METRICS AND METHODOLOGY IMPLEMENTATION FOR ANALYSING DAYLIGHTING AND ENERGY USE IN URBAN DENSE BUILDING BLOCKS

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ABSTRACT

Energy use and daylighting is very important in a dense building block. While planning a dense building block, we investigate which matrices are relevant to investigate daylighting and energy use. A set of methodology is use to assess the performance of a dense urban building block in terms of energy use and daylighting. A work flow is also described to use for a new dense building block. In metropolitan areas, daylight is a limited resource. A considerable percentage of the sky and light is typically blocked out by the urban building mass in rooms located in an urban setting. Because of the limited direct lighting potential, sunshine reflected from exterior surfaces is a significant source of light in the space. The authors provide a collection of logistic mathematical models for estimating the quantity of daylight and the energy requirement for illuminating a space. The models were based on a database of Daysim simulation results for a sample room, with parameters like as location, orientation, exterior obstructing angle, window size, glazing visible transmittance, and room depth being modified parametrically. The estimates that were obtained using the models showed, compared to the corresponding simulations results, a coefficient of variation CV lower than 16% for all the models, with one exception, having a CV up to 30%. The aim of the study was to elaborate models that could be used to incorporate daylighting strategies since the earliest stages of the building design process. Using the models, it is possible to predict the annual daylight amount in a room and the corresponding energy consumption of the lighting systems starting from some given room features to guarantee a target value of energy demand for lighting or of a daylighting metric.

Key words: Building block, block typology, building form, daylight, daylight metrics, energy performance, geometric design parameters, Glass to floor ratio, passive solar, residential, urban density, UDI, heating and cooling matrices

INTRODUCTION:

(Littlefair 2001) and (Li, Cheung et al. 2009) found that the quantity of sunshine and solar radiation received via windows is significantly influenced by urban morphology. Simplified estimates show that the link between urban morphology and energy use in non-domestic buildings has a nearly 10% influence (Ratti, Baker et al. 2005). More comprehensive simulation results have shown that the geometry of city centers has a relative impact on total energy utilization of up to +30% for offices and +19% for housing when compared to unobstructed sites (Petersen, Momme et al. 2014), as well as that the urban perspective has a substantial effect on the provision and allocation of indoor daylight (Petersen, Momme et al. 2014).

These findings highlight the importance of understanding the influence of the urban setting on interior climate and building energy performance early in the design process. This is where pc architectural simulation comes in handy. Sophisticated simulation programs such as ESP-r (Decruz, Kokogiannakis et al. 2012) and EnergyPlus (Michalak 2014) may incorporate daylight and heat modeling. In its thermal phase, ESP-r may base lighting control on the interior daylight dispersion determined with Brightness and the daylight coefficient approach (Clarke and Janak 1998). EnergyPlus can regulate luminaires based on illumination level calculated in specific indoor reference sites (maxi mum two). The irradiance is computed by approximating estimated daylight factors (DF) for the overhead vaulted and direct sunlight contributions and then multiplying by the outside horizontal irradiance (Ramos, Ghisi et al. 2010). Nevertheless, even the simplest simulation takes specialist knowledge and significant volumes of input data, making these tools unfeasible in the early phases of design when data is limited.

This necessitates the creation of more basic tools appropriate for the early phases of design. There are fast whole-year daylight algorithms that integrate reflections from nearby structures (Robinson and Stone 2006); (Walkenhorst, Luther et al. 2002), but they lack thermal domain interaction. There have been a few efforts to incorporate quick whole-year daylight algorithms in thermal models (Athienitis and Tzempelikos 2002, Franzetti, Fraisse et al. 2004, Hviid, Nielsen et al. 2008), but still only Hviid et al. (2008)'s tool BC/LC has implemented an algorithm for portraying daylight reflections from neighbouring buildings. Nevertheless, when developing structures in an urban setting, the algorithm is oversimplified and has significant limits. The next sections explain and evaluate a novel calculation approach for accounting for daylight reflections from the urban surroundings on interior daylight levels in BC/LC calculations. In addition, integrated daylight and thermal simulations show how the software could be used to examine the influence of urban canyon factors on the inside environment and energy performance efficiency.

Environment-based daylighting modelling (CBDM) was developed to more correctly measure daylighting inside a building space while accounting for the individual climate in terms of dynamic fluctuation of sunshine and daylight availability at the construction site (Verso, Fregonara et al. 2014). Despite its recognised value, daylighting design is rarely incorporated into a project from the beginning phases (Li, Lam et al. 2003, Reinhart, Fitz et al. 2006, Bellia, Fragliasso et al. 2016, Krarti 2020). Rather than daylighting or energy-saving measures, the creation of an architectural proposal for a building is more likely to be founded on formal, aesthetical, or technological considerations. This pattern might be attributable to a variety of interconnected variables.

On the one side, the effect of daylighting on a building's Indoor Environmental Quality (IEQ) and total energy demand is a complicated phenomenon to handle at the conceptual stage (Pellegrino, Verso et al. 2016): simulation tools are required, which require a lengthy input process and are too time consuming for most architects and designers to use. But at the other side, there aren't enough measurements to handle this phenomenon in a synergistic approach. The new metrics obtained from the CBDM (Reinhart, Mardaljevic et al. 2006, IES 2012), which focus on daylighting characteristics, are difficult to completely handle by non-expert users and require complex modeling tools to be effectively computed. As a result, when daylighting tactics are addressed, they are based on personal experience or the use of empirical methodologies based on rules of thumb (Reinhart, LoVerso et al. 2010).

The absence of easy and rapid evaluation tools to employ at the start of the design process to obtain information on the feasibility of daylighting and its potential for energy savings is a major factor. In the literature, certain attempts to close this gap have been made, such as the creation of simpler prediction tools for the early phases of design. (Krarti, Erickson et al. 2005) created a basic mathematical model to assess the possibility of daylighting to minimise electric lighting energy usage in office buildings. The research was based on a parametric analysis in which DOE 2.1E was used to model and simulate numerous combinations of building geometry, window opening size, and glazing type for four different geographical regions in the United States. As a function of window glazing transmittance, window area to perimeter floor area, and perimeter to floor area, the mathematical model calculates the percent reduction in yearly electric lighting usage owing to the use of daylighting through dimming controls. The model was extended and further expanded in a later research(Ihm, Nemri et al. 2009), which included numerous US and foreign sites and evaluated the effects of both continuous dimming and stepped daylighting settings. (Moret, Noro et al. 2013) designed a simplified mathematical model to predict the effect of electric illumination and fenestration control mechanisms on total energy efficiency (lighting, heating, and cooling) in office buildings using various approaches, whereas (da Fonseca, Didoné et al. 2013) and (Wong, Wan et al. 2010) used multivariate non-linear regression techniques via an artificial neural network ANN.

(da Fonseca, Didoné et al. 2013) created a model that can forecast the influence of daylighting on a building's ultimate energy need based on the results of Daysim and Energy Plus simulations of a structure in Florianopolis, Brazil. (Wong, Wan et al. 2010) constructed a model for calculating a building's daily total energy demand (energy consumption for lighting, cooling, and heating) based on the findings of Energy Plus simulations of a building in Hong Kong. (Cammarano, Pellegrino et al. 2015, Pellegrino, Cammarano et al. 2017) took a different strategy, with distinct aims, in two complementary investigations based on the same database of simulation results. Pellegrino et al. studied the impact of the amount of daylight leading to variations architectural and lighting control features of a building on the energy consumption for lighting, cooling, and heating. Cammarano et al. designed a simplified graphical analysis to measure indoor daylighting and to determine which pairings of architectural features are able to provide high, reasonable, or low daylight levels inside a room.

The above research appear to have primarily focused on the energy elements of daylighting, allowing the energy demand for lighting to be forecast (alone or in combination with the energy demand for lighting and cooling). The models allow the energy savings associated with a number of lighting controls to be evaluated rather than the energy demand in absolute value in one scenario(Krarti, Erickson et al. 2005, Ihm, Nemri et al. 2009). There have been no mathematical models identified for quickly calculating the dynamic daylighting metrics produced from the CBDM [7-8], with the work by (Cammarano, Pellegrino et al. 2015) being an outlier, relying on a graphical tool and referring to a small set of factors. This work offers a series of mathematical models that were built to predict the influence of room factors, such as geometry, optical qualities of materials, and lighting system features, on both daylighting and electric lighting performance of a room. The models might potentially be utilised in the early phases of the building design process, when daylighting solutions are being examined and established. The mathematical models were created mostly from the findings of a parametric research, in which a sample room was modelled and simulated using Daysim, with a number of its properties modified.

