Combined Daylight and Thermal Calculation Tool for Annual Energy Performance Simulation of Rooms with Advanced Daylight-Controlled Lighting Systems

Steffen Petersen[1]
[1]Aarhus University Department of Engineering, Aarhus, Denmark
stp@eng.au.dk

Abstract

This paper presents an extension to an existing simulation tool that enables energy simulation of advanced daylight-controlled lighting systems with hourly dynamic thermal simulation. The climate-based daylight level in a reference point beneath each individual lamp is calculated and the light output from the lamps is scaled to meet user-defined illuminance levels in all reference points. The corresponding lighting power output is then given as input to the thermal simulation. The proposed lighting algorithm performs satisfying when compared to existing static lighting simulation tools. Furthermore, results from a test case demonstrate how the advanced daylight-controlled lighting systems may improve the annual energy performance of rooms.

Introduction

Lighting accounts for approx. 20% of the global building electricity consumption (WEO, 2015). Design of energy-efficient lighting systems is therefore an important task when designing sustainable buildings. Lighting designers can make use of various computer-based tools to evaluate their lighting designs in the early design stages. The majority of available tools enable the design of the lighting systems that fulfils illuminance and energy requirements either independently of daylight availability or with respect to certain daylight scenes. Examples of such tools are FABA light (FABA, 2016), DIALux (DIALux, 2016), RELUX (RELUX, 2016), AGi32 (AGi32, 2016) and Radiance (Ward and Shakespeare, 1998). The daylight feature of the tools can be used to test the energy performance of daylight-controlled lighting systems under certain weather situations but do not facilitate annual energy performance simulation relative to the dynamic daylight availability in specific climates. Furthermore, none of the tools is able to evaluate how heat from the lighting system affects the thermal indoor environment and thereby the cooling and heating need of the room. Taking this interrelation into consideration when doing performance simulations of lighting systems can thus potentially affect not only the design of the lighting system but also the design of the room itself and its HVAC systems.

The effects of the interrelation between the energy performance of the daylight-controlled lighting system on the thermal performance of a room in a certain climate can be simulated and evaluated using the detailed thermal simulation programmes ESP-r (University of Strathclyde, 2011) and EnergyPlus (US Department of Energy, 2013). These tools can link daylight-controlled lighting and thermal simulation in an integrated manner by calculating the daylight level in a daylighting reference point and then scale the illuminance output from the lighting system to meet a user-defined level of illuminance (Clarke and Janak, 1998; Ramos and Ghisi, 2010). Prior information about the relation between illuminance and power output of the lighting system is then used to determine the heat load input to the thermal calculation. This linking of the daylight and thermal domain is based on the assumption that a single daylighting reference point controls all luminaires in the lighting system. EnergyPlus do provide a feature where two light control zones may be defined separately within the room but the illuminance output from the luminaires in one zone is assumed not to affect the illuminance level in the other zone. This may be appropriate for performance simulation of most conventional lighting systems. However, the assumption is not appropriate for a range of more advanced commercially available lighting systems, which are able to regulate the output level of the individual lamp in a system consisting of multiple lamps with respect to the daylight level in a point above the floor directly underneath the individual lamp. Appropriate performance simulation of such lighting systems requires calculation of the daylight levels in a sensor point below the individual lamp as well as calculations on how the illuminance output from the individual lamp affects the illuminance level in the sensor point of the other lamps in the lighting system.

This paper presents an extension of the existing combined daylight and thermal calculation tool iDbuild (Petersen and Svendsen, 2010) that for the first time enables climate-based dynamic energy performance simulations of the above-described advanced daylight-controlled lighting systems. The paper includes a verification of the performance of the extension, and an example of how the annual energy performance of an office room may be improved using the advanced daylight-controlled lighting system.

