SENSITIVITY ANALYSIS STUDYING THE IMPACT OF REFLECTANCE VALUES ASSIGNED IN CLIMATE-BASED DAYLIGHT MODELLING

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ABSTRACT

The recent development of climate-based daylight modelling (CBDM) and its application in various commercial tools, as well as its introduction in building simulation guidelines, created the need of more common procedures and quality checks on input values. Between these, the optical properties to be assigned to the modelled building can be very influential on the final results and on the building performance evaluation.

In this study, the reflectance values of the opaque surfaces are analysed in detail, taking as a case study the model of a real classroom and performing the evaluations with various methods, all based on the *Radiance* lighting simulation system but employing significantly different procedures. A Sensitivity Analysis (SA) is carried out to rank the outputs, expressed with both traditional and CBDM metrics.

INTRODUCTION

During the last decades, daylighting practices evolved from a static evaluation of the luminous distribution, typically performed with the Daylight Factor (DF), to complex computer simulations of a more realistic behaviour of light, that follow the hourly and seasonal changes. This development was made possible mainly thanks to individual's contributions to the theoretical background (Tregenza and Waters, 1983), to the simulation engine performance (Ward Larson et al., 1998), to its validation (Mardaljevic, 1995; Reinhart and Andersen, 2006) and to the methodology (Mardaljevic, 2000; Reinhart, 2001), creating the basis for what is now known as climate-based daylight modelling. However, this distinctive evolution has resulted in a wide variety of approaches and to the adoption of conventions from existing dynamic simulation disciplines.

The situation has recently changed due to the insertion of climate-based daylight modelling (CBDM) methods and metrics in building guidelines and regulations. In the UK, the Education Funding Agency (EFA) included CBDM metrics in the mandatory requirements for the design of 261 schools part of the Priority Schools Building Programme (PSBP) (EFA, 2013); in the US the Illuminating Engineering Society (IES) added to its approved methods the calculation of Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) (The Daylight Metrics Committee, 2012). The definition of specific targets to comply with these regulations created the need of common procedures and certified input data, specific for daylight annual analyses.

This study is part of a wider research that is investigating how CBDM is currently applied in daylighting practices and how its various approaches differ from each other in terms of requirements and results. The focus herein will be on the reflectance values assigned to the modelled surfaces; an inter-model comparison will be presented, together with a Sensitivity Analysis (SA) of the simulation results expressed with both cumulative and CBDM metrics.

SIMULATION

When a building is being designed, the surfaces optical properties are likely to be some of the last information to enter in the process, with the finishing touches. To effectively make use of daylight however, the building performance should be evaluated from the initial design stage. For this reason, standard values reported in the literature are assigned to the main internal surfaces, i.e. floors, ceilings and walls, which are all assumed to be perfect Lambertian reflectors. Most of the building standards cite these values within the guidelines reserved to electric lighting simulations or testing, or for the DF calculation. This study aims at comparing how these same standards are applied in an annual evaluation using different methods and understanding how the results are affected by their variations.

Setup

The 3D model created for this analysis represents one of the four classrooms chosen as case studies for the overall research, that are currently undergoing a monitoring period to continuously record their luminous environment. The limitations given by the choice of a specific real space will be covered by further analyses that will consider all the classrooms, which differ from each other in orientation, size and window-to-wall ratio. The chosen room has double aspect windows, oriented towards North-East and South-East. The weather file used for all simulations is the EPW for London Gatwick, downloaded from the EnergyPlus website (U.S. Department of Energy, 2015).

The model has been created in Rhinoceros® and then used for the all simulations with command-line *Radiance*. The shading systems, the furniture and the external obstructions have not been modelled, as well as two borrowed lights that face into the corridor mainly lit by electric light. It has been preferred to avoid these

Table 1: Main differences in the sky description of the investigated methods

	SKY DISCRETISATION	**SUN POSITIONING**	**LUMINANCE DISTRIBUTION**
2-phase method (2PM)	MF:[1, 2, 4, ...]	In the sky patch	Perez-all-weather
3-phase method (3PM)	MF:[1, 2, 4, ...]	In the sky patch	Perez-all-weather
4-component method (4CM)	MF:1	2056 points	Blended CIE
Tool A	MF:2	In the sky patch	CIE Standard

Table 2: Radiance calculation parameters

	-ab	-ad	-ar	-as	-aa	-lr	-lw	-dr	-dp
2-phase method	5	100000	(256)	0	(0)	(-10)	1e-5	(3)	(512)
3-phase method (vmx)	12	50000	(256)	0	(0)	(-10)	2e-5	(3)	(512)
3-phase method (dmx)	2	5000	(256)	0	(0)	(-10)	2e-4	(3)	(512)
4-component method	5	2048	128	256	0.2	10	5e-2	2	0
Tool A	5	32768	1024	0	0	0	1e-5	3	512

additional details as the aim here is to carry out an inter-model comparison between different CBDM approaches, rather than comparing the simulation results with measurements.