As a consequence, a database including values for various climate-based daylighting measures and lighting energy demand was created, which was then statistically processed using multivariate non-linear regression techniques. The collection of models includes equations for calculating metrics such as Daylight Autonomy (DA), Continuous Daylight Autonomy (DA_{con}), and Spatial Daylight Autonomy ($sDA_{300,50\%}$), as well as the accompanying energy consumption for lighting. The models may be used to estimate the worth of daylighting measures that have lately been introduced in rules or procedures to evaluate a building's IEQ and energy performance(IES 2012), included in the (Council 2013); the Daylight Autonomy, in the UK Priority School Building Programme(Pagliolico, Verso et al. 2015). In addition, the models may be used to estimate the amount of energy used as a result of daylighting and the kind of lighting systems used, particularly in the presence of a continuous dimming control system. The models provided in this study, in comparison to the other models accessible in the literature and stated before, allow for a more detailed and exhaustive investigation.

On the one hand, a vast number of climate-based daylighting measures, such as the group of Daylight Autonomies, may be used to examine the lighting conditions in a space. The energy demand for lighting linked with the quantity of daylight in a place and its use through the existence of some lighting control systems (such as a manual on/off switch or a photo-dimming responsive control) can, from the other hand, be approximated. In terms of design aspects of a building, the models produced in the study comprised a huge collection of variables, greater than in prior studies, and with a broader range of values. In addition, two types of impediments were included in the models: a building ahead of varying heights and an overhang of varying depths. The researchers previously devised a mathematical model to predict lighting energy demand based on a room's geometrical, photometric, and lighting system properties (Verso, Pellegrino et al. 2014). As a result, the current research aims to improve and expand on the prior model, resulting in a collection of homogenous predictive models that can forecast both the amount and distribution of daylight as well as the related energy demand for lighting.

METHODS:

Calculation Method:

The suggested computation approach is a supplement to the BC/LC algorithms already in place. The daylight modelling principle of BC/LC is based on a split flux technique, which divides the sunshine on room surfaces into four primary components. Backward ray-tracing is used to compute the direct contribution of the sky and sun to the room surfaces. The luminous exitance approach is used for the interior daylight reflection contributions (Park and Athienitis 2003). As shown in Fig. 1, the software determines the spatial daylight distribution in the room.

Light sources and ground-reflected light:

Skylight is represented by an upper sky dome above the horizontal plane, whereas ground reflected light is represented by a lower (inverted) sky dome below the horizontal plane. Tregenza devised a discretization system that divides both sky domes into 145 areas (1987). Because each patch has a comparable solid angle, each patch may be handled as a point source with minimal mistake. On the top sky dome, the sun disc is depicted as a separate point source. (Robinson and Stone 2006) used the following technique to describe the illuminance on an exterior plane caused by light from the sky dome (Esky):

$$E_{sky} = \sum_{i=1}^{145} L U \phi \sigma \cos \xi$$

$$E_{sun} = E_n \cos\xi$$

$$E_{ground} = \sum_{i=1}^{145} \frac{\rho}{\pi} \left(E_{sky} + E_{sun}\right) \phi \, \sigma \cos\xi$$

Light inter-reflections in the urban environment

The following summarizes the suggested depiction of the contribution from light reflected from exterior surfaces. The portrayal is based on the 'urban canyon,' a geometric abstraction of urban area (Oke 2002). The urban canyon is depicted in Figure 1 as two opposing building surfaces.

The façade with the room in which we wish to compute incoming daylight is represented by surface 1, and the other side of the urban canyon is represented by surface 2. According to Eqs. (1) and (2), both primary surfaces are fragmented into a number of smaller sub-surfaces, each receiving incident light from the sky and sun (2). The luminous exitance technique is then used, with the assumption that the surfaces have Lambertian optical qualities, meaning that they reflect incident light exactly diffusely and ignore any specular features. (Park and Athienitis 2003) discuss the methodology and implementation of this daylight distribution algorithm in great detail (2003). Divided into several sub of the opposite building's ultimate luminous exitance (lm m 2) can now be regarded light sources. The light sources are traced one way in the same way as the sky light sources. There is no light exchange between the interior room surfaces and the constructed world outside.

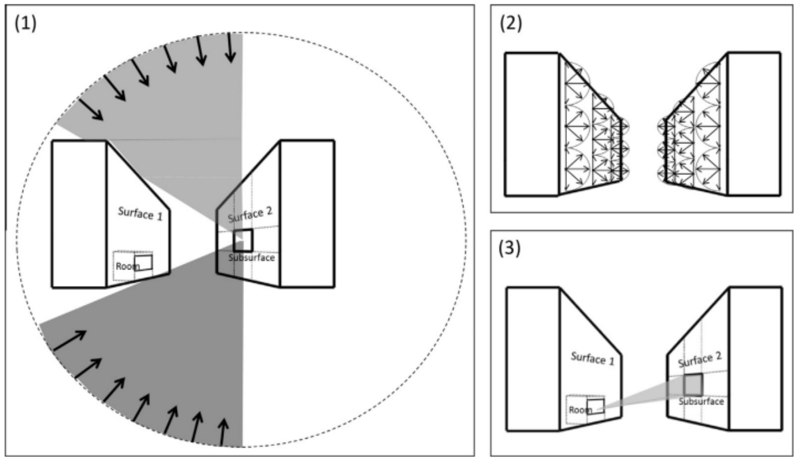

Fig. 1. Model of the urban canyon. 1: The building surfaces are divided into a number of smaller sub-surfaces, all receiving incident light from the sky, sun and ground. 2: The luminous exitance method is then applied. 3: The sub-surfaces of the opposing building can now be considered as light sources to the room sub-surfaces.

Validation:

Those from a test scenario were compared to results obtained with the lighting simulation application Radiance to validate the calculating approach (Ward and Shakespeare 1998). A room on the ground level of an urban canyon in Copenhagen, Denmark, served as the test case. Figure 2 depicts the measurements that define the metropolitan surroundings and the room.

The sky light was simulated using the Perez sky model (Perez, Seals et al. 1993), which had already been used in the BC/LC linked thermal and daylight simulations. The Perez sky is created in the Radiance simulations using Delaunay's gendaylit programme (1994). The external irradiances were calculated using meteorological data from the Danish Design Reference Year (Moeller Jensen and Lund 1995), which is expressed in hourly numbers. Table 1 shows the other data assumptions for the test scenario. The simulation input settings for the Radiance simulations are shown in Table 2. These settings guarantee that the simulations are of extremely high quality (Jacobs, 2012) and hence appropriate for validation. The validation method was carried out in two rooms, one facing south and the other facing north.

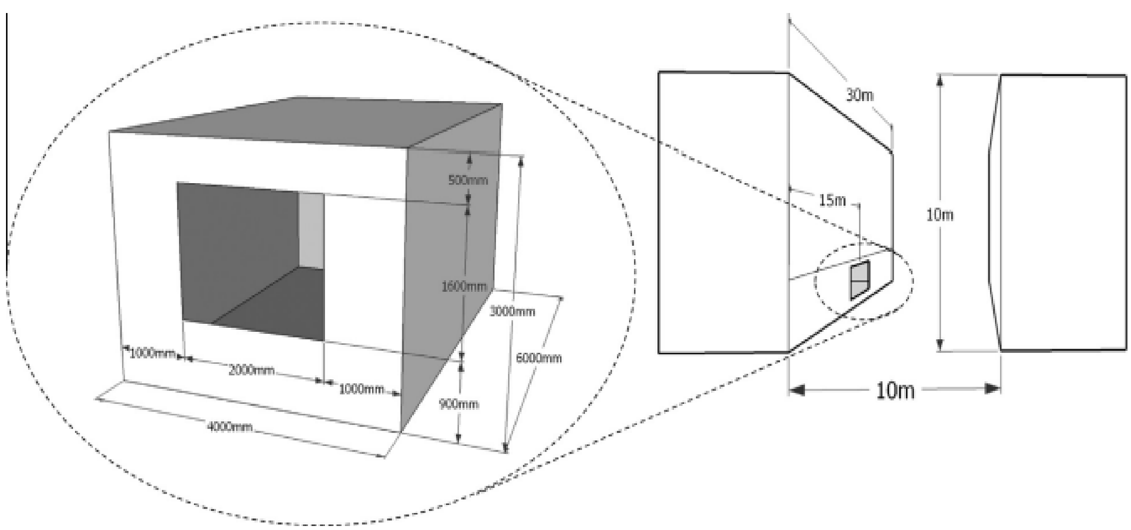

Fig. 2. Dimensions of urban setting and room for the test case

Table 1

BC/LC data assumptions for validation. Radiance material properties in parentheses.