https://doi.org/10.26868/25222708.2017.344

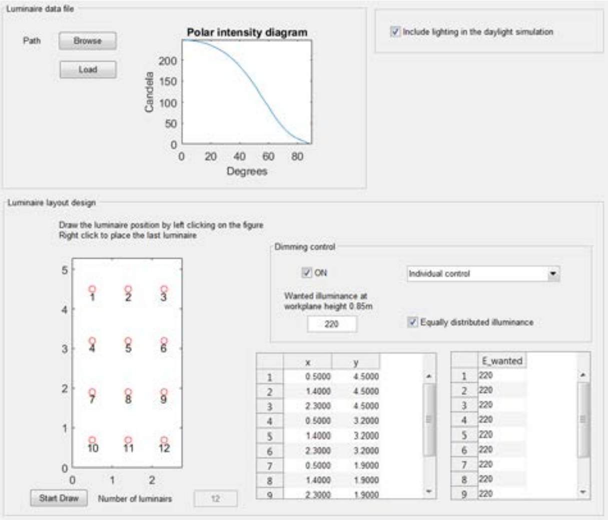
Method

The algorithm presented in this paper is an extension to the existing combined daylight and thermal tool called iDbuild (Petersen and Svendsen, 2010) which is able to include daylight-controlled lighting systems in the thermal calculation as described in Hviid et al. (2008). A description of the simplified thermal simulation engine used in iDbuild is provided in Nielsen (2005) and a detailed description of the split flux daylight calculation method called LightCalc is presented in Hviid et al. (2008). The representation of the light contribution reflected from opposing buildings was later improved as described in Petersen et al. (2014).

The current method for including daylight-controlled lighting systems in iDbuild is similar to the one described for EnergyPlus and ESP-R in the introduction, including the described drawbacks in relation more advanced daylight-controlled lighting systems. The following sections describes the algorithm for including more advanced daylight-controlled lighting systems in iDbuild, and the outlines of a test case for verification of the algorithm as well as for exemplifying how to make a simulation-based performance analysis of an advanced daylight-controlled lighting system with the new algorithm.

Algorithm for advanced daylight-controlled lighting

The code itself is too extensive to display in the text but it is freely available on www.idbuild.dk. However, for the convenience of the reader, the overall principle of algorithm explained in the following. Before the algorithm can be applied, the user of the extended iDbuild program have to specify the polar intensity diagram (PID) of the lamp used in the lighting system (figure 1, top), place a number of lamps on the ceiling of the room (figure 1, bottom left), and specify an illuminance set point beneath each lamp. The algorithm can handle a lighting systems consisting of n numbers of lamps, and thereby n number of light reference points.



☑ Include lighting in the daylight simulation

Draw the luminaire position by left clicking on the figure
Right click to place the last luminaire

☑ ON

Individual control

Wanted illuminance at workplane height 0.85m: 220

☑ Equally distributed illuminance

Number of luminairs: 12

	x	y
1	0.5000	4.5000
2	1.4000	4.5000
3	2.3000	4.5000
4	0.5000	3.2000
5	1.4000	3.2000
6	2.3000	3.2000
7	0.5000	1.9000
8	1.4000	1.9000
9	2.3000	1.9000

	E_wanted
1	220
2	220
3	220
4	220
5	220
6	220
7	220
8	220
9	220

Figure 1: Input interface for lighting system.

The algorithm is repeated for each hour of the year, i, but only if the lighting system is scheduled to be available in hour i. The algorithm utilises the current daylight algorithm in iDbuild to calculate the vector $\boldsymbol{e}$ which contains the climate-based daylight level in each light reference point n for the hour i. If at least one value in $\boldsymbol{e}$ is below the corresponding user-defined illuminance set point, then the lamp(s) above the respective reference point will be turned on with maximum possible output. The lamps turned on will now emit light to all light reference points and surfaces in the room according to the PID of the lamp. The amount of light coming directly from each lamp to each sensor point is calculated using the PID and simple trigonometry resulting in an n x n matrix of illumances, $\boldsymbol{C}$. The radiosity algorithm already implemented in iDbuild (Park and Athienitis, 2003) is used to determine the room surface light reflection contribution from all lamps to each light reference point n resulting the vector $\boldsymbol{d}$. The values in vector $\boldsymbol{d}$ is added to the diagonal of $\boldsymbol{C}$ together with the calculated daylight levels in vector $\boldsymbol{e}$ forming the matrix $\boldsymbol{A}$. A dimming logic based on a linear program is then used to determine the output of each lamp to obtain a desired set point in all sensor points:

$$\boldsymbol{A}x = \boldsymbol{b}. \tag{1}$$

where x is the dimming factors needed to reach the user-defined illuminance set points in each sensor point listed in $\boldsymbol{b}$. The *linprog.m* from the MATLAB optimization toolbox (MATLAB, 2015) is then used to minimize x in eq. 1. The factors in x are then multiplied with the maximum lamp outputs before $\boldsymbol{C}$ is recalculated and summed column by column to get the dimmed light levels in all sensor points, $\boldsymbol{g}$. The vector $\boldsymbol{d}$ is then recalculated using the dimmed lamp outputs. The final light level in the sensor points is the element-wise sum of $\boldsymbol{e}$, $\boldsymbol{d}$ and $\boldsymbol{g}$.

