ISBN: 978-84-697-1815-5

WORLD SB14 BARCELONA October 28/30th 2014

Implementation of daylight as part of the integrated design of commercial buildings

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Abstract: *Today, there is an obvious lack of sufficient integration of daylight in building design. The literature has been reviewed in order to see if knowledge exists to formulate an improved daylight design methodology which may be consistently integrated with thermal comfort and energy use design. Based on findings in the literature, a proposal is given on how daylight calculations and evaluations may be implemented throughout the building design. Important features in the proposed design are: early implementation of simulation tools, implementation of climate-based daylight modelling, and coupling between simulation tools for daylight, thermal comfort and energy use to ensure consistency in the design. The design proposal has been tested and the results show that the method might lead to a design with satisfying indoor environment and low energy use. Yet, more research is needed to validate and to set proper benchmark values for newly proposed climate-based daylight metrics.*

Key words: daylight metrics, daylight prediction, discomfort glare, integrated design

Introduction

It may be a climatic challenge to design buildings with low energy use and high indoor environmental performance. Figure 1 illustrates how daylight, thermal comfort and energy aspects influence each other in a complex manner. There is a need for an integrated and consistent design approach to daylight, thermal comfort and energy use in order to be able to fulfil future energy and comfort demands.

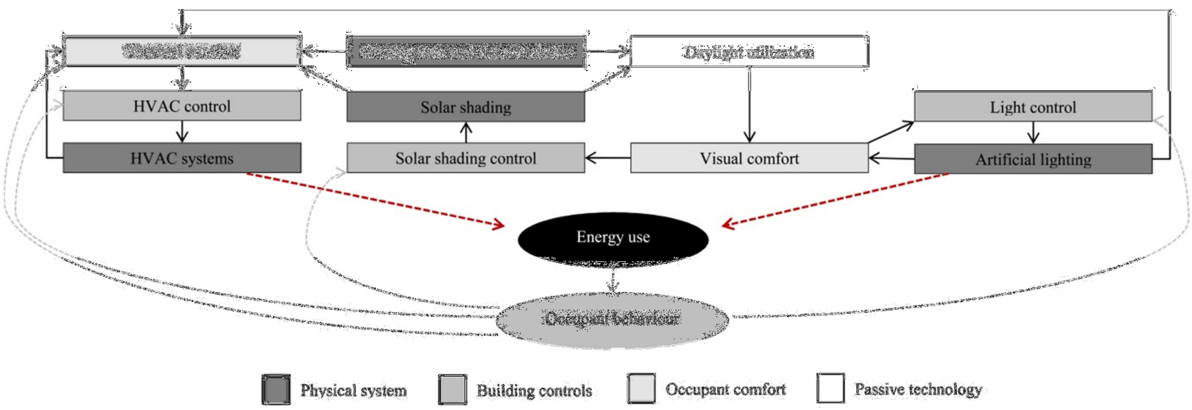

Figure 1: Illustration of interaction of daylight, thermal comfort and energy aspects.

At the present time, simulation tools are used, which makes it possible to evaluate both thermal comfort and energy use at the same time, yet there is an obvious lack of sufficient integration of daylight [1]. Daylight is an essential component within buildings both with its architectonic and aesthetic features and with is functional aspects. With regard to the latter, an effective daylight design combined with intelligent control for artificial lighting might lead to reduction of energy use for lighting and cooling, especially for commercial buildings where the occupied period usually coincides with periods of excessive access to daylight. Additionally, it is important to remember that daylight has positive health effects [2], and that occupants usually prefer daylight as their source of illumination [3]. These last features might actually be the most vital arguments for investing time an effort in daylight design.

However, several surveys conducted among building designers and researchers [4-6] revail that far from all conduct daylight analysis during their design. The aim of the present paper is to propose how daylight design may be implemented throughout the design of commercial buildings as an integrated part of the building design. The literature has been consulted in order to see if there is existing knowledge to formulate a three step design methodology for integrated daylight design. The following sections present the results from the literature review followed by a test of the proposed design methodology.

