realistic reflectance values to the 3D model for computer simulation presented several obstacles.

Presented in an increasing order of complexity, the scenarios considered were the following:

1. Assignment of standard reflectances (control scenario), with and without furniture;
2. Assignment of reflectance values retrieved from a database, with and without furniture;
3. Assignment of reflectances through reference reflectance cards;
4. Assignment of derived reflectances from illuminance-luminance measures;
5. Assignment of reflectances derived from HDR images.

The first scenario assumed standard reflectance values as applied at the concept design stage, when the technical and finishing details might not be known yet. A number of guidelines (IESNA, 2000; BSI, 2008; The Daylight Metrics Committee, 2012) provide recommendations on the selection of values.

The second scenario used data found in material databases, chosen by their visual appearance and best match with real materials found in the classroom. The database used in this case can be found at the website lighting-materials.com. For this method only, both when including the furniture and when not, the specularity and the roughness of the materials were set as those found in the database or slightly corrected for matching of the rendered image with the photograph of the space (as shown in Fig. 1).

The third and fourth scenarios followed the guidelines found in Lighting Guide 11 for field measurements (SLL and NPL, 2001); the former uses cards of known reflectance as references for the visual estimation of the surface own reflectance, while the latter derives reflectances from simultaneous measurements of illuminance and luminance perpendicular to the surface. These measurements were taken respectively with a Hagner EC1-X illuminance meter and with a Konica Minolta LS-100 luminance meter. The reflectance value $\rho$ is derived as per Eq. 1, where $L$ is the luminance and $E$ the illuminance:

$$\rho = \frac{L}{\pi E} \quad (1)$$

The paired measurements were repeated 10 times for each surface (floor, walls and ceiling), taking the two instruments’ simultaneous readings side by side, and changing the target spot around the room each time. The mean and the standard deviation for each element were found to be:

- $\rho_{\text{floor}} = 0.06 \pm 0.01$
- $\rho_{\text{wall}} = 0.79 \pm 0.04$
- $\rho_{\text{ceiling}} = 0.91 \pm 0.03$

For all the other methods the uncertainty is likely to be higher, as they are based on visual assessments (scenarios 2 and 3) or as the measurement instruments have a bigger error range (scenario 5).
The fifth scenario applied a recently proposed technique that makes use of HDR images to record luminance values for complex scenes and patterns. At first, a simplified version of that technique was used to measure the floor reflectance, capturing the luminance through an HDR image of the floor area close by the illuminance meter (see Fig. 2). With an area sufficiently large to include many pattern repetitions, the averaged luminance was found to be accurate enough to derive the reflectance.

The full technique further expands the use of HDR as a proxy to also derive and interpolate the illuminance that falls on surfaces of known reflectance. From the illuminance field thus obtained, the relation in Eq. 1 can be applied and the reflectance map for the entire surface derived. While the theoretical framework for this method has been described in previous work (Mardaljevic et al., 2015a), its application in real spaces has not been explored before. As Fig. 3 shows, white cards of known reflectance were randomly placed on the selected wall and over the vertical fixtures, together with a highly reflective diffusing white tape. Care was taken for some cards to be placed on the vertical plane of the most protruding fixtures such as board frames and cable protective boxes. Furthermore, the cards were placed away from local shadows created by such elements, so that the illuminance field determined by the light falling onto the cards was not affected by local discontinuities of the wall surface. To cover the whole area under analysis with the interpolated illuminance field, some of the cards (or tape) should lie on the edge or outside that area (indicated with a dashed red line in Fig. 3). The reflectances of cards and tape were measured with the coupled luminance-illuminance method, in 10 different spots. The resulting values were:

- White cards: $\rho_{\text{cards}} = 0.87 \pm 0.04$
- White tape: $\rho_{\text{tape}} = 0.98 \pm 0.05$

If considering the white tape as a pure diffuser, the values higher than 1 should be discounted, i.e. only the values within the range 0.93 - 0.99 should be considered for the error probability distribution.