The above-described algorithm will result in a slightly higher illuminance values than the desired ones expressed in $\boldsymbol{b}$ because $\boldsymbol{d}$ is calculated after lamp outputs are dimmed. The surplus in $\boldsymbol{d}$ could be reduced by repeating the above procedure in an iterative manner. However, the light surplus is currently ignored in the algorithm to save computational time.

Test case

A test case was defined 1) to verify the illuminance output from the algorithm, and 2) to demonstrate the how the algorithm enables simulation-based performance comparison of conventional and advanced daylight-controlled lighting system.

The room geometry of the test case is illustrated in fig. 2. The placement of the 12 lamps of the tested ligthing system on the ceiling is shown in fig. 1 (bottom). Data for the lamps is displayed in table 1, and room data assumptions is provided in table 2. The room is occupied from 8 am to 5 pm all weekdays; systems including lighting are also in operation within this period.

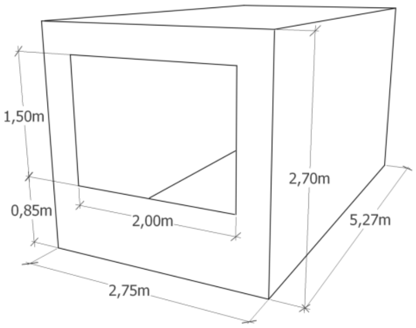


Figure 2: Room geometry.

The verification of the algorithm was made by comparing illuminance output from the algorithm with illuminance output from a DIALux model using the same inputs. The verification was done with no daylight in the room. The performance of the type of advanded daylight-controlled lighting system facilitated by the new algorithm (see the introduction for details) is compared to the performance of a conventional daylight control where all 12 lamps of the lighting system are dimmed with respect to a single light reference point placed centered and 0.7 m from the wall opposite the window.

Table 1: Lamp data

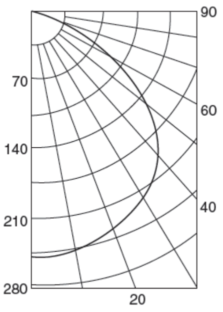
Lamp data	**Polar intensity diagram**
Light output: 647 lm	
Input Power: 11.5 W	
Efficiency: 54 lm/W	
Colour rendering, Ra: 95	
CCT: 2700K or 3500K	
Dimmable to 20%	

Table 2: Data assumptions for room

Category	**Parameter**	**Description**
Window	Glazing	U/g/LT= 1.19/0.63/0.78
	Frame	U=1.6 W/m^2 K, width=0.08 m, ψ=0.05 W/m K
	Shading	Ext. horizontal lamella blinds
Constructions	Façade	U=0.2 W/m^2 K
	Thermal mass	432000 J/m^2 K
Reflectance	Floor	0.20
	Ceiling	0.70
	Walls	0.60
Systems	Infiltration	0.1 l/s m^2
	Ventilation	CAV 1.67 l/s m^2 Heat exch. 80%
	Cooling	60 W/m^2
	Lighting	Light reference set point: 200 lux
Internal loads	Persons	Two persons, 1.2 MET, 1 clo
	Equipment	200 W
Ext. conditions	Shadows	None
	Weather data	Danish design reference year

Results

The illuminance level in each reference point of the test case from DIALux and iDbuild, respectively, are shown in table 3. The relative difference of 3.3 % or less between the results indicates that the implementation of the new algorithm in iDbuild performs in accordance with the radiosity-based method implemented in DIALux 4.13.

Figure 3 shows results from simulations with different lighting settings. The difference between Figure 3A and 3B illustrates an effect saving of 4.5 W/m^2 by dimming the individual lamp to meet a set point of approx. 200 lux beneath each lamp instead of 100% output from each lamp. Figure 3C illustrates the illuminance level from daylight alone 8 February 12 AM. Figure 3D shows the lamps dimming setting needed on top of the daylight in Figure 3C if the dimmed ligthing setting from Figure 3B is controlled with respect to a single light reference point placed centered and 0.7 m from the wall opposite the window. The resulting effect is 4.0 W/m^2. Figure 3E shows the lamps dimming setting needed on top of the daylight in Figure 3C using the advanced daylight-controlled lighting system facilitated by the new algorithm. The resulting effect is 3.3 W/m^2.