Literature review of daylight design

With respect to an integrated design, criteria for daylight may be used to assess if the daylight environment is satisfying, if artificial lighting needs to be added or if there is risk of glare and need for activation of solar shading.

Is the daylight satisfying or do artificial light need to be added?

The daylight factor (DF) has existed since the beginning of the 20th century [7], it is used as a measure for satisfying daylight and is currently the most commonly used daylight metric worldwide [8, 9]. The daylight factor is defined as the ratio between the internal illuminance at a point in a room and the unshaded, external horizontal illuminance under a *Commission Internationale de l'Eclairage* (CIE) overcast sky [9].

As an isolated measure, the DF does not contribute with much information regarding the real daylight level in a room as it only considers the static CIE overcast condition. Under these conditions there might e.g. not be need for use of solar shading, which may explain why use of solar shading commonly is neglected in daylight design [10]. Yet, it is well known that solar shading is indispensable for office workers to control solar gain and glare and its use influence daylight supply, thermal comfort and energy use. Further limitations of DF are widely discussed elsewhere [9, 11], and one thing seems certain: new climate-based daylight metrics (CBDm) should be used in the future as criteria for annual daylight, a selecton of CBDm are presented in Table 1.

The question is then which CBDm to use? UDI and $sDA_{300/50\%}$ might be preferable to use since they are developed based on occupant preferences in daylight environments. One advantage of $sDA_{300/50\%}$ is that the annual daylight level in the room can be expressed with

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one single number and according to the Illuminanting Engineering Society of North America (IES), $sDA_{300/50\%}$ ≥55 % has to be met in order for a space to be nominally acceptable daylit. $sDA_{300/50\%}$ has been accepted as daylight metric by the IES as part of an methodology for evaluating annual daylight [12]. However, from an integrated design perspective, UDI seems to give more interdisciplinary information. The UDI concept is divided into four categories [13]; UDI_fell short (UDI-f, 0-100 lux) indicate the time when required illuminance has to be maintained by artificial lighting, UDI_supplementary (UDI-s, 100-300 lux) indicate the time when artificial lighting needs to be added to the daylight to maintain required illuminance, UDI_autonomous (UDI-a, 300-3000 lux) indicate the time when the light level can be obtained by daylight alone and UDI exceeded (UDI-e, 3000 lux<) is associated with glare or overheating and indicate the time when solar shading might be needed. It might be a reasonable assumption that the IES threshold for satisfying daylight area of 55 % can be adopted for the UDI-a category as well.

Table 1: Selection of newly developed climate-based daylight metrics

Metric	**Information in the metric**	**Lower threshold [lux]**	**Upper threshold [lux]**	**Comment**	**Reference**
Daylight autonomy (DA)	Percentage of occupied time when a minimum work plane illuminance can be maintained by daylight alone.	500	-	Threshold commonly derived from standards for artificial lighting.	[14]
Useful daylight illuminance (UDI)	Percentage of work hours when daylight levels are useful for the occupants.	100	3000	Thresholds derived from literatu-re study on occupant preferences in daylit offices. Upper limit is associated with glare/overheating.	[13, 15]
Spatial daylight autonomy 300/50% ($sDA_{300/50\%}$)	Percentage of analysis area that achieves the illumination threshold of 300 lux for 50 % of the analysis period.	300	-	Target value of *300 lux* was derived from a survey with daylight experts and building occupants in 61 day lit spaces.	[16]

<u>Is there risk of glare?</u>

Nowadays, extensive use of computers in the working environment has become common. Consequently, the line of sight is more horizontal than for reading and handwriting tasks on the desk, which makes discomfort glare from windows a more considerable concern [17]. Discomfort glare produces discomfort without necessarily influencing visual performance and visibility and still there is a lack of knowledge about its underlying process [17].

At the present time there is no international accepted measure to evaluate the discomfort glare from windows and/or solar shadings. However, there are recommendations given in the literature [18, 19] towards use of the newly developed metric Daylight Glare Probability (DGP) [20]. One major drawback is that it might be very time-consuming to carry out an annual DGP analysis. In order to address this problem, Weinold [21] has developed and validated two simplified versions of DGP; (1) DGP simplified (DGPs) based on vertical eye illuminance and (2) enhanced simplified DGP based on vertical illiminance at eye in combination with a simplified image. The validation showed in general good results for the enhanced simplified DGP and reasonable results were seen for DGPs when no peak glare sources where present. In a design process, a glare analysis might be most suitable for the detailed design stage, both because the annual glare analysis is rather time-consuming and because glare is direction dependent and should be carried out at probable work stations.