In all the methods the set grid of sensor points has a spacing of 0.25 m, a height of 0.80 m and a boundary from the room walls of 0.50 m. Even specifying these same settings in each method, the points coordinates are inevitably different due to the differences in grid construction algorithms.

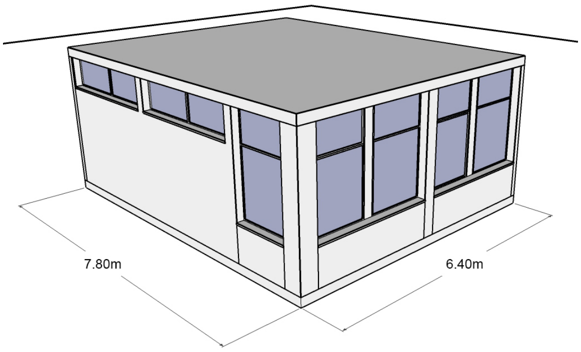

Figure 1: 3D model of the investigated classroom.

To simplify the number of parameters used in the SA, the surfaces in the model have been grouped together in 5 main input factors. The external ground has been built in all the models so that the linear dimension visible from inside the room is at least five times the room main dimension; the internal floor consists in the whole walking surface without any furniture or other geometries placed on it; only the interiors of the walls have been considered, including the reveals (both internal and external) and grouped with the parts of the doors that face the room; the windows frames, mullions and sills have been grouped together; the ceiling comprises a concrete beam but excludes any fixtures. In the following, these groups will be named respectively as *ground*, *floor*, *walls*, *frame* and *ceiling*.

Investigated Methods

The investigated methods are some of the most commonly used to perform CBDM evaluations, either from the command-line version of *Radiance* or as a back-end tool for commercial software. Among commercially available software, only one has been investigated, named hereafter Tool A; however, the part related to annual simulations is still under development and marked as *beta* version. Tool A required the remodelling of the room from the beginning, creating at first a basic geometry and then inserting the same details as in the other methods using a components modeller. The 4-component method (4CM) has been used as a benchmark, as it has been validated against simultaneous measurements of sky luminance and interior illuminance (Mardaljevic, 2000). The 2-phase method (2PM) is based on the *rcontrib* Radiance command and it is partly embedded in Tool A; the 3-phase method (3PM) is being currently considered as a new simulation tool for more pieces of commercial software, especially to allow for the evaluation of Complex Fenestration System (CFS). Each of these methods use *Radiance* as the simulation engine, but they are performing the evaluation using different procedures. The summary of their main differences in the sky description is shown in Table 1.

Radiance ambient parameters have been set accordingly to the room geometry and to the chosen method each time, given that their approaches differ sometimes radically from each others. Table 2 reports the main parameters assigned and, when not inserted directly, the default parameters that *rtrace* (for the 4-component method) and *rcontrib* (for all the other methods) adopt are written in brackets. Tool A does not allow the user to change parameters for CBDM evaluation, using instead a predefined set specific for *rcontrib* runs.

Metrics

For all simulations, the produced illuminance data have been post-processed by external data analysis software (IDL® or IPython (Pérez and Granger, 2007)) to calculate the final metrics. The occupancy schedule applied for all days of the year is 8:00 - 16:00 and the chosen time step is one hour. The derived metrics are: Useful Daylight Illuminance (UDI), with thresholds at 100 lx, 300 lx, 3000 lx; Daylight Autonomy (DA) with threshold at 300 lx; and annual exposure in klx hr. The DF values calculated directly by the commercial software are reported, together with the ones derived by command line *Radiance*.

UDI values express the portion of the occupied hours in a year during which the illuminance levels recorded on the horizontal working plane fall within certain ranges that define the UDI bins: UDI-n represents the portion of time during which the illuminance is non-sufficient, e.g. below 100 lx; UDI-s represents the portion during which supplementary electrical light is probably needed to perform visual tasks; UDI-a defines the portion in which the natural light is sufficient (autonomous) for the task; UDI-x represents the times in which the daylight might be excessive, causing overheating or glare problems.