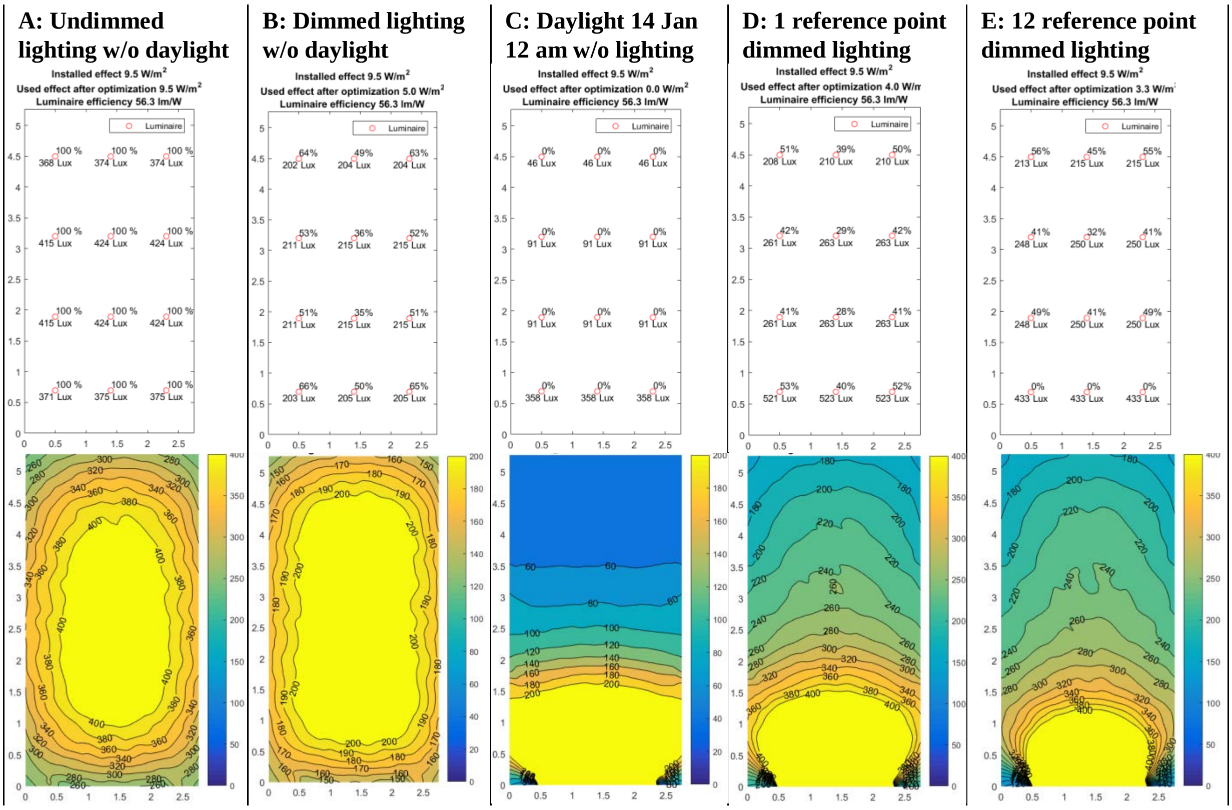
Table 3: Illuminance data (lux) for verification

Reference point	**DIALux**	**iDbuild**	**% diff.**
1	333	339	1.8
2	378	385	1.9
3	333	339	1.8
4	393	406	3.3
5	447	448	0.2
6	393	406	3.3
7	393	406	3.3
8	447	448	0.2
9	393	406	3.3
10	333	339	1.8
11	378	385	1.9
12	333	339	1.8

Figure 4 depicts the lighting load output from the combined daylight and thermal calculation using a single light reference point and the advanced daylight-controlled lighting system, respectively. Immediate visual comparison indicates that the advanced daylight control as a lower energy use. Table 4 shows that the annual electrical energy saving for lighting when compared to the single light reference point control is 20%. This saving resulted in less heat generated by the lighting and thereby a 3 % increase in heating energy use and a 2 % drop in electricity for cooling.