Glazing	Type	Double glazing with low-E coating, 4-15Ar-SN4
	Light transmittance ⊥	0.782[a] (void glass glazing 0 0 3 .852 .852 .852)
Diffuse reflectances	Interior walls	0.7 (void plastic walls 0 0 5 .7 .7 .7 0 0)
	Ceiling	0.8 (void plastic ceiling 0 0 5 .8 .8 .8 0 0)
	Floor	0.3 (void plastic floor 0 0 5 .3 .3 .3 0 0)
	Glazing	0.215 (cannot be specified)
	Albedo	0.2 (-g option to gensky)
	Urban canyon walls	0.3 (void plastic floor 0 0 5 .3 .3 .3 0 0)
Sub-surface size[b]	Interior, diffuse	0.5 × 0.5 m
	External, diffuse	0.5 × 0.5 m
	External, direct	0.1 × 0.1 m
Measuring point	Height	0.85 m
	11 half meter interval points along the centre line of the room	

[a] Light transmittance as a function of profile angle in BC/LC is modelled similar to the material 'glass' in Radiance (Ward, 2004).
[b] Sub-surface sizes are set manually by the user.

Table 2

Input parameters to Radiance simulation.

Ambient bounces	Ambient division	Ambient sampling	Ambient accuracy	Ambient resolution	Direct threshold	Direct sampling
7	4096	2048	0.1	256	0.03	0.02

Ground-reflected light

An upside-down sky dome approach is used to represent the contribution from ground-reflected light. Because the approach does not account for the influence of shadows thrown by building surfaces on the ground plane surface, this is a simplified picture of daylight in an urban canyon. To show the severity of the simplification inaccuracy, Fig. 3 illustrates the test case calculated by Radiance in situations with and without a ground plane surface.

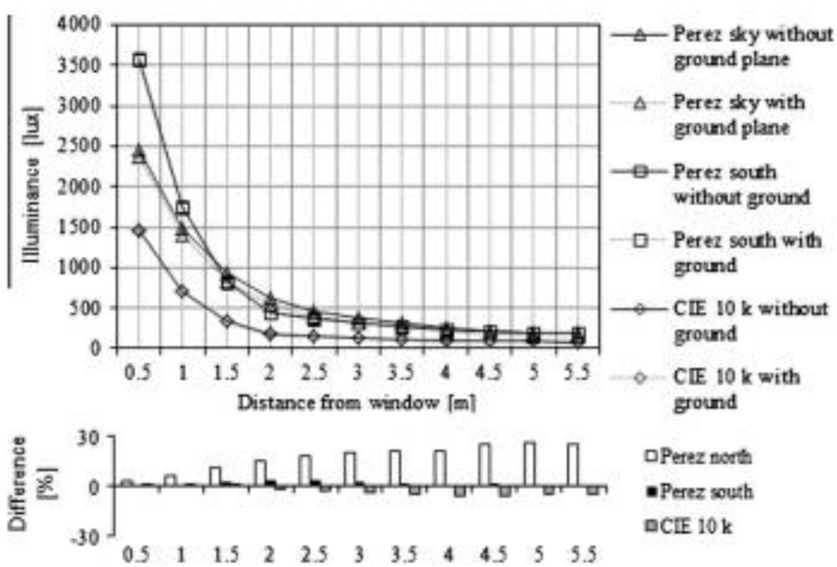

Fig. 3. Comparison of daylight levels with and without a ground plane surface

Simulation runtime:

On a laptop with an Intel Core i7–2620 M Processor operating at 2.7 GHz and 4 GB of RAM, the Radiance simulation runtime for the south-facing test scenario is 125 seconds. BC/LC has a simulation runtime of 712 seconds. Because the software reuses the geometrical computations, which are the most time-consuming aspects of the method, the BC/LC runtime lowers to 7 seconds for future simulations. In terms of simulation time, the number of user-defined sub-surfaces in the model is thus the most important setting. For a sub-surface size of 1.0 m, the parameter changes of the sub-surface size in the external environment as given in Table 3 would result in a simulation duration of 64 s and 39 s, respectively. Because the trade-off between sub-surface size and accuracy is dependent on the geometry of the model, it should be explored for each model separately.

MATRICES:

The approach used in this study is based on a set of statistical analyses that were applied to the results of a set of simulations to predict daylighting and lighting energy consumption for a space with parametrically modified parameters. A total of two groups of models were created.

a) One set of models is used to compute daylighting metrics, which represent the quantity and distribution of daylight in a region. This article presents the models that were constructed for the following metrics in detail: Daylight Autonomy, abbreviated as DA (Reinhart, Mardaljevic et al. 2006), continuous Daylight Autonomy, abbreviated as DA_{con} (Reinhart, Mardaljevic et al. 2006), and spatial Daylight Autonomy, abbreviated as $sDA_{300,50\%}$ (IES 2012).

b) For the room in question, one set of models is used to compute the energy demand for lighting, ED_{room}, which is defined as the integration of daylighting and electric lighting. Based on the daylight illuminance measured across the work plane, two models were constructed for the following control systems: manual on/off switch and continuous dimming.

The existence of an external impediment was one of the geometries that were adjusted for the simulated sample room, with the following two types being considered: a building ahead of the room windows; and an overhang that is part of the room itself.

For each type of barrier, a separate set of models was created, totalling ten equations (5 for cases with a building ahead, 5 for cases with an overhang). The modelling, parametric investigation, and subsequent statistical analysis are detailed in the subsections that follow.

Modeling description (parametric approach):

As a 'case study,' a single room was chosen. The following characteristics were maintained: net width = 12 m; net height = 3 m; light reflection qualities of ceiling, walls, and floor were set to 0.7, 0.5, and 0.3, correspondingly. Other factors, such as room depth, window area, obstacle angle at the window's center, orientation, goal illuminance, and so on, were parametrically modified, as shown below.

Climate data

In terms of the alternation and amount of sunshine and skylight, the availability of outdoor daylighting is mostly determined by the site's individual climate. The parametric research simulations were performed assuming the room was placed in three distinct locations: Berlin, Germany (latitude L: 52.1°N), Turin, Italy (L: 45.2°N), and Catania, Italy (L: 37.5°N) in order to make the models more universal. The matching climate file was utilised for each location (Verso, Mihaylov et al. 2017).

Geometric and photometric variables of the sample room:

The room's size and window characteristics (surface and visible transmittance) were altered to accommodate a wide variety of typical existing spaces in non-residential buildings and glazing products on the market. The impact of the orientation was also considered. The following variables were changed in further detail:

- orientation: To accommodate for the changing angle of the Sun in the sky throughout the year, the sample rooms were placed with the opening facing South, West, or North. Since indicated in a past studies by Dubois et al., the East orientation was not modelled as the quantity of daylight and the resultant energy demand for lighting were thought to be equivalent to what happens for the West orientation (Dubois, Flodberg et al. 2013).
- room depth (RD): This has been changed between 3 m and 7.5 m, with a 1.5 m increase, resulting in four different types of rooms: narrow periphery, for 2-4 people, huge open-plan areas
- window area (window-to-wall ratio WWR): WWR values of 0.2, 0.3, 0.4, 0.5, and 0.6 were determined by sidelighting all spaces through vertical windows whose area was changed. The window was maintained at a height of 1.6 m, with a sill set at 1 m from the floor. The number of WWR configurations actually modelled was determined by the room depth: the WWR was limited to a minimum for each room depth in order to achieve the condition that the window-to-floor area ratio was always larger than 0.125.
- glazing visible transmittance (Tv): This was adjusted at 90 percent, 70 percent, 50 percent, and 35 percent in order to depict a wide range of conceivable transparencies that are routinely employed in building glass.

External obstructions

The study considered two sorts of obstructions: the existence of a building in front of the analysis room and the presence of an overhang. Even though this feature is normally built for south-facing windows since it has no shading effect for other orientations, there may be some volumes of the structure itself (such as balconies, terraces, loggias, and roof components) that operate as overhang for any orientation. Both types of obstructions, however, were modelled using the obstruction angle'seen' from the window centre, that is, the angle between the normal axis through the glazing centre and the line intercepting the building's edge (γba) for the building ahead, and the angle between the line intercepting the edge of the overhang from the centre of the glazing and the vertical plane of the window (γo) for the overhang.

With both the cases with a structure ahead and the cases with an overhang, the obstruction angles that were evaluated for the research varied from 0° to 60° (in 15° increments for both groups).

Electric lighting

The electric lighting was chosen after the average workplane illuminance (Ewp) requirement was verified. As per reference lighting standards (EN 2011), the following Ewp were assumed in the study to cover the most common activities carried out in non-residential buildings: 150 lx, 300 lx, 500 lx, and 750 lx. Accordingly, the lighting power density (LPD) installed in the room was considered to be 3.6, 7.2, 12, and 18 W/m². Daysim was used to mimic two distinct lighting control systems: a manual on-off switch and a daylight responsive dimming system, which takes account of the quantity of daylight available over the workplane and decreases the amount of electric light used by reducing the luminaires' light output.

Shading systems (blinds)

The computer models included the effect of an automated shading system consisting of a Venetian blind with a dissipate visible transmittance of 25% (when closed) to account for the need to reduce glare and overheating phenomena over the workplane caused by direct solar radiation permeation into the considered rooms. In detail, the algorithm used in Daysim and in this study to account for the use of the shading system assumes that the blind is automatically pulled down whenever an irradiance of more than 50 W/m² strikes any point on the workplane and that once closed, it remains in that position for the rest of the day, only to be yanked up over the course of the next work shift (Reinhart 2004, Reinhart 2006).