The photographs were taken with a Canon EOS 600D Digital SLR camera fitted with an ultra wide-angle Canon EF-S 10-18mm f/4.5-5.6 IS STM lens. Nine jpg images were combined to form an HDR image through the hdrawgen program. The two images used in this study were taken under stable luminous conditions, with a variation in illuminance levels recorded at the window sill of 4390 - 4420 lx and 7220 - 7360 lx. The images were corrected for vignetting effect afterwards. From the HDR captures, the illuminance field was derived interpolating the illuminance values found on the areas of known reflectance. Finally, the luminance of each pixel in the original HDR was multiplied by $\pi$ and divided by the illuminance value of the corresponding pixel on the interpolated illuminance field. Another potentially suitable technique would be the use of a portable spectrophotometer, which can measure the colour properties and the amount of reflected light from a surface, in its diffuse and specular (i.e. gloss) parts; however, this was not investigated here.

The reflectance values obtained for each of the scenarios were then applied to the model for the CBDM simulation. The model was created in SketchUp and the Radiance 4-component method (Mardaljevic, 2000) was used to run the analyses and calculate the annual metrics (Radiance ambient parameter: -ab 5 -ad 2048 -ar 128 -as 256 -aa 0.2). In the Radiance raytracing system (Ward Larson et al., 1998), most of the opaque construction materials can be defined using the plastic type, which is characterised as follows:

void plastic material_id 0
0
5 R G B specularity roughness

CBDM metrics were derived from illuminances predicted across a virtual sensor plane at a height of 0.80 m and with a 0.25 m grid spacing. An external ground plane was built into the model, with a 20% reflectance towards. From the HDR captures, the illuminance field was derived interpolating the illuminance values found on the window sill of 4390 - 4420 lx and 7220 - 7360 lx. The images were corrected for vignetting effect afterwards. From the HDR captures, the illuminance field was derived interpolating the illuminance values found on the areas of known reflectance. Finally, the luminance of each pixel in the original HDR was multiplied by $\pi$ and divided by the illuminance value of the corresponding pixel on the interpolated illuminance field. Another potentially suitable technique would be the use of a portable spectrophotometer, which can measure the colour properties and the amount of reflected light from a surface, in its diffuse and specular (i.e. gloss) parts; however, this was not investigated here.

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void plastic material_id 0
0
5 R G B specularity roughness

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The following metrics were calculated from the annual illuminance profile obtained from the simulation runs (UDI stands for Useful Daylight Illuminance):

- UDI-n (non-sufficient): $E < 100$ lx;
- UDI-s (supplementary): $100 < E < 300$ lx;
- UDI-a (autonomous): $300 < E < 3000$ lx;
- UDI-x (exceeded): $E > 3000$ lx;
- Total Annual Illumination;
- Average Daylight Factor.
RESULTS ANALYSIS

For scenario 5, six reflectance maps were obtained using the same two HDR images, but selecting different reference surfaces (white cards, diffusing tape and wall paint). For the three cases, the averaged reflectance values over the same area were:

- White cards: $\rho_{\text{wall}} = 0.67$
- Diffusing tape: $\rho_{\text{wall}} = 0.69$
- Wall paint: $\rho_{\text{wall}} = 0.70$

The use of small cards to cover a large wall can easily lead to a sparse coverage of the area of interest, especially on the edge and at the corners. That resulted in a less accurate interpolation field between the known illuminances and in a reduction of final reflectance values. A more continuous frame just outside the desired area is easier to define, but still needs additional reference points within the edges. Using the wall reflectance itself as reference simplifies the fieldwork activities and improves the interpolation grid refinement, if there is enough wall exposed. However, for the wall paint to be used as a reference, preceding measurements of the wall reflectance need to be taken with other methods, in order to ensure that the values are sufficiently homogeneous.

Independently of the chosen reference surface however, an increase of reflectance values towards the wall side that is closer to the windows (on the right of Fig. 4) was noticed. For highly specular materials, e.g. for the smartboard and for laminated posters, it was expected that the resulting reflectance values would be higher than 1.0, as their specular component invalidated Eq. 1. The pixels with a reflectance higher than 1.0 were blacked out in Fig. 4 to distinguish them, but were considered for the calculation of the average reflectance of the wall. However, other materials were also affected by the same behaviour, even if their reflectance did not result in values higher than 1.0. It is hypothesised that a small specular component, hardly visible to bare eyes, was present in most of the materials used in this classroom and that this effect weakened the luminance-illuminance relation in the areas where daylight coming from the windows was striking directly on the wall.

