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Detailed simulations of lighting conditions in office rooms lit by daylight and artificial light

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Ph.D. Thesis

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Preface

This thesis is submitted as a partial fulfilment of the requirements for the Danish Ph.D. degree. The first part introduces the research field, highlights the major findings and provides an overview of the work along with a discussion. The second part is a collection of papers which constitute the basis of the work and describe the work in greater detail.

Lyngby the 24th of February 2012

Anne Iversen

Life is lived forwards but understood backwards..
Soren Kirkegaard

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Abstract

In this thesis the effect on the annual artificial lighting demand is investigated by employing detailed simulations of lighting conditions in office rooms lit by daylight and artificial. The simulations of the artificial lighting demand is accomplished through daylight simulations in Radiance. The detailed simulations includes studies of the resolution of different weather data sets in climate-based daylight modeling. Furthermore, influence of the electrical lighting demand by simulating with dynamic occupancy patterns is studied. Finally the thesis explores the influence of obstructions in an urban canyon on the daylight availability within the buildings, and hence on the energy consumption for artificial lights.

The results from the thesis demonstrates that the effect on the outcome of the daylight simulations when simulating with typical weather data files for the location of Copenhagen is insignificant. Each of the different weather data sets where found to give a reasonable prediction of the lighting dependency. Furthermore the effect of simulating with weather data sets of an hourly resolution opposed to a one minute resolution showed that the lighting dependency was underestimated when using weather data sets of hourly means. However, the findings from this study show that the dynamic, short-term effects of the weather data applied, have a surprisingly small impact on the simulation outcome. At present, using values of hourly means for the daylight simulations is therefore a reasonable predictor for the lighting dependency.

Secondly, the thesis demonstrates that no real difference is seen in simulation results of the artificial lighting demand when the artificial lights are controlled automatically dependent on presence of occupancy and daylight level, applying occupancy profiles as annual average, hourly resolution or occupancy presence of two minute resolution. Comparison between the lighting demand for artificial lights by applying a diversity factor opposed to dynamic occupancy profiles showed a difference in lighting demand of 4 %, and the evaluation of the saving potential is therefore slightly conservative.

A simple method based on the vertical daylight factor, daylight factor and CIE overcast sky has been presented with the aim being to facilitate the urban design process. By looking at the influence of the surroundings on the daylight factor within the room followed by a categorization of the facades according to their daylight performance it is possible to point out urban areas that are good in terms of daylight inside the buildings and areas that have a poor daylight performance.

The results from the dynamic investigations of the influence of obstructions on the daylight availability show that in dense cities the orientation of the buildings has a minor importance. However, the results indicate that there is a preference for the northern orientations in terms of daylight availability at the lower floor plans. Using finishes of high reflectivity on the opaque part of the street facades increased the daylight penetration depth for the lower floor plan.

Resumé

I nærværende PhD-afhandling er behovet for kunstig belysning vurderet ved at anvende detaljerede simuleringer af lysforhold i rum oplyst vha. det naturlige dagslys og kunstig belysning. Undersøgelserne udgør en vurdering af tidsskridtets indflydelse når, dagslyssimuleringerne vurderes på årsbasis, og vejrdata anvendes som input til simuleringerne. Desuden vurderes behovet for kunstig belysning når der anvendes varierende tilstedeværelsesprofiler for brugerne af bygningen og automatisk dagslysstyring af den kunstige belysning. Derudover er der set på modståendes bygningers indflydelse på dagslysmængden i bygninger i bymæssige sammenhænge.

Resultaterne fra undersøgelserne viser, at der ikke er nogen signifikant forskel i det simulerede behov for kunstig belysning, når der anvendes tilgængelige typiske vejrdatafiler for København i de årlige dagslyssimuleringer. Desuden viser simuleringerne, at energibehovet til kunstig belysning underestimeres ved at anvende vejrdata med tidsskridt på 1 time i forhold til 1 minut. Dog viser resultaterne, at den dynamiske effekt ved at simulere med korte tidsskridt har en lille indflydelse på resultatet. Til at estimere det årlige energibehov til kunstig belysning kan simuleringer med tidsskridt på timebasis derfor give tilfredsstillende præcision.

Derudover viser undersøgelserne, at der ikke er nogen forskel i energibehovet til kunstig belysning ved at anvende tilstedeværelsesprofiler for personer som årsgennemsnitlige profiler, profiler der varierer for hver time og tilstedeværelesesprofiler i 2 minutters intervaller. Anvendes en tilstedeværelsesfaktor i forhold til en mere dynamisk betragtning af persontilstedeværelse overestimeres energibehovet til kunstig belysning med 4 %. Ved at anvende en faktor bliver besparelsespotentialet derfor vurderet en anelse konservativt.

Der er præsenteret en simpel metode, der sammenholder gadebredder og bygningshøjder med en vertikal dagslysfaktor på facaden og en dagslysfaktor beregning inde i rummet. Metoden kan anvendes som et redskab til at optimere byrum og placering af bygninger i den tidlige designfase af et byområde. Resultaterne fra de dynamiske dagslysberegninger af omgivelsernes indflydelse på dagslysmængden i bygningerne i en bymæssig sammenhæng viser, at for tætte bystrukturer har orienteringen af bygningerne en lille indflydelse på dagslysmængden i bygningen. Dog er der den tendens, at for tætte gader kommer dagslyset længere ind i rummet med den nordvendte orientering i forhold til sydvendt orientering, hvilket skyldes en forøgelse i det reflekterede lys fra den modstående sydvendte facade.

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Paper V

Additional work (not included in the thesis)

[1] Jørgensen M., Iversen A., Bjerregaard L.: 'Investigation of architectural strategies in relation to daylight and integrated design – a case study of three libraries in Denmark'. In press: *Journal of Green Buildings, 2012*

[2] Iversen A.: Co-author on 'Viden om Lys', on the topic 'Light and Energy'. *www.lysviden.dk*, expected to be published ultimo 2012

[3] Iversen A., Wille L.F., Nielsen T.R., Svendsen S.: 'Simulated influence of the surrounding buildings on the daylight availability in the master plan and on the working plane'. In proceedings: *Lux Europa, 2009, Istanbul (Turkey).*

[4] Iversen A., Laustsen J.B., Svendsen S., Traberg-Borup S., Johnsen K.: 'Udvikling af nye typer solafskærmningssystemer baseret på dagslysdirigerende solafskærmende glaslameller'. Published Report: *in series: (ISBN: 9788778772893) , 2009, Kgs. Lyngby*

[5] Iversen A., Nielsen T.R., Svendsen S.: 'Occupants' satisfaction with the visual environment in a single office with individual lighting and solar shading control'. In proceedings: *Indoor Air 2008.*

Part I

Introduction and summary

Chapter 1

Introduction

Over the years research has identified that daylight and sunlight in buildings is essential to good health and peoples well-being [Webb, 2006]. With the discovery of the 3rd photoreceptor in the eye by Berson et al. [2002] the light exposure is directly linked to the regulation of peoples circadian rhythms [van Bommel and van den Beld, 2004]. Today, however, people still spend up to 90 % of their times indoors [Leech et al., 2002] in buildings with much less light than our forefathers [Loe, 2009]. The development of the fluorescent light tube by GE Consultants in 1938 and the invention of air conditioning by Willis Carrier in 1928 influenced the building design. Until then, the natural light was the primary light source and inclusion of the natural light dictated the shape of the buildings. However, with the new technology it was now possible to lit, heat, and cool the buildings on demand inducing deeper floor plans and self-contained building units that excluded the context they were built in [Baker and Steemers, 2002] and the new technology increased the buildings energy consumption. Today, however, a growing need to create sustainable buildings has led to increased emphasis on daylit spaces in buildings that use lighting controls in order to reduce electrical energy needs. A daylit space is primarily lit by natural light and combines high occupant satisfaction with the visual and thermal environment with low overall energy use for lighting, heating and cooling [Reinhart and Wienold, 2011].

Globally, lighting consumes about 19 % of the total generated electricity [IEA, 2006]. It accounts for 30 % to 40 % of the total energy consumption in office buildings. The annual lighting electricity consumption per square meter of the building varies between 20 kWh/m^2 per year to 50 kWh/m^2 per year [IEA, 2010]. A recent literature review of the energy saving potential and strategies for electric lighting in future low energy office buildings in Northern Europe state that 80 % to 90 % of the environmental impact from lighting is generated during the operation of the lighting system [Dubois and Blomsterberg, 2011]. While the cost of an electric lighting installation typically represents 15 to 30 % of total costs, the electricity use during operation represents around 50 to 70 % of total costs [IEA, 2010, Dubois and Blomsterberg, 2011]. Furthermore another study indicated that investments in energy efficient lighting is one of the most cost-effective ways to reduce CO2 emissions [Enkvist et al., 2007]. Therefore, to enhance reduction of CO2 emissions while improving the energy consumption of buildings a large potential can be provided by cutting down the electricity usage during operation of the lighting systems, which can be accomplished using existing technology.

The effect on the annual lighting demand is investigated in this thesis by employing detailed simulations of lighting conditions in office rooms lit by daylight and artificial light. The most efficient way to keep down the electricity use for artificial light is to optimize the buildings in terms of daylight and employ control of artificial lights based on presence of occupants in conjunction with photoelectric dimming [Manicca et al., 1999, Jennings et al., 2000, Galasiu et al., 2007, DS/EN15193, 2007]. The detailed simulations include investigations of the resolution of different weather data sets in climate-based daylight modeling. Furthermore, influence of the electrical lighting demand by simulating with dynamic occupancy patterns will be investigated. Finally the thesis explore the influence of obstructions in an urban canyon on the daylight availability within the buildings, and hence on the energy consumption for artificial lights.

1.1 Aim and objective

The hypothesis of the project is that better estimations of the energy consumption for artificial lights in office buildings is achieved by applying detailed simulations of lighting conditions. With lighting conditions is meant a scene illuminated both by daylight and artificial light. Detailed simulations in this context refer to comparisons between a standard daylight factor calculation to dynamic annual simulation of the daylight availability, and hence on the energy demand for artificial lights when applying different lighting control strategies. Furthermore the detailed aspect include simulations of the influence of obstruction in a urban environment, both under standard overcast sky conditions and under 'real' sky conditions. The detailed aspect of the simulations is further divided into influence on the energy consumption for artificial lights when applying different weather data sets for the same location and weather data sets of different resolution in climate based modeling as well as the influence of occupancy patterns on the energy demand for artificial lights. Aspects on detailed simulation are discussed and analyzed in the thesis.

1.2 Thesis outline

A brief description of daylight, artificial light and energy requirements is given in chapter 2 together with a discussion of variables relevant for detailed simulations of lighting conditions.

Chapter 3 describes a base case for the office room studied in chapter 4 and chapter 5, where a standard CIE overcast sky daylight simulation is compared to climate based daylight simulations.

Chapter 4 focus on the research question: What effect have the different weather data sets and their resolution on the simulation results for the artificial lighting demand?

Chapter 5 discuss the modeling of occupancy and focus on the research questions: What effect has the resolution in occupancy patterns on the simulation results for the artificial lighting demand?

Chapter 6 focus on the impact on the surrounding city on the daylight availability within the room. The research question is: What effect has the surrounding city on the daylight availability within a building?

Finally a conclusion is given in chapter 7, followed by suggestions for future work in chapter 8.

Chapter 2

Background

2.1 Lighting requirements

In the European Standard EN12464-1 [2002] lighting requirements are determined by the satisfaction of three basic human needs: *Visual comfort*, where the workers have a feeling of well-being; *visual performance*, where the workers are able to perform their visual tasks and *safety*. Lighting should be designed to meet the lighting requirements of a particular task or space in an energy efficient manner. It is important not to compromise the visual aspects of a lighting installation simply to reduce energy consumption. Light levels as set in the European Standard are minimum average illuminance values and need to be maintained. Energy savings can be made by harvesting daylight, responding to occupancy patterns, improving maintenance characteristics of the installation, making use of controls, applying minimum possible power densities and using light sources with high luminous efficacy [EN12464-1, 2002, IEA, 2010]. Most standards and building codes specify desired levels of indoor illuminance levels for different work tasks. The illuminance level should either be maintained from daylight, artificial light or both. In the European Standard DS/EN15193 [2007] a uniform horizontal working plane illuminance is required, which might induce an over illumination and waste of energy as illumination is provided to locations not required. In Denmark, the use of the Danish Standard DS700 is mandatory for specifying light at work places. In this standard requirements to the lighting levels for office work is 500 lux on task, 200 lux in immediate surroundings, 100 lux in remote surroundings and 50 lux for general lighting [DS700, 2005]. This conscious division of task/ambient lighting is special for the Danish system [Dubois and Blomsterberg, 2011]. The approach of separating task and ambient lighting can allow for greater flexibility in the layout or use of the space since the work areas do not have to relate to a ceiling array of luminaires. Furthermore this approach can result in higher energy savings because high illuminance levels only are provided at locations where it is required. The task/ambient approach is not a new approach. According to Loe, this approach was already used in the early part of the 20^{th} century, when the electricity and equipment used for lighting was extremely expensive [Loe, 2009].

2.1.1 Energy consumption

The Danish Building code specify that the total energy consumption in an office must not exceed the value calculated by equation 2.1.1 where A is the heated floor area [BR10, 2010]. A building's total energy consumption is calculated as the energy used for heating, cooling, domestic hot water, ventilation and lighting where the consumption of electricity is multiplied by a site-to-source factor of 2.5.

$$\text{Energy frame} = \mathbf{71.3} + \frac{\mathbf{1650}}{\boldsymbol{A}} \qquad [\text{kWh/m}^2 \text{ per year}] \tag{2.1.1}$$

An office can be classified as a low-energy building class 2015 if its energy consumption does not exceed the value calculated by equation 2.1.2.

$$\text{Low-energy class 2015} = \mathbf{41} + \frac{\mathbf{1000}}{\boldsymbol{A}} \qquad [\text{kWh/m}^2 \text{ per year}] \tag{2.1.2}$$

In 2020 the total energy requirement to a low-energy class office building is 25 kWh/m^2 BR10 [2010]. These requirements must be kept in mind in the design phase of any building system. The Danish building code furthermore specifies a maximum luminous efficacy of the light sources of 50 lm/W. No specific demand is given to the installed lighting power density (LPD) of the lighting system. However in order to create low-energy buildings the LPD's cannot be too high. In the European Standard DS/EN15193 [2007] limits to the LPD are defined, ranging from 15 W/m^2 to 25 W/m^2, with 15 W/m^2 being the basic requirement and 25 W/m^2 being the comprehensive requirement with regard to visual comfort. The Danish Center for Energy Savings (Go'Energi) has published an on-line list of energy efficient lighting systems. Here the best practice system has a LPD of 3.6 W/m^2 for delivering 200 lux in an office room [www.goenergi.dk, 2011]. In table 2.2 the energy consumption for artificial lights is calculated for a single office and given as the LENI (Lighting Energy Numeric Indicator) number. The LENI number expresses the lighting's energy efficiency in the building. An annual time of usage of 2500 hours has been assumed. Different LPD's and reduction factors for a single office when applying; 1) manual lighting control with manual on/off switch (man), 2) occupancy control where the lights are automatically switched on when presence is detected and switched off no later than 15 min after the last presence is detected (occ) and 3) automatic occupancy and daylight control (day) are given according to their values in DS/EN15193 [2007].

Table 2.1: *Guidelines for installed LPD's, reduction factors and LENI number according to DS/EN15193 [2007], and best practice system according to www.goenergi.dk [2011]*

		LPD [W/m^2]	Reduction factors man	occ	day	LENI [kWh/m^2 pr year] man	occ	day
Room type								
Single	Comprehensive	25				50.0	37.5	19.7
office	Basic	15	0.80	0.70	0.53	30.0	22.5	11.8
room	Best practice	3.6				7.2	5.4	2.8

By comparing the calculated LENI numbers in table 2.2 to the energy consumption requirements of the low energy buildings it is obvious that low LPD's and control of the artificial lights has to be mandatory to comply with the energy requirements.

2.1.2 Daylight dependent artificial lighting control

A certain amount of daylight must be available in order to call a space daylit. Daylight levels of illumination will typically vary considerably over the room depth, due to distances from the window. For the artificial light, this means that the light, needed to supplement the lighting scene to maintain the required illuminance level, varies over the room depth. Therefore spaces have to be subdivided into daylight zones dependent on their daylight availability. In the Danish building code this is formulated as a requirement to zone division in offices of the lighting system dependent on the activities and daylight level [BR10, 2010]. To categorize a space as being well-lit, the Danish building regulation requires that the glazing area is 10 % of the heated floor area or that the daylight factor is 2% within the room. For 2020 low-energy offices the daylight factor has to be 3 % within the room in order to call a room daylit [BR10, 2010]. The daylight factor is defined under CIE overcast sky conditions as the ratio of the illuminance level at an upward facing working plane sensor point inside a space to an unobstructed external upward facing sensor point. Combining the daylight factor calculation for the different zones with accumulated daylight distributions and a lighting control scheme can give an estimate of the potential energy consumption for artificial lights for a given building zone. However the above named requirements based on the daylight factor evaluation are inconsistent with the time varying natural behavior of daylight. Therefore daylight availability metrics have been proposed, where the daylight availability evaluation is based on illuminance levels under the multiple sky conditions to be found during the hours of the year when a space is occupied. The daylighting metrics relevant for this thesis will be discussed in section 2.3.2.

2.1.3 Occupancy

Research show that occupants typically stay away from their workspace 25 to 50 % of a workday [Manicca et al., 1999, Wang et al., 2005, Page et al., 2008] and the switching of light based on occupancy can be considered as a varying dynamic incidence as occupants do not arrive in buildings or leave buildings at fixed times. Nevertheless, in simulation the most common way to consider presence of occupants is to have a static profile for weekends and weekdays [Hoes et al., 2009, Haldi, 2010]. In the European Standard DS/EN15193 [2007], presence of occupants are considered through a dependency factor. This factor depends on the lighting control system applied and the degree of absence of the room or building, and is empirically determined. In table 2.2 the absence factor determined at either building or room level is summarized for different office configurations. The absence factor reflects that zoning of building systems can have a significant effect on overall energy consumption. For example, small zones will clearly enhance the benefits of occupancy sensor controlled lighting; a smaller zone, i. e. a single workstation is vacated more frequently than a larger zone [Newsham et al., 1995, Littlefair, 2006]. This descriptive approach is appealing because designers and engineers hereby avoid to deal with the dynamic behavior of occupants by applying a simple and easily applicable factor.

Table 2.2: *Absence factors for different office configurations DS/EN15193 [2007]*

Building type Offices	F_A
Overall building calculation	0.2
Cellular office 1 person	0.4
Cellular office 2 to 6 persons	0.3
Open plan office $>$ 6 persons sensing/30 m^2	0
Open plan office $>$ 6 persons sensing/10 m^2	0.2

2.1.4 Obstructions

Obstructions reduce light incident on the facade and should be considered in daylight analysis of spaces. According to SBi-anvisning 219, obstruction angles above 20^o reduce the light within the room significantly [Johnsen and Christoffersen, 2008]. This obstruction angle corresponds to a height/width (H/W)-ratio of 0.37.

2.2 Daylight simulations

Daylight simulations are computer-based calculations, which aims to predict the lighting situation in a building under a specific daylight situation. Input to the program are typically information on building, info on the prevailing sky condition, simulation algorithm which calculates indoor illuminances and luminances based on the former two data.

For the investigations in this thesis daylight simulations are accomplished with Radiance [Larson and Shakespeare, 1998] and Radiance/Daysim [Reinhart, 2010]. Both Radiance and Radiance/-Daysim have been validated in various research papers [Mardaljevic, 1995, Reinhart and Walkenhorst, 2001]. The annual simulations made in chapter 3 to chapter 5 are based on the Three Phase Method, whereas the annual simulations in chapter 6 is made with Radiance/Daysim. Both the Three Phase Method and Radiance/Daysim employs a daylight coefficients (DC) approach which is a means to perform annual daylight simulations efficiently. In the daylight coefficient approach the sky is subdivided into patches whose partial contributions are computed independently [Tregenza, 1983]. Daysim was developed specifically for annual simulation using daylight coefficients in order to run annual simulations efficiently [Reinhart and Herkel, 2000]. Ward et al. [2011] developed a new DC method that separates the effect of the sky, window, transmission matrix of the window and the view, making annual simulations practical, even with complex, operable fenestration. Here, a matrix is used to characterize each phase of light transport. The input condition is a sky luminance vector. The result is either a vector containing illuminance values or a rendering. The result is achieved by multiplying the sky vector by each matrix representing each phase of flux transfer [McNeil, 2010, Ward et al., 2011]. This process is described by the following equation:

$$\boldsymbol{i} = \boldsymbol{VTDs} \tag{2.2.3}$$

where,
V is the view matrix, relating outgoing directions on window to the desired results at interior
T is the transmission matrix - the Bi-directional Scattering Distribution Function (BSDF)
D is the daylight matrix, relating sky patches to incident directions in window
s is the sky vector, assigning luminance values to patches representing sky directions.

The **V** and **D** matrices are created with the *rtcontrib* tool within Radiance simulation. The **T** matrix can be created using Window6, by simulation (ie TracePro or Radiance *genBSDF*) or can be measured with a goniophotometer. For the investigations in this thesis, the BSDF is generated with Window6 and is a standard glazing unit, with light transmittance of 72 %. The **s** vector is generated from a Radiance sky description as described in Jacobs [2010].

2.3 Aspects of detailed daylight simulations

The energy consumption for artificial lights, and a rooms lighting dependency, are influenced by a number of parameters such as; i.e. building geometry, weather data applied, sky simulated, occupancy patterns, control system applied for the lighting system and operation of solar shading. In the following the parameters will be discussed from a 'detailed' point of view.

2.3.1 Overcast vs. 'real' sky simulation

The daylight level is typically evaluated based on the conventional static daylight factor method together with cumulative daylight distributions. The daylight factor evaluations is a 'snapshot' evaluation of the daylight conditions excluding the climate, orientation and sun in its evaluation. During the last decade, research in the field of daylighting, have discussed the shortcomings of this method [Nabil and Mardaljevic, 2005, Mardaljevic, 2006, Reinhart et al., 2006, Mardaljevic et al., 2009]. However, still, the good practice evaluation method for daylight in national standards (i.e. [BR10, 2010, BS8206-2:2008, 2009]) is the daylight factor method. In 2006, Mardaljevic addresses this 'because of its simplicity rather than its capacity to describe reality' [Mardaljevic, 2006]. In studies of Mardaljevic [2000] and Reinhart and Herkel [2000], they demonstrated that reliable predictions based on hourly climatic data are attainable when applying the Climate-Based Daylight Modeling principle (CBDM). "CBDM is the prediction of various radiant or luminous quantities (e.g. irradiance, illuminance, radiance and luminance) using sun and sky conditions that are derived from standard meteorological data sets'" [Mardaljevic, 2006, BS8206-2:2008, 2009]. The meteorological datasets are derived from a longer measurement period and they are structured to have the same properties as the measured data, with averages and variations that are typical for the site. CBDM thereby includes the dynamic effects of daylight described in the meteorological data files like changes in cloud cover, variations over time and seasons. The CBDM approach is based on available weather data, which means that the weather data used as input to the daylight simulations is of great importance.

In chapter 3 the daylight conditions will be evaluated for a reference case following the conventional static daylight factor approach. This case will constitute a benchmark for the further evaluations. In chapter 4 a more detailed comparison of the daylight simulations is investigated if the designer uses one of the available weather datasets that typically will be applied for building simulation in practice. Furthermore the effect of using data with an hourly resolution compared to a 1 min resolution is investigated (Paper I).

2.3.2 Climate-based daylighting metrics

Yet, there is no demand of applying climate based metrics in the daylight simulations. One climate based metric is the Daylight Autonomy (DA) proposed by Reinhart and Walkenhorst [2001]. The DA describes the percentage of occupied hours per year when a minimum work plane illuminance threshold can be maintained by daylight alone. According to a recently published paper by Reinhart and Weissman [2012] a draft document concerning a new lighting measurement protocol from the Daylighting Metrics committee of the Illuminating Society of Northern American (IESNA), considers a point to be "daylit" if the daylight autonomy exceeds 50 % of the occupied times of the year at an illuminance threshold of 300 lux.

For the evaluation of the lighting demand in chapter 3 to chapter 5, the presented results are based on the Lighting Dependency (LD). LD defines the percentage of the occupied hours per year when electrical light has to be added to the lighting scene to maintain a minimum work plane illuminance threshold. In its nature the LD is the reverse of the Daylight Autonomy. A LD of 100 % represents a case where the lights are switched on for the entire occupied hours. This could i.e. be the case in the core zone of a building, where no daylight is present and no occupancy control is applied.

For an on/off lighting system with photoelectric dimming the LD describes the relative energy consumption for delivering light to the room excluding energy consumption of the ballast and control system. The energy savings can therefore directly be read from the difference in the LD compared to a reference case, where the lights are on the entire occupied hours. The energy consumption can be calculated by equation (2.3.4).

$$\boldsymbol{E = LD \cdot P_{installed} \cdot n_{\textbf{hours of usage}}} \qquad [Wh/m^2] \tag{2.3.4}$$

$\boldsymbol{LD}$ is the Lighting Dependency, $\boldsymbol{P}$ is the installed power [W/m^2] and $\boldsymbol{n}$ is the hours of usage. However the LD does not consider the hours where daylight below the threshold value is present and still would contribute to the perceived visual environment and result in energy savings if a photoelectric dimming system was installed. Rogers formulated the Daylight Saturation [Rogers, 2011] or Continuous Daylight Autonomy (DA_{con}) where daylight levels below the threshold are credited with a relative weight dependent on the ratio between the amount of available daylight ($E_{daylight}$) and the indoor threshold illuminance level ($E_{threshold}$)[Rogers, 2006]. Similarly the artificial light contribution in an ideal photoelectric dimming system can be described when the daylight threshold is not maintained during working hours by a continuous lighting dependency.

$$\boldsymbol{LD_{con} = 1 - \frac{\sum_{i=1}^{T} \frac{E_{daylight}}{E_{threshold}}}{T_{\textbf{time steps}}}} \qquad \Big| \quad E_{daylight} < E_{threshold} \tag{2.3.5}$$

$\boldsymbol{T}$ is the investigated time steps.

2.3.3 Occupancy

Control of lights based on presence of occupants can be considered as a varying dynamic incidence as occupants do not arrive in buildings or leave buildings at fixed times. To consider the dynamic, natural behavior of occupants different occupancy models have been suggested based on empirical data, i.e. Delff et al. [2012], Tabak and de Vries [2010], Page et al. [2008], Richardson et al. [2008], Wang et al. [2005], Reinhart [2004], Newsham et al. [1995], Hunt [1979]. The models can be grouped in models describing presence/absence of occupancy solely [Delff et al., 2012, Page et al., 2008, Richardson et al., 2008, Wang et al., 2005] and models also including behavior as probabilities of the manual on/off switching of lights and operation of blinds [Bourgeois, 2005, Reinhart, 2004, Hunt, 1979] or intermediate activities of the occupants [Tabak and de Vries, 2010].

The occupancy models developed in Tabak and de Vries [2010], Page et al. [2008], Richardson et al. [2008], Wang et al. [2005], Newsham et al. [1995] and Hunt [1979] all focus on modeling arrival and departure of occupants in office buildings or dwellings. The models of Wang et al. [2005] and Richardson et al. [2008] are occupancy models developed as first order markov chains. Wang et al. [2005]'s data fits very well with the exponential distribution when observing individual offices and vacant intervals. However the exponential model was not validated for occupied intervals. In the study of Page et al. [2008] they tried to overcome this limitation by modeling the occupancy as an inhomogeneous markov chain and introducing a mobility parameter. This parameter gives an idea of how much people move in an out of the zone, by correlating the desire for being at work with the desire of going home. The model developed in Delff et al. [2012] (Paper II) proposes a new way to estimate occupancy by fitting presence of occupants with inhomogeneous markov chains with generalized linear models of splines and exponential smoothing of past observations. The model is capable of predicting a realistic scenario for the presence of occupants throughout a working day. The model overcomes the limitations in i.e. Wang et al. [2005], by being able of modeling both presence and absence of occupants, without introducing a mobility parameter, which was suggested in the paper by Page et al. [2008]. Other studies have sought to capture the dynamic sequences of each occupant. The original LIGHTSWITCH model developed by Newsham et al. [1995] intended to capture these dynamics. The LIGHTSWITCH model operates with three different probability profiles: 1) arrival probability, 2) departure probability and 3) a probability of temporary absence, with peak at noon. However, in the PhD thesis of Reinhart and Walkenhorst [2001] he found that the model did not comply with measured data.

Except from applying absence factors the mostly used occupancy model in lighting simulations is the Lightswitch-2002 model implemented in Daysim [Reinhart, 2004, 2010]. According to Reinhart [2004] the Lightswitch-2002 model has been developed based on the same ideas as Newsham's original model, i.e. to predict electric lighting use based on behavioral patterns which have all been observed in actual office buildings. For now, the simulated presence of occupants in Lightswitch-2002 can be profiles with constant presence during the occupied hours where arrivals and departures are randomly scheduled in a time interval of ±15 min around their official starting times to add realism to the model [Reinhart, 2004]. Furthermore, dependent on the length of a working day breaks can be added to the occupancy profile. If the working day is less than 3 hours long, the user leaves the work place once for a 15 minute break. If the working day is between 3 and 6 hours long, the user leaves the work place twice for 15 minute breaks. If the working day is longer than 6 hours, the user leaves for two 15 minute breaks and a 60 minute lunch break [Reinhart, 2010]. Even though the occupancy model in Lightswitch-2002 has some randomness in its routine, the model is not capable of modeling the dynamic sequences of occupants throughout a year. Furthermore the model does not consider temporary absence shorter than 15 min. The Lightswitch-2002 model was applied in whole building simulation in the PhD thesis of Bourgeois [2005]. Here he investigated the influence on the lighting demand when having a fixed occupancy profile, where the lights were always on compared to cases with manual control of the artificial lights and automatic control of the artificial lights. Not surprising, he found that introducing occupancy profiles to the building simulations, the energy consumption for artificial lights decreased. The manual control decreased the energy consumption up to 62 % and a further reduction of 50 % could be achieved by automatic control. However, the influence of resolution of occupancy patterns was not investigated. Resolution is important when using simulation programmes, as simulation time increases with resolution. Therefore the lowest resolution which still yield a correct result is of interest, when evaluating the lighting performance of a space on an annual basis. In chapter 5 the effect on the artificial lighting demand will be investigated by applying occupancy models of different resolution to the Climate Based Daylight Modeling (CBDM) (Paper III).

2.3.4 Solar shading

The windows in a building constitute a light source and as with all other light sources these should be designed to meet the requirements to visual comfort and energy consumption. Usually some form of solar shading is provided to the windows to reduce solar heat gains and to enable occupants to eliminate discomfort experienced when they have a direct view of the sun or bright sky [Boyce, 2003]. In very daylit spaces the actual savings from the lighting systems strongly depend on the use of the solar shading. However, in this thesis solar shading has not been employed, based on the rationale that when solar shadings are applied the overall lighting level will decrease, and less fluctuations in daylight over the day and room depth might be expected. When investigating the influence of resolution of weather data and occupancy profiles, the effect of employing automatic solar shadings on the result is therefore assumed to be minimal. However applying solar shadings will of course increase the lighting demand.