The usage of the blind was only replicated for South- and West-facing areas, with the equivalent North-facing spaces being left out. This decision was made based on conventional design principles for controlling sunlight. This assumption is also in line with the findings of a previous investigation by the same authors (Council 2013).

Statistical analyses to build the mathematical models

As previously stated, the simulation results were divided into two sub-datasets, one for each of the two types of obstructions considered in the study. By mixing the variables at random, according to a uniform distribution throughout the spectrum of their conceivable combinations and situations, a statistically big database was created. By modifying the geometric variables parametrically for each obstacle type, 34 combinations were generated (orientation, RD, WWR, Tv, γba or γo). For the three locations (Berlin, Turin, and Catania) and the four workplane illuminance values, these combinations were simulated. As a consequence, the two datasets include 408 values for the measures DA, DA_{con}, and ED_{room}, whereas the sub-dataset for $sDA_{300,50\%}$, which is intrinsically specified for a 300 lx threshold, has 102 values. The organisation of the two datasets of findings is depicted in Figure 4.

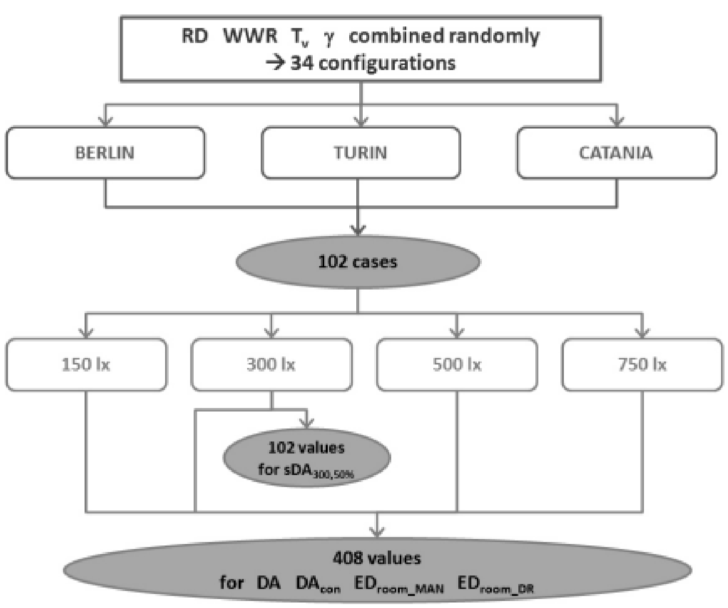

Fig. 4. Structure of each of the two datasets used to build the mathematical models (building ahead and overhang).

Construction of the two groups of models

Again for statistical analyses, regression algorithms were used to describe mathematical models suited to approximate daylight metrics and lighting energy requirements as a function, first, of the following explicative variables: site, orientation, room-depth, WWR, obstruction angle, lighting control system; second, of the lighting power density LPD and average workplane illuminance (it's also an actual explanatory variable for the DA, DA_{con}, and ED_{room}, while the former is a real explanatory variable for the DA, DA_{con}.

A non-linear multivariate regression analysis was used to create the mathematical models. Different regressions, corresponding to different non-linear models, have been run, all based on the fact that explicative variables have a logarithmic effect on daylight measurements and energy consumption. To achieve the best-fit parameters of the models, appropriate transformations of explicative and response variables were done, and subsequent multivariate linear regressions were performed using the SPSS® software (Ozgur, Dou et al. 2017).

To evaluate what closely the scores of each estimated metric fit the simulated values, statistical analysis using the Mean BiasError (MBE) (and also the Normalized Mean Bias Error–NMBE), the Mean Squared Error (MSE), the Root Mean Square Error (RMSE), and the coefficient of variation (CV) was performed:

$$MBE = \frac{\sum_{i=1}^{n}(metric_{estimated} - metric_{simulated})}{n}$$

$$NMBE = \frac{MBE}{mean\ (metric_{simulated})}$$

$$RMSE = \sqrt{MBE} = \sqrt{\frac{\sum_{i=1}^{n}(metric_{estimated} - metric_{simulated})^2}{n}}$$

$$CV = \frac{RMSE}{mean(metric_{simulated})}$$

Where n = 408 for the metrics DA, DA_{con} and ED_{room}, and n = 102 for the $sDA_{*\ 300,50\%}$.

When compared to the value acquired by a simulation with Daysim, the mean bias error indicates how close the estimate may be. A positive MBE means the estimated value is greater than the simulated value, and vice versa. In any case, the smaller this number is, the closer the estimate is to the simulation findings. Similarly, the RMSE number is used to combine the magnitudes of prediction mistakes across time into a single measure of predictive capacity. The CV measures the size of the difference between the estimated values and the average of all simulated values in percentages. The smaller this number is, the more accurate the estimate is.

Validation of the set of models

A fresh database of Daysim simulations was used to verify the resilience of the models that were constructed. This 'control database' was created by performing new simulations for scenarios other than the ones that were used to create the models in the first place. Twelve examples were found for this purpose, which were generated by combining different climatic, geometric, and photometric factors, and then further coupled with the four workplane illuminances (and matching LPD), yielding a database of 48 cases. The 'control database"s' robustness is based on both its size (48 instances) and the dispersion of the explicative variables throughout the vast range of values evaluated for the model set's calibration.

The value of each daylighting and energy measure was computed using the appropriate model for each example, and then compared to the simulation outcome. The RMSE and CV statistical measures were used to assess the robustness of the estimated vs. simulated data (new simulations).

RESULTS AND DISCUSSION

Integrated simulation of daylight levels and energy demand:

On an hourly basis, the simulation tool combines daylight and heat calculations. Every hour, the daylight levels at the reference sites are compared to the electrical lighting's user-defined set points. If electrical illumination is required, the photo-responsive control activates it, and the associated heat load is supplied into a basic, yet dynamic, thermal simulation model of the room (Nielsen 2005) as a heat gain. If the solar shade is triggered due to overheating or glare, the daylight levels and thermal performance are recalculated. As part of the basic thermal simulation model, solar heat uptake and heat losses are considered individually (Nielsen 2005). Longwave heat exchange is not considered. The hourly values of the daylight level at the reference places, as well as the electrical energy consumption for lighting, heating, cooling, and interior operative temperature, are the final outputs.

The programme is used to simulate the test scenario outlined to show that it can quantify how characteristics defining the urban canyon impact combined daylight and thermal performance. On weekdays, the room is presumed to be an office inhabited by one person from 8 a.m. to 17 p.m. Table 3 provides more information on the assumptions employed in the case study. Figure 5 shows the simulation results for a south-facing and north-facing room, respectively, based on parameter modifications in diffuse reflectance of building surfaces in the urban canyon and street width. In the selected climate and location (Denmark), these orientations are extremes since a south-facing room receives a lot of direct solar gain and little inter-reflected light, whereas a north-facing room receives the reverse.

Table 3
Energy-related data assumptions for test case.

	Parameter	Description
Window	Glazing	Double glazing with low-E coating (4-15Ar-SN4)
	Frame	Standard wooden frame, $U = 1.6$ W/m^2 K, width = 0.08 m, $\psi = 0.05$ W/m K
Constructions	Façade with window	$U = 0.15$ W/m^2 K
	All other constructions	Adiabatic
	Thermal mass	Specific effective heat capacity 432 kJ/K per m^2 floor area
Systems	Infiltration	0.10 l/s m^2, always active
	Mechanical ventilation in occupied hours	Constant ventilation rate of 1.05 l/s m^2. Average specific fan power of 1.5 kJ/m^3 air. No mechanical cooling available
	Mechanical ventilation in unoccupied hours	Constant ventilation rate of 0 l/s m^2
	Heat exchanger	Efficiency of 85%
	General lighting	Sensor point in the middle of the room, dimming control, set point 200 lux, min. power 0.5 W/m^2, max. power 6 W/m^2, 3 W/m^2/100 lux. Only active in occupied hours
	Task lighting	Sensor point in the middle of the room, on/off control, set point 500 lux, min. power 0 W/m^2, max. power 1 W/m^2. Only available in occupied hours
	Internal load	200 W in occupied hours, 0 W in unoccupied hours
External conditions	Weather data	Danish design reference year (Jensen and Lund, 1995)

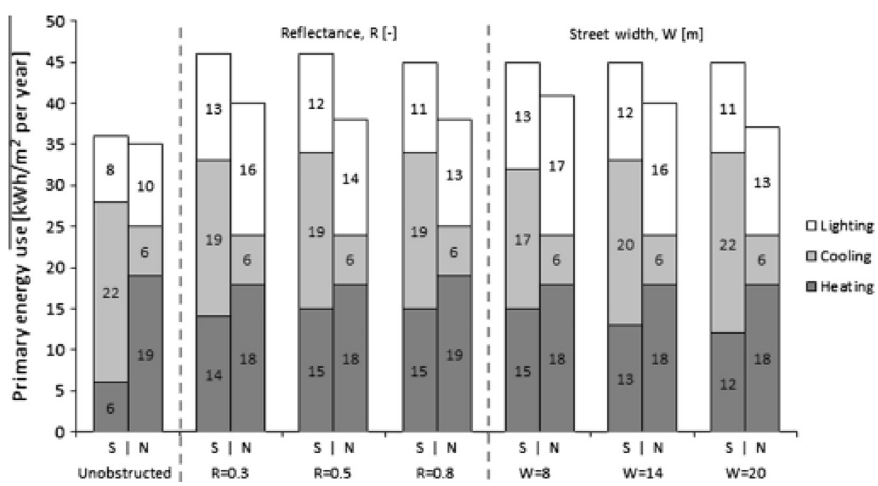

Fig. 5. Energy use for heating, cooling and lighting of the south-facing (S) and the north-facing (N) test case, respectively, with and without obstructions, different exterior surface reflectance (R) and street width (W).