DA represents the percentage of the occupied hours in a year when the illuminance levels at a sensor on the work plane are over a specified threshold (taken differently depending on the space type) thanks to natural light only (Reinhart et al., 2006).

The annual exposure, or Total Annual Illumination (TAI), is a cumulative metric that is calculated as the sum of all the illuminance values for the occupied hours in a year. It is significant in understanding the analysis results as it is more directly affected by differences in methodology, while CBDM metrics tend to smooth those differences by binning absolute values in percentages.

All the metrics are calculated for each of the sensor points for a whole year and only then those values are averaged over the sensor plane.

Sensitivity Analysis

Sensitivity Analysis (SA) is a widely recognised method to analyse the influence of the input parameters on the final results. It has been applied on building performance simulation models in a number of studies to identify the key parameters and their interaction and it is considered a good source of information for designers decision making processes (Hopfe, 2009; Hopfe and Hensen, 2011; McLeod et al., 2013). The initial sampling and the analysis have been performed using the enhanced Morris method, or Elementary Effect (EE) method, which is considered to effectively show the ranking of the effects even when the model is non-monotonic (Campolongo et al., 2007). The method is particularly suitable when the simulations require long running times, as in comparison with alternative methods (e.g. Sobol') it needs a limited number of initial samplings to provide the user with a robust result; it is estimated that a combination of 10 trajectories (the increments pattern followed for each of the initial sampled points) and 8 levels (the number in which the range of possible SA input parameters can be divided) holds a top-down concordance coefficient (TDCC) of 0.97 (Confalonieri et al., 2010). However, results obtained from a Morris analysis have to be considered merely as a first screening evaluation as it shows a good differentiation between relevant and non-relevant parameters, but not a completely reliable ranking of the important ones (Herman et al., 2013).

In this study 15 trajectories (k) and 8 levels have been used, for a total number of 90 simulations for each CBDM method as obtained from equation 1, where D is the number of input parameters (i.e. 5).

$$\mathbf{n} = \mathbf{k}(\mathbf{D} + \mathbf{1}) \tag{1}$$

The 5 SA input parameters are the reflectance values assigned to the modelled surfaces that more often appear in the guidelines for daylight simulations, for either DF or CBDM metrics calculations. Typically, these would be similar to the ones reported in Table 3 (BSI, 2008; Illuminating Engineering Society of North America, 2000; CIBSE/SLL, 2012; The Daylight Metrics Committee, 2012; SLL, 2014), but not all standards agree on these values or they sometimes suggest to use manufacturers' optical properties, if the data are already available. These standard values have been used to produce base cases for each of the methods, to recognise the difference between the software and to have a benchmark value to refer to when analysing all other results.

Table 3: Optical properties assigned to the model surfaces

Floor	Walls	Ceiling	Frames	External Ground
0.2	0.5	0.7	0.5	0.2

For the SA inputs, all the parameters have been assigned a range [0.01,0.99] for the sampling algorithm to select the values. This assumption does not reflect any real situation, but it was thought as a "stress test" to allow the Morris analysis to recognise the ranking of importance of the elements involved without any initial bias. The presence of very high reflectance values for most or all of the model surfaces is however in conflict with *Radiance* behaviour, which mainly deals with building models, typically having an average reflectance around 0.50 (Ward, 2005). The results coming from combinations of very high reflectances (e.g. effectively behaving as an integrating sphere) are therefore not to be considered physically accurate.

All the procedures to perform the Morris sampling and the Morris SA were run in IPython using the SALib module v3.0 (Herman, 2014). The initial sampling have been performed without optimal trajectories, but increasing the number of initial seeds up to 15.

DISCUSSION AND RESULT ANALYSIS

The results obtained using the standard values clearly show that each method will always differ from the others, due to its own specific characteristics. However, taking the 4-component method as a benchmark, all of them (except for Tool A) agree with it with a relative difference of less than 4% (see Table 4), which is to be considered quite good given that they use different *Radiance* techniques (*rtrace* for the 4-component method and *rcontrib* for all the other) and different sky descriptions in some cases.

Table 4: Total Annual Illuminance in klx hr for all the methods and relative difference in percentage to the 4CM result.