2.3.5 Obstructions

For decades, the focus has been given to optimization of the individual buildings and its various daylight systems, operation, and maintenance. By considering buildings isolated from the context they are built in the interaction between environment and building's daylight performance is ignored. Hereby, daylight condition in buildings and the city's urban elements become two unrelated sizes. Overall, simulation models are not integrated in the early planning stages, because it has been customary to leave the building physics of each individual building to the later design stages. However, access to daylight is inevitably for creating social spaces, well-lit environments, and reduction in energy consumption for artificial lights and heating/cooling. Optimizing the urban plan in terms of daylight is therefore of major importance since daylight cannot be added to a lighting scene just like i.e. fresh air can be supplied from ventilation systems. This fact was already acknowledged by the ancient Greeks and Romans. They mandated minimum lighting standards for their cities. The British Law of Ancient Light (which dates to 1189) and its later embodiment into statute law, The Prescription Act of 1832, provided that if a window enjoyed uninterrupted access to daylight for a twenty year period, right to that access became permanent [Bryan et al., 1981].

The effect of obstructions has been described in various research papers. Previous research on daylight availability has focused on the solar irradiation and illuminance levels on the urban fabric. Compagnon [2004] looked at the solar irradiation on the urban fabric (roofs and facades) in order to assess the potential for active and passive solar heating, photovoltaic electricity production and daylighting. Nabil and Mardaljevic [2005] also looked at the irradiation on the urban fabric and used an image-based approach to generate irradiation "maps" that were derived from hourly time-series for one year. The maps can be used to identify facade locations with high irradiation to aid, e.g., in positioning of photovoltaic panels. Most recently, Kaempf and Robinson [2010] applied a hybrid evolutionary algorithm to optimize building and urban geometric form for solar radiation utilization. These studies only investigate the urban design from external environmental impact.

Nevertheless, there have been some investigations that link the exterior radiation/illumination to interior daylight availability. In a study by Li et al. [2009b], they introduced the vertical daylight factor (VDF) and demonstrated that daylight is significantly reduced in a heavily obstructed environment. A study of VDF predicted by RADIANCE simulation demonstrates that by comparing an upper obstruction at 60° and a lower obstruction at 10° the daylight level is reduced by up to 85 %. The results also indicate that the reflection of the obstructive buildings can be significant in heavily obstructed environments, such as rooms on lower floor levels facing high-rise buildings. In another study by Iversen et al. [2011] (Paper IV), they looked at the influence of the surroundings on the daylight factor within the room followed by a categorization of the facades according to their daylight performance, with the aim being to facilitate the design process aiding to point out urban areas that are good in terms of daylight inside the buildings and areas that have a poor daylight performance. In a study by Strømann-Andersen and Sattrup [2011] they showed the effect of height/width ratio (elevation of an obstruction), on the energy demand for artificial light. The effect is quite strong: for example, for an obstruction with a height/width ratio 1.0 (equal to an elevation angle of 45°), the lighting energy demand can be increased by up to 85 % compared to free horizon.

2.4 Aspects of control of artificial lights

The main purpose of most lighting systems is to provide illumination for the tasks in a space. Lighting controls are installed to reduce energy consumption for artificial light and/or to provide means of adjusting the lighting conditions to ensure individual comfort and/or to ensure safety.

2.4.1 Control types

The controls can be either discrete or continuous in that the light output of the electrical lighting system can either be switched or dimmed. Dependent on control type, factors that affect how the lights will be controlled can be; arrangement of furniture and partitions, surface reflectance, direction of incoming daylight, use of task lighting, positions of occupants and the location and direction the photosensor faces. The three principal control types: Time switches, photosensor dimming, and occupancy sensors [Boyce, 2003] will be described in the following. They all have the potential to save energy by minimizing the electric lighting load when there is no one present or there is an alternative light source available. Furthermore they all have in common that they are automatic and therefore do not consider the natural behavior of occupants. Therefore it is of paramount importance in order to have a successful automatic control of the artificial lights that the system is correctly installed.

Time switching

Time switches switch lights between states at determined times. The most commonly used states are simply on and off, however intermediate levels are sometimes used as well. Time switching is typically applied in buildings where it is possible to predict when the lighting is not needed.

Occupancy sensing control

Occupancy sensing control systems switch lights on in a space when motion is detected, then switch lights off if no motion is detected after a preset interval has elapsed.

Commercial buildings typically use PIR or ultrasonic or PIR/ultrasonic hybrid sensors for lighting control applications. Sensors that use microwave and passive acoustic technologies are also available, but they are not used as often. Other systems that use video cameras or biometric identification may provide higher resolution for occupant identification and localization; however, at the present time, these are primarily used in security and alarm applications. The different occupancy sensing control types are nicely described and summarized in the review of Guo et al. [2010].

Table 2.3 provides a comparison of the different systems described in the paper of Guo et al. [2010] in terms of 'resolution' and initial cost. 'Resolution' is defined as whether or not the system can measure the number of occupants in a space, identify and localize individuals in a space. The resolution of the sensors currently used in building energy management is low: they can only roughly tell if a space is occupied, but cannot provide information about the number and identification of occupants, or where they are located in a space. Video camera and biometric systems have high resolution, but they are more expensive, and might be considered an intrusion of privacy. Spatial localization of individuals is important in security; for example, a rescue action would be more effective if occupant location was known. Initial cost is also an important factor in sensor selection, and selection will be a compromise between function and price.

Table 2.3: *Comparison of current occupancy sensing technologies [Guo et al., 2010]*

Type of sensor	Resolution	Number of occupants	Person identification	Person localization	Initial cost
PIR	Low	No	No	No	Low
Ultrasonic	Low	No	No	No	Low
Microwave	Low	No	No	No	Low
Sound	Low	No	No	No	Low
Light barriers	Low	Yes	No	No	Low
Video	Very high	Yes	Yes	Yes	High
Biometric	High	Yes	Yes	No	High
Pressure	Low	No	No	No	Medium

Photoelectric control

A photosensor is an electronical device that adjusts the light output of a lighting system based on the amount of light sensed at a particular location. Some photosensors switch lights on and off, while others, in conjunction with dimming electronic ballasts, adjust the light output of lighting systems over a continuous range. Photosensors are classified based on where they are located and how their signal is used to adjust the electrical lighting. The classification has two main categories referred to as either open or closed-loop design. In an open loop system the photosensor is not influenced by the lighting that it is controlling, it has therefore no feedback. In a closed loop control system the photosensor is influenced by the lighting that it is controlling, this system therefore has feedback. Some photosensors are used to control the electrical lights based on the amount of daylight entering a space, an application often called daylight harvesting. Other photosensors attempt to maintain the output of light fixtures at a constant level to, e.g. compensate for lamp and dirt depreciation effects. And some simply switch lights on at dusk and off at dawn [NLPIP, 2007].

In NLPIP [2007] it is stated that only a small fraction of lighting installations use photosensor controls. The report summarizes three principal barriers for which reasons photosensors are seeing limited application:

1) The actual energy savings that photosensors can achieve is difficult to predict due to significant variations in building designs, weather conditions, and occupants' needs and behaviors. Without reliable, predictable cost savings, it is often difficult to justify the purchase of photosensor controls

2) Unlike motion sensors which do not affect the lighting when people are present, photosensors adjust the lighting when people are present. Occupants may not like the light being adjusted automatically, so adjusting the lights to save energy while people are present demands careful consideration and a high level of reliability in order to meet occupants' expectations and avoid complaints

3) Anecdotal reports and past experiences of difficulties in installing and adjusting photosensors properly may have limited many specifiers' willingness to use them.

Furthermore Boyce [2003] summarizes four factors that make it difficult to achieve the possible energy savings from automatic controlled lights in practice:

1) Wide differences in individual preferences for illuminance at which dimming starts, thereby reduce the potential for energy savings.

2) The inertia in the use of window blinds used to control glare from the sun and sky means that the daylight available may be less than expected.

3) The commissioning of the control system is not simple partly because of the frequently unknown control algorithm of the systems.

4) Photosensor dimming systems are more expensive than more simpler control systems.

Chapter 3

Static daylight calculations

To represent the standard daylight evaluation of a space, the daylight factor method has been applied to the room studied in this thesis in chapter 4 and 5.

3.1 Simulation model

For the investigations the indoor illuminance level is simulated at two locations in the southward-orientated room; one in the front, 1 m from the facade, and one in the back of the room, 5 m from the facade. The geometry and photometrical properties of the room corresponds to the daylight laboratory at the Danish Building Research institute (SBi). A sketch of the test office is seen in Figure 1. The reflectances (r) of the surfaces in the room are; $r_{wall} = 0.62$, $r_{ceiling} = 0.88$ and $r_{floor} = 0.11$. The light transmission of the window system is 72 %. The office is placed on a plinth 7 m above ground level

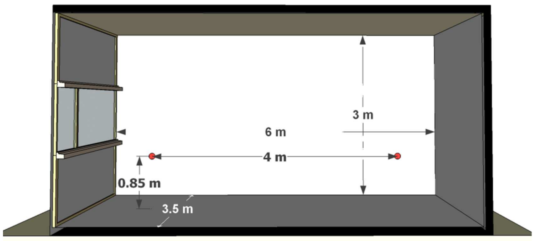


Figure 3.1: *Sketch of the simulated model*

3.2 Comparison between static and dynamic daylight simulations

The daylight factor evaluation represents the conventional way of evaluating daylight conditions in a space. The daylight factor calculation uses the CIE standard overcast sky, and thereby excludes any information of orientation and climatic location and conditions in its calculation. By combining the daylight factor and the external diffuse horizontal illuminances an estimate of the daylight levels within the room and hence the energy consumption for artificial lights can be obtained.

It is possible to estimate the cumulative internal illuminance by multiplying the external cumulative illuminance with the daylight factor value [Mardaljevic, 2000]. This gives cumulative internal diffuse illuminances as shown on Figure 3.3.

From the cumulative graphs the lighting dependency (LD) has been calculated in the front and in the back of the room. The lighting dependency has been calculated both for the on/off strategy,

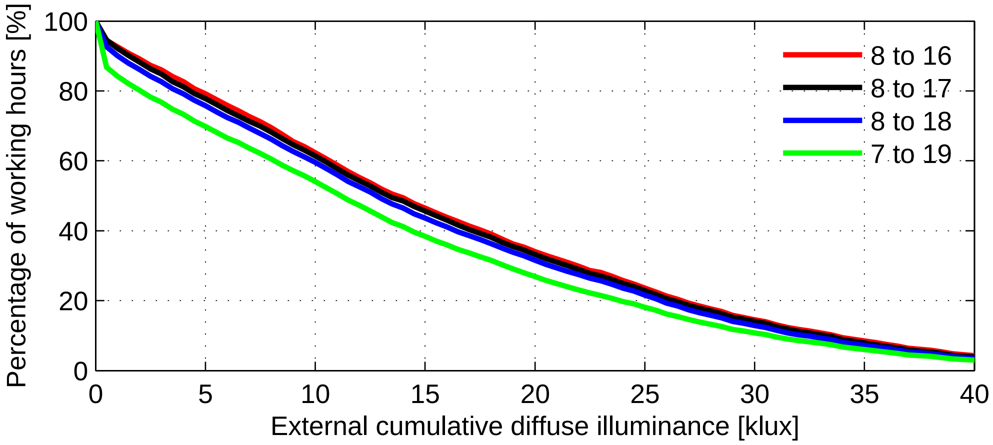


Figure 3.2: *External cumulative diffuse illuminance for the location of Copenhagen at different occupied time intervals*

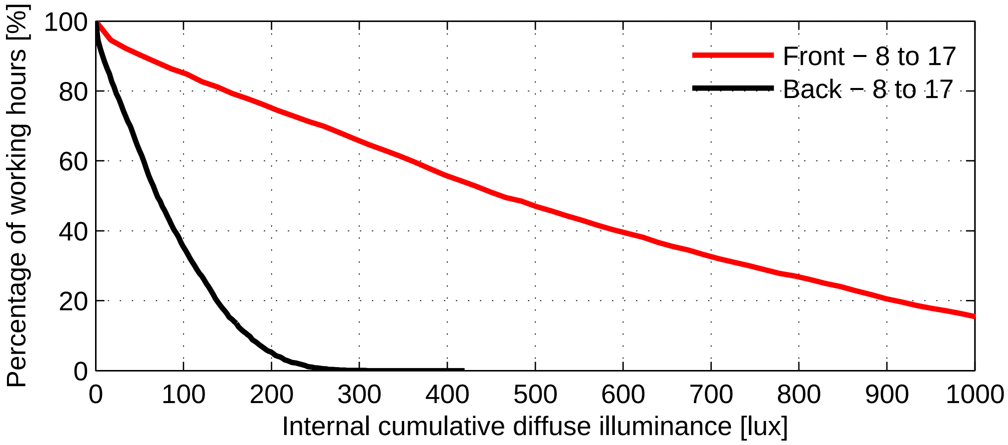


Figure 3.3: *Internal diffuse illuminance in the front and in the back of the test room for the location of Copenhagen from 8:00-17:00*

where lights are switched on, when the threshold illuminance is not reached and for the continuous dimming strategy (con), where the light output tops up to obtain the target illuminance level. The lighting dependency of the room is then determined as the average of the lighting demand in the front and in the back of the room. The calculated lighting dependencies of the test room, based on the static daylight factor approach is given on figure 3.4 along with lighting dependencies for the CBDM-approach for the same room located in Copenhagen with northern and southern orientation.

In Mardaljevic [2000] comparisons between the cumulative illuminance obtained from the standard daylight factor approach to the climate based approach showed that the daylight factor approach underestimated the daylight levels within the room for southern orientated rooms. For rooms facing north the situation is reversed, here the daylight factor approach overestimates the illuminance values compared to the climate based approach. The results for the room studied in this thesis in chapter 4 and 5 show the same trend. However for the northern orientation with the automatic on/off control strategy the lighting dependencies are almost similar. For the southern orientation the lighting dependencies obtained from the CBDM-approach are 20 % lower than the DF-approach. The results

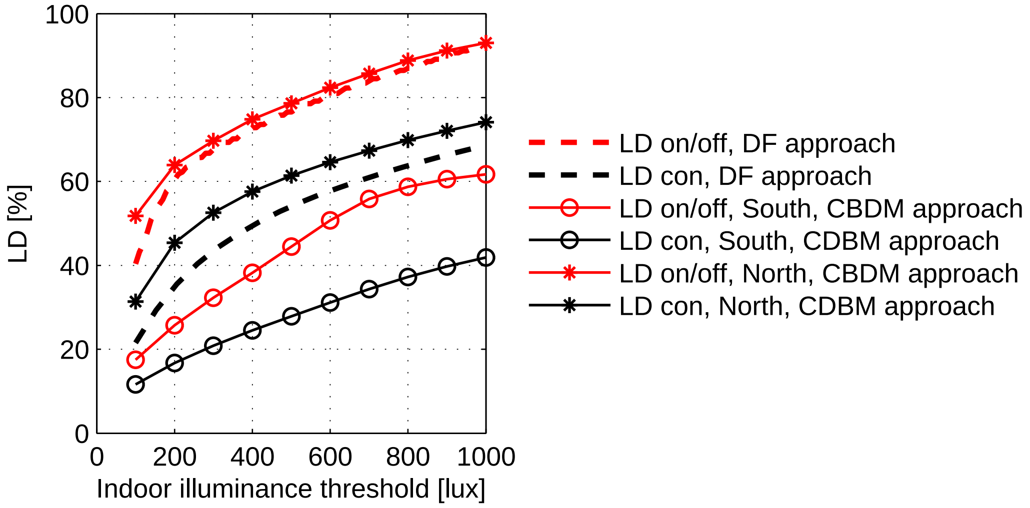


Figure 3.4: *Lighting Dependency for on/off and continuous control based on the daylight factor approach and climate based daylight modeling approach for northern and southern orientation*

are given for a situation when no solar shading is employed. The results therefore describes the saving potential for the optimum solution in terms of daylight availability. However, some kind of solar shading should be employed for the southern orientation to be able to control for both thermal and visual comfort. If the solar shading only blocks the part of the window which causes the discomfort seen from the occupant, then this saving potential might be achievable. If, on the other hand, traditional solar shadings are applied that obstruct the entire window when occupants experience discomfort from high luminances in the field of view or illuminance level at the eye level, then the lighting dependency increases. Therefore, to investigate the performance of a non-trivial shading solution more detailed simulations of the system has to be applied.

Chapter 4

Weather data sets and their resolution in climate-based daylight modeling

In this chapter the effect on the outcome of the daylight simulations is investigated if the daylight simulations are made with different weather data sets for the same location, and if the daylight simulations are made with different resolution, i.e. hourly resolution which is the standard resolution of most weather data sets and a more dynamic one minute resolution (Paper I).

The two hypotheses to be tested in this chapter are:

1. Simulations with different weather data sets for the same location will have an insignificant influence on the estimation of the energy consumption for artificial lights

2. With the artificial lights being automatically controlled, simulations with one minute resolution compared to 1 hour resolution will have a significant impact on the energy consumption for artificial lights.

The first hypothesis will be tested through simulations with different weather data sets for the location of Copenhagen. The data sets represents typical weather data that are applied for building simulation in practice. The second hypothesis will be tested through comparisons between daylight simulations with resolution of hourly means and one minute means for different climatic locations.

The results show that the effect on the outcome of the daylight simulations when simulating with different weather data files for the location of Copenhagen was insignificant. It was found that the lighting dependencies generated based on the different weather data files for Copenhagen varied up to 2 % dependent on the chosen indoor illuminance threshold. Each of the different weather data sets where therefore found to give a reasonable prediction of the lighting dependency. Furthermore the effect of simulating with weather data sets of an hourly resolution compared to a one minute resolution showed that the lighting dependency was underestimated when using weather data of hourly means. However, the findings from this study show that the dynamic, short-term effects of the weather obtained from the modified Skartveit-Olseth method implemented in Daysim Reinhart [2010], have a surprisingly small impact on the simulation outcome. In terms of control of artificial lights no distinct difference in simulated lighting dependencies was found when applying continuous dimming for each one minute time step compared to the PI control with the response averaged over the past 10 min. At present, using values of hourly means for the daylight simulations is therefore a reasonable predictor for the lighting dependency.

4.1 Methodology

4.1.1 Evaluation methods

The presented results are based on the Lighting Dependency (LD) described in section 2.3.2. In this study an ideal closed loop control is considered, based on the illuminance level striking a sensor point on the working plane in the front and in the back of a room. The lighting dependency of the room is then given as the average of the lighting dependency at the two sensor points.

In reality, the lights will be controlled after a sensor signal, which could be illuminance, dependent on the detection area and calibration of the sensor. As the scope of this study is to investigate the effect of different weather data files and time step resolution on simulation outcome, the distinction between 'real' and ideal control is beyond the scope of this study. For the automatic dynamic control of the artificial lights four different control strategies have been applied. 1) Photoelectric switch on/off for each time step, as illustrated by LD, 2) Photoelectric dimming, as illustrated by LD_{con} (Proportional response), 3) Photoelectric dimming for every 10 min, $LD_{con,10min}$ and 4) Proportional integral dimming, where the response is averaged over the past 10 min (LD_{PI}). It is assumed that the relationship between the light output and sensor signal is linear.

4.1.2 Weather data

Weather data for a large number of locations across the world are available for download from several websites. The weather data are derived from a longer measurement period and they are structured to have the same properties as the measured data, with averages and variations that are typical for the site.

Design Reference Year (DRY) The Design Reference Year (DRY) consists of data describing the external climatic conditions compiled from 12 typical months for a given location. The irradiance values in DRY for Copenhagen are compiled from 15 years of measurements made at the measurement station at Landbohoejskolen, Taastrup [Jensen and Lund, 1995]. A research project has just been initiated with the focus on generating a new DRY taking into account climate changes.

Meteonorm For the available weather data from Meteonorm the daily and hourly global radiation values are generated from monthly average values by the stochastic TAG-model (Time dependent, Autoregressive, Gaussian model) [Aguiar and Collares-Pereira, 1992]. From the global radiation the direct and diffuse components are deduced following the method of Perez et al. [1991], where they convert the hourly global irradiance to direct irradiance values. The irradiance data for Copenhagen are measured at the Technological Institute in Taastrup and Lund University and interpolated values from these two stations are the basis for the weather data set. The measurement period was from 1981 to 2000. Uncertainties given for all sites are the same: 10 % for global irradiation and 20 % for beam irradiation [Remund et al., 2010].

Energy Plus Weather data is available from the Energy Plus home page courtesy of the US Department of Energy Plus [EnergyPlus]. The data is derived from 20 different sources from all over the world. For Denmark, the data are generated from the IWEC (International Weather for Energy Calculations) file for Copenhagen. 227 locations outside the U.S. are available in the IWEC weather files that were developed under the ASHRAE research project RP-1015 [Thevenard and Brunger, 2002]. The IWEC files are 'typical years' that normally stay away from extreme conditions [ASHRAE, 2001]. The data are generated based on measurement period from 1982 to 1999. From these 18 years, twelve typical months were selected using the Typical Meteorological Year procedure, and were assembled into a 'typical' file. The Kasten model [Davies and McKay, 1989] is used for calculating global solar radiation and the output is then fed to the Perez et al. [1992] model for the calculation of diffuse and direct radiation. The largest distance allowed between the radiation measurement station and the location of the site was 50 km [ASHRAE, 2001]. The IWEC files are categorized based on how well the solar radiation model performs. For the locations analyzed in this study the category is 1, which implies that the performance is satisfactory and can be used with confidence [ASHRAE, 2001].

One minute simulation time step

In a study by Walkenhorst et al. [2002] it is concluded that neglecting the short-term dynamics can introduce substantial errors in the simulation of the specific annual electric energy demand for automated control strategies of artificial lighting systems. In the study they implemented a modified Skartveit-Olseth method [Skartveit and Olseth, 1992] to create one minute irradiance data from hourly means. Both the DRY and the Energy Plus files have been converted to annual one minute irradiance values from the hourly weather data files following the stochastic modified Skartveit-Olseth model implemented in Daysim [Walkenhorst et al., 2002, Reinhart, 2010]. The only required input data are the site coordinates, elevation and hourly irradiance data. In Walkenhorst et al. [2002] they investigated the non-deterministic influence of the stochastic model on the simulation outcome and they found that the impact is negligible. The relative standard deviation of the specific annual electric energy demand for artificial lighting resulting from ten different realizations of the model newer exceeds 0.7 %. Therefore one single realization of the model should yield sufficient simulation accuracy [Walkenhorst et al., 2002].

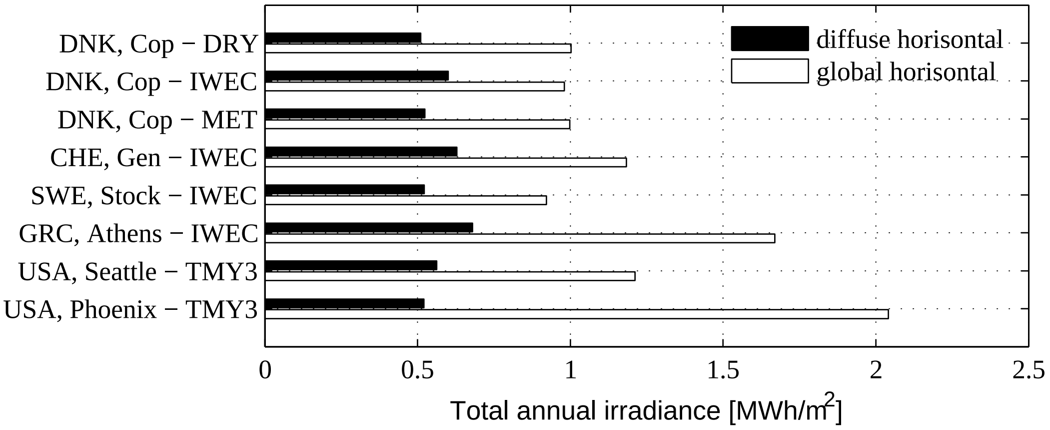


Figure 4.1: *Total annual horizontal diffuse and global irradiance at different locations*

Total annual global and diffuse irradiance

The total annual global and diffuse irradiance for different locations are plotted on Figure 4.1. In US the standard extreme climates in terms of solar radiation are Phoenix and Seattle. In Europe the extreme climates could be i.e. Stockholm and Athens. From Figure 4.1, it can be seen that both Copenhagen and Geneva have almost the same or higher diffuse to global irradiance ratio as Seattle. The location of Phoenix has a lower diffuse to global ratio than Athens. Therefore, it has been chosen to simulate with the climatic location of Phoenix as the sunny climate and with locations of Copenhagen and Geneva to represent the more overcast climates. The location of Geneva was chosen as this was one of the locations which also was studied in Walkenhorst et al. [2002]. It has not been possible to access the measured data used in their study, and the weather data file used for the simulations is therefore the available IWEC weather data file from the Energy Plus homepage.

4.2 Results

4.2.1 Hourly simulations for the same location

The hourly simulations obtained from the irradiance data available in the weather data files for Copenhagen show differences in LD of up to 2 %, see Figure 4.2.

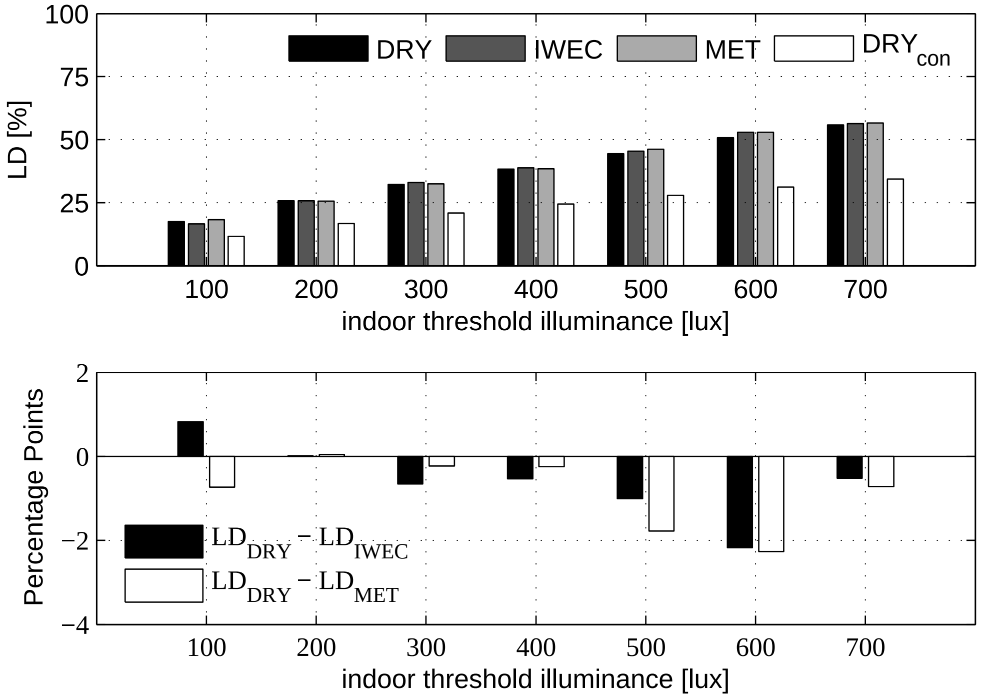


Figure 4.2: *Comparison between hourly simulations for different weather data files for Copenhagen. top) Predicted lighting dependencies for the sensor point in the back of the room for the daylight simulations with hourly means from the Design Reference Year, IWEC, and Meteonorm weather data sets. Indoor threshold illuminance levels from 100 lux to 700 lux. bottom) Difference in percentage points (LD_{DRY}-LD_x) for the daylight simulations of hourly means*

This implies that even though the different weather data sets have a unique pattern for each day, the difference is balanced out when looking at a the data for a full year.

The largest discrepancy occurs at illuminance threshold of 600 lux, with higher illuminance values obtained from the DRY weather data file. In general a slightly lower lighting dependency is seen when simulating with the DRY weather data file, which reflects that the DRY weather data file is compiled to represent typical months including extreme conditions, whereas the Meteonorm and IWEC weather data file exclude extreme conditions.

The potential energy savings, by implementing a photoelectric dimming system compared to a photoelectric switching on/off system, are presented by the difference in the bars of DRY and

DRY$_{con}$. The energy savings for the artificial lighting can directly be read from the difference in the histograms. Dependent on the threshold illuminance level the energy savings for the artificial lighting system vary between 5 % to 21 %.

4.2.2 Simulations with time step of one minute

The comparison between lighting dependencies, both on/off and continuous, obtained from hourly means and one minute data show absolute differences of up to 6 % dependent on the indoor threshold illuminance level and chosen weather data, see Figure 4.3 and Figure 4.4.

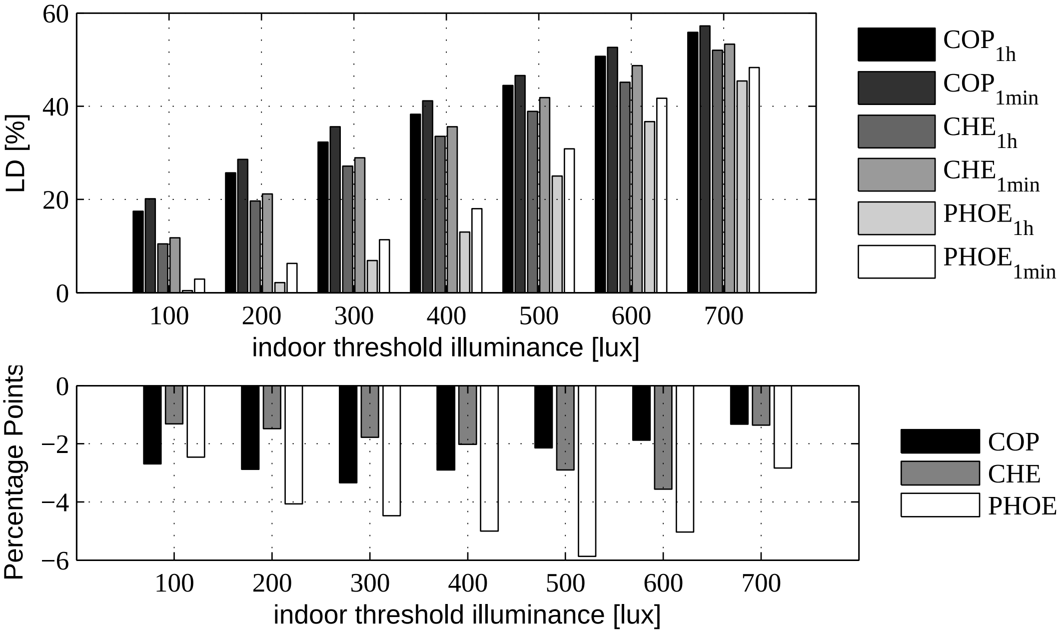


Figure 4.3: *Comparison between hourly and one minute simulations for different climatic locations with on/off control. top) Lighting dependencies for hourly means and one minute data for the DRY file of Copenhagen (COP), the IWEC file for Geneva (CHE) and the TMY3 file for Phoenix (PHOE), bottom) Difference in percentage points in lighting dependencies for hourly means and one minute data for Copenhagen, Geneva and Phoenix, (1h-1min)*

Even though the absolute differences are small the relative differences between simulations of hourly means and one min resolution can be quite high. For the sunny location of Phoenix the relative difference is i.e. in the magnitude of 1250 % and 350 % with continuous control at a threshold value of 100 lux and 200 lux. For the overcast locations of Copenhagen and Geneva the relative differences are in the magnitude of 20 % and 13 % at illuminance thresholds of 100 lux and 200 lux. The general trend is that the relative differences decrease with higher illuminance thresholds.