Discussion

The simulation time for the annual simulation featuring the advanced daylight-controlled lighting system is ~160 s on a laptop with Intel Core i7–5600U Processor running at 2.6 GHz and 16 GB of RAM. However, the user-defined size of sub-surfaces in the model is critical in terms of simulation time and precision of the result. The size of sub-surfaces was 2 m but changing that to 1 m increased simulation time to ~246 s and increased energy consumption for lighting to 114 kWh(el)/year (with a minor impact on heating and cooling as consequence). Given the relatively short simulation time, it is thus recommended always to investigate the impact of sub-surface size on the result.



A: Undimmed lighting w/o daylight

B: Dimmed lighting w/o daylight

C: Daylight 14 Jan 12 am w/o lighting

D: 1 reference point dimmed lighting

E: 12 reference point dimmed lighting

Figure 3: Outputs from simulations with different lighting settings.

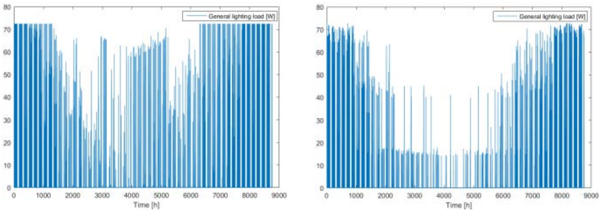


Figure 4: Load profile for lighting system. Left: Single light reference point control. Right: Advanced control.

Table 4: Annual energy use

Energy need	1 reference point dimmed lighting	12 reference point dimmed lighting	% diff.
Room heating kWh(h)/year	61	63	3
Room cooling kWh(el)/year	216	211	-2
Lighting kWh(el)/year	132	105	-20

Conclusion

A new algorithm that enables energy simulation of advanced daylight-controlled lighting systems in an existing combined daylight and thermal calculation tool has been developed and tested. A simple verification indicates that the illuminance calculation of the new algorithm performs satisfactory. Furthermore, results from a test case demonstrate that the advanced daylight-controlled lighting systems may improve the annual energy performance of a room.

Acknowledgement

The author acknowledges Kristín Ósk Þórðardóttir as the algorithm described in this paper is a development of her master thesis project work from 2009.

References

AGi32. (2016). AGi32 version 17.3. www.agi32.com (last accessed 13 November 2016)

FABA. (2016). FABA light version 4.14. www.faba.dk (last accessed 13 November 2016)

DIALux. (2016). DIALux version 4.13. www.dial.de. (last accessed 13 November 2016)

Hviid, C.A., Nielsen, T.R. and Svendsen, S. (2008). Simple tool to evaluate the impact of daylight on building energy consumption. *Sol. Energy 82*(9), 787–798.

MATLAB (2015). MATLAB and Statistics Toolbox Release 2015b, The MathWorks, Inc., Natick, Massachusetts, United States.

Nielsen, T.R. (2005). Simple tool to evaluate energy demand and indoor environment in the early stages of building design. *Sol. Energy 78*(1), 73–83.

Park, K.-W. and Athienitis, A.K. (2003). Workplane illuminance prediction method for daylighting control systems. *Sol. Energy 75*(4), 277–284.

Petersen S., Momme A.J. and Hviid C.A. (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. *Sol. Energy* 108, 61–68.

Petersen, S. and Svendsen, S. (2010). Method and simulation program informed decisions in the early stages of building design. *Energy Build. 7*(42), 1113–1119.

Ward, G.L. and Shakespeare, R.A. (1998). Rendering With Radiance – The Art and Science of Lighting Visualization, second ed. Morgan Kaufmann, San Francisco.

Ramos, G., Ghisi, E. (2010). Analysis of daylight calculated using the EnergyPlus programme. *Renew. Sust. Energy Rev. 14*(7), 1948–1958.

RELUX. (2016). RELUX version 2016.1.1. (last accessed 13 November 2016)

University of Strathclyde (2011). ESP-r Version 11.11, Energy Systems Research Unit, Glasgow, Scotland.

US Department of Energy. (2013). EnergyPlus 8.1.0, Energy Efficiency and Renewable Energy, Washington DC, USA.

WEO (2016). World Energy Outlook 2015. International Energy Agency, Paris, France.