The difference in main energy usage between the obstructed and unobstructed situations is up to 31% for the south-facing room and up to 17% for the north-facing room in the obstructed scenario. The urban canyon factors have no effect on the overall energy consumption of the south-facing room. Because of the influence of the urban canyon features on daylight levels, energy usage for lighting varies, but these fluctuations are offset by differences in energy use for heating and cooling. The north-facing room's total energy consumption is more sensitive to criteria that define the urban canyon than the south-facing room's, with a difference of up to 10% in total energy use. These findings are quite similar to those of research that used the same meteorological data (Strømann-Andersen, Sattrup et al. 2011).

On a laptop with an Intel Core i7–2620 M Processor operating at 2.7 GHz and 4 GB of RAM, a whole-year combined daylight and thermal simulation of the test case in BC/LC takes 15 minutes in the Matlab version of the programme. This, paired with the tool's relative accuracy and the fact that it just takes a few inputs, makes it ideal for early-stage design explorations. The utility may be downloaded from the website http://www.idbuild.dk or by contacting the creator.

Metrics:

Different models, such as exponential and logarithmic models, were examined. Finally, logistic models were shown to be the most accurate for all of the criteria studied. Actually, a logit model is particularly consistent for analysing data that lie in a range between a minimum and a maximum value (as seen for both DA, DA_{con}, $sDA^*_{300,50\%}$, which are expressed in percent, but also for the ED_{room}), indicating saturation toward the maximum value (as seen for both DA, DA_{con}, $sDA^*_{300,50\%}$, which are expressed in percent, but also for the ED_{room}). As a result, each model has the mathematical equation:

Set of models for rooms with a building ahead as obstruction:

Daylight Autonomy $DA_{building\ ahead}$:

Figure 6a shows the variables (or products of variables) that were determined to be statistically significant for this estimate, along with their standardised coefficients.

The factors with the greatest influence, based on the SC values, are by far ba and Ewp, followed by Tv. Geometric data like RD, WWR, room orientation, and location had a smaller influence. The scatter plot of the estimated values acquired using the model vs. the simulated values used to develop the model, as well as the values of the statistical indicators, can be seen in Figure 6a. The R2 score and the CV value both attest to the model's robustness.

Continuous Daylight Autonomy $DA_{con\_building\ ahead}$:

The variables (or products of variables) that were determined to be statistically meaningful for this estimate, together with their standardised coefficients, are displayed in Fig. 6b. Unlike the DA, where a small group of three factors dominates the others, the DAcon finds that all variables have a similar influence, with a little preference for Ewp, site, ba (as products of one another), and Tv. Figure 6b also displays a scatter plot of the model's estimated values vs. the simulated values used to develop the model, as well as the statistical metrics' values.

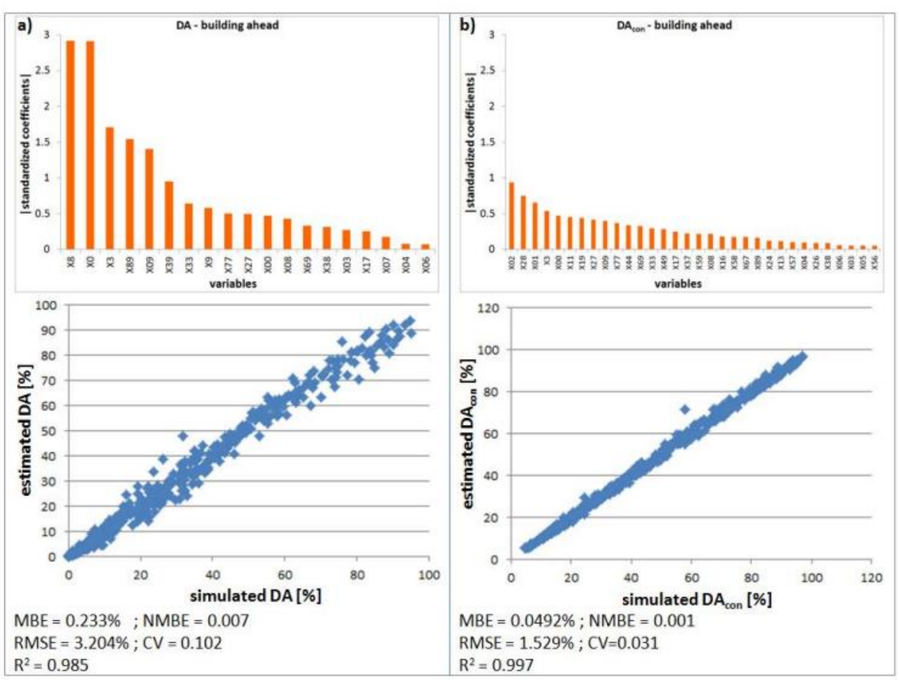

Fig. 6. Scatter plot of simulated vs. estimated values for the model to estimate the DA (a) and the DAcon (b) for cases with a building ahead of the room windows.

Spatial Daylight Autonomy sDA* $_{300,50\%\_building\ ahead}$:

Figure 7 shows the variables (or products of variables) that were determined to be statistically significant for this estimate, along with their standardised coefficients. The elements with the greatest influence on this metric are RD and Tv, according to an in-depth examination of the SC of each variable, whereas ba occurs in a product with the preceding variables. The same may be said for the orientation, with WWR having a smaller influence. In comparison to what was seen for the DA and DAcon, an important distinction emerges: the RD plays the predominant role on the sDA* 300,50 percent of the time. This appears to be related to the metric's formulation, which considers the spatial distribution of illuminances (and hence DA values) over the workplane rather than the average DA value. Figure 7 also includes a scatter plot of the model's estimated values vs. the simulated values used to develop the model, as well as the statistical metrics' values.

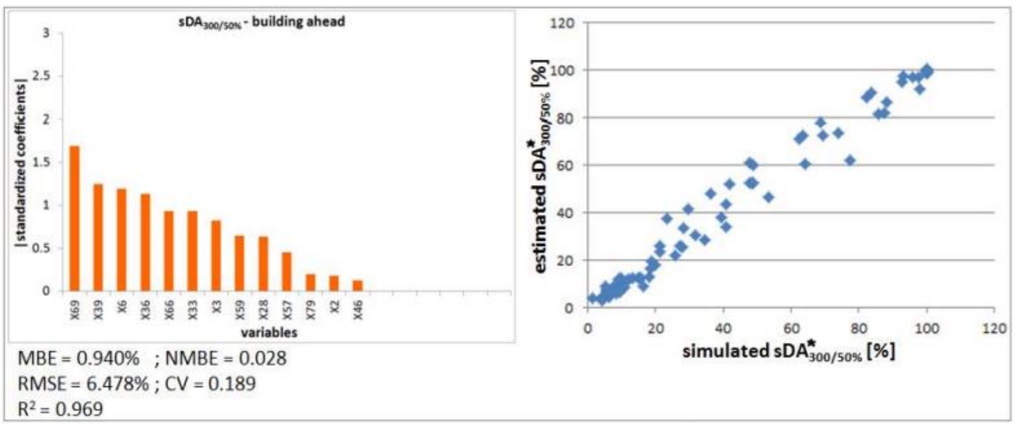

Fig. 7. Scatter plot of simulated vs. estimated values for the model to estimate the sDA* 300,50% for cases with a building ahead.

Energy Demand for lighting $ED_{room\_building\ ahead}$:

For the assessment of the EDroom, two separate models were built: one for a manual on/off switch and one for a daylight sensitive continuous photo-dimming. Unlike the daylight metrics DA and DAcon, which are affected by the needed workplane illuminance, the EDroom metrics take into consideration both the Ewp and the lighting power density LPD placed in the room. Naturally, the two measures are linked: the higher the desired Ewp value, the higher the LPD required to achieve that illuminance, and vice versa (if all other boundary conditions remain unchanged, such as the position and type of luminaires).