When the scope of the simulations is to investigate the finer dynamics of the control system, like including integrated dimming to omit oscillating lights, one has to simulate with a finer time step. Figure 4.5 shows the simulated lighting dependencies for 4 different automatic control strategies at the location of Copenhagen and Phoenix simulated with the DRY and TMY3 weather data. The 4 different control strategies are:

1. on/off switch when the illuminance threshold is reached
2. continuous control at each one minute time step

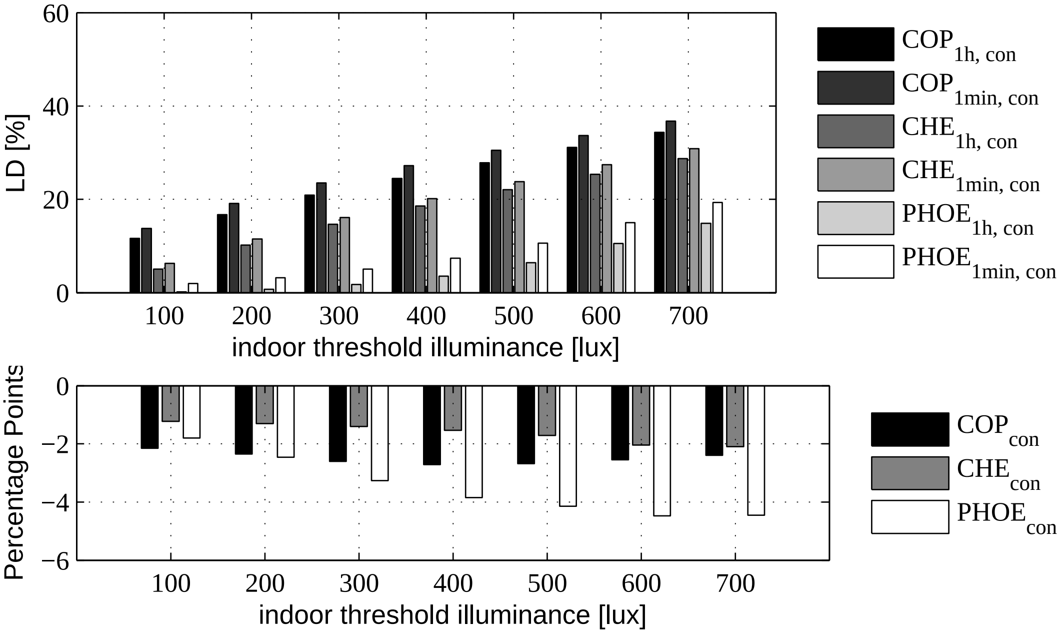


Figure 4.4: *Comparison between hourly and one minute simulations for different climatic locations with continuous dimming control. top) Lighting dependencies for hourly means and one minute data for the DRY file of Copenhagen (COP), the IWEC file for Geneva (CHE) and the TMY3 file for Phoenix (PHOE), bottom) Difference in percentage points in lighting dependencies for hourly means and one minute data for Copenhagen, Geneva and Phoenix, (1h-1min)*

3. continuous control every 10 min and
4. proportional integral dimming, where the response is averaged over the past 10 min

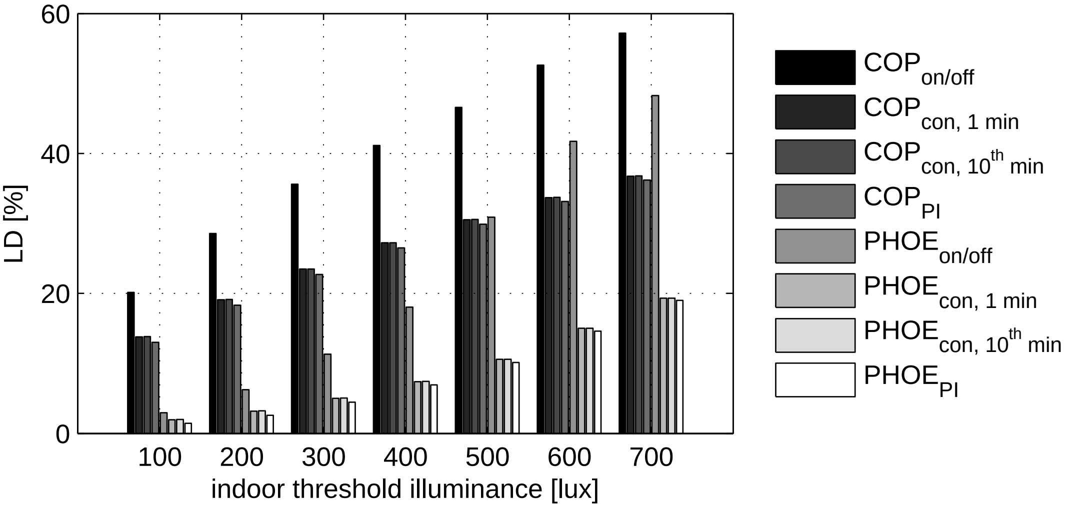


Figure 4.5: *Lighting Dependencies for weather data of one minute resolution with different control schemes for the location of Copenhagen and Phoenix*

The results show that there is no real difference in simulated lighting dependencies when simulating with continuous dimming for each time step, for every 10^{th} minute or the PI control, where the response is averaged over the past 10 min. The reason for this is that when applying the control scheme for every 10^{th} minute the lighting level will either be over- or underestimated and when evaluating for an entire year the differences will be balanced out.

4.3 Discussion

As in the study by Walkenhorst et al. [2002] it can be concluded that simulations of hourly means compared to one minute resolution does not give a conservative estimate of the energy consumption for artificial lighting, since the lighting dependency is underestimated, resulting in decreased lighting demand. In the study by Roisin et al. [2008], they found a difference of less than 1 % using a threshold value of 500 lux. In the PhD thesis of Reinhart [2001] he elaborates further on the comparison between the weather data sets, and finds that for the closed loop system the electrical lighting demand at a threshold illuminance level of 500 lux is being underestimated by up to 9 % when applying hourly means compared to 1-min simulations. This study shows that at 500 lux threshold the electrical lighting demand is underestimated by up to 6 % for the sunny location of Phoenix and up to 3 % for the more overcast climate as Copenhagen and Geneva when applying resolution of hourly means compared to one minute resolution.

Typically, differences of up to 10 % are considered to be good results in daylight simulations. The uncertainties regarding the simulation outcome could be derived from measurement error of irradiance values, the influence of the exact location of the sensor points and influence of surface reflectances within the room. Even though the differences between the simulations of hourly means and one minute resolution are within the uncertainty for daylight simulation, the results show that by applying simulations of hourly means the energy consumption for artificial lighting is categorically being underestimated. Although the differences are small, the relative differences between the simulations can be quite high. For the sunny location of Phoenix the relative difference is about 1250 % and 350 % with continuous control at a threshold illuminance value of 100 lux and 200 lux. However, at these threshold values the overall energy demand for artificial light is small and the high relative difference can be of minor importance.

It is surprising that the short-term dynamics of the available daylight does not have a greater impact on the difference in continuous lighting dependencies between simulations of hourly means and one minute resolution. One would have assumed that simulations of hourly means for most annual working hours would underestimate the lighting dependency to a higher degree, due to spikes with high illuminances increasing the hourly mean value. With an increased hourly mean value the entire hour might have a sufficient daylight level, whereas the estimation with one minute resolution might fall below the threshold illuminance value at some time steps causing lights to be switched off. However this is not reflected from the results. The maximum discrepancy is 4.5 % depending on the indoor threshold illuminance and type of lighting control.

As mentioned in section 4.1.2, the non-deterministic influence of the stochastic Skartveit-Olseth model on the simulation outcome is negligible. The relative standard deviation of the specific annual electric energy demand for artificial lighting resulting from ten different realizations of the model was found to never exceed 0.7 % Walkenhorst et al. [2002]. The discrepancies found in this study are larger than 0.7 %, which implies that it is differences in the weather data and not differences in the stochastic model that is being simulated. In Walkenhorst et al. [2002] they furthermore compared lighting electricity consumption of simulations using measured irradiances from one hour and one minute data sets and found that the consumptions are underestimated by 6 % to 18 % when using one hour irradiance values. The discrepancies found in this study are smaller which points to that the simulations of one minute resolution, with the current data and models available do not behave as dynamically as expected. As pointed out in the PhD thesis by Reinhart [2001] the amount of intra hour variations in the modified Skartveit-Olseth model are less pronounced than in reality as the model is stochastic. While differences between measured and simulated values may be substantial for a single day, the differences tend to vanish if a greater number of hours are considered [Reinhart, 2001]. In the development of the IWEC files the Skartveit-Olseth model was discarded, as they found that the model seemed to be tuned to European conditions and had not undergone extensive testing at other locations [ASHRAE, 2001]. To include the true dynamic behavior of the sky there is therefore a need for creating better models or to have measured irradiance data with a finer resolution than the hourly means. The results show that there is no distinct difference in simulated lighting dependencies when applying continuous dimming for each time step compared to the PI control with the response averaged over the past ten minutes. It is the authors' belief that this result reflects the limitations in the modified Skartveit-Olseth model to imitate the intra hour variations in available daylight. At present, using values of hourly means for the daylight simulations is therefore a reasonable predictor for the lighting dependency.

When evaluating the simulations based on hourly means for the different weather data files for the location of Copenhagen, no difference is observed when the threshold value for the general lighting level is 200 lux as prescribed according the Danish Standard DS700 [DS700, 2005]. The energy consumption for artificial light will therefore yield the same result independent on the weather data used for the calculations.

Chapter 5

Occupancy patterns and their resolution in climate based daylight modeling

In this chapter the effect on the energy consumption for artificial lights will be investigated by applying different occupancy models to the Climate Based Daylight Modeling (CBDM)(Paper III). The hypothesis to be investigated is

> Will CBDM with occupancy profiles and weather data of different resolution, have a significant influence on the estimated energy demand for artificial lights?

The hypothesis will be tested by applying static and dynamic occupancy profiles to the daylight simulations. A method has been developed in Delff et al. [2012] which describes the dynamic behavior of presence of occupants in an office environment (Paper II). Data recordings for every two minutes from 57 sensors over 16 full days are considered. The first day is in August 2009, the last in January 2010. Hence, there is a shift from summer time to normal time included in this period. Daily occupancy patterns for summer and winter were investigated, and it was found that there was no significant difference in the seasons. The generated occupancy profiles has been applied in daylight simulations to estimate the artificial lighting demand if these were controlled by occupancy (Paper III). Comparison between the lighting demand for artificial lights by applying a diversity factor and dynamic occupancy profiles show a difference in lighting demand of 4 % compared to a reference case where the lights were switched on for all occupied hours. Furthermore comparisons of annual mean occupancy profile, hourly-means occupancy profiles and two minute resolution occupancy profiles show a difference in lighting dependency of up to 1 %. Compared to a lighting system where the lights are on in the entire hours of usage, the difference observed from the different profiles is therefore maximum 1 %. These results reveals that no real difference is seen from occupancy profiles as annual average, hourly resolution or two minute resolution, when evaluating the lighting demand based on automatic occupancy and daylight control on an annual basis. For future investigations it would be of interest to see the effect of introducing manual switching of lights, which could be accomplished by applying Hunt [1979]'s switch on probability or by running simulations with DAYSIM and the LightSwitch2002 model developed by Reinhart [2004].

The occupancy model developed is based on one type of office environment in San Francisco, and the estimated profiles are therefore restricted to this office. In general this office has a higher absence factor, 0.63, compared to the empirically determined absence factor of 0.4 given in the European Standard DS/EN15193 [2007]. Nevertheless, the model developed in Delff et al. [2012] propose a new way to estimate occupancy, and the model is capable of predicting a realistic scenario for the occupancy pattern throughout a working day. The model overcomes the limitations in i.e. Wang et al. [2005], by being able of modeling both presence and absence of occupants, without introducing a mobility parameter, which was suggested in the paper by Page et al. [2008].

5.1 Methodology

5.1.1 Evaluation methods

As stated in Mardaljevic et al. [2009] it is important to note that if the designer only evaluate the building performance based on the predicted occupied period opportunities to improve the daylight potential of the building might be left out. Therefore the reference case for the simulation will be an evaluation of daylight performance of the space with occupants present in the entire simulation period followed by evaluations with occupancy models added. The lighting demand for artificial lights will be evaluated in a building zone where the occupancy profile:

1. is constant for the weekdays and weekends - occupants are always present
2. is constant for the weekdays and weekends - here an absence factor has been applied, both the absence factor given in DS/EN15193 [2007] and the absence factor estimated from the measured data.
3. estimated annual mean presence, where the occupancy pattern follow the same profile each day throughout the year
4. estimated 1-hour mean presence, where the occupancy pattern varies for each occupied hour throughout the year
5. dynamic two minute presence of occupants as developed in Delff et al. [2012]

The evaluation of the lighting demand is based on the lighting dependency, described in section 2.3.2. The artificial lights are controlled in two zones - one in front of the room and one in the back of the room. The total lighting dependency of the room is then given as the average of the lighting dependency at the sensor points.

5.1.2 Statistical methods

In the following section a short description will be given of the statistical model applied for the investigations. The model has been developed by PhD student Philip Delff and a more thorough description is given in Paper II.

Measurements

The model is based on measured occupancy patterns from an office building in San Francisco, California during 2009. Data from 86 work spaces were collected, of these 29 work spaces were un-occupied or occupied by interns. The occupancy pattern for those 29 work spaces occupied by interns were very random and have been excluded from the data. The model will therefore take into account the 57 work spaces that have been occupied by full-time staff for the entire measurement period. The measurement period include days in August, September, December and January, in total 32 days. For the study 16 days were used.

Data have been collected for every two minutes. The data come from ballast status records in the control system. The occupants could not override anything manually. If an occupant is present at the workspace, the lamp is switched on, and the ballast status is on. Once the workspace is unoccupied the lights are turned off after a delay of 20 min. The data collected have been corrected for the delay by removing the previous 20 min if the ballast dropped to preliminary power. The ballast status therefore equals presence of occupants. Absence shorter than 20 mins have not been encountered. However presence of short intervals can occur.

Description of models

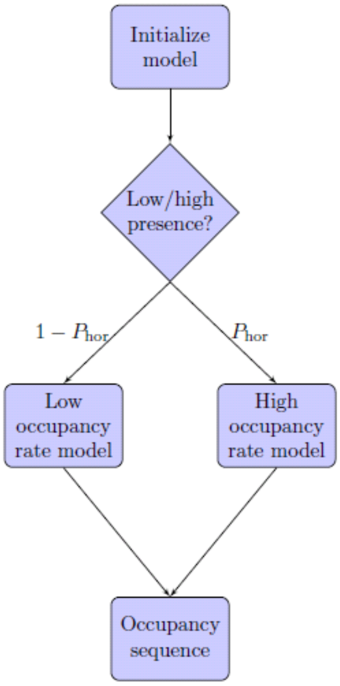


Figure 5.1: *The hierarchical structure of the model [Delff et al., 2012]*

The model of the presence of one employee is a hierarchial model, see Figure 5.1. First the probability of the occupancy rate is modeled as a Bernoulli experiment. If the outcome of the Bernoulli experiment result in a low occupancy rate (lor) the model for describing absence is applied, else the model with high occupancy rate (hor) is applied when generating the occupancy profiles. To determine a threshold of when to consider a sequence of measurements from one day as not a working day, the distribution of the mean occupancy throughout a whole day of all sensors is considered. As found in Delff et al. [2012] there is a high density close to zero, and then the density is generally decreasing to a bit less at 0.2. This implies that the measured data of occupancy patterns is a mixture of one distribution with mode close to zero (not at work) and another with mode close to 0.6 (a work day). Based on this it is decided to have a threshold at a mean of minimum 0.2 activity for a day-sequence. With a certain probability, P_{hor}, the employee is modeled with a model describing occupancy patterns with a mean presence higher than 0.2. Whereas another model with mean presence lower than 0.2 will be used to model a day with low occupancy rate with probability 1-P_{hor}.

Inhomogeneous Markov Chain A Markov Chain is a time series that meets the Markov condition which states that conditioned on the present state, the future is independent on the past [Grimmet and Stirzaker, 2005]. If the transition probability matrix is constant the Markov chain is said to be homogeneous. However, to model the time varying presence of occupants the underlying overall distribution of the data has been modeled as an inhomogeneous markov chain. The varying transition probability matrices are estimated with generalized linear models using natural splines as input (Z) to the markov chain (X). 3^{rd} order degree polynomials were fitted to the data between knots. To determine the necessary number of knots sensitivity analysis were performed. It was found that 11 knots gave the overall best fit, for the two different events of; 1) being absent from work and start working again and 2) being present at work and stop working.

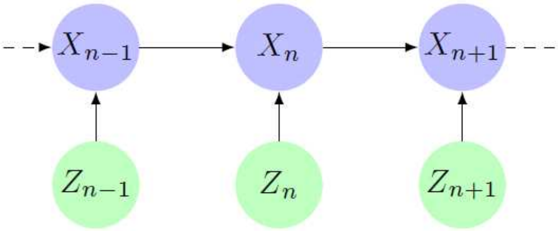


Figure 5.2: *Illustration of dependence in an inhomogeneous Markov chain. The input process is a deterministic process which is assumed to be known. As seen it only directly influences the Markov chain at the present. [Delff et al., 2012]*

To model the low occupancy rate a similar approach has been applied. Here the input to the markov chain is a natural spline with 5 knots for the case where an occupants is absent from work and starts to work again. For the opposite case, where the occupant is present at work and stop working, the input is a second degree polynomial. This underlying inhomogeneous markov chain with splines as input gives a very good description of the presence and absence of the occupants.

Exponential smoothing To further improve the model, exponential smoothing has been added as a low pass filter to the model (Λ), see Figure 5.3. The exponential smoothing improves the description of the dynamics of the sequences for each occupant. The exponential smoothing gives a feedback to the transmission of probabilities. One could say that the filter represents a measure for how much you would like to work. If you have worked a lot, it is more likely that you continue working. In other words - the model is capable of dividing days with high work load, i.e. the employee is at the office or days where the employee is absent from the office.

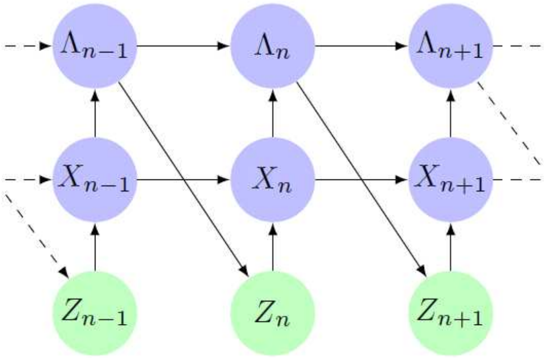


Figure 5.3: *A Markov chain with an exogenous process (Z) and exponential smoothing (Λ) as covariate in the transition probabilities. [Delff et al., 2012]*

5.2 Results

The first section presents an overview of the modeled presence of occupants. The second section presents results of the lighting dependencies applying the occupancy patterns to the dynamic daylight simulations.

5.2.1 Modeled occupancy patterns

For the simulated period from 6am to 7pm the total absence factor (F_A) of the modeled occupancy profiles is 0.63. The estimated annual mean presence and the confidence interval is seen on Figure 5.4. When applying the annual mean presence in the daylight simulation the occupancy profile is the same throughout the year. The annual mean profile does not include peak loads, which might induce simulation errors when predicting the energy demand for artificial lights, as both the occupancy pattern and daylight distribution varies throughout the year.

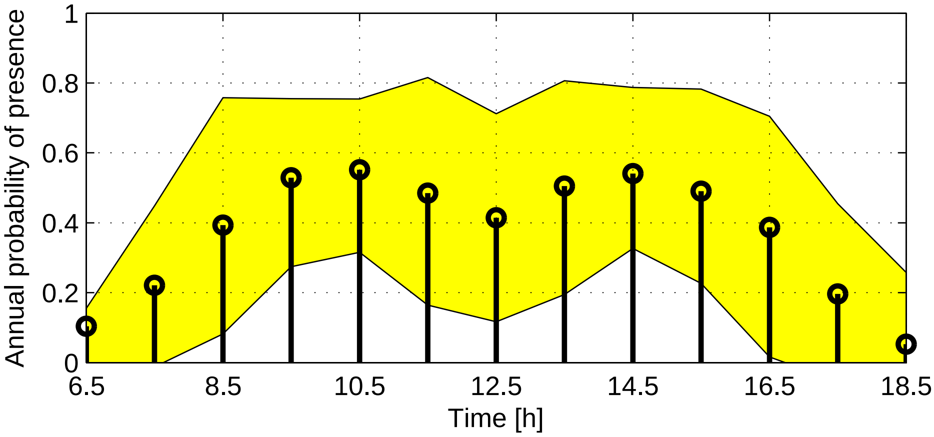


Figure 5.4: *Estimated annual mean presence and confidence interval for 4 different independent occupants, according to the model developed in Delff et al. [2012]*

However, in reality the presence of occupants varies. The annual accumulative plots for the hourly means of presence is seen for one occupant on Figure 5.5.

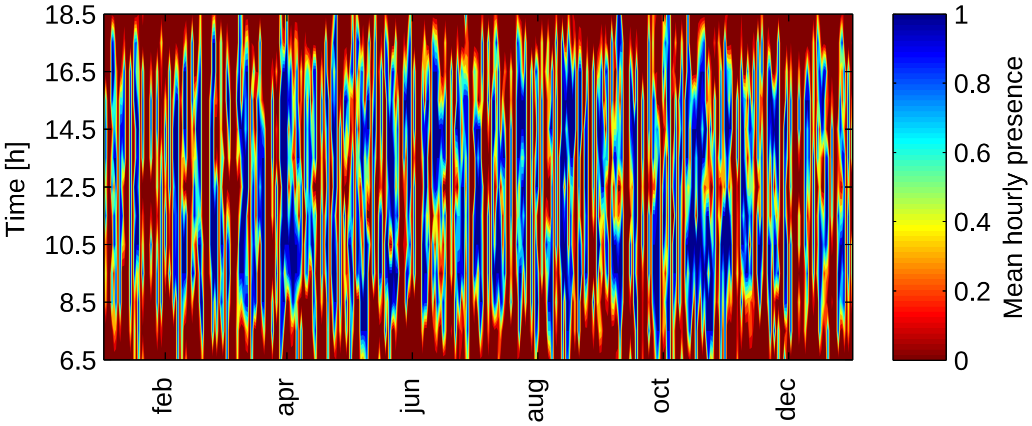


Figure 5.5: *Annual hourly mean presence for one occupant*

It can be seen that for some periods during the mornings and afternoons the probability of presence is 1. If the daylight level is not sufficient at these times of the day peak lighting demands will be introduced at these time steps.

The output from the model developed in Delff et al. [2012] can be presence of occupants with the resolution of two minutes. On Figure 5.6 occupancy profiles for an entire year is depicted for one occupant. The black areas represent that the occupant is present in the two minute interval.

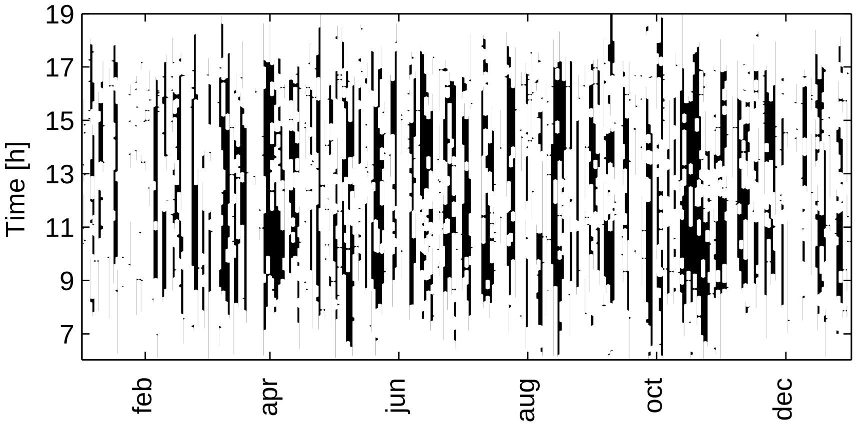


Figure 5.6: *Annual two minute presence of one occupant. Presence is depicted with black color*

5.2.2 Lighting dependencies and occupancy patterns

On Figure 5.7 on/off and continuous lighting dependencies are depicted for 4 different scenarios: 1) with only daylight control, 2) daylight control and an absence factor for the occupant of 0.40 as in DS/EN15193 [2007], 3) daylight control and an absence factor of the occupant of 0.63 which is the total absence factor for the measured field data from the San Francisco office and the model developed in Delff et al. [2012], and 4) dynamic two minute occupancy profiles as generated with the model developed in Delff et al. [2012]. Not surprising, the lighting dependencies decrease when introducing occupancy profiles to the daylight simulations.

However, applying the total absence factor of 0.63 compared to the dynamic occupancy profile overestimates the energy consumption for artificial lights by 4 % and the evaluation of the saving potential is therefore slightly conservative.

On Figure 5.8 the lighting dependencies are depicted for the dynamic simulations when applying simulations of two minute resolutions and hourly mean resolution both in terms of occupancy profiles and weather data and for a case where the occupancy profile is the annual mean and the weather data is hourly mean resolution.

The influence on the annual lighting dependency from the three different approaches is insignificant. The difference is in the range of 1 %, which means that compared to a lighting system which is always on, the simulated energy demand for the artificial light only varies with 1 % dependent on the resolution of both occupancy pattern and weather data. Hence, applying the same occupancy pattern for each day throughout the year with hourly resolution will yield accurate estimations of the electrical lighting demand, if the control of artificial lights based on occupancy and daylight level is automatic.

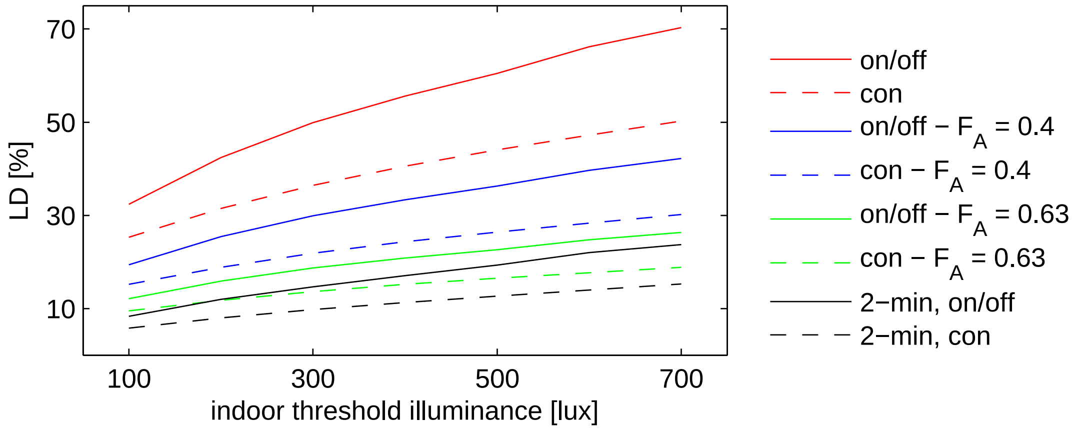


Figure 5.7: *Lighting dependencies for on/off and continuous control of a lighting system 1) with only daylight control, occupants always present, 2) absence factor of 0.40 as in DS/EN15193 [2007], 3) absence factor of 0.63 and 4) dynamic occupancy profile*

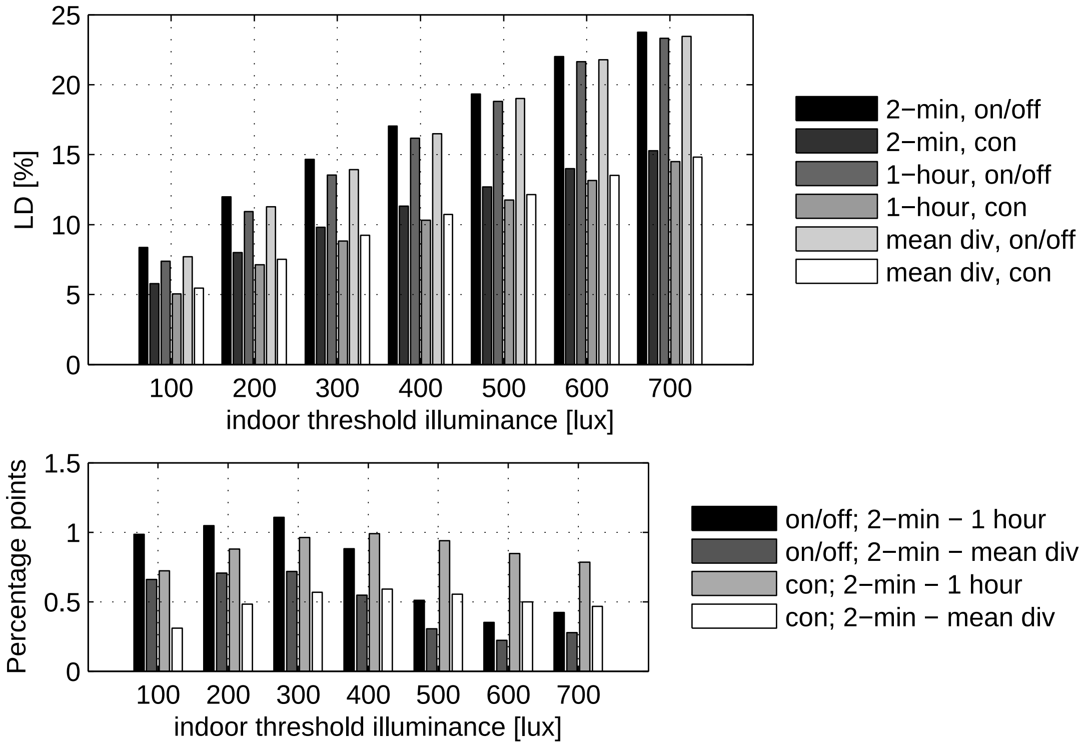


Figure 5.8: *top) Lighting dependencies for the dynamic simulations when applying simulations of two minute resolution (2-min), hourly mean (1-hour) and annual mean (mean div) occupancy profiles. bottom) difference in percentage points for two minute resolution and hourly mean, and two minute resolution and annual mean occupancy*

5.3 Discussion

This study reveals that no real difference is observed in the lighting dependency in an office with automatic daylight and occupancy control, when applying climate based daylight modeling and evaluating the lighting demand based on an average occupancy profile having the same distribution for each day throughout a year opposed to a more dynamic occupancy profile of hourly resolution or two minute resolution of occupancy presence with minimum 20 min absence.