Looking at Fig. 4 it is possible to distinguish two different shades for the pinboard hanging on the left of the smartboard and for the one on its right. The former appears to be in the order of $\rho_{\text{board}} = 0.30 - 0.40$ and the latter of $\rho_{\text{board}} = 0.50 - 0.60$, while direct measures on the boards showed a value of $\rho_{\text{board}} = 0.28 \pm 0.03$. Further measurements were taken with the luminance meter placed at the camera position and directed towards the two purple pinboards, together with an illuminance reading taken from the wall; the resulting reflectances were $\rho_{\text{board}} = 0.29$ for the left board and $\rho_{\text{board}} = 0.42$ for the right board. The same effect was noticed on the white cards set up for the evaluation; while on the left side of the wall they had a higher reflectance but lower than 1.0, on the right side almost all of them resulted in blacked out areas.

Tracing a vertical line that coincides with half of the HDR image, it is possible to divide the reflectance map into two parts: the right part is likely to be affected by specular reflections effects as light coming in from the windows bounces off the wall and directly towards the camera; the left part is instead less affected by strong direct reflections as their angle would be directed towards the darker rear of the room. If the average reflectance was calculated for these two areas separately, the values would be $\rho_{\text{wall}} = 0.76$ for the right part and $\rho_{\text{wall}} = 0.63$ for the left part of the wall. According to the comparisons previously mentioned between the
paired luminance-illuminance measurements and the results obtained from the HDR images, the more reliable value would be the one found on the left part of the wall only. Nevertheless, for the assignment of the wall reflectance in the scenario 5 simulation, the values were averaged over the whole reflectance map and a mean between the results obtained using different reference surfaces for the illuminance interpolation was taken as final value. Indeed, even if the specular reflections were accounted for, the overall reflectance is lower than in the cases that assume an empty wall (scenarios 2 unfurnished, 3 and 4).

Table 1: Input sets of reflectance values for each of the considered scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Floor</th>
<th>Walls</th>
<th>Ceiling</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Standard</td>
<td>0.2</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>2. Database</td>
<td>0.07</td>
<td>0.79</td>
<td>0.87</td>
</tr>
<tr>
<td>3. Refl cards</td>
<td>0.17</td>
<td>0.72</td>
<td>0.79</td>
</tr>
<tr>
<td>4. Measures</td>
<td>0.06</td>
<td>0.79</td>
<td>0.91</td>
</tr>
<tr>
<td>5. HDR proxy</td>
<td>0.06</td>
<td>0.69</td>
<td>(0.91)</td>
</tr>
</tbody>
</table>

Table 1 reports the reflectance values corresponding to each scenario. The standard values were used as reference, to show how much discrepancy there would be between an initial evaluation of the space before built and the actual occupied space performance. For the database scenario the values reported in the Table are weighted averages of the RGB components, as the colours were considered. The reflectance of the ceiling for the HDR scenario was not recorded; the measured one was used instead. The average reflectance value derived from the HDR technique was assigned to all the wall surfaces in the model, not only to the wall with the smart-board used for the actual HDR image; this was applied here as a proof of concept, but the analysis could be repeated for each wall of the room and the derived average reflectance assigned to each corresponding wall in the simulation model.

At first the analysis is done on the simulation results expressed in terms of Total Annual Illumination (TAI), as that is a cumulative metric particularly sensitive to the reflectance variations. From the graph in Fig. 5 it can be generally noticed that the scenarios that use specific reflectances based on the actual room materials result in higher values than the standard scenario’s ones, as the reflectances of both walls and ceiling are higher than the guideline default values. Even though the floor reflectance is always lower than in the standard case this does not affect the overall increasing trend, as the floor reflectance is a less influential factor on illuminance-based simulations that use a horizontal working plane.