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Calculation procedure

Early implementation of simulation tools are indispensable in order to make annual evaluations of horizontal illuminane and glare. Simulation tools based on validated and effective calculation engines should be used. Yet, it will be almost impossible at the present time to totally avoid the use of rules of thumbs and simple static calculations in the early design phase to make the first design proposal. Studies have shown that not all earlier published rules of thumb may be trustworthy or suitable for todays building design [11]. It is therefore important to use validated methods which yield reasonable results. Reinhart and LoVerso [11] have suggested a validated sequence of rule of thumb to come up with the first daylight scheme for sidelit rooms. This sequence is based on the DF, with all its limitations, and do therefore only consider the diffuse daylight. Further into the design, yet still early design phase, it will be necessary to implement use of simulation tools in daylight design in order to carry out climate-based modelling and reach a more integrated design approach.

Design proposal

Table 4 compresses a preliminary proposal for a daylight design in three levels of detail based on findings in the literature. Important features of the proposal are early implementation of simulation tools and adoption of climate-based daylight modelling from an early stage, which straightens integration with thermal comfort and energy analysis.

Table 2: Proposal of how daylight calculations and evaluations may be implemented as an integrated part of the building design based on findings in the literature.

Design stage	Proposed method	Daylight evaluation metric
Initial design	Use the validated rule of thumb sequence proposed by Reinhart and LoVerso [11] to draw up the first daylight scheem to find minimum required glazing areas; -initial assumtions regarding wall thickness, window head height, room width (w), mean surface reflectance (R_{mean}) and visual light transmittance (τ_{vis}) of the glazing have to be made. Use an effective simulation tool to check that the glazed areas are consistent with annual daylight requirements for UDI-a as well as for thermal comfort and energy use.	DF/UDI
Schematic design phase	Use a climate-based daylight simulation tool to verify the chosen glazed areas and glazing characteristics when use of solar shading is accounted for. In case of dynamic solar shading, use a simplified solar shading model and utilize UDI-e (3000 lux) as a threshold for activation of solar shading due to glare/ overheating. Exchange solar shading, lighting and occupancy profiles between daylight, thermal comfort and energy use predictive tools in order to achieve a model consistency for the integrated design.	UDI
Detail design phase	Keep using a climate-based daylight simulation tool, but if necessary make a more customised and product oriented simulation with respect to solar shading and installed lighting systems. Verify the daylight environmental quality with respect to useful daylight illuminance and glare.	UDI, DGPs/ DGPenhanced simplified

Test of design proposal

The design sequence is tested in design of a sidelit cellular office located in Oslo, Norway. It is assumed that the wall thickness is 500 mm (U-value= 0.10 W/Km^2) and that the glazing is placed in the middle of the wall, which gives an obstruction to the sky angle (θ) of approximately 10˚. Following room dimintions are set; floor to ceiling height = 2.75 m, window head height = 2.7 m and room width = 2.75 m. A glazing is selected with the characteristics; U-value=0.6 W/Km^2, g-value=0.49, direct solar tranmission=0.41 and visual light transmission = 0.71. Internal gains and values for heating, cooling and ventilation are set according to the Norwegian standard NS3701[22]. Table 3 gives the requirements set for indoor environment and energy use and Table 4 shows the results from the different steps of the design. Daysim [23] is utilised for the daylight analysis and IDA ICE [24] is used for the thermal and energy analysis.

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Table 3: Requirements for indoor environment and energy use.