	2PM	3PM	4CM	Tool-A
TAI [klx hr]	6075.31	6261.95	6033.54	2983.57
Relative difference	0.69%	3.79%	0	-50.55%

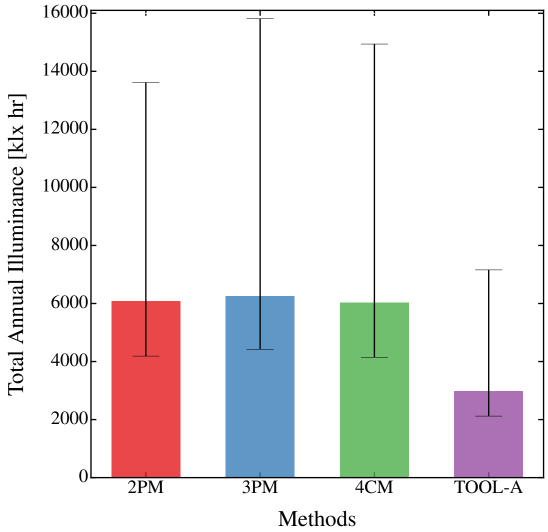

Figure 2: Base-case results for all the methods expressed in Total Annual Illuminance [klx hr] and scatter of the results from all the 90 samples.

Figure 2 shows the same values of Table 4 with the indication of the maximum and minimum results within the 90 simulations carried out for the SA. When all the surfaces have low reflectance, the annual cumulative illuminance is still showing a good level of illumination, mainly due to the direct sun contribution on the sensor points. On the opposite hand, when all surfaces have very high reflectance, the final results are more than double the base-case results. As mentioned before, this situation is unlikely to happen in reality and the figures calculated by *Radiance* are not completely reliable any more.

Table 5: CBDM metrics – UDI and DA – for all methods.

	2PM	3PM	4CM	Tool-A
UDI-n	3.22%	3.04%	4.0%	4.93%
UDI-s	8.83%	8.34%	10.20%	21.49%
UDI-a	70.07%	69.01%	70.0%	68.68%
UDI-x	17.87%	19.60%	15.90%	4.91%
DA	87.94%	88.62%	85.80%	73.58%

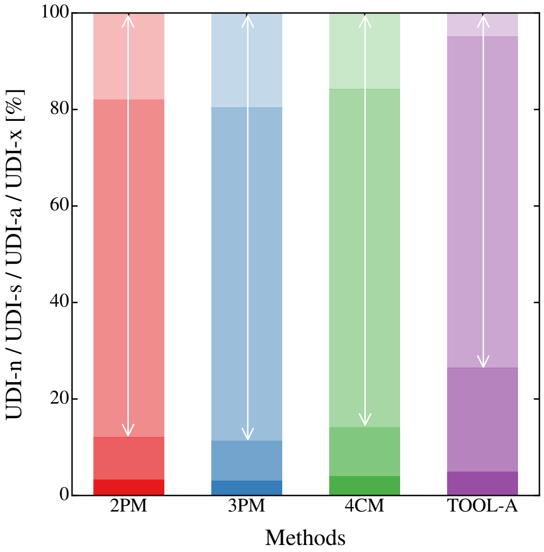

Figure 3: Base-case results for all the methods expressed in UDI [%] (left axis) and DA [%] (white arrows).

In the case of CBDM metrics, the differences between results are further attenuated by the statistical calculations that group the illuminance ranges in bins. Therefore, a small percentage difference could represent a substantial variation in luminous levels, e.g. in Table 5 the UDI-a values are very similar between all methods, including Tool A. Analysing all UDI ranges together shows instead that the obtained illuminance levels are significantly different. Figure 3 includes the representation of the four UDI ranges in stacked bars, in which the darkest hues show the UDI-n, followed by UDI-s, UDI-a and UDI-x in lighter colour. The white arrows that go over the UDI-a and UDI-x portions indicates the percentage that corresponds to the DA, which stands for the illuminances over 300 lux, therefore equivalent to the sum of the UDI-s and UDI-a values.