Not surprising the findings show that introducing on/off or continuous daylight control in the perimeter areas of a daylit building reduce the energy consumption by up to 70 % compared to a reference case where the lights are always on, which i.e could be the case in the core building zone. By adding automatic occupancy sensing control the energy consumption is reduced further by 25 % to 50 % dependent on indoor threshold illuminance level.

The results show that although large variations occur between different days, the difference vanishes when evaluating on an annual basis. The total annual lighting demand remains the same independent of occupancy profile applied and resolution of the daylight simulations. However when the aim of the simulations is to investigate the finer dynamics of the lighting system or i.e. solar shading control, detailed knowledge on presence of occupants might be important. For this study simple immediate on/off control of the artificial light or continuous dimming dependent on daylight availability and presence of occupants have been employed. More sophisticated control, like introducing inertia to the lighting systems as delays or dimming the lights before they switch off could be investigated, and might induce different result.

It should be stressed that the dynamic occupancy profiles applied does not include absence shorter than 20 min. This is due to the fact that a delay of 20 min was included in the original measurements. The ideal case would have been measurements that recorded presence solely. Hereby periods of shorter absence like going for a coffee would have been encountered.

Why apply the occupancy model, when you have access to measured data? By applying the statistical occupancy models it is ensured that the occupancy profiles applied are representative, because outliers have been removed from data. The model is based on the measured presence of 57 occupants, and it is therefore ensured that even though the model includes some randomness, the variations in the daily sequences of each occupant is within the statistical boundaries. Hereby it is possible to include the random behavior of occupants in the simulations while knowing that the data correlates with measured data from a real building. The results, on the other hand, show that if the aim of the investigations is to give an estimate of the annual lighting demand it can be sufficient to multiply with the mean presence of occupants observed in the building. If outliers have been removed, then this number could just as well have been obtained from the measured data.

One issue not included in these investigations is the human factors in lighting, like employees manually operating the lights. In Lightswitch-2002 behavioral model predicting user response to lighting systems has been added [Reinhart, 2004]. Manual lighting control mainly coincides with an employee's arrival at or departure from the work place [Hunt, 1979]. Some employees always activate their lighting throughout the whole working day independently of prevailing daylight levels. Others only switch on their electric lighting when indoor illuminance levels due to daylight are low. For the latter user type, the probability of switching on electric lighting is correlated to minimum indoor illuminance levels at the work plane upon arrival through Hunt's switch on algorithm [Hunt, 1979]. For future investigations it would be of interest to employ the dynamic occupancy model developed in Delff et al. [2012] in Lightswitch-2002, to evaluate the behavioral aspect as well. Bourgeois [2005] investigated the behavioral aspects in his PhD thesis. Here he demonstrated that by enabling manual lighting control, as opposed to having the lights switched on for the entire occupied hours, the energy consumption for artificial lights is reduced by as much as 62 %, this number is further reduced by 50 % when applying automatic control. The findings from his study show that manual control compared to automatic control increase the lighting demand.

Chapter 6

Urban Daylighting

In this chapter the effect of the urban canyon on the daylight availability will be investigated. The hypothesis to be tested are:

1. Well-lit spaces can be achieved within the rooms in dense cities by working with the window areas in the facades
2. In dense cities the orientation of the buildings has a minor importance on the daylight availability - it is the reflected light that plays the most important role?

The hypothesis will be evaluated by challenging the urban density with different Height/Width (H/W) ratios, window-to-wall ratios (WWR), orientations and facade reflectances. First the daylight availability within the rooms will be evaluated under CIE overcast sky conditions (Paper IV) followed by evaluations under dynamic sky conditions (Paper V). A framework to facilitate the urban design process with respect to daylight within the rooms has been presented. By looking at the influence of the surroundings on the daylight factor within the room followed by a categorization of the facades according to their daylight performance it is possible to point out urban areas that are good in terms of daylight inside the buildings and areas that have a poor daylight performance. In the SBi-anvisning 219 and Indoor Climate Handbook obstruction angles above 20^o and 25^o are given as guidelines for critical obstruction angles in terms of daylight availability within the room [Johnsen and Christoffersen, 2008, Valbjørn et al., 2000]. However, when creating urban spaces, the daylight availability within the buildings are often a trade-off between a wish from the developer to have a high plot-ratio and at the same time have energy efficient buildings that are well-lit by daylight. This often results in urban spaces where the obstruction angles are higher than given in the above named guidelines. The framework suggested in this chapter subdivide the obstruction angle further and introduces guidelines for sizing of the WWR in the facades at higher obstruction angles. The simple method has been compared to findings in literature and show good agreement.

The simulations of the daylight performance in the city under dynamic sky conditions describes preliminary investigations. For the evaluation under dynamic sky conditions the results showed that in dense cities the orientation of the buildings has a minor importance on the daylight availability. However, the results indicate that there is a preference for the northern orientations in terms of daylight availability at the lower floor plans. Using finishes of high reflectivity on the opaque part of the facades increased the daylight penetration depth for the lower floor plan.

6.1 Methodology

6.1.1 Daylight availability within the room

The daylight availability within the room will be evaluated based on two metrics: 1) The traditional daylight factor evaluation, and 2) a daylight autonomy threshold of 50 % at 200 lux.

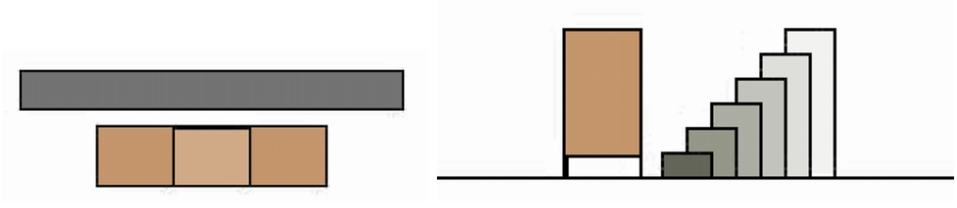
6.1.2 Daylight availability on the exterior vertical facade

The daylight availability on the facade will be evaluated based on two metrics: 1) The Vertical Daylight Factor (VDF), and 2) a Vertical Daylight Autonomy (VDA). The Vertical Daylight Factor describes the amount of illuminance falling on a vertical surface of a building under overcast sky conditions [Li et al., 2009a,b]. The VDF is therefore limited and constricted by the same considerations as the Daylight Factor evaluation. Therefore a climate based metric, the Vertical Daylight Autonomy, has been proposed. The VDA describes the percentage of the occupied hours per year when a threshold illuminance on the facade can be maintained by daylight alone. Dependent on the threshold value of the VDA, the VDA can describe how often during the occupied times of the year when blinds are lowered to both prevent occupants from experiencing glare and exclude solar gains to prevent overheating. However, for this study the aim with the VDA is to visualize differences in illuminance levels on the facade for the northern and southern orientation. Therefore, the VDA threshold value is set to 10.000 lux.

6.2 Results

6.2.1 Urban canyon and the CIE overcast sky

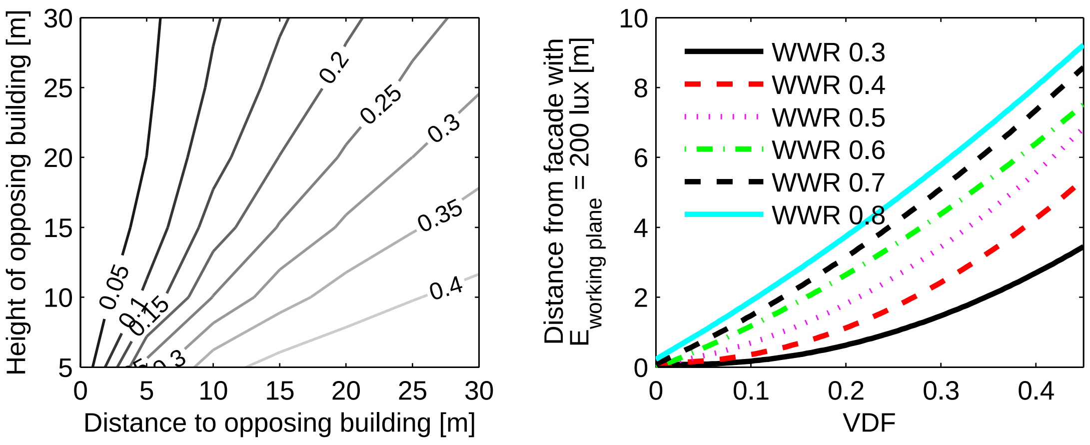
In paper IV, the urban canyon in a city is studied based on the CIE overcast sky. Here a room of 20m x 15m x 4m (w x d x h) placed on the ground floor in the middle of a larger building with dimensions 60m x 15m x 30m (w x d x h) was simulated as a 'worst case' base case, see Figure 6.1a.



(a) (b)

Figure 6.1: *(a) Plan of the model, seen from above with a street width of 5m and (b) section of the model showing street widths from 5 m to 30 m and heights of opposing building from 5 m to 30 m.*

In the presented simulations, the room properties were fixed because the focus was to look at the influence of the surrounding buildings and window area on the daylight availability. The exterior walls were given a thickness of 0.3m in order to take into account a well insulated facade. The light transmittance of the window was 0.72. Illuminance readings were taken in the centerline of the room in working plane height 0.85 m above the floor. The reflectance of the interior walls, floor and ceiling was 0.7, 0.25 and 0.9, respectively. Glazing areas varied and was presented as WWR of the facade of: 30%, 40%, 50%, 60%, 70% and 80%. Windows were simulated as a band on the whole length of the facade, placed from 0.8m above the floor. Simulations were carried out with an opposing building of varying height from 5 m to 30 m and street widths varying from 5 m to 30 m, see Figure 6.1b.



(a) (b)

Figure 6.2: *Reflectance of opposing facade is 0.2. (a) The ratio of the illuminance level on the facade to a 10 klux CIE overcast sky (VDF) for different building heights and distance to opposing building. (b) Distance from the facade where 200 lux is achieved on the work plane for different VDF levels.*

The facades in the proposed urban plan can be categorized according to their daylight performance, i.e. according to the division given in table 6.1. The division is based on a requirement to maintain 200 lux 3 m from the facade. This requirement is based on experience from daylight simulations of low-energy buildings with well-insulated facades in order to comply with the energy requirements. For these buildings it will typically be possible to achieve a daylight factor of 2 % 3 m to 4 m from the facade.

Table 6.1: *Categorizing the facades in the cities according to their daylight performance*

Category	Evaluation of facade	Color code
1.	Really good facade Criteria can be met for WWR > 0.3	🟨
2.	Good facade Criteria can be met for WWR > 0.5	🟧
3.	It is possible to achieve a good daylight performance, however special precautions must be taken to facade reflectance and WWR Criteria can be met for WWR > 0.7	🟥
4.	Poor facade It is not possible to fulfill the requirements	🟦

Then, by going through the different street widths and building heights of a proposed urban plan, it is possible to point out positive urban areas and areas where the city have not been optimized daylightwise. Based on the findings, it is possible at the early stage of design to change the street widths and building heights or to specify the required reflectance for facades in narrow streets in order to fulfil the daylight requirements. Furthermore, it is possible to define the areas where building functions that does not require daylight should be located.

Figure 6.3: *An application example of the results, for planning of a new urban area. Note: The color mapping shown here corresponds to the daylight performance for the ground level.*

The simple method has been applied at a number of Danish architectural urban planning competitions, where the author has participated as a consultant from Esbensen Consultants, i.e. Køge Kyst (http://www.koegekyst.dk), FredericiaC (http://www.fredericiac.dk) and most recently Thomas B Thriges Gade in Odense C (http://www.fragadetilby.dk). It was the experience that when the architects were given presentations that showed that parts of their proposed urban plan had a bad daylight performance they were in general interested in optimizing their proposal by working with different street widths and building heights. An example of a how the results can be visualized is seen in Figure 6.3.

Recently, BRE-trust has published a guide to good practice regarding site layout planning for daylight and sunlight [Littlefair, 2011]. Here a categorization of the facades is also given based on their daylight performance. Table 6.2 shows a comparison between the categorization in Littlefair [2011] and table 6.1 based on the obstruction angle. From table 6.2 it can be seen that the criteria proposed in this thesis is slightly conservative compared to the values given in the BRE-guideline. In the recommendations outlined from the Danish Building research Institute, given in the SBi-anvisning 219 and the Indoor Climate Handbook [Johnsen and Christoffersen, 2008, Valbjørn et al., 2000], it is stated that obstruction angles above 20^o and 25^o reduce the light within the room significantly. These obstruction angles corresponds very well with category 1 from the two studies compared in table 6.2. For higher obstruction angles special precautions has to be made to room configuration.

Table 6.2: *Categorizing the facades in the cities according to their daylight performance. Comparison between the obstruction angles given in the BRE-trust guideline [Littlefair, 2011] and categorization deduced from Iversen et al. [2011]*

Category	Evaluation of facade according to Littlefair [2011]	Obstruction angle	
		Littlefair [2011]	Iversen et al. [2011]
1.	Conventional window design will usually give reasonable results	$< 25^o$	$< 20^o$
2.	Special measures (larger windows, changes to room layout) are usually needed to provide adequate daylight	25^o to 45^o	20^o to 40^o
3.	It is very difficult to achieve reasonable daylight unless very large windows are used	45^o to 65^o	40^o to 55^o
4.	It is often impossible to achieve reasonable daylight, even if the whole window wall is glazed	$> 65^o$	$> 55^o$

6.2.2 Urban canyon and the 'real' sky

In Paper V, the urban canyon in a city is studied based on static daylight simulations and dynamic daylight simulations. In the present section some of the results will be shown for the dynamic simulations. Rooms are simulated on the 1^{st}, 3^{rd} and 5^{th} floor in a building. A simulation matrix has been set up; see Figure 6.4, containing different Window-to-Wall-Ratios (WWR) and facades with different reflectances of the opaque part.

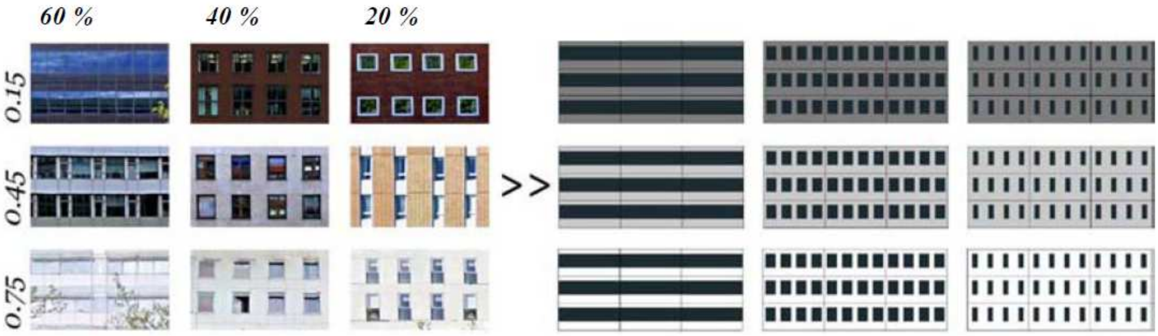


Figure 6.4: *Simulation matrix of different WWR's (20%, 40% and 60%) and facade reflectances of the opaque part (0.15, 0.45 and 0.75)*

For all simulations the building height is fixed to 15 m corresponding to a building with 5 floors. The simulated rooms are placed on the 1^{st}, 3^{rd} and 5^{th} floor. Each room has inner dimensions of; height = 2.8 m, width = 6.0 m, depth = 8.0 m, see Figure 6.5. The light transmission of the window is 0.72. The street width varies corresponding to H/W ratios of 2.0, 1.0, and 0.5. A diagram showing the different simulation set-ups is given in Figure 6.5.

Illuminance readings are made at upward facing sensor points placed on a line in work plane height, through the room, drawn from the middle of a window placed as close to the middle of each room as possible. This was done to avoid boundary effects influencing the results. Furthermore

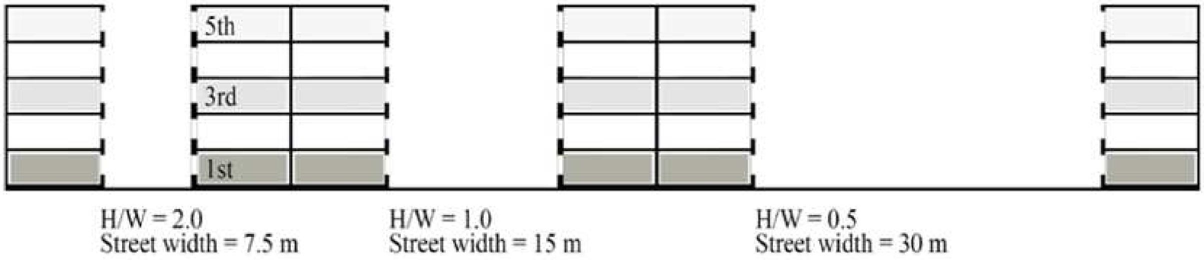
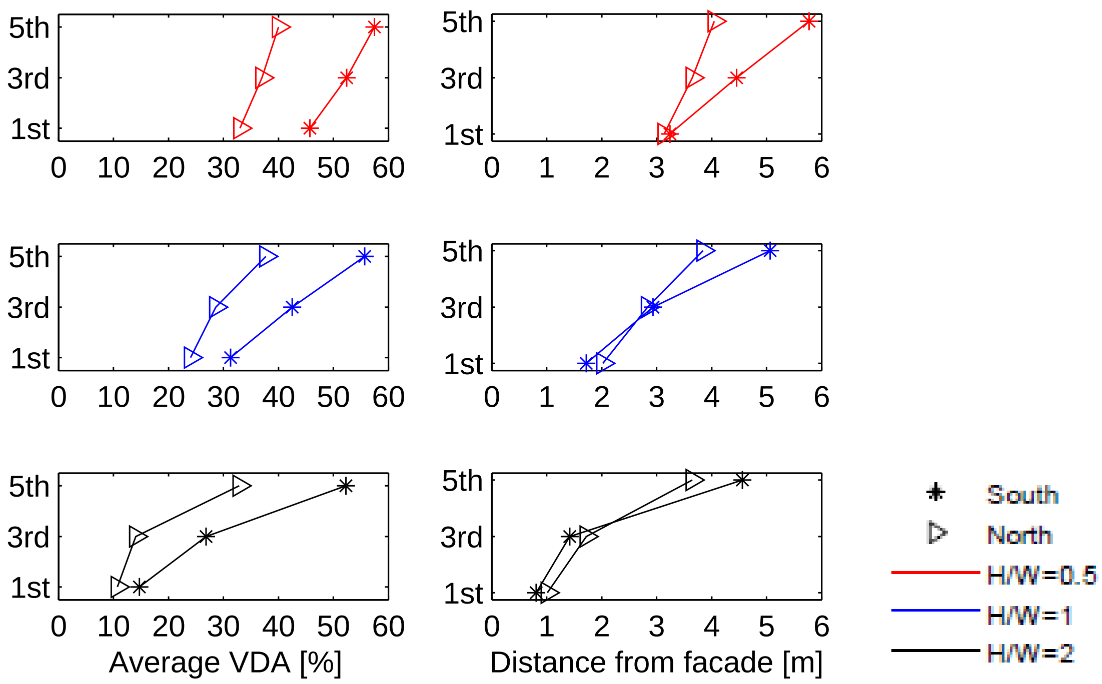


Figure 6.5: *Urban street canyon, simulation setup*

illuminance readings are made externally on the facades, at sensor points facing normal to the facade, for each simulation. The dynamic simulations are performed for each hour throughout a year with the Perez-All Weather sky model, following a daylight coefficient method [Tregenza, 1983] implemented in Daysim [Reinhart, 2010]. The location is Copenhagen and the weather data applied is the design reference year. For the different room typologies the daylight availability has been evaluated for the northern and southern orientation.

The results show that the denser a city is, the smaller is the difference between the illuminance level falling on the northern and southern facades for each floor level, see Figure 6.6a.



(a) (b)

Figure 6.6: *WWR 40% and facade reflectance of 0.45: a) Illuminance level on the facade, average VDA for different H/W ratios, b) Distance from facade with DA of 50 % for different H/W ratios*

Furthermore, when moving from the external to the internal, see Figure 6.6b, it can be seen that the distance from the facade where the DA is below 50 % approximates each other for the northern and southern orientation the lower floor level. In dense cities the orientation of the buildings therefore has a minor importance on the difference in daylight availability. The results indicate that there is a preference for the northern orientations in terms of daylight availability at the lower floor plans. For H/W ratio of 1 and H/W ratio of 2 the light penetrates deeper into the room for the northern facade on the 1^{st} floor and 1^{st} and 3^{rd} floor respectively. This is a consequence of the direct part of the daylight being reduced when the H/W ratio increases, because a smaller amount of the sky is visible from the lower floor plans. For the dynamic simulations this has the effect that a higher proportion of the reflected light bounces of the southern facade, and then falls into the northern oriented rooms. Hereby the limit at which a DA threshold of 50 % is reached increases. For the control of artificial lights this might have an impact on the energy consumption, which is what is seen in Strømann-Andersen and Sattrup [2011], where they found that for south-facing facades in dense urban context the lower floor plans have a slightly higher energy consumption for artificial light compared to north-facing facades.

The preceding results describe a situation where the reflectance of the external wall is 0.45. In Paper V simulations have also been described where the facade reflectance varies. The results show that for the windows facing the northern orientation the influence of the reflectance is remarkably for the 1^{st} floor. Here, the reflected light increases the DA of 50 % from 1.3 m to 2.8 m from the facade when changing the reflectance from 0.15 to 0.75. However, the external wall reflectance of 0.75 is a high reflectance, describing a very light colored building. Over time, dirt and debris will be collected on the wall reducing the reflectance of the facade unless it is maintained at newly build state.

The findings from this study show that by applying dynamic simulations in urban contexts the influence of inter reflections between the buildings favors the northern orientation for the lower floor plans. These results would not have been encountered from standard daylight factor calculations, where the influence of the direct sun and orientation is not considered. Furthermore, these results highlights, that when designing new urban areas, or build any new building, the building facades should not only be considered to create the optimum solution with regard to both energy consumption and indoor environment for the building in question, but also in terms of their contribution to creating good and varied daylight conditions for neighboring buildings.

Chapter 7

Conclusions

7.1 Weather data and their resolution

In this study the effect on the outcome of the daylight simulations was investigated when simulating with different weather data files for the location of Copenhagen. It was found that the lighting dependencies generated based on the different weather data files for Copenhagen varied up to 6% dependent on the chosen indoor illuminance threshold. However each of the different weather data sets where found to give a reasonable prediction of the daylight availability.

Furthermore the effect of simulating with weather data sets of an hourly resolution compared to a one minute resolution showed that the daylight availability was mainly overestimated when using weather data of hourly means. However, the findings from this study show that the dynamic, short-term effects of the weather obtained from the modified Skartveit-Olseth method have a surprisingly small impact on the simulation outcome.

In terms of control of electrical lights no distinct difference in simulated lighting dependencies was found when applying continuous dimming for each one minute time step compared to the PI control with the response averaged over the past 10 min. At present, using values of hourly means for the daylight simulations is therefore a reasonable predictor for the daylight availability. To include the true dynamic behavior of the sky there is therefore a need for creating better models or have measured irradiance data with a finer resolution than the hourly means.

7.2 Influence of occupancy modeling

Comparison between the lighting demand for artificial lights by applying a diversity factor and dynamic occupancy profiles showed a difference in lighting demand of 4 % compared to a reference case where the lights were switched on for all occupied hours. Furthermore comparisons of annual mean occupancy profile, hourly-means occupancy profiles and two minute resolution occupancy profiles show a difference in lighting dependency of up to 1 %. Compared to a lighting system where the lights are on in the entire hours of usage, the difference observed from the different profiles is therefore maximum 1 %. These results reveals that no real difference is seen from occupancy profiles as annual average, hourly resolution or 2 min resolution, when evaluating the lighting demand based on automatic occupancy and daylight control on an annual basis.

7.3 Urban Daylighting

A simple method based on the vertical daylight factor, daylight factor and CIE overcast sky has been presented with the aim being to facilitate the urban design process. By looking at the influence of the surroundings on the daylight factor within the room followed by a categorization of the facades according to their daylight performance it is possible to point out urban areas that are good in terms of daylight inside the buildings and areas that have a poor daylight performance. The facades are categorized according to their daylight performance. The categorization is useful as a mean to convey the daylight performance of a proposed urban plan urban. When the architects experience that parts of their urban plan is in the poorer categories they are interested in optimizing their proposal by working with street dimensions and building heights.

Furthermore, the results from the dynamic investigations of the influence of obstructions on the daylight availability show that in dense cities the orientation of the buildings has a minor importance. However, the results indicate that there is a preference for the northern orientations in terms of daylight availability at the lower floor plans. Using finishes of high reflectivity on the opaque part of the street facades increased the daylight penetration depth for the lower floor plan.

Chapter 8

Future work

From the investigation of the influence of resolution of weather data sets in climate based daylight modeling it was found that no distinct difference was observed when applying hourly resolution compared to one minute resolution. An ongoing research project at the Technical University of Denmark aims at developing a new design reference year for Denmark. This reference year will include measured irradiance values down to two minute resolution. For future investigations it will be relevant to compare this new reference year to data obtained from the modified Skartveit-Olseth model implemented in Daysim, to see if it is limitations in the modified Skartveit-Olseth model to imitate intra hour variations that causes the insignificant difference between simulations of hourly means resolution compared to one minute resolution.

Applying the developed occupancy model to more detailed control. The individual modeling of occupants opens up for the possibility for modeling individual control of the lights. I.e. having the ambient light controlled automatically and task lighting controlled independent by each occupant. This has to some degree been explored in Wen and Agogino [2011], where they demonstrated how wireless communication, computer power and dimming systems can be combined to provide the benefit of individual control of lighting while automatically minimizing energy consumption. Furthermore more sophisticated control could be investigated. For this study immediate on/off control of the artificial light or continuous dimming dependent on daylight availability and presence of occupants have been employed. Introducing inertia to the lighting systems as delays or dimming the lights before they switch off could be investigated, and might induce different result.

One issue not included in these investigations is the human factors in lighting, like employees manually operating the lights. In Lightswitch-2002 behavioral model predicting user response to lighting systems has been added [Reinhart, 2004]. Manual lighting control mainly coincides with an employee's arrival at or departure from the work place [Hunt, 1979]. Some employees always activate their lighting throughout the whole working day independently of prevailing daylight levels. Others only switch on their electric lighting when indoor illuminance levels due to daylight are low. For the latter user type, the probability of switching on electric lighting is correlated to minimum indoor illuminance levels at the work plane upon arrival through Hunt's switch on algorithm [Hunt, 1979]. For future investigations it would be of interest to employ the dynamic occupancy model in Lightswitch-2002, to evaluate the behavioral aspect as well.

Furthermore the investigations have not covered the impact of including solar shading in the simulations. For future investigations it would be relevant to include the shading impact from different shading systems. The results from chapter 3 reveal that the saving potential of the energy demand for artificial lights is high if a solar shading is employed that only blocks the part of the window which causes discomfort for the occupants.

For future work it would also be if interest to explore the application potential of the VDA further. This could i.e. be in terms of; correlating the VDA to the experience of glare within a room having different window configurations; correlating the VDA with the risk of overheating within the buildings, and correlating the VDA with the illuminance levels within the room. Hereby it might be possible, simply by looking at the external skin of a building or a city, to give guidance on where to place openings in the fabric, where to place solar shadings, to quantify how often solar shadings will be lowered, and to give guidance on the window sizes in the facades. The experience of glare within the room could be investigated by looking at the Daylight Glare Probability (DGP) developed by Wienold and Christoffersen [2006]. In their study a correlation between the vertical eye illuminance and the percentage of disturbed persons was found. By disturbed, is meant persons who experience discomfort with the visual environment. However, it should be noted that the correlation found in their study is based on a single person office room with large windows and no external obstructions.

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Nomenclature

A	Area	$[m^2]$
E	Energy consumption	$[kWh/m^2]$
E	illuminance level	$[lux]$
F	Factor	$[-]$
H	Height	$[m]$
n	hours of usage	$[-]$
P	Power	$[W/m^2]$
r	Reflectance	$[-]$
T	time steps investigated	$[-]$
W	Width	$[m]$
X	state of the random process in the markov chain	$-$
Z	covariate to the markov chain	$-$

Index

A	absence	$-$
$back$	back	$-$
$ceiling$	ceiling	$-$
con	continuous	$-$
Day	daylight	$-$
$daylight$	daylight	$-$
$floor$	floor	$-$
$front$	front	$-$
hor	high occupancy rate	$-$
$hoursofusage$	hours of usage	$-$
$installed$	installed	$-$
lor	low occupancy rate	$-$
Man	manual	$-$
n	a time stamp in discrete time	$-$
Occ	occupancy	$-$
on/off	on/off	$-$
PI	proportional integral dimming	$-$
P	probability	$-$
$room$	room	$-$
T	a time stamp	$-$
$threshold$	threshold	$-$
$wall$	wall	$-$
$workingplane$	working plane	$-$

$1hour$	one hour	$-$
$1min$	one min	$-$
Greek		
Λ	low pass filter	

Abbreviations

BTDF	Bi-directional scattering (transmission) distribution functions
CBDM	Climate-Based Daylight Modelling
CIE	International Commission on Illumination
DA	Daylight Autonomy [%]
DC	Daylight Coefficient
DGP	Daylight Glare Probability [%]
DF	Daylight Factor [%]
DRY	Design Reference Year
H/W	Height/Width
IDMP	International Daylight Measurement Programme
IWEC	International Weather for Energy Calculations
LBNL	Lawrence Berkeley National Laboratory
LD	Lighting Dependency [%]
LENI	Lighting Energy Numeric Indicator [kWh/m^2]
LPD	Light Power Density [W/m^2]
MET	Meteonorm
NLPIP	National Lighting Product Information Program
SBi	Danish Building Research institute - Statens Byggeforskningsinstitut
TMY	Typical Meteorological Year
TRY	Test Reference Year
VDF	Vertical Daylight Factor
VDA	Vertical Daylight Autonomy
WWR	Window to Wall Ratio

Part II

Appended papers

Paper I

"The effect of different weather data sets and their resolution in climate-based daylight modelling"

A. Iversen, S. Svendsen & T.R. Nielsen

In press *Lighting Research & Technology*

The effect of different weather data sets and their resolution in climate-based daylight modelling

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Abstract

The climate-based daylight modelling approach is based on available weather data, which means that the weather data used as input to the daylight simulations are of great importance. In this study the effect on the outcome of the daylight simulations was investigated if the designer uses one weather data file in lieu of another for the same location. Furthermore the effect of using weather data sets of an hourly resolution compared to a one minute resolution was investigated. The results showed that the lighting dependencies varied up to 2 % dependent on the chosen weather data file and indoor illuminance threshold. The energy consumption for artificial lights was underestimated when simulating with time steps of hourly means compared to one minute resolution. The findings from this comparison show that the dynamic, short-term effects of the weather have a surprisingly small impact on the simulation outcome.