As a result, eq. should be changed as follows:

$$\mathbf{ED_{room}} = \mathbf{LPD}\frac{100e^{f(X)}}{1+e^{f(X)}}$$

The components (or products of variables) that were found to be statistically significant for this estimate of the ED_{room} in the presence of a manual on/off switch, as well as the corresponding standardised coefficients, are shown in Fig. 8a. As one might expect considering its strong link with the LPD in the room, based on the SC values, the Ewp is by far the most important variable in terms of lighting energy usage. Tv has the greatest impact, followed by site latitude and RD, with site latitude having a combined effect with Tv (as a product of variables). If a daylight responsive lighting system is implemented, however, the mix of elements and their influence on the ED_{room} is different (Fig. 8b). The Ewp is still by far the most important variable, although the site latitude and ba play a significant effect after that. Tv and RD, to a lesser extent, have an influence on the ED_{room} value. Figure 8 also displays a scatter plot of the model's estimated values vs. the simulated values used to develop the model, as well as the statistical metrics' values.

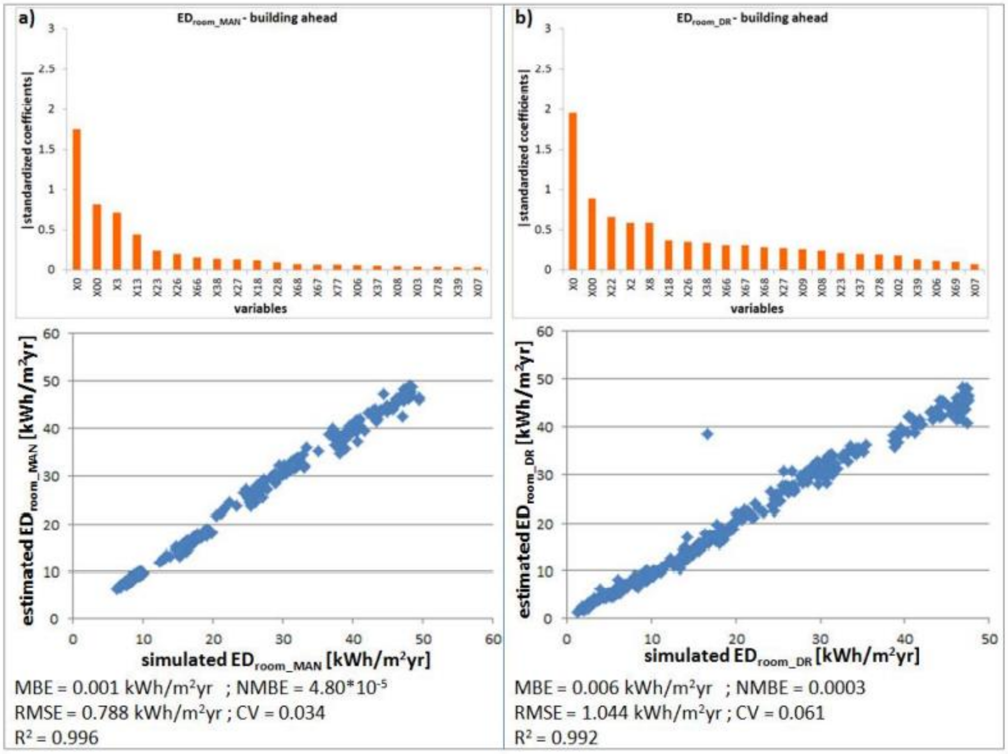

Fig. 8. Scatter plot of simulated vs. estimated values for the model to estimate the EDroom_MAN (a) and the ED_{room}_DR (b) for cases with a building ahead of the room windows.

Set of models for rooms with an overhang as obstruction

Daylight Autonomy $DA_{overhang}$

Figure 9a shows the variables (or products of variables) that were determined to be statistically significant for this estimate, along with their standardised coefficients.

WWR (which specifies the window area) and Ewp are the most important factors, but orientation and γo (which is a function of the overhang depth) appear as a product, thus their influence is significant if both are present. The glazing Tv and the site latitude are also important, albeit to a lesser proportion. When comparing the identical situations with and without an obstruction ahead, the overhang direction and location have the greatest influence, whereas other factors (Tv, Ewp) are meaningful in both circumstances. Figure 9a also displays a scatter plot of the model's estimated values vs. the simulated values used to develop the model, as well as the statistical metrics' values.

Continuous Daylight Autonomy $DA_{con\_overhang}$:

The statistically important factors (or products of variables) for this estimate are displayed in Fig. 9b. When compared to the identical scenarios with a building ahead as an obstruction, the collection of factors that have the greatest influence on DA_{con} values is slightly different, with Tv being the most important, followed by WWR, latitude (in combination with WWR through a product), and Ewp. In contrast to WWR, γo is not a highly important variable (the opposite trend was observed with a building ahead). Figure 9b also displays a scatter plot of the model's estimated values vs. the simulated values used to develop the model, as well as the statistical metrics' values.

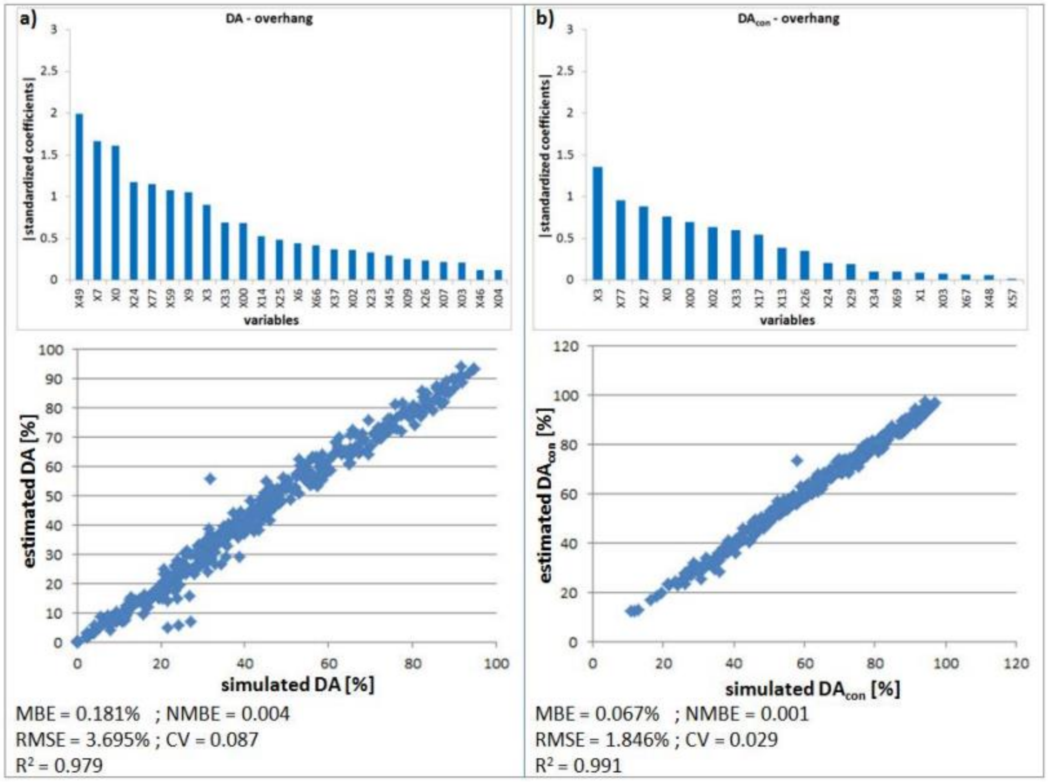

Fig. 9. Scatter plot of simulated vs. estimated values for the model to estimate the DA for cases with an overhang.

Spatial Daylight Autonomy sDA* $_{300,50\%\_overhang}$:

Figure 10 shows the variables (or products of variables) that were determined to be statistically significant for this estimate, along with their standardised coefficients. The SC analysis reveals that the most important factors for this measure are RD, WWR, Tv, site latitude, and o (as already seen in the situations with a building ahead). It is important to note that, with the exception of γo, all of the variables appear as products. This combination of relevant factors matches what was seen in the presence of a building ahead as an obstacle, with WWR playing a larger role. Figure 10 depicts a scatter plot of the model's estimated values vs. the simulated values used to develop the model, as well as the statistical metrics' values.