UDI-a	≥ 50% for ≥ 55% of analysis area
Operative temperature (T_{op}) during occupant hour	21-26˚C
Total annual specific energy demand	<70 kWh/m^2 year
Spesific energy demand heating	<20 kWh/m^2 year
Spesific energy demand cooling	<10 kWh/m^2 year

Table 4: Test of proposed design

Initial design

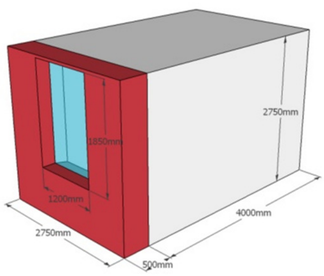
Rule of thumb sequence, for detailes see [11]:

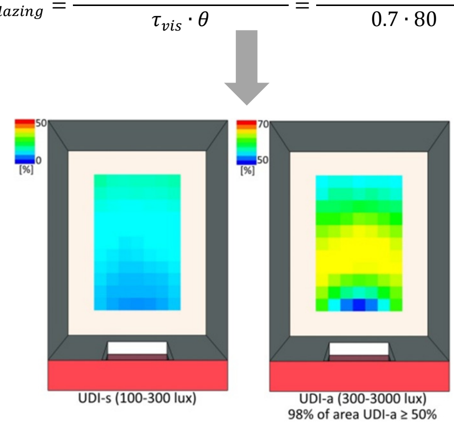
$$Window\ to\ wall\ ratio\ (\%) > \frac{0.088 \cdot DF}{\tau_{vis}} \cdot \frac{90^\circ}{\theta} = \frac{0.088 \cdot 2}{0.7} \cdot \frac{90^\circ}{80^\circ} = 0.28 \rightarrow OK$$

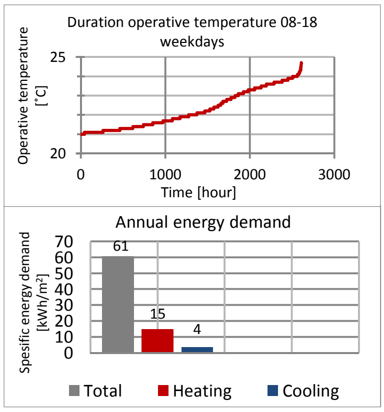
$$Depth\ of\ daylight\ area < minimum \begin{pmatrix} \frac{2}{1-R_{mean}} / \left(\frac{1}{w} + \frac{1}{h_{window-head-height}}\right) \\ (h_{window-head-height} - work\ plane\ height) \cdot tan\theta \\ 2 \cdot h_{window-head-height} \end{pmatrix} = \begin{pmatrix} \frac{2}{1-0.5} / \left(\frac{1}{2.75} + \frac{1}{2.7}\right) = \underline{\mathbf{5.4m}} \\ (2.7-0.8) \cdot \tan(80) = 21.7m \\ 2 \cdot 2.7 = \underline{\mathbf{5.4m}} \end{pmatrix}$$

Maximum depth of the daylight area is according to the rule of thumb 5.4 m. However, it is chosen to limit the depth of the cellular office to 4 m since this is a more reasonable size of a one person office; internal dimentions: 2,75m · 4,00m ·2,75m.

$$A_{glazing} = \frac{DF \cdot 2A_{total}(1-R_{mean})}{\tau_{vis} \cdot \theta} = \frac{2 \cdot 2 \cdot 61.8(1-0.5)}{0.7 \cdot 80} = \underline{2{,}2m^2}$$



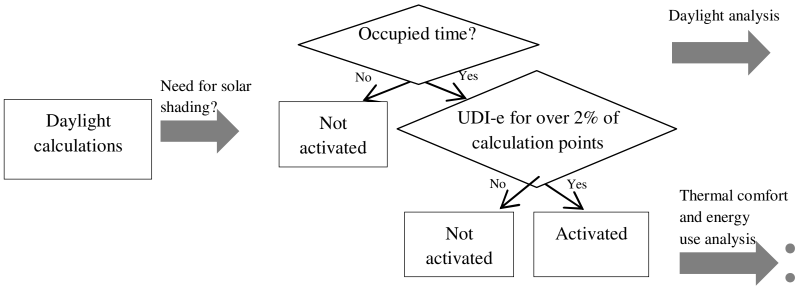


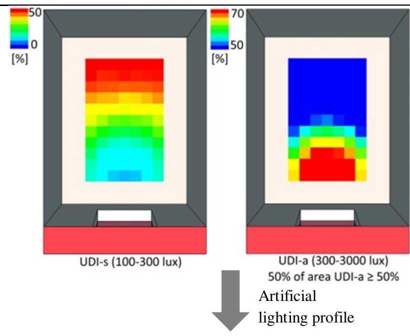


The initial design proposal satisfy the requirements for daylight, thermal comfort and energy use and is an acceptable design to develop further.Influence of consistent solar shading and lightig control will be evaluated in the following design stages.