1. Introduction

During the last decade, research in the field of daylighting, have discussed the shortcomings of the conventional, static daylight factor method.[1–4] However, still, the good practice evaluation method for daylight in national standards (i.e.[5,6]) is the daylight factor method. In 2006, Mardaljevic[2] addresses this 'because of its simplicity rather than its capacity to describe reality'. The daylight factor calculation evaluates the daylight conditions for one standard CIE overcast sky omitting the natural local variations in available daylight. In 2000, Mardaljevic[7] and Reinhart and Herkel[8] demonstrated that reliable predictions based on hourly climatic data are attainable when applying the Climate-Based Daylight Modelling principle (CBDM). "CBDM is the prediction of various radiant or luminous quantities (e.g. irradiance, illuminance, radiance and luminance) using sun and sky conditions that are derived from standard meteorological datasets'".[2,6] CBDM thereby includes the dynamic effects of daylight described in the meteorological data files like changes in cloud cover, variations over time and seasons. The CBDM approach is based on available weather data, which means that the weather data used as input to the daylight simulations is of great importance. Several weather data sets are available for the same location. For Copenhagen the available datasets are i.e. the Design Reference Year (DRY), dataset from Meteonorm and the homepage of Energy Plus. The daylight simulation program Daysim encourages the designer to use the weather data files from the Energy Plus homepage, as Daysim supports the .epw file format.[9] In this study the effect on the outcome of the daylight simulations is investigated if the designer uses one of the three above-mentioned weather datasets.

Furthermore the effect of using data with an hourly resolution compared to a one minute resolution is investigated. In a study by Walkenhorst *et al.*[10] it is concluded that neglecting the short-term dynamics can introduce substantial errors in the simulation of the specific annual electric energy demand for automated control strategies of artificial lighting systems. In the study they implemented a modified Skartveit-Olseth method[11] to create one minute irradiance data from hourly means. By comparing lighting electric consumption of simulations using irradiances from 1 h and one minute data sets they found that the consumptions are underestimated by 6 % to 18 % when using 1 h irradiance values. In another study by Roisin *et al.*[12] they compared simulations from hourly means to one minute time step obtained by applying the same method as in Walkenhorst *et al.*.[10] Contrary to Walkenhorst *et al.*[10] they found less than 1 % differences between 1 h and one minute simulations for simulation for a whole year. In this study the one minute datasets will also be generated following the Skartveit-Olseth method implemented in Daysim.[9]

2. Method

The two hypotheses to be tested are:

1. Simulations with different weather data sets for the same location will have an insignificant influence on the estimation of the energy consumption for artificial lights
2. With the artificial lights being automatically controlled, simulations with one minute resolution compared to one hour resolution will have a significant impact on the energy consumption for artificial lights.

The first hypothesis will be tested through simulations with different weather data sets for the location of Copenhagen. The second hypothesis will be tested through comparisons between the simulations of hourly means and one minute means for different climatic locations and different types of automatic control. The different climatic locations chosen are Copenhagen, Geneva, and Phoenix. The location Geneva was chosen as this was one of the locations which also was studied in Walkenhorst *et al.*.[10] It has not been possible to access the measured data used in their study, and the weather data file used for the simulations is therefore the available IWEC weather data file from the Energy Plus homepage. The location of Phoenix was chosen as this location compared to the location of Copenhagen and Geneva represents a sunny climate. Comparisons between the total annual global and diffuse horisontal irradiance for the different weather data sets and locations are given in the results section.

2.1 Dynamic daylight simulations with Radiance

The dynamic simulations of indoor illuminances due to daylight are performed using the RADIANCE simulation environment.[13] A daylight coefficient approach is applied following the Three Phase Method which permits reliable and fast dynamic indoor illuminance simulations.[14,15] The sky simulated is the Perez all weather sky discretised using the Reinhart division scheme subdivided in 2306 patches. The RADIANCE routine gendaylit creates a sky according to the Perez all weather model. However, for some time steps gendaylit fails to produce the right output, which occurs at dusk or dawn. For the location of Copenhagen using the DRY file with one minute resolution this happens 190 times. At these times the illuminance level is set to zero, assuming that it is night time.

The illuminance levels obtained from Radiance are post processed in matlab. The data is corrected for daylight saving time and the office hours from 8:00-17:00 are investigated.

2.2 Weather data

Weather data for a large number of locations across the world are available for download from several websites. The weather data are derived from a longer measurement period and they are structured to have the same properties as the measured data, with averages and variations that are typical for the site.

2.2.1 Design Reference Year (DRY)

The Design Reference Year (DRY) consists of data describing the external climatic conditions compiled from 12 typical months for a given location. The irradiance values in DRY for Copenhagen are compiled from 15 years of measurements made at the measurement station at Lanbohoejskolen, Taastrup.[16] A research project has just been initiated with the focus on generating a new DRY taking into account climate changes.

2.2.2 Meteonorm

For the available weather data from Meteonorm the daily and hourly global radiation values are generated from monthly average values by the stochastic TAG-model (Time dependent, Autoregressive, Gaussian model).[17] From the global radiation the direct and diffuse components are deduced following the method of Perez *et al.*[18] from 1991, where they convert the hourly global irradiance to direct irradiance values. The irradiance data for Copenhagen are measured at the Technological Institute in Taastrup and Lund University and interpolated values from these two stations are the basis for the weather data set. The measurement period was from 1981 to 2000. Uncertainties given for all sites are the same: 10 % for global irradiation and 20 % for beam irradiation.[19]

2.2.3 Energy Plus

Weather data is available from the Energy Plus home page courtesy of the US Department of Energy Plus.[20] The data is derived from 20 different sources from all over the world. For Denmark, the data are generated from the IWEC (International Weather for Energy Calculations) file for Copenhagen. 227 locations outside the U.S. are available in the IWEC weather files that were developed under the ASHRAE research project RP-1015.[21] The IWEC files are 'typical years' that normally stay away from extreme conditions.[22] The data are generated based on measurement period from 1982 to 1999. From these 18 years, twelve typical months were selected using the Typical Meteorological Year procedure, and were assembled into a 'typical' file. The Kasten model[23] is used for calculating global solar radiation and the output is then fed to the Perez *et al.*[24] model from 1992 for the calculation of diffuse and direct radiation. The largest distance allowed between the radiation measurement station and the location of the site was 50 km.[25] The IWEC files are categorised based on how well the solar radiation model performs. For the locations analysed in this study the category is 1, which implies that the performance is satisfactory and can be used with confidence.[22]

2.2.4 *Generation of one minute weather datasets*

Both the DRY and the Energy Plus files have been converted to annual one minute irradiance values from the hourly weather data files following the stochastic Skartveit-Olseth model implemented in Daysim.[9,10] The only required input data are the site coordinates, elevation and hourly irradiance data. In Walkenhorst *et al.*[10] they investigated the non-deterministic influence of the stochastic model on the simulation outcome and they found that the impact is negligible. The relative standard deviation of the specific annual electric energy demand for artificial lighting resulting from ten different realisations of the model newer exceeds 0.7 %. Therefore one single realization of the model should yield sufficient simulation accuracy.[10]

2.3 Evaluation methods

The presented results are based on the Lighting Dependency (LD). LD defines the percentage of the occupied hours per year when electrical light has to be added to the lighting scene to maintain a minimum work plane illuminance threshold. In its nature the LD is the reverse of the Daylight Autonomy (DA), defined by Reinhart *et al.*.[26] The DA describes the percentage of occupied hours per year when a minimum work plane illuminance threshold can be maintained by daylight alone.

For an on/off lighting system with daylight harvesting the LD describes the relative energy consumption for delivering light to the room excluding energy consumption of the ballast and control system. The energy consumption can be calculated by equation (2.1).

$$\boldsymbol{E = LD \cdot P_{installed} \cdot n_{hours\ of\ usage}} \qquad [Wh/m^2] \tag{2.1}$$

LD is the Lighting Dependency, ***P*** is the installed power [W/m^2] and ***n*** is the hours of usage. However the LD does not consider the hours where daylight below the threshold value is present and still would contribute to the perceived visual environment and result in energy savings if a photoelectric dimming system was installed. Rogers formulated the Daylight Saturation[27] or Continuous Daylight Autonomy (DA_{con}) where daylight levels below the threshold are credited with a relative weight dependent on the ratio between the amount of available daylight ($E_{daylight}$) and the indoor threshold illuminance level ($E_{threshold}$).[28] Similarly the artificial light contribution in an ideal photoelectric dimming system can be described when the daylight threshold is not maintained during working hours by a continuous lighting dependency.

$$\boldsymbol{LD_{con} = 1 - \frac{\sum_{i=1}^{T} \frac{E_{daylight}}{E_{threshold}}}{T_{time\ steps}}} \qquad | \quad E_{daylight} < E_{threshold} \tag{2.2}$$

T is the investigated time steps.

Appropriate lighting controls are essential to make use of the available amount of daylight. The major distinctions among control strategies are whether they are open- or closed-loop systems, and whether they utilize on/off switching and continuous dimming.[29] In this study we are looking at an ideal closed loop control, based on the illuminance level striking a sensor point on the working plane in the front and in the back of a room. The lighting dependency of the room is then given as the average of the lighting dependency at the two sensor points:

$$\boldsymbol{LD_{room} = \frac{LD_{front} + LD_{back}}{2}} \tag{2.3}$$

In reality, the lights will be controlled after a sensor signal, which could be illuminance, dependent on the detection area and calibration of the sensor. As the scope of this study is to investigate the effect of different weather data files and time step resolution on simulation outcome, the distinction between 'real' and ideal control is beyond the scope of this study. For the automatic dynamic control of the artificial lights four different control strategies have been applied. 1) Photoelectric switch on/off for each time step, as illustrated by LD, 2) Photoelectric dimming, as illustrated by LD_{con} (Proportional response), 3) Photoelectric dimming for every 10 min, $LD_{con,10min}$ and 4) Proportional integral dimming, where the response is averaged over the past 10 min (LD_{PI}). It is assumed that the relationship between the light output and sensor signal is linear.

2.4 Simulation model

In the present study the indoor illuminance level is simulated at two locations in the southward-orientated room; one in the front, 1 m from the facade, and one in the back of the room, 5 m from the facade. A sketch of the test office is seen in Figure 1. The reflectances of the surfaces in the room are; $r_{wall} = 0.62$, $r_{ceiling} = 0.88$ and $r_{floor} = 0.11$. The light transmission of the window system is 72 %.

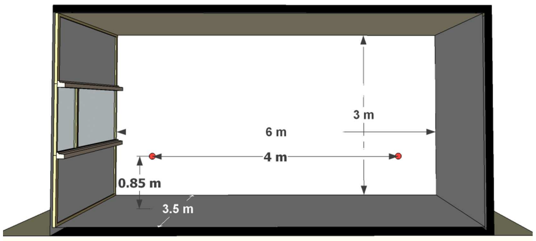

Figure 1 Sketch of the simulated model

3. Results

The first section presents comparisons of the irradiance values in the different weather data sets and climatic conditions. The second section presents the results of the comparison of the three different weather data sets of hourly resolution for the location of Copenhagen. The third section presents results of simulations of hourly means to one minute resolution for different climatic locations.

3.1 Comparisons of weather datasets

The total annual global and diffuse irradiance for different locations are plotted on Figure 2. In US the standard extreme climates in terms of solar radiation are Phoenix and Seattle. In Europe the extreme climates could be i.e. Stockholm and Athens. From Figure 2, it can be seen that both Copenhagen and Geneva have almost the same or higher diffuse to global irradiance ratio as Seattle. The location of Phoenix has a lower diffuse to global ratio than Athens. Therefore, it has been chosen to simulate with the climatic location of Phoenix as the sunny climate and with locations of Copenhagen and Geneva to represent the more overcast climates.

In Figure 3 the hourly means and one minute means irradiances for a random day are shown for the DRY and IWEC weather data set the location of Copenhagen. It can be seen that even though the total annual irradiance values (Figure 2) adds up to almost the same values high daily variations exist between the data sets.

3.2 Hourly simulations

The hourly simulations obtained from the irradiance data available in the weather data files for Copenhagen show differences in LD of up to 2 %, see Figure 4.

This implies that even though the different weather data sets have a unique pattern for each day, the difference is balanced out when looking at a the data for a full year.The largest discrepancy occurs at illuminance threshold of 600 lx, with higher illuminance values obtained from the DRY weather data file. In general a slightly lower lighting dependency is seen when simulating with the DRY weather data file, which reflects that the DRY weather data file is compiled to represent typical months including extreme conditions, whereas the Meteonorm and IWEC weather data file exclude extreme conditions. The potential energy savings, by implementing a photoelectric dimming system compared to a photoelectric switching on/off system, are presented by the difference in the bars of DRY and DRY$_{con}$. The energy savings for the artificial lighting can directly be read from the difference in the histograms. Dependent on the threshold illuminance level the energy savings for the artificial lighting system vary between 5 % to 21 %.

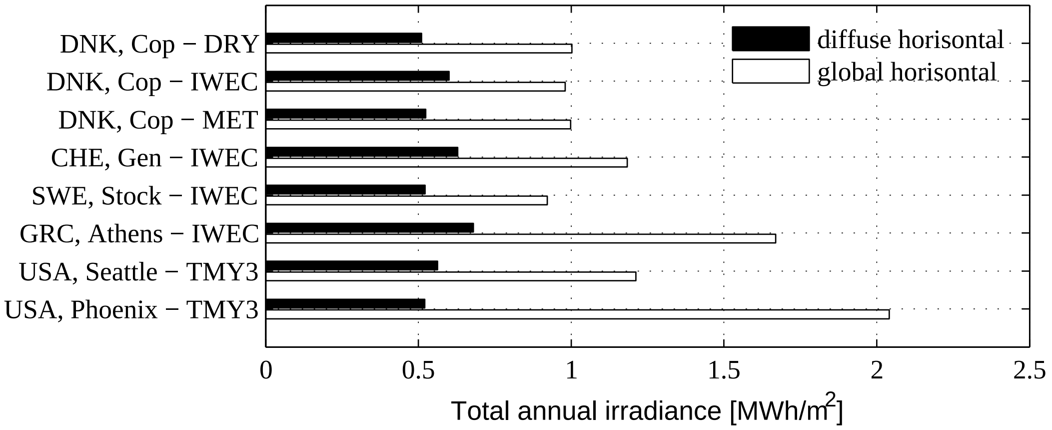

Figure 2 Total annual horizontal diffuse and global irradiance at different locations

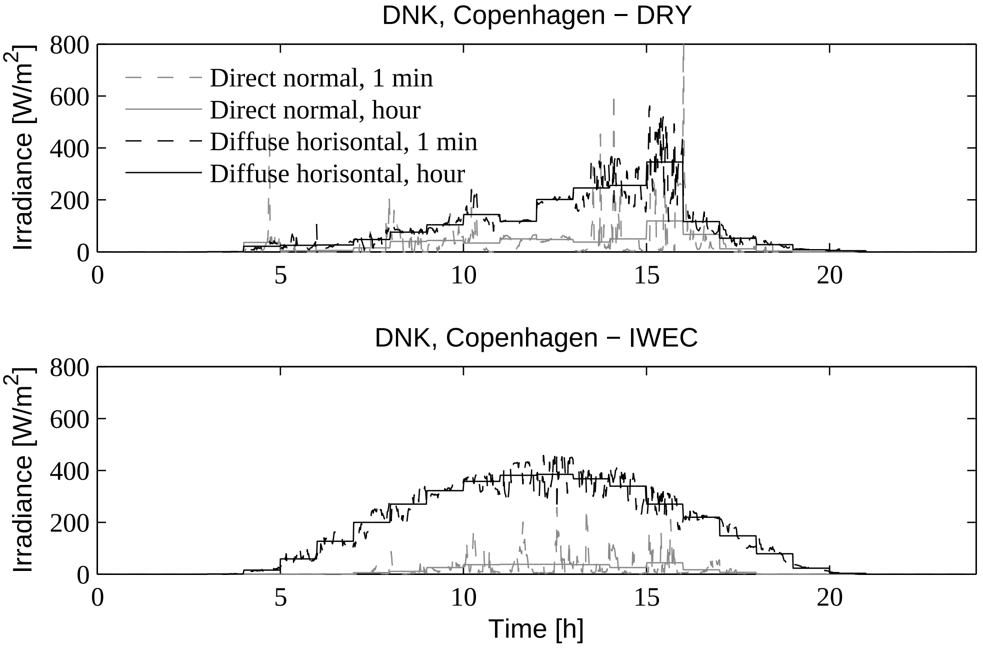

Figure 3 Horizontal diffuse and direct normal irradiance for the DRY and IWEC weather data at the location of Copenhagen on June 18th

3.3 One minute simulation time step

The comparison between lighting dependencies, both on/off and continuous, obtained from hourly means and one minute data show differences of up to 6 % dependent on the indoor threshold illuminance level and chosen weather data, see Figure 5 and Figure 6. Even though the differences are small the relative differences between simulations of hourly means and one min resolution can be quite high. For the sunny location of Phoenix the relative differences is i.e. in the magnitude of 1250 % and 350 % with continuous control at a threshold value of 100 lx and 200 lx. For the overcast locations of Copenhagen and Geneva the relative differences are in the magnitude of 20 % and 13 % at illuminance thresholds of 100 lx and 200 lx. The general trend is that the relative differences decrease with higher illuminance thresholds.

When the purpose of the simulations is to investigate the finer dynamics of the control systems, one has to simulate with a finer time step. Figure 7 shows the simulated lighting dependencies for 4 different automatic control strategies at the location of Copenhagen and Phoenix simulated with the DRY and TMY3 weather data. The 4 different control strategies are:

1. on/off switch when the illuminance threshold is reached
2. continuous control at each one minute time step
3. continuous control every 10 min and
4. proportional integral dimming, where the response is averaged over the past 10 min

The results show that there is no real difference in simulated lighting dependencies when simulating with continuous dimming for each time step, for every tenth minute or the PI control, where the response is averaged over the past 10 min. The reason for this is that when applying the control scheme for every tenth minute the lighting level will either be over- or underestimated and when evaluating for an entire year the differences will be balanced out.

4. Discussion

As in the study by Walkenhorst *et al.*[10] it can be concluded that simulations of hourly means compared to 1 min resolution does not give a conservative estimate of the energy consumption for artificial lighting, since the lighting dependency is underestimated, resulting in decreased lighting demand. In the study by Roisin *et al.*[12], they found a difference of less than 1 % using a threshold value of 500 lx. In the PhD thesis of Reinhart[30] he elaborates further on the comparison between the weather data sets, and find that for the closed loop system the electrical lighting demand at a threshold illuminance level of 500 lx is being underestimated by up to 9 % when applying hourly means compared to 1-min simulations. This study shows that at 500 lx threshold the electrical

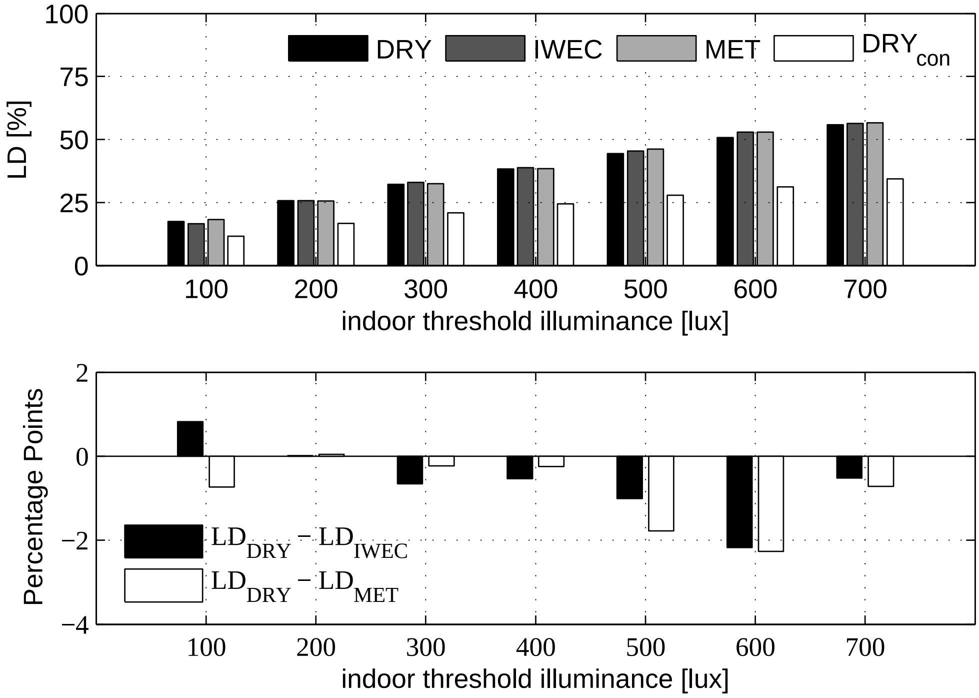

Figure 4 Comparison between hourly simulations for different weather data files for Copenhagen. Upper panel: Predicted lighting dependencies for the sensor point in the back of the room for the daylight simulations with hourly means from the Design Reference Year, IWEC, and Meteonorm weather data sets. Indoor threshold illuminance levels from 100 lx to 700 lx. Lower panel: Difference in percentage points (LD_{DRY}-LD_x) for the daylight simulations of hourly means

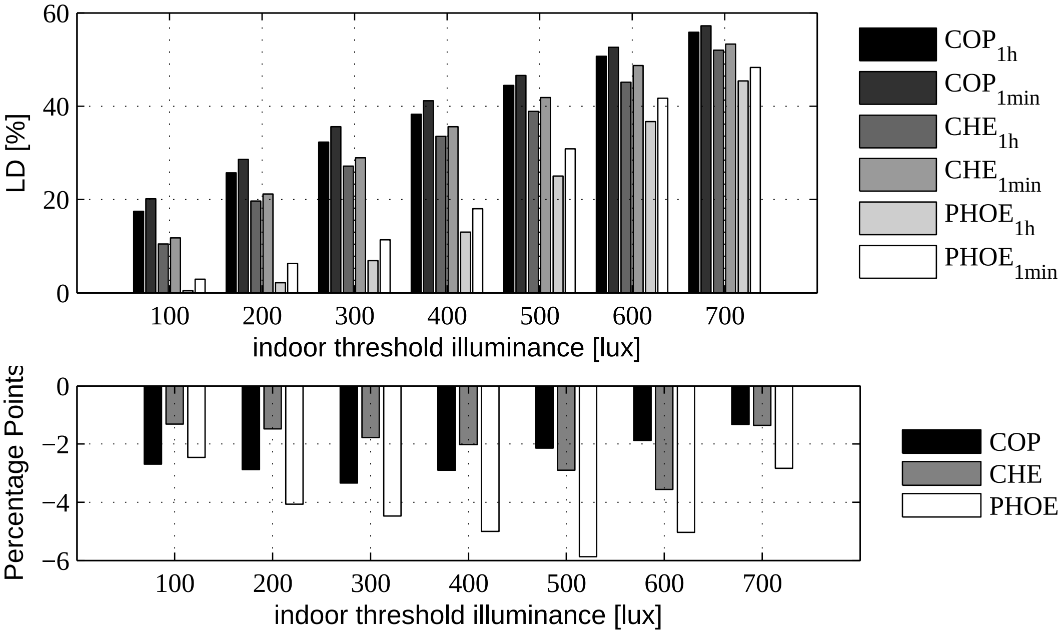

Figure 5 Comparison between hourly and one minute simulations for different climatic locations with on/off control. Upper panel: Lighting dependencies for hourly means and one minute data for the DRY file of Copenhagen (COP), the IWEC file for Geneva (CHE) and the TMY3 file for Phoenix (PHOE), Lower panel: Difference in percentage points in lighting dependencies for hourly means and one minute data for Copenhagen, Geneva and Phoenix, (1h-1min)

lighting demand is underestimated by up to 6 % for the sunny location of Phoenix and up to 3 % for the more overcast climate as Copenhagen and Geneva when applying resolution of hourly means compared to a one min resolution.

Typically differences of up to 10 % are considered to be good results in daylight simulations. The uncertainties regarding the simulation outcome could i.e. be encountered from measurement error of irradiance values, the influence of the exact location of the sensor points and influence of surface reflectances within the room. Even though the difference between the simulations of hourly means and one minute resolution are within the uncertainty for daylight simulation, the results show that by applying simulations of hourly means the energy consumption for artificial lights is categorically being underestimated. Although the differences are small, the relative differences between the simulations can be quite high. For the sunny location of Phoenix the relative difference is i.e. in the magnitude of 1250 % and 350 % with continuous control at a threshold value of 100 lx and 200 lx. However, at these threshold values the overall energy demand for artificial light is small and the high relative difference can be of of minor importance.

It is surprising that the short-term dynamics of the available daylight does not have a greater impact on the difference in continuous lighting dependencies between simulations of hourly means and one minute resolution. One would have assumed that simulations of hourly means for most annual working hours would underestimate the lighting dependency to a higher degree, due to spikes with high illuminance values increasing the hourly mean value. With an increased hourly

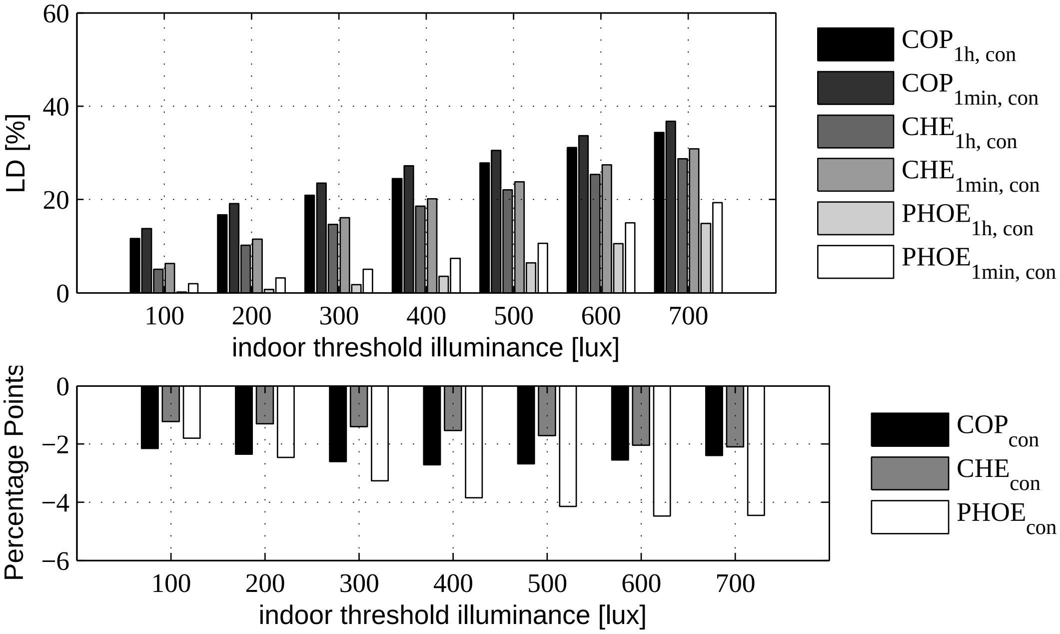

Figure 6 Comparison between hourly and one minute simulations for different climatic locations with continuous dimming control. Upper panel: Lighting dependencies for hourly means and one minute data for the DRY file of Copenhagen (COP), the IWEC file for Geneva (CHE) and the TMY3 file for Phoenix (PHOE). Lower panel: Difference in percentage points in lighting dependencies for hourly means and one minute data for Copenhagen, Geneva and Phoenix, (1h-1min)

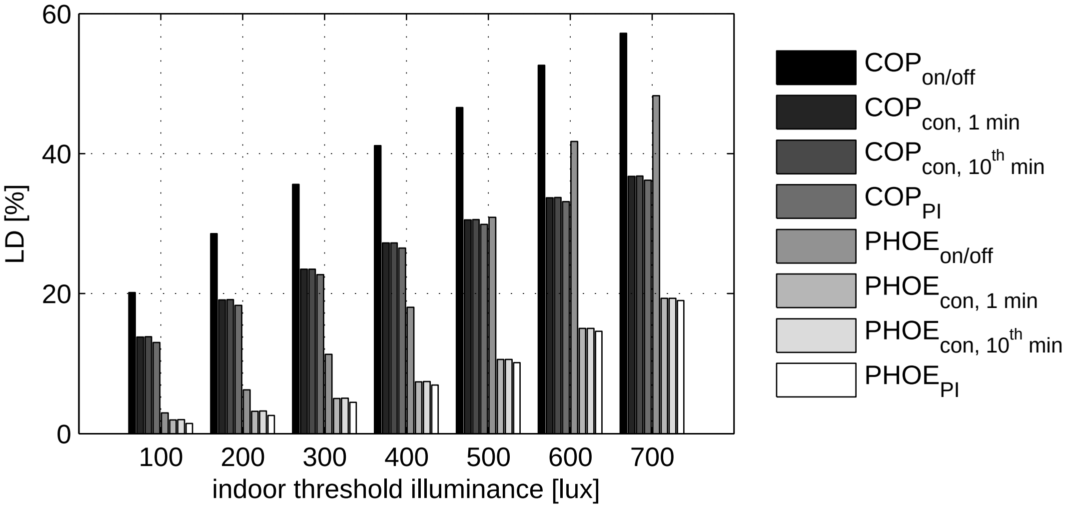

Figure 7 Lighting dependencies for weather data of one minute resolution with different control schemes for the location of Copenhagen and Phoenix

mean value the entire hour might have a sufficient daylight level, whereas the estimation with one minute resolution might fall below the threshold illuminance value at some time steps causing lights to be switched off. However this is not reflected from the results. The maximum discrepancy is 4.5 % depending on the indoor threshold illuminance and type of lighting control.

In Walkenhorst *et al.*[10] they investigated the non-deterministic influence of the stochastic model on the simulation outcome and found that the impact is negligible. The relative standard deviation of the specific annual electric energy demand for artificial lighting resulting from ten different realisations of the model newer exceeds 0.7 %. The discrepancies found in this study are larger than 0.7 %, which implies that it is differences in the weather data and not differences in the stochastic model that is being simulated. In Walkenhorst *et al.*[10] they furthermore compared lighting electric consumption of simulations using measured irradiances from one hour and one minute data sets and found that the consumptions are underestimated by 6 % to 18 % when using one hour irradiance values. The discrepancies found in this study are smaller which points to that the simulations of one minute resolution, with the current data and models available, do not behave as dynamic as expected. As pointed out in the PhD thesis by Reinhart[30] the amount of intra hour variations in the modified Skartveit-Olseth model are less pronounced than in reality as the model is stochastic; while differences between measured and simulated values may be substantial for a single day, the differences tend to vanish if a greater number of hours are considered.[30] In the development of the IWEC files the Skartveit-Olseth model was discarded, as they found that the model seemed to be tuned to European conditions and had not undergone extensive testing at other locations.[25] To include the true dynamic behavior of the sky there is therefore a need for creating better models or have measured irradiance data with a finer resolution than the hourly means.

The results show that there is no distinct difference in simulated lighting dependencies when applying continuous dimming for each time step compared to the PI control with the response averaged over the past 10 min. It is the authors' belief that this result reflects the limitations in the modified Skartveit-Olseth model to imitate the intra hour variations in available daylight. At present, using values of hourly means for the daylight simulations is therefore a reasonable predictor for the lighting dependency.