To study the behaviour of the considered metrics in more detail, the results from all 90 simulations performed with the different methods have been reported in Figure 4, together with the reflectance values assigned to the surfaces in the model by the original Morris sampling, in the order that they were generated by the random algorithm. The dashed lines indicate the values of the base cases results (obtained using standard reflectances) for the four methods in each

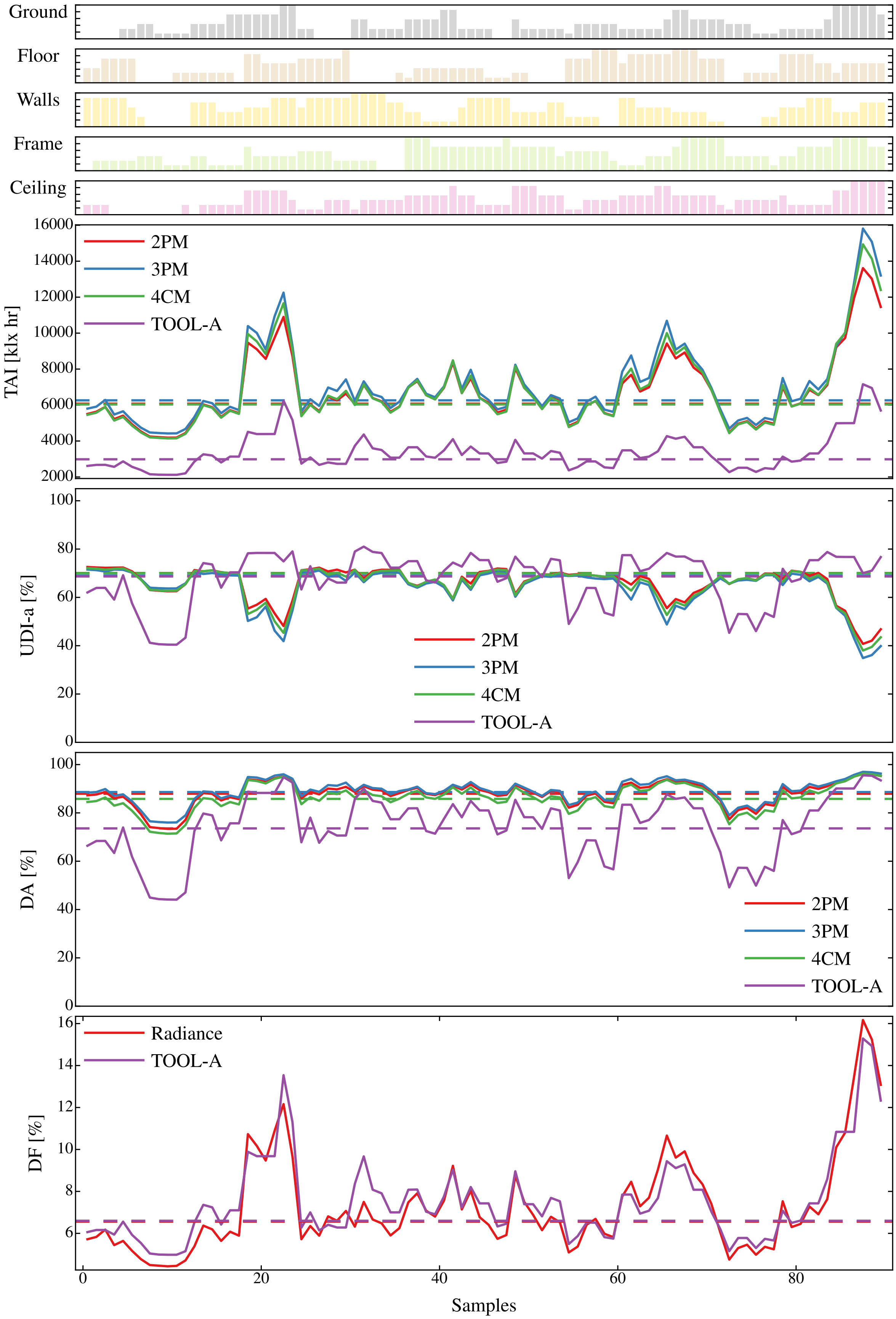

Figure 4: Input reflectance values assigned to the different surfaces in the model (ranging between 0.01 and 0.99) and corresponding results expressed in Total Annual Illuminance [klx hr], UDI-a [%] DA [%] and DF [%].