The same graph shows how the inclusion of furniture does not make much difference in terms of annual metrics for the case study presented here, especially when standard reflectance values were assigned. This is probably due to the fact that most of the furniture, i.e. desks, was below the horizontal plane (height = 0.80 m) and that the fixtures on the walls have exactly the same reflectance value as the wall itself ($\rho = 0.5$). When using material descriptions found in a database and chosen accordingly to the real room’s materials, the addition of furniture results in a slightly lower TAI value as many pieces of furniture have a lower reflectance value ($\rho = 0.44$ for the purple board and $\rho = 0.23$ for the desks) than the standard one. The overall effect is however negligible. An additional case, not reported in the graphs, was investigated to understand the difference in output when assigning specularity and roughness to the materials or when assuming them to be null. For the furnished model with materials retrieved from a database, the difference between considering specularity and roughness or assuming all surfaces to be perfect diffuser resulted in a difference of TAI lower than 0.2%.

Table 2: Annual evaluation results expressed in Useful Daylight Illuminance.

<table>
<thead>
<tr>
<th></th>
<th>UDI-n [%]</th>
<th>UDI-s [%]</th>
<th>UDI-a [%]</th>
<th>UDI-x [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>3.9</td>
<td>10.0</td>
<td>69.6</td>
<td>16.6</td>
</tr>
<tr>
<td>Database</td>
<td>3.0</td>
<td>7.8</td>
<td>66.2</td>
<td>23.0</td>
</tr>
<tr>
<td>Refl cards</td>
<td>3.1</td>
<td>8.2</td>
<td>67.4</td>
<td>21.3</td>
</tr>
<tr>
<td>Measures</td>
<td>2.9</td>
<td>7.8</td>
<td>66.1</td>
<td>23.2</td>
</tr>
<tr>
<td>HDR proxy</td>
<td>3.2</td>
<td>8.5</td>
<td>67.5</td>
<td>20.8</td>
</tr>
<tr>
<td>Standard (f)</td>
<td>3.8</td>
<td>9.9</td>
<td>69.5</td>
<td>16.9</td>
</tr>
<tr>
<td>Database (f)</td>
<td>3.1</td>
<td>8.1</td>
<td>66.0</td>
<td>22.9</td>
</tr>
</tbody>
</table>

Looking at the results in terms of Useful Daylight Illuminance (UDI) (Table 2 and Fig. 6) shows that an hypothetical design option of the same classroom where the standard reflectances were assigned would be just at the limit of acceptance, with a UDI-c (i.e. 69.5%)}.

Figure 4: Illuminance field derived from the HDR capture and the use of known reflectance tape. The dashed green line marks the midsection of the complete HDR image.
combined, the sum of UDI-s and UDI-a) of 79.6%, whereas all the other scenarios would fail due to high UDI-x values, that indicate the presence of illumination levels higher than 3000 lx and potentially discomfoting (Mardaljevic et al., 2012). Excluding the first default case, there is a generally good agreement between the annual results obtained from realistic reflectances. Taking the case that used measured reflectance (4) as a reference, the scenario that varies the most from it is the one that used the HDR images, although all the variations in UDI and TAI results are equal or less than 10%. Arguably, the lower illumination values that come from the use of the HDR-based technique could be considered even more realistic than the other results, as they take into account the presence of fixtures and other objects on the walls.

The results expressed with the traditional method of average DF simulation lead to very similar considerations; adding the furniture to the model does not influence the final result; as the reflectance values specific for this classroom are generally higher than the standard ones, the final results for the realistic cases are generally higher than the standard design base-case; the maximum variation found between the ‘realistic’ results is in the order of 4% and corresponds to the difference between the measured case and the HDR case.

**DISCUSSION**

It is already known that lighting simulations are sensitive to the assignment of reflectance values and that, although to a lesser degree, annual metrics are too. This means that for all analyses on existing building, particular care should be taken when measuring the surface properties. However, it is generally accepted to also rely on methods exclusively based on visual assessments, such as the use of reference reflectance cards and the choice of material properties from databases, mainly because the alternatives can be rather expensive, e.g. the use of a portable spectrophotometer, or not feasible for field measurements, e.g. a goniospectrophotometer. Another reason that justified the use of simpler techniques was that, for the Average Daylight Factor (ADF) calculation, assuming all sur-
faces to be lambertian was an acceptable approximation. For luminance and glare analyses this assumption might not hold any more (Jakubiec and Balakrishnan, 2015) and of course for visualisation purposes specifying realistic colours, brightness and reflections will change the final result. However, for CBDM evaluations based on illuminance values this was found to be not particularly influential.