When evaluating the simulations based on hourly means for the different weather data files for the location of Copenhagen, no difference is observed when the threshold value for the general lighting level is 200 lx as prescribed according the Danish Standard DS700.[31] The energy consumption for artificial light will therefore yield the same result independent on the weather data used for the calculations.

5. Conclusions

In this study the effect on the outcome of the daylight simulations was investigated when simulating with different weather data files for the location of Copenhagen. It was found that the lighting dependencies generated based on the different weather data files for Copenhagen varied up to 2 % dependent on the chosen indoor illuminance threshold. Each of the different weather data sets where therefore found to give a reasonable prediction of the lighting dependency.

Furthermore the effect of simulating with weather data sets of an hourly resolution compared to a 1 min resolution showed that the lighting dependency was underestimated when using weather data of hourly means. However, the findings from this study show that the dynamic, short-term effects of the weather obtained from the modified Skartveit-Olseth method have a surprisingly small impact on the simulation outcome.

In terms of control of electrical lights no distinct difference in simulated lighting dependencies was found when applying continuous dimming for each 1 min time step compared to the PI control with the response averaged over the past 10 min. At present, using values of hourly means for the daylight simulations is therefore a reasonable predictor for the lighting dependency.

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Paper II

"Dynamic modeling of presence using inhomogeneous Markov chains"

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Dynamic modeling of presence using inhomogeneous Markov chains

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Abstract

Modeling of occupancy is a necessary step towards reliable simulation of energy consumption in buildings. This paper outlines a method for fitting occupancy data and simulation of single to multiple-persons office environments. The method includes modeling of dependence on time of day and by use of a filter of the observations it is able to capture per-employee sequence dynamics.

Simulations using this method is compared with simulations using homogeneous Markov chains and shows much better ability to reproduce key properties of the data.

Keywords: Occupancy, Inhomogeneous Markov chains, Simulation, Generalized linear models, Natural splines.

1. Introduction

Occupants interact with the indoor environment through heat and carbon dioxide emission, switching lights on/off, opening windows etc. Occupancy profiles are therefore a necessary input to building simulation models. The most common way of considering occupancy in simulation tools is by using and if necessary repeating one static occupancy profile (Haldi, 2010; Hoes et al., 2009). Typically the profile is constant for weekdays and weekends, respectively. However, occupants do not arrive in buildings or leave buildings at fixed times. A study by Manicca et al. (1999) reported that on average the offices were occupied 46% of the time, which is supported by the study by Page et al. (2008) where it was found that only half of the work day was spend at the work station. Therefore lights controlled by occupancy have shown great potential to save energy when a building zone is vacant.

The most commonly used devices for detecting occupancy use passive infrared and/or ultrasonic technologies (Guo et al., 2010). From empirical studies in office rooms i.e. Manicca et al. (1999), Jennings et al. (2000), and Galasiu et al. (2007) the reported energy savings are in the range 20-53% by use of occupancy sensors.

Recently, occupancy models have been developed by Tabak and de Vries (2010), Page et al. (2008), Wang et al. (2005), Bourgeois (2005) and Reinhart (2004). These models include behavior of occupants based on empirical data. Wang et al. (2005) and Richardson et al. (2008) both developed occupancy models as a first order Markov Chain (MC). Wang's data fits very well with the exponential distribution when observing individual offices and vacant intervals. However the exponential model was not validated for occupied intervals. As stated by Wang et al. (2005) these findings are not in conflict with each other. Compared to the vacancy intervals, the occupied intervals are more complex. A single motion sensor only records the longest time span of occupancy status in the room. If occupancy is caused by more than one occupant, then the sensor cannot tell for when and how long individual occupants arrive and stay. If the occupancy interval of each occupant were exponential, the recorded occupancy would be a mixture of more than one exponential distribution. This underlying occupancy interval structure is likely to cause the deficiency of an exponential model (Wang et al., 2005). Page et al. (2008) proposed an alternative model. They considered occupant presence as an inhomogeneous MC interrupted by occasional periods of long absence. By using a profile of probability of presence as input to a MC they were able to reproduce intermediate periods of presence and absence distributed exponentially with a time-dependent coefficient as well as fluctuations of arrivals, departures and typical breaks. They defined a parameter called the "parameter of mobility". This parameter gives an idea of how much people move in an out of the zone, by correlating the tendency of coming to work with the tendency of leaving.

Tabak and de Vries (2010) looked at presence of occupancy in more detailed way based on prior knowledge about time consumption on different tasks in a working day. As input to their model they include information on the intermediate activities of the occupants such as 'receiving unexpected visitor', 'walk to printer', 'have lunch', etc. They were able to simulate occupancy patterns using the S-curve and probabilistic method for different intermediate activities. The model by (Tabak and de Vries, 2010) is a step towards a more behavioral approach to simulating occupancy.

The focus of the study presented in this paper is to develop an occupancy model for simulating of single person occupancy sequences in an office environment. The study seek to answer the following questions:

1. How can the dependence of the tendency of being present on the time of day be modelled?
2. Is there a need for modeling dependence on past for obtaining better predictions?

The focus will be on modeling what can be considered "typical" occupancy sequences, where "typical" is to be judged from data. Sequence of very little presence are expected to be frequent because of vacation, sickness, etc. Also sequences if significantly more presence than "typical" could reflect different dynamics than "typical". The aim is to present a framework for modeling of occupancy in an office environment and apply it to fit data that is believed to be somewhat representative. Since the focus is on single-person simulation, correlation structures in data will not be modeled.

The outcome is techniques for an occupancy simulation model that can be used in building simulation programs when simulating demand responsive systems as lighting or ventilation systems.

2. Method

In this section, the data collection method and the mathematical framework to be used in the analysis will be described.

2.1. Data collection

Occupancy patterns have been measured in an office building in San Francisco, California. Data from 86 workspaces were collected, out of which 29 were unoccupied or occupied by interns. The occupancy pattern for those 29 workspaces have been excluded from the data because they reflect a different use of workspaces. Only data from the 57 workspaces that have been occupied by full-time staff for the entire measurement period is used.

Data come from ballast status records in the control system and have been registered every 2 minutes. If an occupant is present at the workspace, the lamp is switched on, and the ballast status is on. Once the workspace is unoccupied the lights drops to preliminary power and are turned off after a delay of 20 minutes. The occupants could not override anything manually. The data collected have been corrected for the delay by setting the last 20 minutes of intervals of "presence" to "absence". However absence shorter than 20 minutes have not been encountered because of the delay in the equipment.

The modeling is based on full days in September and December 2009 and January 2010, 16 days in total. On the days used, no data points are missing.

Table 1 *Nomenclature*

t	A time stamp in continuous time.
T	Maximum of t, i.e. $t \in [0, T]$
n	A time stamp in discrete time.
N	Maximum of n, i.e. $n \in \{0, 1, \ldots, N\}$
$\{X_n\}$	A random process in discrete time.
X_n	The state of the random process $\{X_n\}$ at time n.
x_n	The observation of the random process $\{X_n\}$ at time n.
$\boldsymbol{X}^{(i)}$	The i'th sequence of observations.
$\boldsymbol{\Gamma}$	A transition probability matrix.
$p_n \in [0, 1]$	The unconditioned probability of $X_n = 1$.
$\boldsymbol{A}^T$	A transposed.
M	Number of states in a Markov Chain
I	The characteristic function.
Q	The number of sequences of observations.
$\log : \mathbb{R} \to \mathbb{R}$	The natural logarithm.
$\mathbb{N}$	The set of natural numbers, $\{1, 2, \ldots\}$
$i, j \in \mathbb{Z}$	Integers.
μ_i	The mean of the i'th sequence of observations.
$\boldsymbol{\theta}$	A parameter vector.

2.1.1. Description of models

All models in the present work are in discrete time. Let $t \in [0, T]$ be a continuous time scale. Choose a natural number, N, and let $\tau := \frac{T}{N}$. Then $t_n = n\tau, n \in \{0, 1, \ldots, \frac{T}{\tau}\}$ is a discretization of t with sample period τ. The sample period is equal to the measuring period, 2 minutes, in this work.

The notation X_n is introduced as shorthand for the state of the discrete-time random process X at time t_n. In other words, X_n refers to X at time $n\tau$, in this case $n \cdot 2$ minutes.

Markov Chains. A Markov Chain is a time series that meets the Markov condition which states that conditioned on the present state, the future is independent on the past (Grimmett and Stirzaker, 2005). Let Ω represent the set of possibles states of X. Then, in discrete time, $\{X_n\}$ is a Markov chain if

$$\begin{aligned} &\forall k \in \mathbb{N} : n+k < N, \quad \forall s \in \Omega : \\ &\mathbb{P}\left(X_{n+k} = s | X_0, X_1, \ldots, X_n\right) = \mathbb{P}\left(X_{n+k} = s | X_n\right) \end{aligned} \tag{1}$$

A Markov chain with M states is completely characterized at time n by an $M \times M$ transition probability matrix, $\Gamma(n)$, which denotes the probabilities of all transitions:

$$\Gamma_{ij}(n) = \mathbb{P}\left(X_{n+1} = j \mid X_n = i\right), \quad i, j \in \{1, \ldots, M\} \tag{2}$$

This means that each row of the transition probabilities contains the distribution of the transition from one of the states in the Markov chain. Hence, each row sums to one:

$$\forall i \in \{1, \ldots, M\}, \forall n \in \{1, \ldots N\} : \sum_{j=1}^{M} \Gamma_{ij}(t) = 1 \tag{3}$$

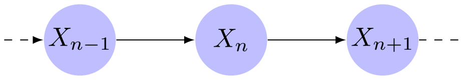

Figure 1 *Illustration of dependence in a Makov chain. The Markov condition says that all information about the future to time n, is contained in the present state, X_n. Therefore, in the graph, X_{n-1} and X_{n+1} are only connected through X_n.*

Because of the constraint in Equation (3), the transition probability matrix has, at each time step, $M-1$ degrees of freedom for each state, $(M-1)M$ in total for each time step. When applied on binary data, $M = 2$, and hence, the model has two degrees of freedom at each time step. If the transition probability matrix is constant, i.e. $\Gamma(n) = \Gamma, \Gamma \in \mathbb{R}^M \times \mathbb{R}^M$ the Markov chain is said to be *homogeneous*. A homogeneous Markov chain has $(M-1)M$ degrees of freedom.

Two-states Markov chains with covariates. Covariates in two-states Markov models can be modeled as

$$\operatorname{logit}(\Gamma_{11}(n)) = \alpha Z_{1,n}, \alpha, Z_{1,n} \in \mathbb{R}^p \tag{4a}$$

$$\operatorname{logit}(\Gamma_{22}(n)) = \beta Z_{2,n}, \beta, Z_{2,n} \in \mathbb{R}^q \tag{4b}$$

where the logistic function denoted logit is defined as

$$\operatorname{logit} :]0,1[\to \mathbb{R}, \quad \operatorname{logit}(x) = \log\left(\frac{x}{1-x}\right) \tag{5}$$

and log is the natural logarithm. Γ_{12} and Γ_{21} are calculated by application of Equation (3). This formulation has the advantages that the parameters are unconstrained while the resulting probabilities span and never exceed $]0,1[$. This is a *generalized linear model* (Madsen and Thyregod, 2011), and logit is the *link function* which maps from the full range of the real numbers into $]0,1[$. This model has $p+q$ free parameters.

Z is a *design matrix* that can contain any observable real input. Here, functions of time will be used. One design matrix could be

$$Z = (1, n, n^2)^T$$

where Z^T denotes Z transposed. This would result in a 2nd order polynomial to be passed through the logit function.

The dependence of $\{X_n\}$ on past values and on the exogenous process is illustrated in Figure 2. Since Equations (4) describe a transition probability matrix which is varying with some exogenous process, this Markov chain is *inhomogeneous.*

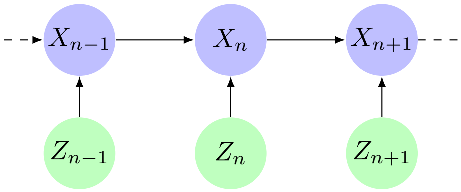

Figure 2 *Illustration of dependence in a Makov chain, $\{X_n\}$ with a covariate, $\{Z_n\}$. The input process is a deterministic process which is assumed to be known. As seen it only directly influences the Markov chain without time difference. Hence, the Markov condition (1), is still respected.*

Natural splines. Splines are piecewise polynomial functions. In this work, B-splines with natural boundary conditions will be used. These are piecewise third order polynomials with the boundary condition that the second derivatives are zero in the end-points Eldén et al. (2004).

Exponential smoothing. is a lowpass filter. It is a weighted average, with the weights exponential decaying with time difference. The speed of the decay contained in the only parameter, $\lambda \in [0,1]$:

$$\Lambda_n = \lambda X_n + (1-\lambda)\Lambda_{n-1} \tag{6}$$

Since $\{\Lambda_n\}$ is a weighted average of $\{X_n\}$, it has the same range as $\{X_n\}$.

In the framework of Equations (4), the design matrix for a model using exponential smoothing and no covariates is

$$Z_n = (1, \Lambda_{n-1})^T \tag{7}$$

Figure 3 is a graphs the information flow using exponential smoothing and no covariates. As seen from Figure 3, the Markov condition is still respected when using the exponential smoothing as input as long as the most recent, and only the past states of $\{X_n\}$ are used in the design matrix as in Equation (7).

Finally, both filtered states and exogenous can be used in the design matrix. A graph of this model is shown in Figure 4.

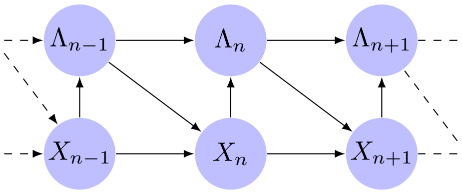

Figure 3 *A Markov chain with exponential smoothing as covariate in the transition probabilities. The Markov condition is still respected.*

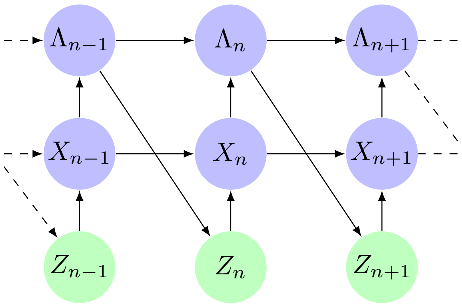

Figure 4 *A Markov chain with and exogenous process and exponential smoothing as covariate in the transition probabilities. The Markov condition is still respected.*

2.1.2. Model performance assessment

The estimation is based on the maximum likelihood principle. Let X_n follow the Bernoulli distribution with parameter, p. Then the likelihood function of p given the observation, x_n, is:

$$\mathcal{L}(p; x_n) = f_p(x_n) = \begin{cases} 1-p, & x_n = 0 \\ p, & x_n = 1 \end{cases} \tag{8}$$

The joint likelihood of observations $x_1, x_2, \ldots, x_N$ is the product of the individual likelihood values:

$$\mathcal{L}(p; x^{(N)}) = \prod_{n=1}^{N} \mathcal{L}(p; x_n) \tag{9}$$

The *maximum likelihood estimate* refers to the value of the parameters that maximizes the likelihood function.

$$\hat{p}(x^{(N)}) = \arg\max_{p} \mathcal{L}(p; x^{(N)}) \tag{10}$$

Here, p can also be a function of other parameters, $\boldsymbol{\theta}$. Then the maximum likelihood estimate of $\boldsymbol{\theta}$ is parameters that maximizes the likelihood function.

$$\hat{\boldsymbol{\theta}}(x^{(N)}) = \arg\max_{\boldsymbol{\theta}} \mathcal{L}(p(\boldsymbol{\theta}); x^{(N)}) \tag{11}$$

In stead of the likelihood function it self, the logarithm of the likelihood function, simply called the log-likelihood and denoted ℓ, is often used. This has the advantage that sums are used in stead of products:

$$\begin{aligned} \ell(x^{(N)}; p(\boldsymbol{\theta})) &= \log\left(\prod_{n=1}^{N} \mathcal{L}(p(\boldsymbol{\theta}); x_n)\right) \\ &= \sum_{n=1}^{N} \log\left(\mathcal{L}(x_n; p(\boldsymbol{\theta}))\right) \end{aligned} \tag{12}$$

Since the natural logarithm is an increasing function of all positive numbers, the log-likelihood can just as well be maximized as the likelihood it self.

Information criteria. Since change of positions of the splines leads to models that are not sub-models of each other, an *information criterion* is needed to compare the performance of different models.

The Akaike Information Criterion (AIC) is a popular choice of information criterion Wasserman (2003). For the model, S, it is given by

$$\text{AIC}(S) = -2 \cdot \ell_S + 2 \cdot k \tag{13}$$

where ℓ_S is the log-likelihood value of the parameters of S at the maximum likelihood estimate. k is the number of parameters in the model.

However, it may be an advantage to use the Bayesian Information Criterion (BIC) which takes the amount of data into account.

$$\text{BIC}(S) = -2 \cdot \ell_S + \log(N) \cdot k \tag{14}$$

where N is the number of data points.

3. Results

3.1. Data Overview

Data recordings for every two minutes from 56 sensors over 16 full days are considered. The first day is in August 2009, the last in January 2010. Hence, there is a shift from summer time to normal time included in this period. It was stated from the data suppliers that the time stamps in the data files were in PST/PDT (Pacific Standard Time/Pacific Daylight Time). Daily occupancy patterns for summer and winter were investigated, and they matched well when using the local time zone. Therefore “time of day” is used for modeling referring to the local time zone, i.e. PST/PDT.

It was investigated if some time of the day, some sensors, or even whole days should be skipped. The total number of activated sensors is inspected throughout each of the available days to ensure that none of them deviated from the others in a way so one would think that it was a holiday. The total number of occupants is plotted for all of the 16 considered days in the upper region of Figure 5. Two days look a bit different than the rest with lower occupancy in the afternoon but none of the days were so different that they could be considered non-working-days. Apart from these two days of slightly lower afternoon occupancy, the days are quite similar. All days were kept for the analysis.

Narrow spikes of high occupancy, even after 8 p.m., are seen in many – if not all – of the sequences of total occupancy. This means that the status of the sensors are correlated. The spikes are unlikely to be caused by employees coming to and leaving their desk but rather by one or more persons activating several sensors. It is known that a guard walks through the building every night and this could be the cause of some of these spikes.

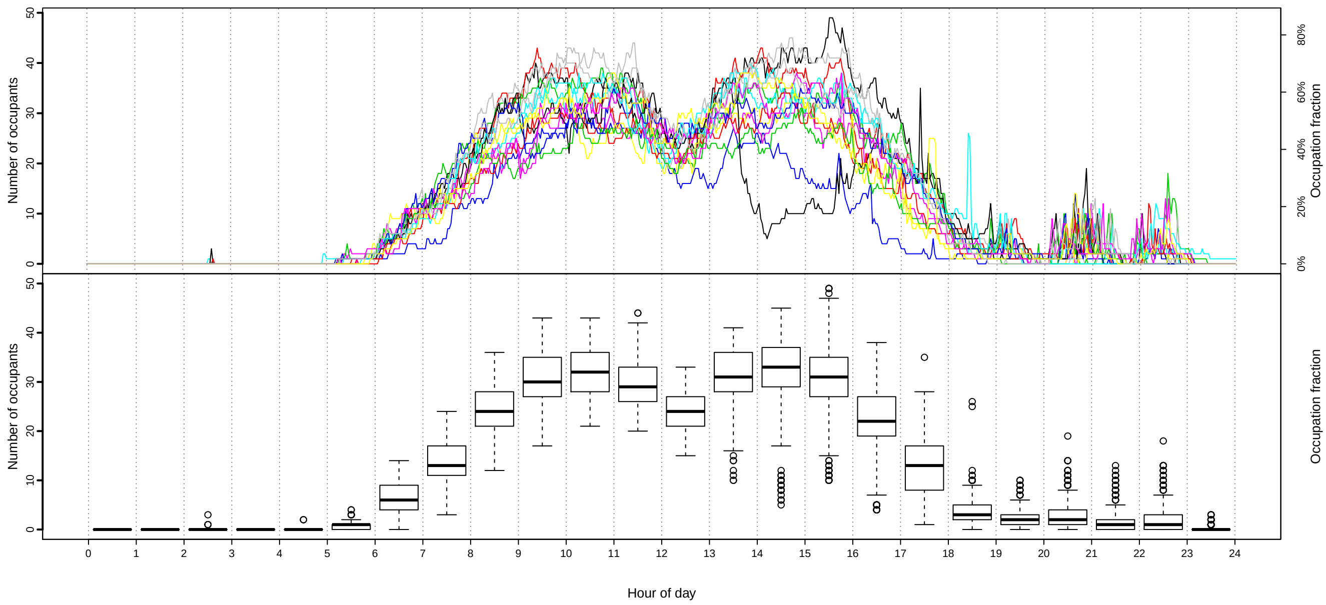

Figure 5 *The upper region shows the total occupancy of the office versus time of day for the 16 days considered. The lower region shows a boxplot summary of the distribution of number of occupants, aggregated on hour of the day.*

Since these spikes are likely not to caused by usage of the workspaces, they are not of considered particularly interesting in this work.

The lower region of Figure 5 is a boxplot of total occupancy in the building binned on hour of the day. It is seen that until 6 a.m., the activity is very close to zero, except for between 5 a.m. and 6 a.m. where there is a little activities on some of the days. However it is still below sensors that are positive at maximum. From between 6 a.m. to between 10 and 11 a.m. the activity is increasing to around 30 simultaneous positive measurements. From between 10 to 11 a.m. to between noon and 1 p.m. the total occupation is decreasing to a bit more than 20 as median. This drop could be explained by a lunch break. Then the activity is increasing until between 2 and 3 p.m. whereafter it starts dropping. After between 3 and 4 p.m. the activity drops quickly until between 6 and 7 p.m. where the median is below 5 sensors again. Also, from this plot it is clearly seen that the many narrow peaks in occupancy after 7:30 p.m. a relatively few outliers from the generally low occupancy. It is noticed that the variance of the occupancy is larger in the afternoon than in the morning. Since the dynamics of the occupancy is supposed to be modeled, it is decided to leave out the time intervals where the occupancy is small. Based on Figure 5 it is decided only to model occupancy from 6 a.m. to 7 p.m. Only this part of data is considered from this point.

It was then checked if data from some sensors is significantly different from the rest and should be considered outliers. It is expected that single sensors will be off almost throughout whole days because of employees being away. Also whole sensors might reflect different behavior. A boxplot of the mean activity over each day for each sensor is shown in Figure 6. The distribution of the daily means of the different sensors are quite different, both in medians and in variance. Many low occupancy days are seen, and also workspaces with generally very low occupancy. This seems to be too many for simply removing as outliers and will be further investigated below. However, a few sensors have very high occupancy(6, 20, 26 , 56, 57) and some of these (especially 6, 20, and 56) have low variance in occupancy. These could be located in areas that are passed by other employees throughout the day. At least they are considered significantly different from the rest. The vertical lines at the upper edge of the plot shows the sensors that are decided to leave out.

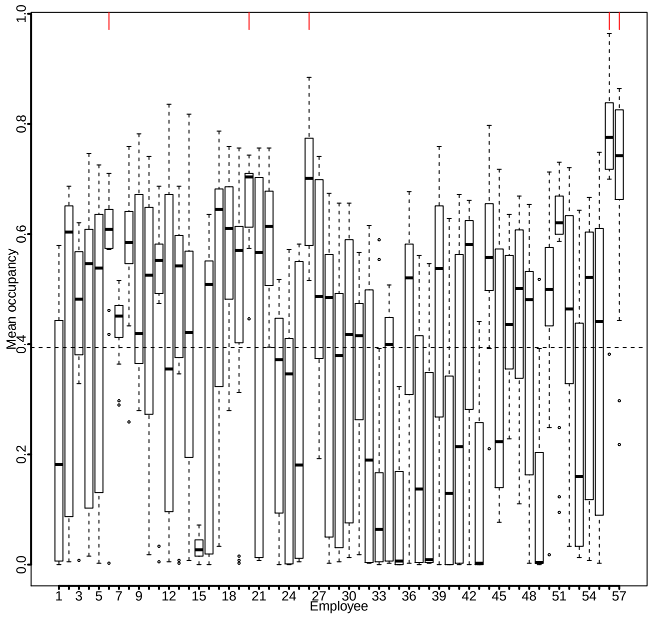

Figure 6 *Distribution of daily occupancy for each sensor. Only 6 a.m. to 7 p.m. is considered.*

In the data modeling description, the data considered is stripped from the outliers described here, and the delay periods are ignored.

3.2. *A hierarchical model*

To determine a threshold of when to consider a sequence of measurements from one day as not a working day, the distribution of the mean occupancy throughout a whole day of all sensors is considered. This is seen in Figure 7. There is a high density close to zero, and then the density is generally decreasing to a bit less than 0.2. It could be a mixture of one distribution with mode close to zero (not at work) and another with mode close to 0.6 (a work day). Based on this it is decided to make a threshold at a mean of 0.2 activity for a day-sequence. This corresponds to 2.6 hours of activity. Sequences with less occupancy than 20% (within 6 a.m.-7p.m.) will be used to fit a *low occupancy rate model*, sequences with more than 20% presence is used to fit a *high occupancy rate model.* This is excepted for the outliers detected in Section 3.1. Figure 7 shows this division of data. The blue color represents the sequences that falls into the “low occupancy rate” category, the green ones into the “high occupancy rate” category whereas the red ones are the outliers.

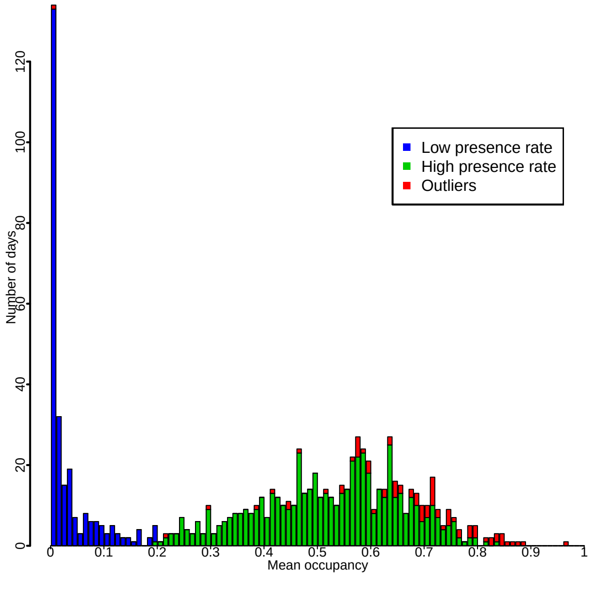

Figure 7 *Distribution of occupancy per day for all sensors.*

The model of the presence of one employee becomes a *hierarchial model*, see Figure 8. With a certain probability, P_{HPR}, the employee is modeled with a model describing occupancy patterns with a mean presence higher than 0.2, whereas another model with mean presence lower than 0.2 will be used with probability $1 - P_{\text{HPR}}$. The model of particular interest in the present paper is the model describing presence. The procedure of estimating this model is outlined. For the low-presence sequences, the same is procedure has been carried out and the results will be given.

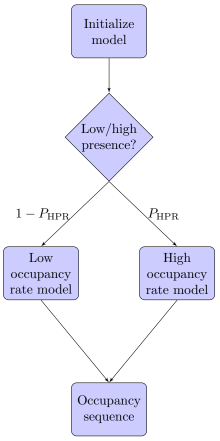

Figure 8 *The hierachal structure of the model*

The probability, P_{HPR} was estimated as

$$\hat{P}_{\text{hor}} = \frac{1}{N_{\text{s}}} \sum_{s=1}^{N_{\text{s}}} I(\mu_s > 0.2) \approx 0.695 \tag{15}$$

where μ_{s} is the mean presence in the sequence, s.

$$\mu_{\text{s}} = \frac{1}{N} \sum_{n=1}^{N} X_t^{(s)} \tag{16}$$

3.3. *High occupancy rate model*

Two different events must be described, namely the transition from idle (0) to presence (1) and from presence to idle. Different models will be applied, their performances assessed, and the best one will be picked.

For every two-minutes interval, the conditional probability of a transition to a one, given that a zero is observed can be estimated as

$$\begin{aligned}\hat{\Gamma}_{01}(n) &= \hat{\mathbb{P}}\left(X_{n+1} = 1 \mid X_n = 0\right) \\ &= \frac{\sum_{i=1}^{Q} I(X_n^{(i)} = 0, X_{n+1}^{(i)} = 1)}{\sum_{i=1}^{Q} I(X_n^{(i)} = 0)}\end{aligned} \tag{17}$$

which is only valid if at least one occurrence of 0 is observed.

These local estimates are shown as points in Figure 9. Also a fit of a generalized linear model with splines with 11 knots is shown. The tendency to start working is small at 6 a.m. and it only slowly increases the first hour. Then, from 7 a.m. to 9 p.m., this tendency grows rapidly. The growth is then slower but persists until around 10.30 a.m. where it starts decaying from about 7% chance of starting working given that one does not. A “valley” is then seen over lunch time around twelve. The global maximum is seen just before 2 p.m. after which it decays for a small valley before a local peak at 4 p.m. From there, it drops again and goes close to zero at 7 p.m.