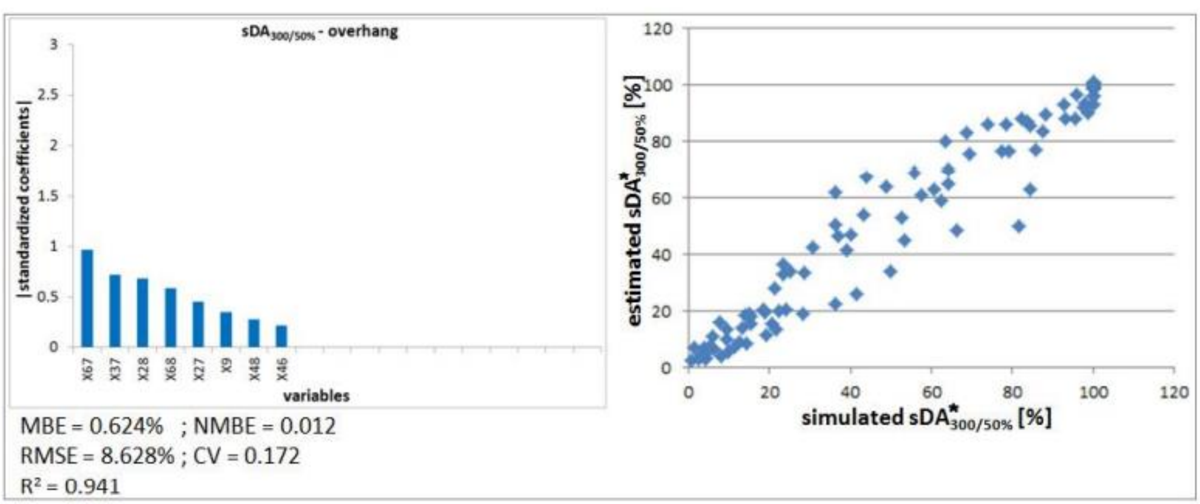

Fig. 10. Scatter plot of simulated vs. estimated values for the model to estimate the sDA* $_{300,50\%}$ for cases with an overhang.

Energy Demand for lighting $ED_{room\_overhang}$:

To account for the LPD, must be utilised for this estimate for the same reasons as previously stated. Figure 7a shows the variables (or products of variables) that were determined to be statistically significant for this estimate, along with their standardised coefficients. The SC reveals that two variables stand out in terms of influence on lighting energy consumption: Ewp (as predicted) and site latitude. The other variables have a smaller influence. Figure 7b shows the collection of factors (or products of variables) that were determined to be statistically significant for a DR control, together with their standardised coefficients. Ewp is the most important variable once again, followed by RD, WWR, and site latitude (all of which are related as a product), and Tv (that appears as a product with the site). Variables like o and orientation appear to be less important. Figure 7 also displays a scatter plot of the model's estimated values vs. the simulated values used to develop the model, as well as the statistical metrics' values.

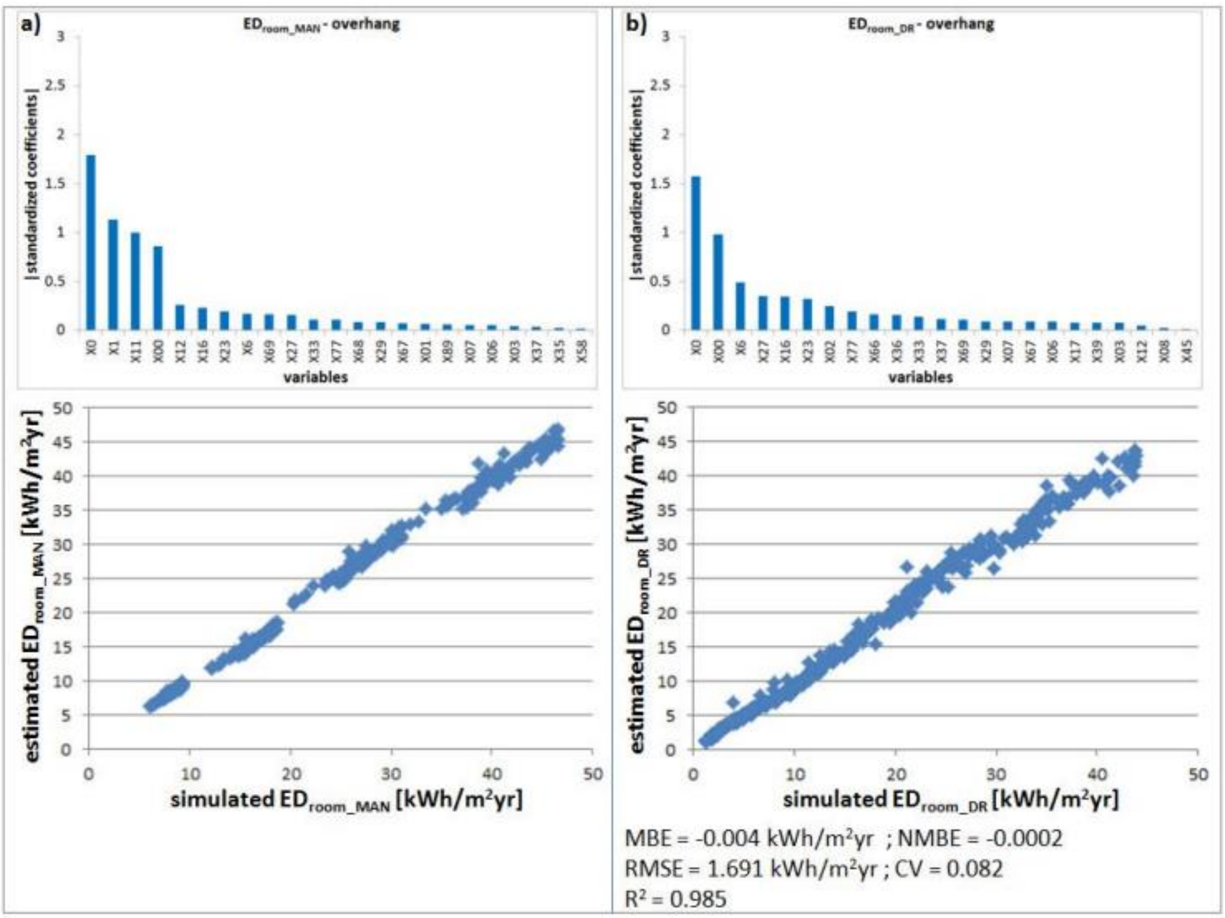

Fig. 11. Scatter plot of simulated vs. estimated values for the estimation of EDroom_MAN (a) and of EDroom_DR (b) (cases with an overhang).

The study is unique in that it provides a set of mathematical models for estimating a space's daylight performance in terms of both yearly sunshine quantity (Daylight Autonomies metrics) and connected lighting energy consumption. The models' strength is in the vast number of input parameters (and many values for each parameter) in terms of room geometry, glazing area and optical qualities, target illuminance, lighting power densities, and lighting control solutions. The models may be used to establish the daylighting techniques that will be employed in the design process as early as the conceptual design stage. When using simulation tools for more extensive calculations is still premature, the quantity of daylight in a room and the energy consumption due to lighting equipment may be approximated during the early design phase. In this approach, rather than being restricted to aesthetic or formal considerations, initial but critical decisions on building mass, orientation, façade, and plan arrangement may be based on daylighting requirements as well. For illustration, it is possible to calculate how the room complexity or the window area influence the room daylight/lighting energy performance over a given urban setting (hence for known blockage angles for the target room); or, the other way around, one architectural variable (the glazing area, the glazed windows visible transmittance, or the room depth) could be defined, setting a value for the other variables, in order to assure a target value of energy demand for lighting, or of m. By comparing the two EDroom values in the presence of a manual switch on/off and a daylight responsive dimming control, the energy savings associated with the employment of a daylight responsive control system vs a simple manual control system may be analysed. The predicted values contain an inaccuracy when compared to the simulation output rather than the actual daylight quantity present in the real room since the models were created from a database of simulation outcomes.

The models are simple to use even for non-expert users: for each model, if all variables except one are set, a second-degree equation is obtained through simple logarithmic transformations, because the explicative variables contained in the exponential function of the logistic function have a maximum degree of two. When more than one variable is unknown, the mathematical solution becomes more difficult (it's a quadratic optimization problem with constraints) and necessitates the use of specialised software (such as MatLab).

CONCLUSION:

The research proposes a simplified calculation approach that takes into account the influence of the urban canyon on daylight levels and energy consumption in order to maintain a particular level of illumination and thermal comfort in rooms. The method calculates the light contribution from the sky, sun, and ground to the two opposed vertical urban canyon surfaces using a ray-tracing methodology. The inter-reflections in the urban canyon are then modelled using the luminous exitance approach, thus allowing the luminous contribution of the urban canyon surfaces to be included on inside daylight levels.

The approach is applied in an existing building simulation tool's daylight algorithm, which allows for quick combined daylight and temperature modelling. When compared to Radiance, the new daylight algorithm exhibits high agreement for diverse sky models and room orientations. The maximum relative inaccuracy is 17 percent – typically considerably lower – which is acceptable in the early stages of daylight design where simulation speed and simplicity of usage are important.