Schematic design

A simplified model of dynamic solar shading is used in the daylight calculation which block all direct sunlight and transmitt 25% of the diffuse daylight.





- Min/max T_{op} 21˚C / 25.5 ˚C
- Total energy demand 59 kWh/m^2 year
- Heating demand 20 kWh/m^2 year
- Cooling demand 3 kWh/m^2 year

The daylight does not satisfy the requireent completely. Yet, the simplified solar shading model might underestimate the daylight supply when closed and it will therefore be tested in if a more sofisticated solar shading might increase the area of satisfying daylight. If not, glazing characteristics or glazing area should be revised.

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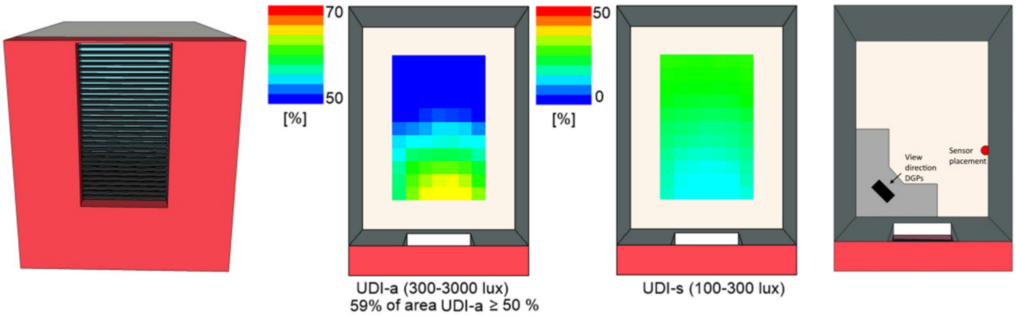
Detail design

It will be tested how a light grey external venetian blind system with a cut-off control strategy will influence the daylight, thermal comfort and the energy use. The solar shading is activated if external vertical irradiance>150 W/m^2 AND indoor air temperature> 24.5˚C OR if vertical illuminance>2000 lux at a sensor placed at the east wall behind the occupant work station at a height at 1.2 m. Since a cut-off strategy is used for the solar shading it is expected that peak glare sources will not be dominant and annual glare is evaluated according to DGPs.



Max **DGPs** for 95% of office time at working position = 0,39

- Min/max T_{op} 21˚C / 25.5 ˚C
- Total energy demand 56 kWh/m^2 year
- Heating demand 18 kWh/m^2 year
- Cooling demand 3 kWh/m^2 year

Visual and thermal environment is satisfying and energy requirement fulfilled.

Discussion and conclusion

The literature reveals that a significant amount of research is conducted within the field of daylight during the last decades. To obtain an integrated design it is essential to use the same underlying calculation assumptions of climate data and control strategies for solar shading and lighting in thermal comfort, daylight and energy use analysis. Based on findings in the literature a proposal is given of how daylight evaluations may be implemented throughout the building design. The design proposal has been tested in design of a cellular office located in Oslo, Norway and the results shows that the methodology might lead to a design with satisfying visual and thermal environment and low energy use. It is expected that use of the method might have implications on design of facades and room layout since e.g. problems of glare in rooms with large glazed facades or problems with insufficient daylight illuminance in the core of deep rooms might be discovered in an early design stage and poorly designed proposals might be reconsidered. In order for the proposed design method to be practical applicable for building designers, it needs to be implemented in a user-friendly integrated simulation tool. Additionally, more studies are needed to confirm the suitability of UDI and DGPs/enhaced simplified DGP as a future annual daylight and glare metrics.

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