The decision on a model structure is based on BIC. BIC values for the different models applied are plotted

Table 2 *Overview of the partitioning of the occupancy sequences.*

Group	Number of sequences	Mean occupancy	Variance of mean of sequences	Min. mean of sequences	Max. mean of sequences
HOR	571	0.521	0.018	0.205	0.836
LOR	260	0.031	0.002	0.000	0.197
Outliers	80	0.672	0.024	0.003	0.964
Total	911	0.394	0.068	0.000	0.964

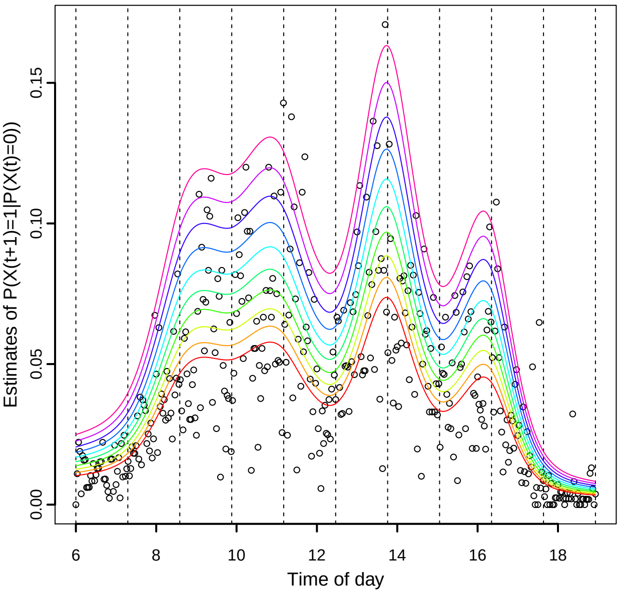

Figure 9 *Two-minutes estimates of the probability of occupancy for an employee at the next time step given that he or she is idle.*

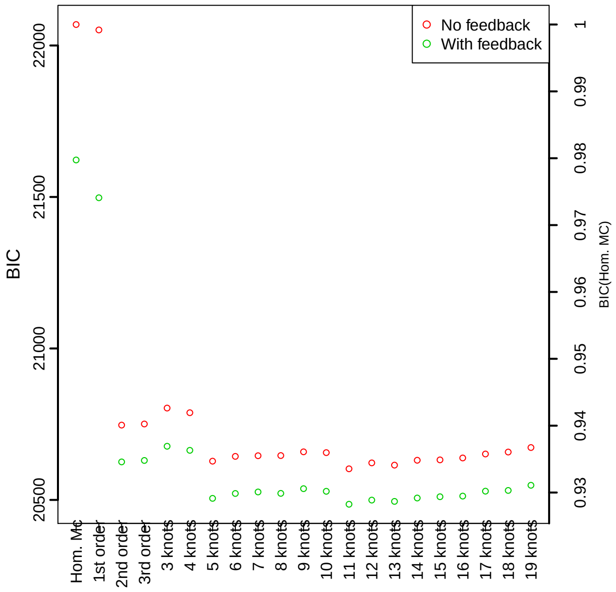

Figure 10 *BIC for different models applied to the transitions from absent to present in the high presence rate part of data.*

Table 3 *Parameter estimates in the model of transitions from idle to occupant, their confidence intervals, and p-values for the test of the hypothesis that the individual parameters are zero.*

Term	Estimate	2.5 %	97.5 %	Pr(>Chi)
(Intercept)	−4.57	−4.84	−4.31	
spl1	1.89	1.59	2.20	0.000
spl2	1.51	1.10	1.94	0.000
spl3	2.04	1.66	2.42	0.000
spl4	0.71	0.33	1.09	0.000
spl5	2.75	2.37	3.13	0.000
spl6	0.56	0.14	0.98	0.009
spl7	2.26	1.86	2.66	0.000
spl8	−0.78	−1.19	−0.38	0.000
spl9	−0.77	−1.44	−0.09	0.028
spl10	−1.24	−1.70	−0.82	0.000
fb	8.42	7.01	9.81	0.000

in Figure 10. A large gain is seen in going from using homogeneousity or a 1st order polynomial to at least a third order polynomial or splines. This gain in BIC is of about 6%. Then there is a drop of about 1% of the BIC of the homogeneous model from using 4 to 5 knots and again a small drop from using 10 to 11 knots. The increase in BIC between these models could be because of a suboptimal positioning of the knots. The feedback improves all the models implemented with about 1% of BIC of the homogeneous model or more. The best model is found to be based on a spline with 11 knots and the feedback. This gives 13 parameters in total.

Table 3 shows the parameter estimates in the generalized linear model of the probability of occupancy at time $n+1$ conditioned that an employee is idle at time n.

Using likelihood-ratio tests, it was checked that all parameters in this model are significant. The exponential smoothing parameter is 0.205. The parameter estimate related to the exponential smoothing is 8.7. Since there will never be a switch back from 0 to 1 after less than 10 zeros, the feedback level cannot be at more than $1 \cdot (1-0.205)^{10} \approx 0.1$. The probability of having a transition from 0 to 1 given the state 1 is shown as function of time of day for different relevant feedback levels in Figure ??.

The same analysis has been carried out for modeling the probability of occupancy at time $n+1$ given that the

Table 4 *Parameter estimates in the model of transitions from occupancy to occupancy, their confidence intervals, and p-values for the test of the hypothesis that the individual parameters are zero.*

Term	Estimate	2.5 %	97.5 %	Pr(>Chi)
(Intercept)	1.72	1.22	2.26	
spl1	0.27	−0.27	0.78	0.317
spl2	0.02	−0.65	0.66	0.946
spl3	0.44	−0.15	1.00	0.139
spl4	−1.41	−2.03	−0.84	0.000
spl5	0.71	0.11	1.29	0.021
spl6	−0.26	−0.88	0.33	0.392
spl7	0.27	−0.33	0.85	0.368
spl8	−1.43	−2.02	−0.87	0.000
spl9	−1.30	−1.74	−0.88	0.000
spl10	−2.05	−3.31	−0.86	0.001
spl11	−2.37	−2.80	−1.94	0.000
fb	2.78	2.63	2.93	0.000

Table 6 *Parameter estimates in the model of the probability of occupancy at $n + 1$ given idle at n.*

Term	Estimate	2.5 %	97.5 %	Pr(>Chi)
(Intercept)	−6.69	−7.31	−6.13	
spl1	2.03	1.47	2.63	0.000
spl2	1.33	0.61	2.11	0.000
spl3	3.18	2.69	3.68	0.000
spl4	2.58	1.25	4.02	0.000
spl5	−1.93	−2.59	−1.32	0.000

employee is occupant at time n. The resulting parameter estimates in the generalized linear model are shown in Table 4.

Table 5 shows an overview of the aggregated performance (all transitions – from idle as well as occupancy) of the different models that have been applied on the high occupancy rate data. It is seen that the inhomogeneous models outperform the homogeneous ones measured on bias and BIC. Measured on rmse, the homogeneous Markov chains perform better.

3.4. Low occupancy rate model

The same procedure as for the high occupancy rate model has been carried through to find a low occupancy rate model. In this case, the exponential smoothing was not found significant to include in the generalized linear model. For the model of the probability of occupancy at time $n + 1$ give idle at time n, a generalized linear model based on a spline with six parameters was found to perform the better. The parameter estimates are listed in Tables 6.

For the modeling of the probabilities of occupancy at time $n + 1$ given occupancy at time n, the chosen generalized linear model is based on a second order polynomial and no exponential smoothing. The parameter estimates are listed in Table 7.

Table 7 *Parameter estimates in the model of the probability of occupancy at $n + 1$ given occupancy at n.*

Term	Estimate	2.5 %	97.5 %	Pr(>Chi)
(Intercept)	−3.43	−5.01	−1.84	
X1	0.80	0.54	1.05	0.000
X2	−0.03	−0.04	−0.02	0.000

Table 8 lists aggregated performance measures of models on the low occupancy rate part of data. Again the inhomogeneous Markov chains perform better when measured on bias and BIC, whereas there is no clear picture from the rmse.

4. Simulations

The estimation was based on data from 16 days. The estimated models were then used to simulate 16 other days. These are simulations of the full system as sketched in Figure 8 for all employees. This gave a total of 575 sequences simulated with the HOR model and 257 simulated with the LOR.

Figure 11 shows the sequences of total occupancy versus time of day for the simulated data. This is to be compared with the plots in Figure 5. The simulations all start with low occupancy (due to initial conditions), they have a peak before lunch, and one after. At 7p.m. the occupancy has dropped close to zero. The general tendency captures the one of the data very well. However, the data seems to vary a bit more, especially after the lunch break.

Figure **??** show the mean of total occupancy over the day and an estimated confidence interval for the total occupancy too. The statistics are shown for the data series, the homogeneous Markov Chain simulations (both for LOR and HOR), and the inhomogeneous MC's with and without exponential smoothing. with a third order polyomial of time, the feedback model with Whereas the Markov chain due to the homogeneity does not capture the dependence of time, the two inhomogeneous models both have this ability. It is seen that the exponential smoothing does not have a big influence on the mean occupancy over the day. This is as expected since the exponential smoothing is rather a filter that will influence on the dynamics on a per-employee level. From the confidence intervals, it is again seen that in the afternoon, the variance in total occupancy is larger for the data than for any of the models.

The distribution of the simulated occupancy for employees throughout single days is shown in Figure 12. This should be compared with Figure 7. It is seen that the fitted LOR model tends to give fewer days of almost no occupancy and fewer days with occupancy over 0.1.

Table 5 *Performance measures for the applied models on the high occupancy rate part of data. The inhomogeneous Markov chain using exponential smoothing has both the better BIC and bias.*

HOR Model	N	k	rmse [100]	bias [1000]	logLik	BIC
Hom. MCs	222508	4	14.61	0.00	−22875	45799
Inh. MCs	222508	25	14.51	0.00	−21683	43673
Inh. MCs, exp. sm.	222508	27	14.40	0.00	−21067	42466

Table 8 *Performance measures for the applied models on the low occupancy rate part of data. The inhomogeneous Markov chain has both the better BIC and bias.*

LOR Model	N	k	rmse [100]	bias [1000]	logLik	BIC
Hom. MCs	101140	2	11.18	0.00	−5875	11774
Inhom. MCs	101140	9	11.13	0.00	−5734	11571

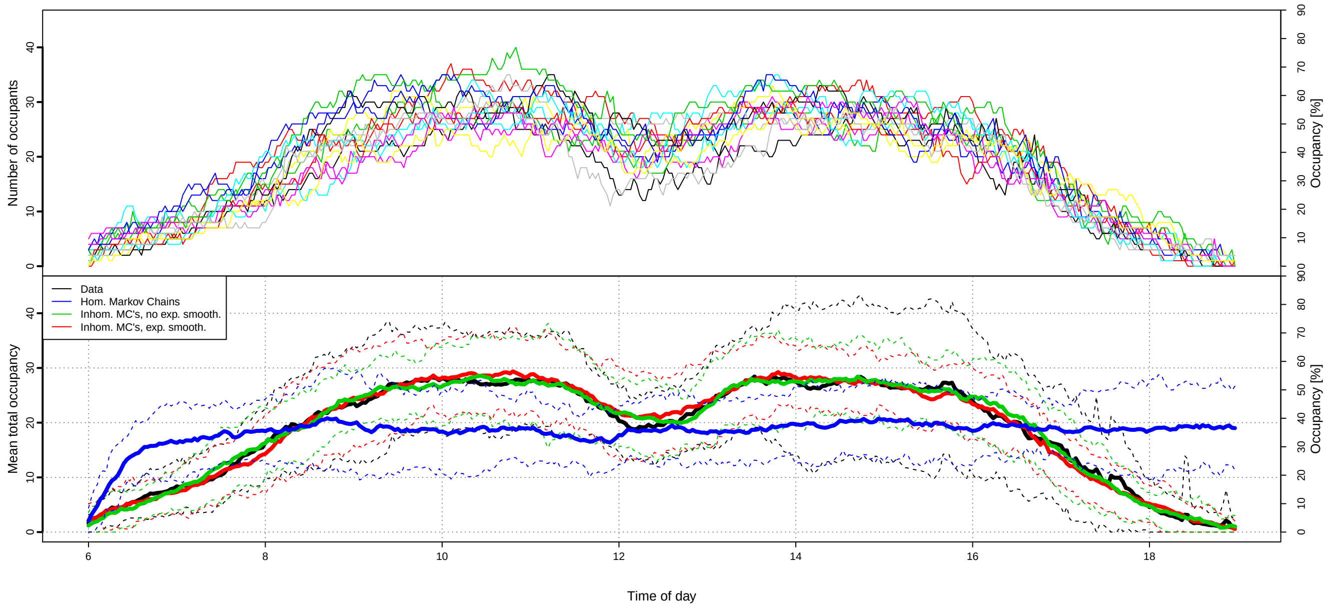

Figure 11 *Simulation of total occupancy throughout 16 days. All employees on all days are independently simulated using the model structure as in Figure 8.*

The HOR model seems to fit the distribution in the data nicely. However, the tails of the distribution seems are a bit longer than what is seen in the data.

5. Discussion

In many applications, total load is what is wanted

If data is available without delays, the Zucchini feedback model might be better.

maybe weekdays difference

'Vores' model i forhold til kendte modeller

only one-day, one-person models. Single-person behaviour could change for a longer period. Vacation, illness etc. Also correlation structures could be used to generate "Fridays" and the like.

6. Conclusions

Occupancy patterns for employees in an office environment have been modeled based on data collected from electrical ballasts triggered by passive infrared sensors. After compensation for a delay in switching off the ballasts and removal of outliers, data was divided into "low occupancy rate" and "high occupancy rate" patterns which were fitted independently and the probability of activation of the two resulting models was estimated.

By use of generalized linear models based on natural splines and exponential smoothing of observations, the daily patterns were fitted. By use of the fitted models, new occupancy patterns were simulated, and they were shown to have similar men occupancy over the day, and the distribution of the occupancy per day had the same

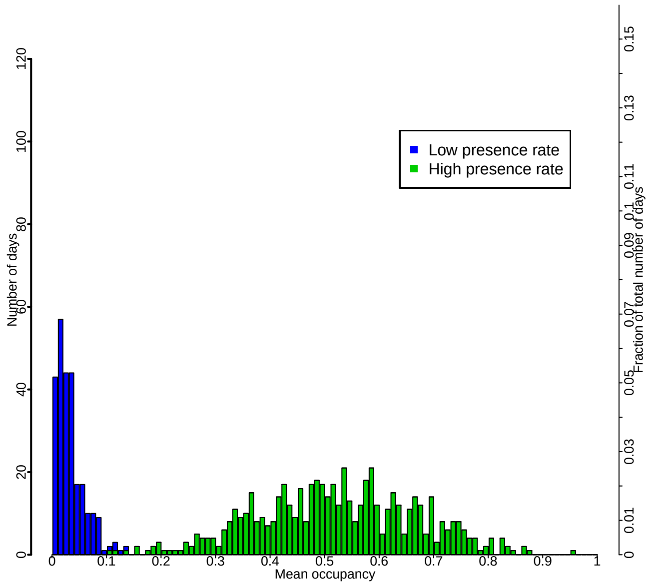

Figure 12 *Histogram of fraction of time on a day that employees are occupant in simulations.*

two-peak property as the data. The mean occupancy per versus time of day fit using homogeneous Markov chains did not capture the two-peaks tendency with a drop around lunch time and the drop in the afternoon.

While using exponential of the observations as a covariate in the Markov chains did not seem to have any large effect on the dependency of the time of day, it proved to improve the one-step predictions. This is supposed to reflect an improved model of the dynamics of the sequences.

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Paper III

"Simulation of the annual artificial lighting demand by use of different occupancy profiles"

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Submitted to: *Lighting Research and Technology*

Simulation of the annual artificial lighting demand by use of different occupancy profiles

Abstract

The effect on the artificial lighting demand was investigated by applying occupancy models of different resolution to the Climate Based Daylight Modeling. The lighting demand was evaluated in a building zone where the occupant was; always present, present corresponding to absence factors, present based on estimated annual mean presence, present based on estimated 1-hour mean presence, and present based on 2-min presence. The results showed that there is little difference in the annual artificial lighting demand when employing the same occupancy profile for each day opposed to profiles where the presence varies for each day. Furthermore the results showed that the annual artificial lighting demand is evaluated slightly conservative when applying a mean absence factor opposed to dynamic occupancy profiles estimated for the same building.

1. Introduction

A recent literature review of the energy saving potential and strategies for electric lighting in future low energy office buildings in Northern Europe[1] state that 80 % to 90 % of the environmental impact from lighting is generated during the operation of the lighting system.

While the cost of an electric lighting installation typically represents 15 % of total costs the electricity use during operation represents around 70 % of total costs. Furthermore another study[2] indicated that investments in energy efficient lighting are one of the most cost-effective ways to reduce CO2 emissions. Therefore, to enhance reduction of CO2 emissions while improving the energy consumption of buildings a large saving potential can be provided by cutting down the electricity usage during operation of the lighting systems, which can be accomplished using existing technology. The most efficient way to keep down the electricity use is to employ control of artificial lights based on presence of occupants in conjunction with photoelectric dimming.[3-6]

The most commonly used devices for detecting occupancy use passive infrared and/or ultrasonic technologies.[7] Sensors for occupancy detection usually have a built in time-delay between 6 to 30 minutes before the lights are switched off [7,8] and the switching of light based on presence of occupants can be considered as a varying dynamic incidence as occupants do not arrive in buildings or leave buildings at fixed times. Research show that occupants typically stay away from their workspace 25 to 50 % of a workday.[3,9,10] Nevertheless, in simulation the most common way to consider presence of occupants is to have a static profile for weekends and weekdays.[11,12] To consider the dynamic, natural behavior of occupants different occupancy models have been suggested based on empirical data, i.e.[9,10,13-17]. The models can be grouped in models describing presence/absence of occupants solely[9,10,13,15] and models also including behavior as probabilities of the manual on/off switching of lights and operation of blinds[17-19] or intermediate activities of the occupants[14].

The occupancy models developed in[9,10,14-17] all focus on modeling arrival and departure of occupants in office buildings or dwellings. The models of Wang *et al*.[9] and Richardson *et al*.[15] are occupancy models developed as first order markov chains. Wang *et al*.'s data fits very well with the exponential distribution when observing individual offices and vacant intervals. However the exponential model was not validated for occupied intervals. In the study of Page *et al.*[10] they tried to overcome this limitation by modeling the occupancy as an inhomogeneous markov chain and introducing a mobility parameter. This parameter gives an idea of how much people move in an out of the zone, by correlating the desire for being at work with the desire of going home. The model developed in Delff *et al.*[13] proposes a new way to estimate occupancy by fitting presence of occupants with inhomogeneous markov chains with generalised linear models of splines and exponential smoothing of past observations. The model is capable of predicting a realistic scenario for the presence of occupants throughout a working day. The model overcomes the limitations in i.e. Wang *et al.*[9], by being able of modeling both presence and absence of occupants, without introducing a mobility parameter, which was suggested in the paper by Page *et al.*[10]. Other studies have sought to capture the dynamic sequences of each occupant. The original LIGHTSWITCH model developed by Newsham *et al.*[16] intended to capture these dynamics. The original LIGHTSWITCH model operates with three different probability profiles: 1) arrival probability, 2) departure probability and 3) a probability of temporary absence, with peak at noon. However, in the PhD thesis of Reinhart (2001)[20] he found that the model did not comply with measured data.

Except from applying absence factors the most used occupancy model in lighting simulations is the Lightswitch-2002 model implemented in Daysim[18,21]. According to Reinhart (2004)[18] the Lightswitch-2002 model has been developed based on the same idea as Newsham's original model, i.e. to predict electric lighting use based on behavioral patterns which have all been observed in actual office buildings. For now, the simulated presence of occupants in Lightswitch-2002 can be profiles with constant presence during the occupied hours where arrivals and departures are randomly scheduled in a time interval of 15 min around their official starting times to add realism to the model.[18] Furthermore, dependent on the length of a working day breaks can be added to the occupancy profile. If the working day is less than 3 hours long, the user leaves the work place once for a 15 minute break. If the working day is between 3 and 6 hours long, the user leaves the work place twice for 15 minute breaks. If the working day is longer than 6 hours, the user leaves for two 15 minute breaks and a 60 minute lunch break.[21] Even though the occupancy model in Lightswitch-2002 has some randomness in its routine, the model is not capable of modeling the dynamic sequences of occupants throughout a year. Furthermore the model does not consider temporary absence shorter than 15 min. The Lightswitch-2002 model was applied in whole building simulation in the PhD thesis of Bourgeois (2005).[19] Here he investigated the influence on the lighting demand when having a fixed occupancy profile, where the lights were always on compared to cases with manual control of the artificial lights and automatic control of the artificial lights. Not surprising, he found that introducing occupancy profiles to the building simulations, the energy consumption for artificial lights decreased. The manual control decreased the energy consumption up to 62 % and a further reduction of 50 % could be achieved by automatic control. However, the influence of resolution of occupancy patterns was not investigated. Resolution is important when using simulation programmes, as simulation time increases with resolution. Therefore the lowest resolution which still yields a correct result is of interest, when evaluating the lighting performance of a space on an annual basis. In this study the effect on the artificial lighting demand will be investigated by applying occupancy models of different resolution to the Climate Based Daylight Modeling (CBDM).

2. Method

The simulations for the daylight and artificial light availability have been carried out using RADIANCE[22].

2.1 Annual simulation procedure

The annual simulation follows the daylight coefficient method developed by Ward *et al.*.[23] A matrix is used to characterise each phase of light transport. The input condition is a sky luminance vector. The result is achieved by multiplying the sky vector by each matrix representing each phase of flux transfer [23,24]. This process is described by the following equation:

$$\boldsymbol{i} = \boldsymbol{VTDs} \qquad (2.1)$$

where,
V is the view matrix and characterizes the relationship between light leaving a window and arriving at a sensor point
T is the transmission matrix, relating incident window directions to exiting directions
D is the daylight matrix, relating sky patches to incident Klems directions on window
s is the sky vector, assigning luminance values to patches representing sky directions.

The ***V*** and ***D*** matrices are created with the *rtcontrib* tool within Radiance simulation. The ***T*** matrix can be created using Window6, by simulation (i.e. TracePro or Radiance *genBSDF*) or can be measured with a goniophotometer. For the case studied in this paper, the transmission matrix corresponds to a standard glazing unit, with light transmittance of 72%. The ***s*** vector is generated from a Radiance sky description as described in Jacobs (2010).[25] The sky simulated is the Perez all weather sky discretised using the Reinhart division scheme subdivided in 2306 patches.

All calculations have been carried out based on hourly and 2-minutes direct normal and diffuse horizontal irradiance data. The 2-min irradiance data are generated from the hourly means values from the Design Reference year, DRY, for Copenhagen following the modified Skartveit-Olseth method developed by Walkenhorst *et al.*.[26] In the study by Iversen *et al.*[27] it was found that simulations of hourly means was just as good at estimating the daylight availability as simulating with a finer resolution generated from the modified Skartveith-Olseth method. However in this study the dynamic behavior of the presence of occupants is to be considered in the control systems for the artificial lights, why the timestep-resolution also is set to be smaller than the hourly resolution.

2.2 Simulated zones

Zoning of building systems can have a significant effect on overall energy consumption. For example, small zones will clearly enhance the benefits of occupancy sensor controlled lighting; a smaller zone, i. e. a single workstation is vacated more frequently than a larger zone.[16,28] For this study the simulated zone is a single person office. Figure 1 show a sketch of the simulated room.

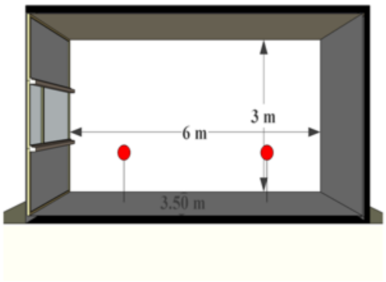


Figure 1 Sketch of simulated room, red dots indicate location of sensor points

2.3 Statistical Methods

As stated in Mardajlevic *et al.*[29] it is important to note that if the designer only evaluates the building performance based on the predicted occupied period, opportunities to improve the daylight potential of the building might be left out. Therefore the reference case for the simulation will be an evaluation of daylight performance of the space with occupants present in the entire simulation period followed by evaluations with dynamic occupancy models. The lighting demand for artificial lights will be evaluated in a building zone where the occupancy profile:

1. is constant for the weekdays and weekends - occupants are always present
2. is constant for the weekdays and weekends - here an absence factor has been applied, both the absence factor given in EN15193 (2007)[6] and the absence factor estimated from the measured data.
3. estimated annual mean presence, where the occupancy pattern follows the same profile each day throughout the year
4. estimated 1-hour mean presence, where the occupancy pattern varies for each occupied hour throughout the year

5. dynamic 2-min presence of occupants as developed in Delff *et al*.[13]

The evaluation of the lighting demand is based on the lighting dependency (LD). LD defines the percentage of the occupied hours per year when electrical light has to be added to the lighting scene to maintain a minimum work plane illuminance threshold.[27] A LD of 100 % represents a case where the lights are switched on for the entire occupied hours. This could i.e. be the case in the core zone of a building, where no daylight is present and no occupancy control is applied.

The artificial lights are controlled in two zones - one in front of the room and one in the back of the room. The total lighting dependency of the room is then given as the average of the lighting dependency at the sensor points.

2.3.1 Description of models

In the following section a short description will be given of the statistical model applied for generating the dynamic occupancy profiles. The model has been developed by Delff *et al*.[13] and is capable of modeling the dynamic sequences of presence for a typical occupant. A more thorough description of the statistical model is given in their paper.

2.3.2 Measurements

The model is based on measured occupancy patterns from an office building in San Francisco, California during 2009. Data from 86 work spaces were collected, of these

29 work spaces were un-occupied or occupied by interns. The occupancy patterns for those 29 work spaces occupied by interns were very random and have been excluded from the data. The model will therefore take into account the 57 work spaces that have been occupied by full-time staff for the entire measurement period. The measurement period include days in August, September, December and January, in total 32 days. For the study 16 days were used.

Data have been collected for every 2 minutes. The data come from ballast status records in the control system. The occupants could not override anything manually. If an occupant is present at the workspace, the lamp is switched on, and the ballast status is on. Once the workspace is unoccupied the lights are turned off after a delay of 20 min. The data collected have been corrected for the delay by removing the previous 20 min if the ballast dropped to preliminary power. The ballast status therefore equals presence of occupants. Absence shorter than 20 minutes has therefore not been encountered. However presence of short intervals can occur.

2.3.3 Description of models

The model of the presence of one employee is a hierarchical model, see Figure 2.

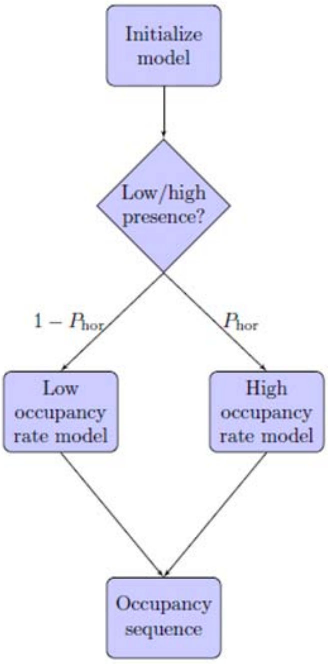


Figure 2 The hierarchical structure of the model[13]

First the probability of the occupancy rate is modeled as a Bernoulli experiment. If the outcome of the Bernoulli experiment result in a low occupancy rate (lor) the model for describing absence is applied, else the model with high occupancy rate (hor) is applied when generating the occupancy profiles. To determine a threshold of when to consider a sequence of measurements from one day as not a working day, the distribution of the mean occupancy throughout a whole day of all sensors is considered. As found in[13] there is a high density close to zero, and then the density is generally decreasing to a bit less at 0.2. This implies that the measured data of occupancy patterns is a mixture of one distribution with mode close to zero (not at work) and another with mode close to 0.6 (a work day). Based on this it is decided to have for a day-sequence at a threshold of mean activity 0.2. With a certain probability, P_{hor}, the employee is modeled with a model describing occupancy patterns with a mean presence higher than 0.2. Whereas another model with mean presence lower than 0.2 will be used to model a day with low occupancy rate with probability 1-P_{hor}.

Inhomogeneous Markov Chain. A markov chain is a time series that meets the markov condition which states that conditioned on the present state, the future is independent on the past[30]. If the transition probability matrix is constant the markov chain is said to be homogeneous. However, to model the time varying presence of occupants the underlying overall distribution of the data has been modeled as an inhomogeneous markov chain. The varying transition probability matrices are estimated with generalised linear models using natural splines as input (Z) to the markov chain (X). 3rd order degree polynomials were fitted to the data between knots. To determine the necessary number of knots sensitivity analysis were performed. It was found that 11 knots gave the overall best fit, for the two different events of; 1) being absent from work and start working again and 2) being present at work and stop working.

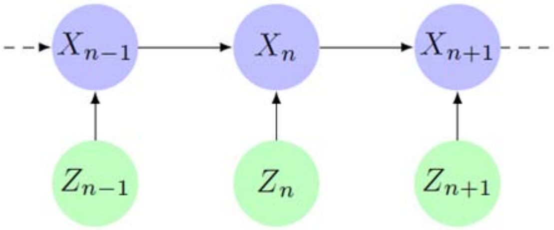


Figure 3 Illustration of dependence in an inhomogeneous Markov chain. The input process is a deterministic process which is assumed to be known. As seen it only directly influences the Markov chain at the present.[13]

To model the low occupancy rate a similar approach has been applied. Here the input to the markov chain is a natural spline with 5 knots for the case where an occupants is absent from work and starts to work again. For the opposite case, where the occupant is present at work and stop working, the input is a second degree polynomial. This underlying inhomogeneous markov chain with splines as input gives a very good description of the presence and absence of the occupants.

Exponential smoothing. To further improve the model, exponential smoothing has been added as a low pass filter to the model (Λ), see Figure 4. The exponential smoothing improves the description of the dynamics of the sequences for each occupant. The exponential smoothing gives a feedback to the transmission of probabilities. One could say that the filter represents a measure for how much you would like to work. If you have worked a lot, it is more likely that you continue working. In other words - the model is capable of dividing days with high work load, i.e. the employee is at the office or days where the employee is absent from the office.

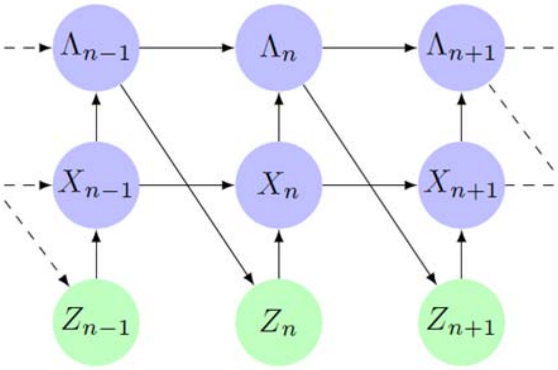


Figure 4 A Markov chain with an exogenous process (Z) and exponential smoothing (Λ) as covariate in the transition probabilities.[13]

3. Results

The first section presents an overview of the modeled presence of occupants. The second section presents results of the lighting dependencies applying the occupancy patterns to the dynamic daylight simulations.

3.1 Modeled occupancy patterns

For the simulated period from 6am to 7pm the total absence factor (F_A) of the modeled occupancy profiles is 0.63. The estimated annual mean presence and the confidence interval are seen on Figure 5.

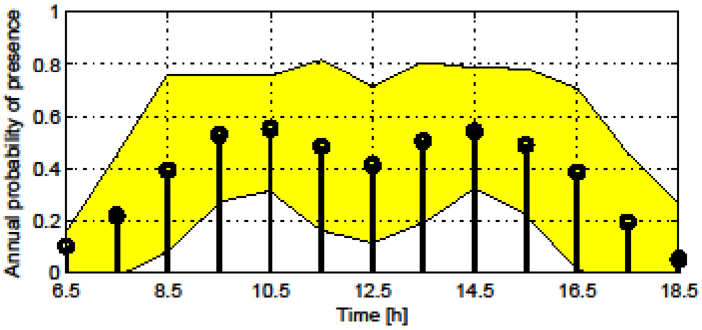


Figure 5 Estimated annual mean presence and confidence interval for 4 different independent occupants, according to the model developed in Delff *et al.*[13]

When applying the annual mean presence in the daylight simulation the occupancy profile is the same throughout the year. The annual mean profile does not include peak loads, which might induce simulation errors when predicting the energy demand for artificial lights, as both the occupancy pattern and daylight distribution varies throughout the year. However, in reality the presence of occupants varies. The annual accumulative plot for the hourly means of presence is seen for one occupant on Figure 6.