A collection of mathematical models was published that linked numerous architectural design factors to the quantity of daylight in a room and the energy consumption for electric lighting. This collection was created with the goal of assisting designers in incorporating daylighting solutions into the design process from the early stages onward. Actually, the models combine some daylighting metrics or the energy demand for lighting for a room with a number of geometrical, photometric, and electric lighting parameters: site, orientation, room depth, glazing area (through the WWR) and visible transmittance, workplane illuminance (correlated to the lighting power density installed in the room), type of light control (manual on/off switch or daylight responsive control), and type of light control (manual on/off switch or daylight responsive control).

Two pairs of models were created as a function of two sorts of obstructions: building ahead of the windows or overhang (or any other horizontal part belonging to the building itself) with a certain depth, based on the results of Daysim simulations for 408 instances. Each set includes five models that may be used to estimate daylighting metrics (DA, DAcon, sDA* 300,50%) or the energy demand for lighting with a manual or automated control (EDroom MAN, EDroom DR). The formulae can be used in two ways: to predict the quantity of daylight or the energy demand for lighting offered a set of variables; or to determine a single variable, provided some other variables are set, in order to assure a target value of a climate-based daylight metric or the energy needs for lighting.

REFERENCES:

Athienitis, A. and A. J. S. e. Tzempelikos (2002). "A methodology for simulation of daylight room illuminance distribution and light dimming for a room with a controlled shading device." **72**(4): 271-281.

Bellia, L., F. Fragliasso, E. J. B. Stefanizzi and Environment (2016). "Why are daylight-linked controls (DLCs) not so spread? A literature review." **106**: 301-312.

Cammarano, S., A. Pellegrino, V. R. M. Lo Verso, C. J. B. R. Aghemo and Information (2015). "Assessment of daylight in rooms with different architectural features." **43**(2): 222-237.

Clarke, J. and M. J. B. P. Janak (1998). "Simulating the thermal effects of daylight-controlled lighting." **1**: 21-23.

Council, U. G. B. (2013). LEED reference guide for building design and construction, US Green Building Council.

da Fonseca, R. W., E. L. Didoné, F. O. R. J. E. Pereira and Buildings (2013). "Using artificial neural networks to predict the impact of daylighting on building final electric energy requirements." **61**: 31-38.

Decruz, A., G. Kokogiannakis, J. Darkwa, P. Strachan and J. Hong (2012). A theoretical framework for the integration of a green roof model in ESP-r, Citeseer.

Dubois, M.-C., K. J. L. R. Flodberg and Technology (2013). "Daylight utilisation in perimeter office rooms at high latitudes: Investigation by computer simulation." **45**(1): 52-75.

EN, U. (2011). "Light and lighting-Lighting of work places-Part 1: Indoor work places."

Franzetti, C., G. Fraisse, G. J. E. Achard and buildings (2004). "Influence of the coupling between daylight and artificial lighting on thermal loads in office buildings." **36**(2): 117-126.

Hviid, C. A., T. R. Nielsen and S. J. S. E. Svendsen (2008). "Simple tool to evaluate the impact of daylight on building energy consumption." **82**(9): 787-798.

IES, D. (2012). "Approved Methods: IES Spatial Daylight Autonomy sDA and Annual Sunlight Exposure."

Ihm, P., A. Nemri, M. J. B. Krarti and Environment (2009). "Estimation of lighting energy savings from daylighting." **44**(3): 509-514.

Krarti, M. (2020). Energy audit of building systems: an engineering approach, CRC press.

Krarti, M., P. M. Erickson, T. C. J. B. Hillman and environment (2005). "A simplified method to estimate energy savings of artificial lighting use from daylighting." **40**(6): 747-754.

Li, D. H., G. H. Cheung, K. L. Cheung, J. C. J. B. Lam and Environment (2009). "Simple method for determining daylight illuminance in a heavily obstructed environment." **44**(5): 1074-1080.

Li, D. H., J. C. J. E. Lam and buildings (2003). "An investigation of daylighting performance and energy saving in a daylit corridor." **35**(4): 365-373.

Littlefair, P. J. S. E. (2001). "Daylight, sunlight and solar gain in the urban environment." **70**(3): 177-185.

Michalak, P. J. E. (2014). "The simple hourly method of EN ISO 13790 standard in Matlab/Simulink: A comparative study for the climatic conditions of Poland." **75**: 568-578.

Moeller Jensen, J. and H. Lund (1995). "Design reference year, DRY. A new Danish reference year; Design reference year, DRY. Et nyt dansk referenceaar."

Moret, S., M. Noro and K. Papamichael (2013). Daylight harvesting: a multivariate regression linear model for predicting the impact on lighting, cooling and heating. Proceedings of the 1st IBPSA Italy Conference, Bolzano (Italy).

Nielsen, T. R. J. S. e. (2005). "Simple tool to evaluate energy demand and indoor environment in the early stages of building design." **78**(1): 73-83.

Oke, T. R. (2002). Boundary layer climates, Routledge.

Ozgur, C., M. Dou, Y. Li and G. J. J. o. M. A. S. M. Rogers (2017). "Selection of statistical software for data scientists and teachers." **16**(1): 40.

Pagliolico, S. L., V. R. L. Verso, A. Torta, M. Giraud, F. Canonico and L. J. E. P. Ligi (2015). "A preliminary study on light transmittance properties of translucent concrete panels with coarse waste glass inclusions." **78**: 1811-1816.

Park, K.-W. and A. K. J. S. E. Athienitis (2003). "Workplane illuminance prediction method for daylighting control systems." **75**(4): 277-284.

Pellegrino, A., S. Cammarano, V. R. L. Verso, V. J. B. Corrado and Environment (2017). "Impact of daylighting on total energy use in offices of varying architectural features in Italy: Results from a parametric study." **113**: 151-162.

Pellegrino, A., V. R. L. Verso, L. Blaso, A. Acquaviva, E. Patti and A. J. I. T. o. I. A. Osello (2016). "Lighting control and monitoring for energy efficiency: A case study focused on the interoperability of building management systems." **52**(3): 2627-2637.

Perez, R., R. Seals and J. J. S. e. Michalsky (1993). "All-weather model for sky luminance distribution—preliminary configuration and validation." **50**(3): 235-245.

Petersen, S., A. J. Momme and C. A. J. S. e. Hviid (2014). "A simple tool to evaluate the effect of the urban canyon on daylight level and energy demand in the early stages of building design." **108**: 61-68.

Ramos, G., E. J. R. Ghisi and S. E. Reviews (2010). "Analysis of daylight calculated using the EnergyPlus programme." **14**(7): 1948-1958.

Ratti, C., N. Baker, K. J. E. Steemers and buildings (2005). "Energy consumption and urban texture." **37**(7): 762-776.

Reinhart, C., A. J. E. Fitz and Buildings (2006). "Findings from a survey on the current use of daylight simulations in building design." **38**(7): 824-835.

Reinhart, C. F., V. J. L. R. LoVerso and Technology (2010). "A rules of thumb-based design sequence for diffuse daylight." **42**(1): 7-31.

Reinhart, C. F., J. Mardaljevic and Z. J. L. Rogers (2006). "Dynamic daylight performance metrics for sustainable building design." **3**(1): 7-31.

Reinhart, C. F. J. O. I. f. R. i. C., National Research Council Canada (2006). "Tutorial on the use of daysim simulations for sustainable design."

Reinhart, C. F. J. S. e. (2004). "Lightswitch-2002: a model for manual and automated control of electric lighting and blinds." **77**(1): 15-28.

Robinson, D. and A. J. S. E. Stone (2006). "Internal illumination prediction based on a simplified radiosity algorithm." **80**(3): 260-267.

Strømann-Andersen, J., P. A. J. E. Sattrup and buildings (2011). "The urban canyon and building energy use: Urban density versus daylight and passive solar gains." **43**(8).

Verso, V. R. L., E. Fregonara, F. Caffaro, C. Morisano and G. M. J. J. o. D. Peiretti (2014). "Daylighting as the Driving Force of the Design Process: from the Results of a Survey to the Implementation into an Advanced Daylighting Project." **1**(1): 2-7.

Verso, V. R. L., G. Mihaylov, A. Pellegrino, F. J. E. Pellerey and Buildings (2017). "Estimation of the daylight amount and the energy demand for lighting for the early design

stages: Definition of a set of mathematical models." **155**: 151-165.
Verso, V. R. L., A. Pellegrino, F. J. E. Pellerey and buildings (2014). "A multivariate non-linear regression model to predict the energy demand for lighting in rooms with different architectural features and lighting control systems." **76**: 151-163.
Walkenhorst, O., J. Luther, C. Reinhart and J. J. S. E. Timmer (2002). "Dynamic annual daylight simulations based on one-hour and one-minute means of irradiance data." **72**(5): 385-395.
Ward, G. and R. Shakespeare (1998). "Rendering with Radiance: the art and science of lighting visualization."
Wong, S. L., K. K. Wan and T. N. J. A. E. Lam (2010). "Artificial neural networks for energy analysis of office buildings with daylighting." **87**(2): 551-557.