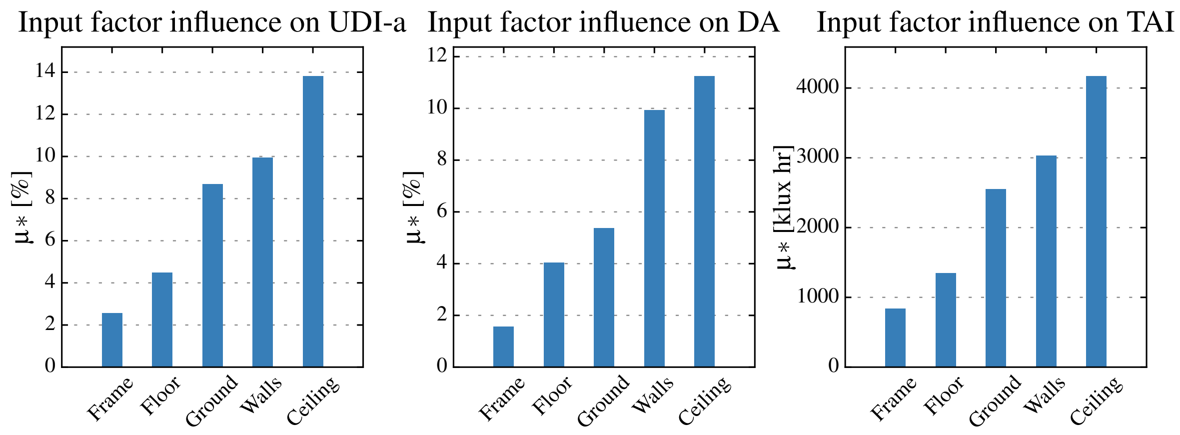

Figure 5: Sensitivity ranking of the combined factors for UDI-a, DA and Total Annual Illuminance, based on the results obtained with the 4-components method.

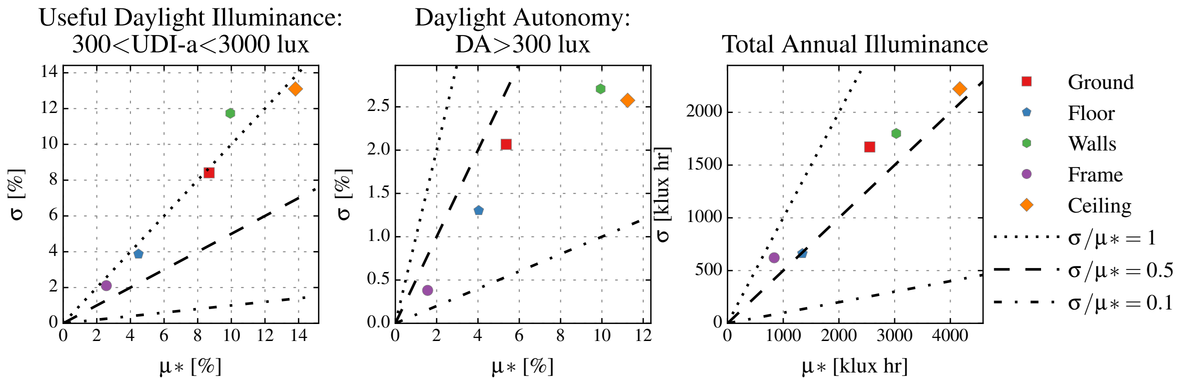

Figure 6: Morris plots for UDI-a, DA and Total Annual Illuminance, based on the results obtained with the 4-components method.

of the graphs, to be used as benchmarks for the other variations.

The first graph reports the Total Annual Illuminance, where it is clearly visible that all methods show the same behaviour when reflectance increases or decreases in specific elements, even though the effect is attenuated in the case of Tool A, given the generally low illuminance levels. The 2-phase, 3-phase and 4-component methods coincide very closely for all combinations that result in values similar to the benchmark one, while they widen the gap when there are peaks due to high reflectances combinations. In those cases, it is the 3-phase method that manifests the highest occurrence of annual cumulative illuminance. The behaviour is obviously reversed when looking at the UDI-a values, as all the illuminance over 3000 lux (and below 300 lux) are not taken into account. The DA figures, in the third graph from the top, level out the peaks, given that the benchmarks results are already at a high percentage due to the geometrical characteristics of the considered space. The input combination with the highest reflectance reaches a DA of 96.98%. The last graph shows the traditional DF, comparing the calculation run by command-line *Radiance* (*rtrace* command) and the one given by Tool A. The benchmark values are coinciding almost exactly, while along the samples axis it is possible to notice some differences between the two. It has still to be clarified if Tool A uses *rtrace* or *rcontrib* (i.e. the Daylight Coefficients (DC) method) to calculate the DF when the simulation is run together with the annual ones.