The use of HDR imaging could provide a more affordable and straightforward method to derive reflectance, especially for complex materials and patterns. The presence of many elements with a specular behaviour might however pose limitations to the general use of the technique. While the materials’ specularity does not influence any of the annual metrics per se, the measurement techniques were found to be affected by higher uncertainties than expected. This appears to be mainly caused by the specular component that, to greater or lesser degree, was present in all surfaces found in the classroom, and that was accentuated in the measurements taken near the main light source, i.e. the windows. Nonetheless, the results and the degree of uncertainty of the new HDR-based method are deemed to be comparable to the luminance-illuminance paired measures method, as both these techniques use the same deriving equation and are likely to be affected by the same confounding factors (e.g. material specularity). The measurement error associated with the HDR imaging is in the order of 10% (Inanici, 2006) (for a camera that has been properly calibrated and corrected for vignetting effects), instead of the 2% error of the luminance meter, but a single HDR image can provide a huge number of point-measures at once, rather than having to repeat the measurements multiple times to cover large and patterned surfaces. An example can be found in the measurement of the floor reflectance reported in this paper; the value derived by the average of 10 different coupled measurements of luminance and illuminance was exactly the same ($\rho_{\text{floor}} = 0.06$) as the one obtained from the luminance recorded by the HDR image, averaged over an area of the image, and one illuminance reading (under stable sky conditions).

Initially, it was expected that the wall reflectances measured with the HDR technique would result in lower values than the standard ones, due to the presence of darker surfaces and the shadowing effect of furniture and fixtures. For this classroom however, the opposite was found to be true because of a combination of high reflectance finishes, such as the wall painting or the smart-board surface, and specular effects from several materials. The investigation should be repeated for more classroom spaces and wall configurations in order to understand whether the overall reflectance is generally higher or lower than the default value or if a 0.50 reflectance value represents the correct average situation for school buildings. Higher reflectance values than assumed at the design stage could lead to increased discomfort glare; an evaluation similar to the one presented here could be carried out using luminance-based metrics, to see the difference between assumed and realistic results.

**CONCLUSION**

The paper presented some of the methods generally used in daylight simulation to assign reflectance values to the building model, introducing a new technique based on HDR photography among them. The assignment of the reflectance for the main surfaces of a case study classroom (i.e. floor, walls, ceiling) was done by means of: visual assessments and choice of matching materials from a database; use of known reflectance cards and visual choice of the best match; paired measures of the luminance and illuminance values over the surfaces to derive the reflectance; use of HDR images to record the luminance and to derive the illuminance field falling onto reference materials. All the resulting reflectance values were found to be higher than the assumed ones for walls and ceiling, while the floor reflectance was lower than the standard 0.20. The HDR technique is deemed to be a valuable alternative to the existing methodology for reflectance mea-
surements in the field of daylight simulation. However, several surfaces were characterised by a specular component that affected the reflectance measurements when these were taken near the windows; care should be taken to avoid these reflections or alternative techniques should be employed in case the materials’ specularity is too prominent.

The values obtained from each of these methods were used in a CBDM evaluation and in a DF simulation. As the reflectances specific to the analysed space were generally higher than the standard ones, the results from the daylight simulations showed consequently higher illuminance values. The final results expressed as UDI, TAI and average DF were similar between the different scenarios considered, with a maximum difference of 10%. In two cases (default and database) the effect of adding the furniture to the model was investigated, first with a standard reflectance of 0.5 and then with realistic reflectance values retrieved from a database; in both cases the furniture did not influence the final annual results, likely because it is mainly placed below the horizontal working plane used for the simulation analysis grid.

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DATA ACCESS

The data collected and generated for this work can be accessed via the Loughborough University repository (DOI: http://dx.doi.org/10.17028/rd.lboro.3364747).

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