For all metrics, the simultaneous effect of the reflectance from the five model elements (external ground, floor, walls, windows frame and ceiling), makes it difficult to recognise which one of them is affecting more or less significantly the final results. Using the enhanced Morris SA gives a more precise indication of the influence of each parameter on the global process.

The results obtained with the 4-component method are taken as example of how the SA was performed for all the methods. Figure 5 shows the ranking order of the input parameters, given by the value μ^* that the enhanced Morris SA calculate. μ^* is an absolute value, therefore the graphs here are not showing whether the elementary effects have an influence on the results with the same or opposite sign. For all the metrics and all the methods however, it can be inferred that the reflectance of the frame has little influence on the overall evaluation, while the reflectances of the internal walls and of the ceiling play a central role in the combined effect over the bouncing and redistribution of light that enters the room. Floor and external ground reflectances are assigned ranking of slightly different importance depending on the CBDM method and metrics.

Figure 6 gives more insight about the monotonicity of the input parameters. If they are positioned below the line $\sigma/\mu^* = 0.1$ is an indication of their linear behaviour, if they are between the lines $\sigma/\mu^* = 0.1$ and $\sigma/\mu^* = 0.5$ they are considered to be monotonic, if they are between $\sigma/\mu^* = 0.5$ and $\sigma/\mu^* = 1$ they are almost-monotonic, otherwise they are highly non-linear and non-monotonic. As noted before, the frame reflectance has a low μ^* as well as a low σ, therefore it does not affect the evaluation significantly. The floor can be considered as not very important too. Instead, external ground, walls and ceiling need to be paid more attention to. None of them can be linearly correlated to any of the metrics, but they all show a monotonic or almost-monotonic effect on the TAI and DA, meaning that for an increment in the factor value there is a corresponding increment in the resulting metric and for a reduction there is a corresponding relative reduction, although not in a proportional way. For the case of UDI-a, the important factors get further from the monotonicity, as it is expected, because of the high illuminance instances that do not fall within the range; that being so, when the input factors contribute to the rise of the illuminance over 3000 lux, the effect on the metric is a reduction in percentage rather than a corresponding increase. This response seems even more pronounced here for the walls reflectance parameter. All these considerations are valid for the 2- and 3-phase methods, as well as for the DF calculation run directly with *Radiance*, which results in a Morris plot very similar to the one for the TAI. Tool A did not show the same behaviour when analysed with the Morris method, but for the moment the case might be that all the resulting values are not reliable for this analysis.

CONCLUSION

The findings presented here are part of a wider study which is believed to be the first systematic comparison of several distinct CBDM tools (Brembilla et al., 2015).

The optical properties of the modelled surfaces, in this case the reflectance of opaque elements, play a very important role in CBDM evaluations. The variation in their input values, often standardised in guidelines, can significantly influence the final results and therefore our understanding of the space luminous performance.

The inclusion of some potentially unrealistic parameter combinations (e.g. particularly high or particularly low reflectance values) was in part to ‘stress test’ the tools since it is known that the algorithms underpinning the ambient sampling in Radiance are optimised for more ‘typical’ reflectance values. It has been shown how specific elements in the model can have a greater or lesser impact on the overall redistribution of natural light in the space. In this case, for the investigated methods, the frame can be considered of low importance when assigning reflectances at design stage, while elements such as walls and ceiling have to be clearly specified and communicated together with the obtained results. The same approach should be adopted not only by single projects, but generally by the guidelines that regulate the modelling process or certification rating schemes. Any prior assumption on reflectance values that will not be met in the constructed building could lead to drastic changes in the perception of the spaces. In reality however, many other factors should be taken into account, such as the room fixtures, the furniture, the surface maintenance, the external obstructions and many other things. Further work could be done to investigate the effect of these other elements on the modelled building and to compare it with the real case.

More generally, the obtained results show a very good agreement between three out of the four investigated methods, both in the case of using standard reflectances and when varying through random combinations of reflectance values. The fourth method, Tool A, is still to be considered under development. Other methods will be compared to the ones reported here in future works.

All the results obtained for the present analysis are obviously linked to the chosen classroom and its specific characteristics. However, it is believed that the conclusions could be valid for most of the common building spaces; the overall research will include the analysis of several classrooms with different dimensions and configurations.

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