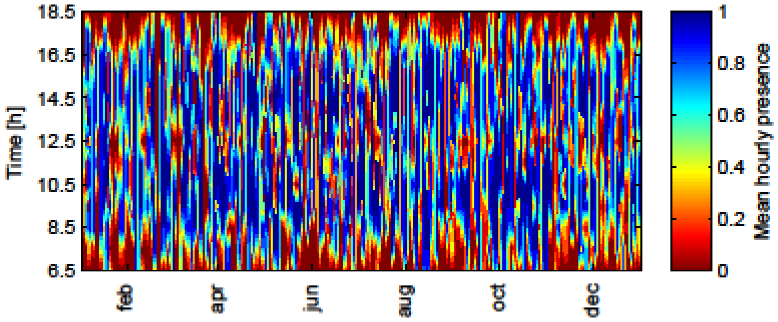


Figure 6 Annual hourly mean presences for one occupant

It can be seen that for some periods during the mornings and afternoons the hourly means of presence is 1. If the daylight level is not sufficient at these times of the day peak lighting demands will be introduced at these time steps.

The output from the model developed in Delff *et al.*[13] can be presence of occupants with the resolution of 2-min. On Figure 7 occupancy profiles for an entire year is depicted for one occupant. The black areas represent that the occupant is present in the 2-min interval.

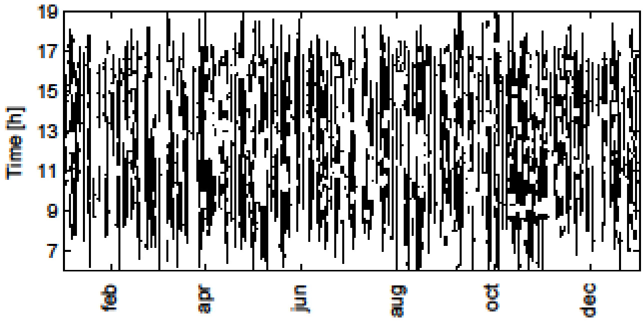


Figure 7 Annual 2-min presence of one occupant. Presence is depicted with black color

3.2 Lighting dependencies and occupancy patterns

On Figure 8 on/off and continuous lighting dependencies are depicted for 4 different scenarios: 1) with only daylight control, 2) daylight control and an absence factor for the occupant of 0.40 as given in EN15193 (2007)[6], 3) daylight control and an absence factor of the occupant of 0.63 which is the total absence factor for the measured field data from the San Francisco office and the model developed in Delff *et al.*[13], and 4) dynamic 2-min occupancy profiles as generated with the model developed in Delff *et al.*[13].

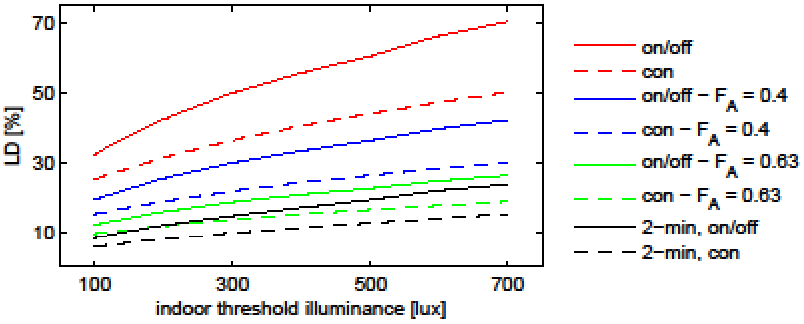


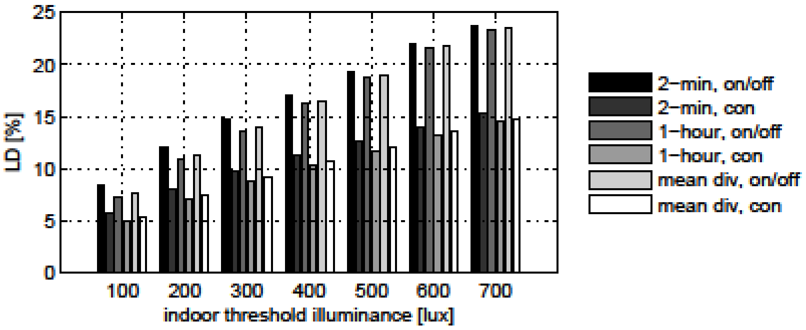
Figure 8 Lighting dependencies for on/off and continuous control of a lighting system 1) with only daylight control, occupants always present, 2) absence factor of 0.40 as in EN15193 (2007)[6], 3) absence factor of 0.63 and 4) dynamic occupancy profile

Not surprising, the lighting dependencies decrease when introducing presence of occupants to the daylight simulations.

However, applying the total absence factor of 0.63 compared to the dynamic occupancy profile overestimates the energy consumption for artificial lights by 4 % and the evaluation of the saving potential is therefore slightly conservative.

On Figure 9 the lighting dependencies are depicted for the dynamic simulations when applying simulations of 2-min resolutions and hourly mean resolution both in terms of occupancy profiles and weather data and for a case where the occupancy profile is the annual mean and the weather data is hourly mean resolution.

The influence on the annual lighting dependency from the three different approaches is insignificant. The difference is in the range of 1 %, which means that compared to a lighting system which is always on, the simulated energy demand for the artificial light only varies with 1 % dependent on the resolution of both occupancy pattern and weather data.



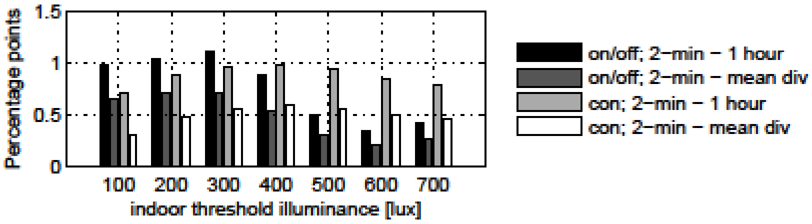


Figure 9 Upper panel: Lighting dependencies for the dynamic simulations when applying simulations of 2-min resolutions, hourly mean and annual mean occupancy profiles. Lower panel: Difference in percentage points for 2-min resolution and hourly mean and annual mean occupancy

Hence, applying the same occupancy pattern for each day throughout the year with hourly resolution will yield accurate estimations of the electrical lighting demand, if the control of artificial lights based on occupancy and daylight level is automatic.

4. Discussion

This study reveals that no real difference is observed in the lighting dependency in an office with automatic daylight and occupancy control, when applying climate based daylight modeling and evaluating the lighting demand based on an average occupancy profile having the same distribution for each day throughout a year opposed to a more dynamic occupancy profile of hourly resolution or 2-min resolution of occupancy presence with minimum 20 min absence.

Not surprising the findings show that introducing on/off or continuous daylight control in the perimeter areas of a daylit building reduce the energy consumption by up to 70 %

compared to a reference case where the lights are always on, which i.e. could be the case in the core building zone. By adding automatic occupancy sensing control the energy consumption is reduced further by 25 % to 50 % dependent on indoor threshold illuminance level.
The results show that although large variations occur between different days, the difference vanishes when evaluating on an annual basis. The total annual lighting demand remains the same independent of occupancy profile applied and resolution of the daylight simulations. However when the aim of the simulations is to investigate the finer dynamics of the lighting system or i.e. solar shading control, detailed knowledge on presence of occupants might be important. For this study simple immediate on/off control of the artificial light or continuous dimming dependent on daylight availability and presence of occupants have been employed. More sophisticated control, like introducing inertia to the lighting systems as delays or dimming the lights before they switch off could be investigated, and might induce different result. It should be stressed that the dynamic occupancy profiles applied does not include absence shorter than 20 min. This is due to the fact that a delay of 20 min was included in the original measurements. The ideal case would have been measurements that recorded presence solely. Hereby shorter absence like going for a coffee would have been encountered.

Why apply the occupancy model, when you have access to measured data? By applying the statistical occupancy models it is ensured that the occupancy profiles applied are representative, because outliers have been removed from data. The model is based on the measured presence of 57 occupants, and it is therefore ensured that even though the model includes some randomness, the variations in the daily sequences of each occupant are within the statistical boundaries. Hereby it is possible to include the random behavior of occupants in the simulations while knowing that the data correlates with measured data from a real building. The results, on the other hand, show that if the aim of the investigations is to give an estimate of the annual lighting demand it can sufficient to multiply with the mean presence of occupants observed in the building. If outliers have been removed, then this number could just as well have been obtained from the measured data.

One issue not included in these investigations is the human factors in lighting, like employees manually operating the lights. In Lightswitch-2002 behavioral model predicting user response to lighting systems has been added.[18] Manual lighting control mainly coincides with an employee's arrival at or departure from the work place.[17] Some employees always activate their lighting throughout the whole working day independently of prevailing daylight levels. Others only switch on their electric lighting when indoor illuminance levels due to daylight are low. For the latter user type, the probability of switching on electric lighting is correlated to minimum indoor illuminance levels at the work plane upon arrival through Hunt's switch on algorithm.[17] For future investigations it would be of interest to employ the dynamic occupancy model developed in Delff *et al.*[13] in Lightswitch-2002, to evaluate the behavioral aspect as well. Bourgeois (2005)[19] investigated the behavioral aspects in his PhD thesis. Here he demonstrated that by enabling manual lighting control, as opposed to having the lights switched on for the entire occupied hours, the energy consumption for artificial lights is reduced by as much as 62 %, this number is further reduced by 50 % when applying automatic control. The findings from his study show that manual control compared to automatic control increase the lighting demand.

5. Conclusion

The key findings from this study show that there is no real difference in the annual artificial lighting demand when employing the same occupancy profile for each day throughout a year opposed to a dynamic occupancy profile, where the probability of presence varies for each day. Furthermore it was found that the annual artificial lighting demand is evaluated slightly conservative (4 % higher) when applying the mean absence factor of a measured building opposed to applying dynamic occupancy profiles estimated for the same building. Hence, when evaluating the annual artificial lighting demand based on presence of occupants and automatic on/off or continuous control of the artificial lights, applying an average absence factor will yield accurate results.

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Paper IV

"Illuminance level in the urban fabric and in the room"

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Illuminance Level in the Urban Fabric and in the Room

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Key Words

Urban planning · Vertical daylight factor · Integrated design · Overcast skies · Obstructions

Abstract

The decisions made on the urban planning level could influence the building design at later stages. Many studies have shown that the utilisation of daylight in buildings would result in significant savings in electricity consumption for lighting, while creating a higher quality indoor environment. The surroundings of a building have a great influence on the indoor environment of that building. A major factor is the shading that the surrounding buildings could provide, blocking and diminishing the available amount of daylight in nearby buildings. This paper reports a study that combine the effect of the exterior illuminance levels on façades with the interior illuminance levels on the working plane. The paper also explains an easy to use tool (EvUrbanplan) developed by the authors, which was applied to their findings in the early stages of urban planning to ensure daylight optimisation in the buildings.

Introduction

The objective of this paper is to develop a method to facilitate the urban planning process, so bad decisions regarding the use of daylighting that could lead to poor solutions later in the design stage can be avoided.

When designing new cities or new areas of existing cities, the layout of the urban plan is the framework for a rich urban life and would form the basis to ensure that the city will fulfill demands for a reduced energy use for building and transportation. If poor decisions are made at this early stage in the design process, it will inevitably affect the city structure that is to be built. For buildings, the outdoor obstructions could play a significant role in daylighting design. Studies have shown that the utilisation of daylight in buildings could result in significant savings in electricity consumption for lighting, while creating a higher quality indoor environment [1,2]. It is therefore of the highest importance to ensure that the buildings in the cities are well lit by natural daylight. Steemers [3] looked at urban density and building energy, and found that the energy consumption for lighting would increase if there are opposing buildings blocking the daylight entry into the building. Tools and techniques to aid urban designers in decreasing the amount of daylight blockage by opposing buildings could thus be useful in decreasing the energy use and would enhance indoor environmental quality. Previous research on daylight availability has focused on the solar irradiation and illuminance levels on the urban fabric. Compagnon [4] looked at the solar irradiation on the urban fabric (roofs and façades) in order to assess the potential for active and passive solar heating, photovoltaic electricity production and daylighting. Mardaljevic and

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Rylatt [5] also looked at the irradiation on the urban fabric and used an image-based approach to generate irradiation “maps” that were derived from hourly time-series for 1 year. The maps can be used to identify façade locations with high irradiation to aid, e.g., in positioning of photovoltaic panels. Li et al. [6,7] looked at the vertical daylight factor (VDF) to determine the illuminance on the vertical façades in heavily obstructed environments. In Li et al. [7], the VDF has been compared to measured data for a CIE standard sky of Hong Kong, and showed good agreement. Most recently, Käempf and Robinson [8] applied a hybrid evolutionary algorithm to optimise building and urban geometric form for solar radiation utilisation.

The findings in this paper relate the exterior illuminance values to the illuminance values in the room. A tool (EvUrbanplan) has been developed to easily aid architects and engineers in the urban planning process, when important decisions would need to be made on the density of the city that will influence the daylight performance of buildings. By looking at the street widths, building heights and reflectance of opposing buildings, the illuminance level on the façade and in the room is evaluated, and the façades in the cities can be categorised according to their daylight performance.

The method developed in this paper is based on the CIE overcast sky. The current trend within the research of daylight performance of buildings is to look at the performance on an annual basis [9,10]. Daylight autonomy (DA) and useful daylight illuminances (UDI) metrics have been proposed as ways to analyse the annual data. DA defines the percentage of the occupied times per year when a minimum work plane illuminance threshold can be maintained by daylight alone [11]. In contrast, the UDI scheme is founded on a measure of how often in the year daylight illuminances within a range are achieved [12]. The main advantage of the annual metrics over the static daylight factor is that it would take façade orientation and user occupancy patterns into account, and consider the enormous variations in daylight illuminances throughout the year. However, the annual simulations would require site-specific information of the weather conditions and the information cannot be generalised as easily as the static daylight factor calculation. Furthermore, information such as occupancy patterns would depend on the building usage, which might be undefined in the initial stage of the design, when decisions are made on the density of the city. The authors therefore still find strength in the daylight factor and see the outcome as a useful guideline to be used in the early stages of urban planning to ensure achievement of daylight-optimised buildings.

Method

The method used in this paper is based on the VDF method developed by Li et al. [6,7] to determine the illuminance on a vertical façade.

Vertical Daylight Factor

The VDF [6,7] can describe the amount of daylight illuminance on a vertical surface of a building. The VDF is the ratio of the total amount of daylight illuminance on a façade to the horizontal illuminance from a complete hemisphere of sky excluding direct sunlight, as defined by Equation (1).

$$\mathrm{VDF} = \frac{E_\mathrm{s} + E_\mathrm{rb} + E_\mathrm{rg}}{E_\mathrm{h}} \tag{1}$$

where E_s is the light coming directly from the sky (lux); E_rb the reflected light from the obstructing building (lux); E_rg the reflected light from the ground (lux); and E_h the horizontal illuminance of an unobstructed sky (lux).

Daylight Simulation

The daylight assessments were carried out using Radiance [13] simulating the models under a 10 klux CIE overcast sky.

Simulation Procedure

A room of 20 m × 15 m × 4 m ($w \times d \times h$) placed on the ground in the middle of a larger building with dimensions 60 m × 15 m × 30 m ($w \times d \times h$) was simulated as a “worst case” base case, see Figure 1(a). In the presented simulations, the room properties were fixed because the focus was to look at the influence of the surrounding buildings and window area on the daylight availability. The exterior walls were given a thickness of 0.3 m in order to take into account of a low U-value. To simulate a low-energy window, the light transmittance of the window was 0.72. Illuminance levels were calculated on a working plane of 0.85 m above the floor. The reflectance of the interior walls, floor and ceiling was 0.7, 0.25 and 0.9, respectively. Glazing areas varied and was presented as: 30%, 40%, 50%, 60%, 70% and 80% of the façade, called window-to-wall ratio (WWR). Windows were simulated as a band on the whole length of the façade, placed from 0.8 m above the floor. Simulations were carried out with an opposing building of varying height from 5 to 30 m and

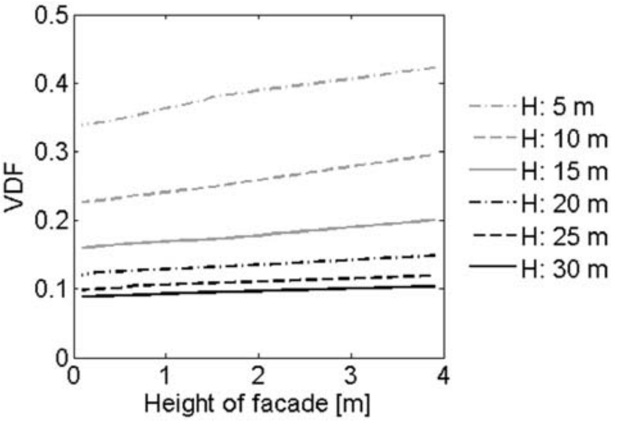


Fig. 1. (a) Plan of the model, seen from above with a street width of 5 m and (b) section of the model showing street widths from 5 to 30 m and heights of opposing building from 5 to 30 m.

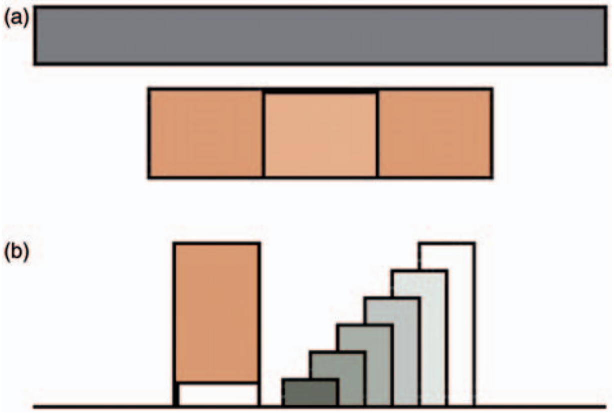


Fig. 2. Illuminance on façade in the entire height of the ground floor for a case with street width of 10 m, façade reflectance of 0.2 and different heights (*H*) of the opposing building.

street widths from 5 to 30 m. The simple method in this paper was based on simulation of an urban canyon, as most useful light entering building interior would come from the sky normal to the façade [7]. The width of the opposing building was 100 m. At the early stage of the design, the exact layout of the building façades will usually not be determined and it will not be possible to obtain the exact reflectance properties. For simplicity, two surface reflectances were used; one for the façades and one for the ground. The façade reflectance was simulated as an average value, averaging the reflectance of the windows, walls, framing, etc. A fixed ground reflectance of 0.2 was found to be a reasonable assumption for dense urban areas [6], so the ground reflectance was set to 0.2.

Generalisation of VDF

Most windows have a very low reflectance, meaning that increasing the window size in a façade could result in a lower overall reflectance of that façade. This does not necessarily mean anything for the building in question, but might have a large impact on the amount of daylight reaching buildings from the opposite side of the street. Different window sizes on the opposing buildings could therefore affect the illuminance level in a given room. A typical opposing building has an overall façade reflectance of 0.2. Li et al. [7] found a mean building reflectance of 0.34. If the opposing building is highly reflective, e.g. a white façade, the reflectance will be high, here simulated as 0.9 to show the upper limit of the influence of the façade reflectance. For different reflectances of the opposing façade, the same VDF can be obtained with different street widths and opposing building heights. Simulations were carried out with façade reflectance, *r*, of the opposing building of 0.2 and 0.9, to test if the same VDF obtained with different opposing façade reflectances would result in the same illuminance profile through the room.

To investigate if the VDF can be applied for the entire height of the building, simulations were made to test if the same VDF at different floors would result in the same illuminance level through the room. This was tested with a simulation where the room was placed on the ground floor, first and second floors. The opposing building varied with heights of 5, 10 and 15 m and the distance between the buildings was fixed to 10 m.

Results and Discussion

In this paper, the VDF is determined in the middle of the façade for the floor in question. For the ground floor, with a façade height of 4 m, the VDF is determined 2 m above ground. As the illuminance level on the façade is linear in the height of the façade (Figure 2), the VDF will be an average value on the façade of the floor in question.

The VDF for different distances to the opposing building and for different heights of the opposing building is presented in Figures 3(a) and 4(a). The opposing façade has a reflectance of 0.2 and 0.9 for the two figures, respectively. The distance from the façade where 200 lux could be achieved is presented in Figures 3(b) and (b) for different WWR. Sensor readings of illuminance values on the working plane are made with a spacing of 0.1 m. The value depicted is the distance from the façade where the illuminance level is 200 lux.

From Figures 3(a) and 4(a), it can be seen that the VDF would decrease with smaller street widths and higher opposing building. Furthermore, it is seen that increasing the façade reflectance of the opposing building would

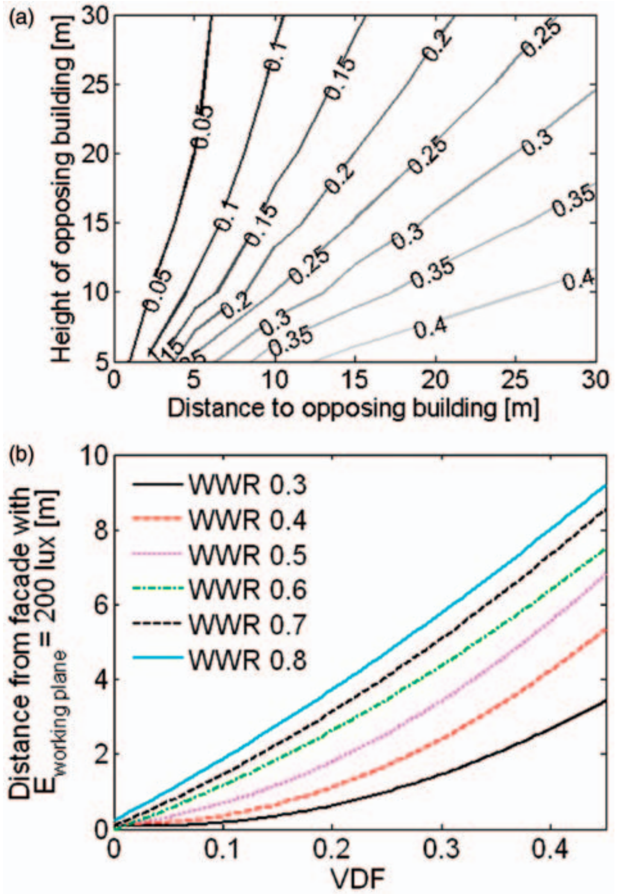


Fig. 3. Reflectance of opposing façade is 0.2. (a) The ratio of the illuminance level on the façade to a 10 klux CIE overcast sky (VDF) for different building heights and distance to opposing building. (B) Distance from the façade where 200 lux is achieved on the work plane for different VDF levels.

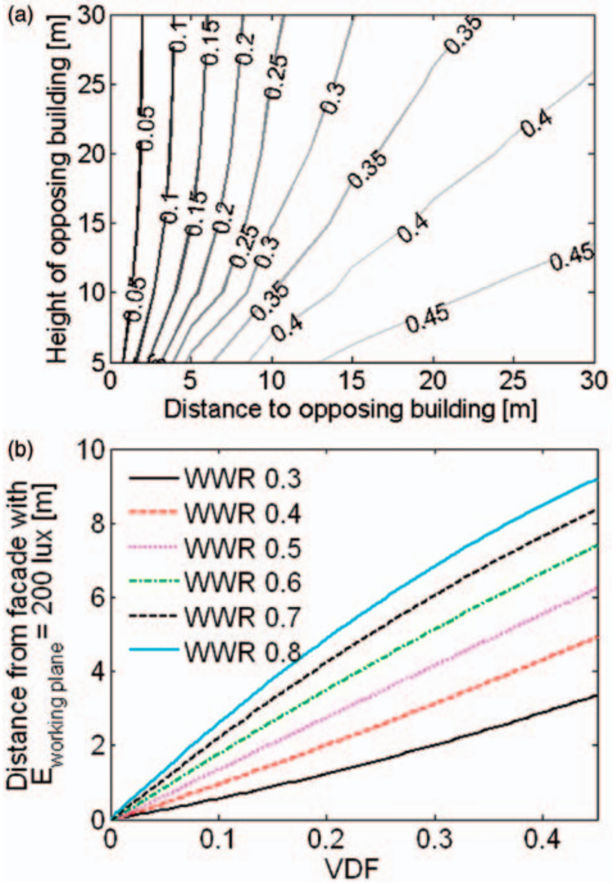


Fig. 4. Reflectance of opposing façade is 0.9. (a) The ratio of the illuminance level on the façade to a 10 klux CIE overcast sky (VDF) for different building heights and distance to opposing building. (b) Distance from the façade where 200 lux is achieved on the work plane for different VDF levels.

result in slightly higher VDF levels. Increasing the façade reflectance of the opposing building could result in more rays bouncing off from that building and more of the light will penetrate deeper into the room in question. This can be seen from the changed profile of the curves in Figure 4(b) compared to Figure 3(b) and from Figure 5(a), where 200 lux could be achieved farther off from the window with higher opposite façade reflectance.

Figure 5 shows the illuminance level through the room for a case with the same VDF of 0.25 and WWR of 0.4. In Figure 5(a), the illuminance level on the working plane close to the window is higher with a façade reflectance of 0.2, whereas the illuminance level would be higher with a façade reflectance of 0.9 farther off from the window. This result is caused by the difference in geometry where a higher proportion of the light is coming from the sky with a façade reflectance of 0.2 compared to the façade reflectance of 0.9. For a façade reflectance of 0.9, a higher proportion of the light would be from the opposing building due to rays bouncing off this building, so the daylight would penetrate deeper into the room. This means that it is not possible to generalise the results by saying that the same VDF achieved with different reflectances of the opposing façade would result in the same profile of the illuminance level through the room. However the result shown in Figure 5(b) illustrates that for a fixed building reflectance, the illuminance level profile would be almost constant regardless of the spacing or building height used to attain a VDF.

From Figure 6, it can be seen that the illuminance profile through the room would be different with rooms placed on the ground floor to rooms placed on higher floors. For each of the cases, the VDF and reflectance of opposing building would be the same; 0.38 and 0.2, respectively. The illuminance level on the ground floor was shown to be slightly higher (2%) than on the second floor, due to reflections from the ground. This result shows that if the VDF-isoline plot in Figures 3(a) and 4(a) was

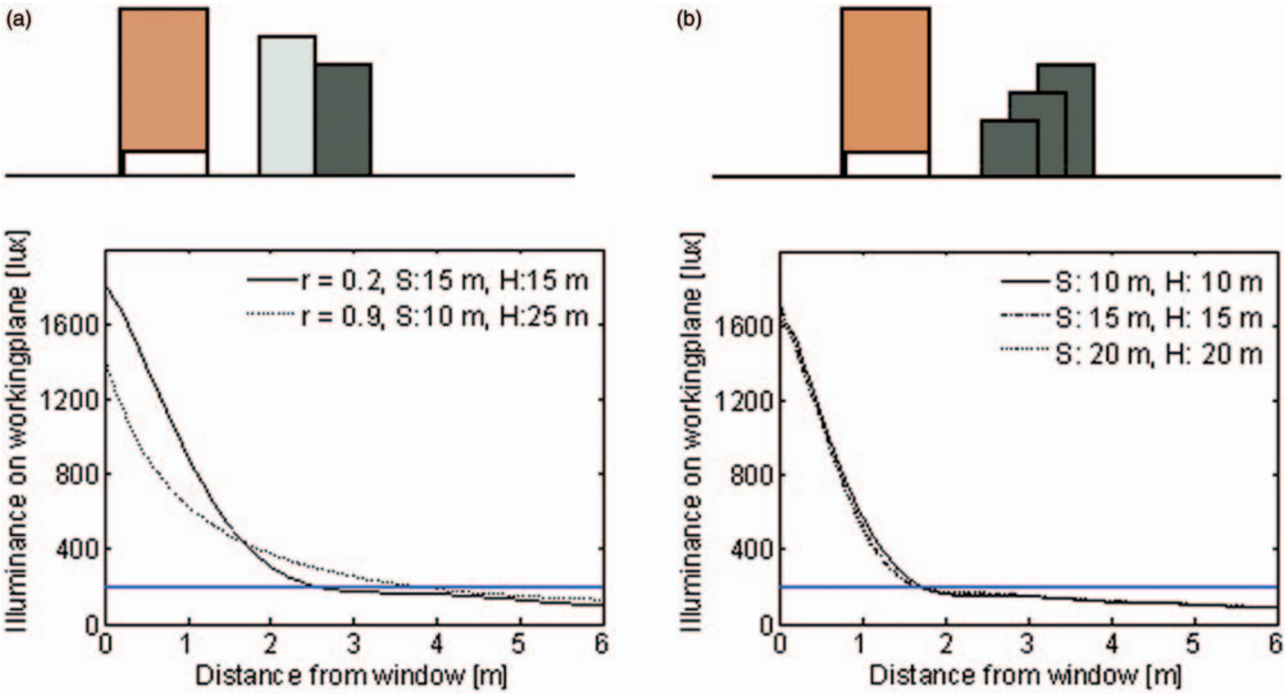


Fig. 5. Illuminance levels through the room with the same VDF (0.25) and WWR (0.4). (a) Different façade reflectances (*r*) of opposing building with street width (*S*) and height of opposing building (*H*). (b) Same façade reflectance, $r = 0.2$, with street width (*S*) and height of opposing building (*H*).

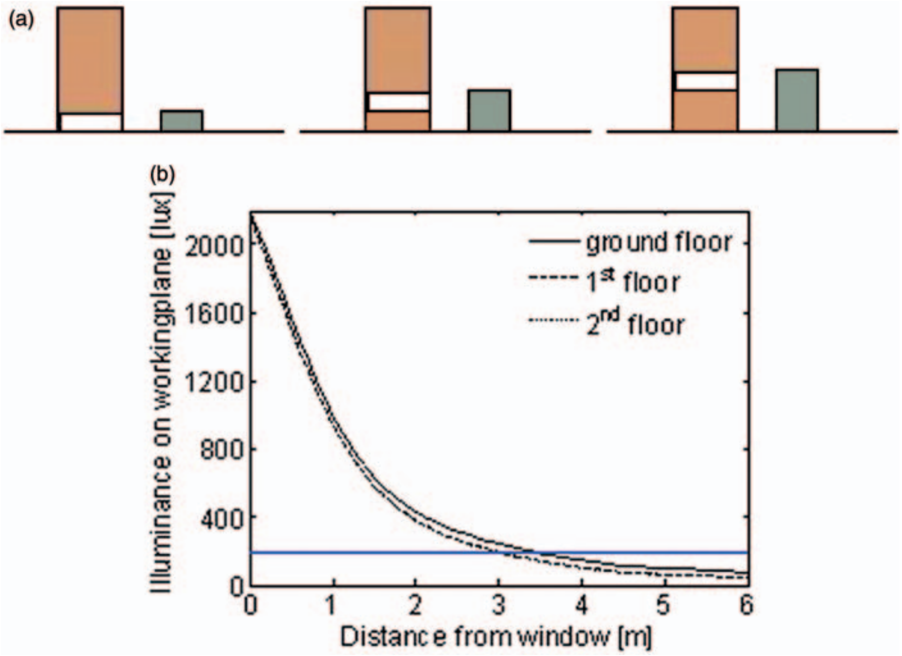
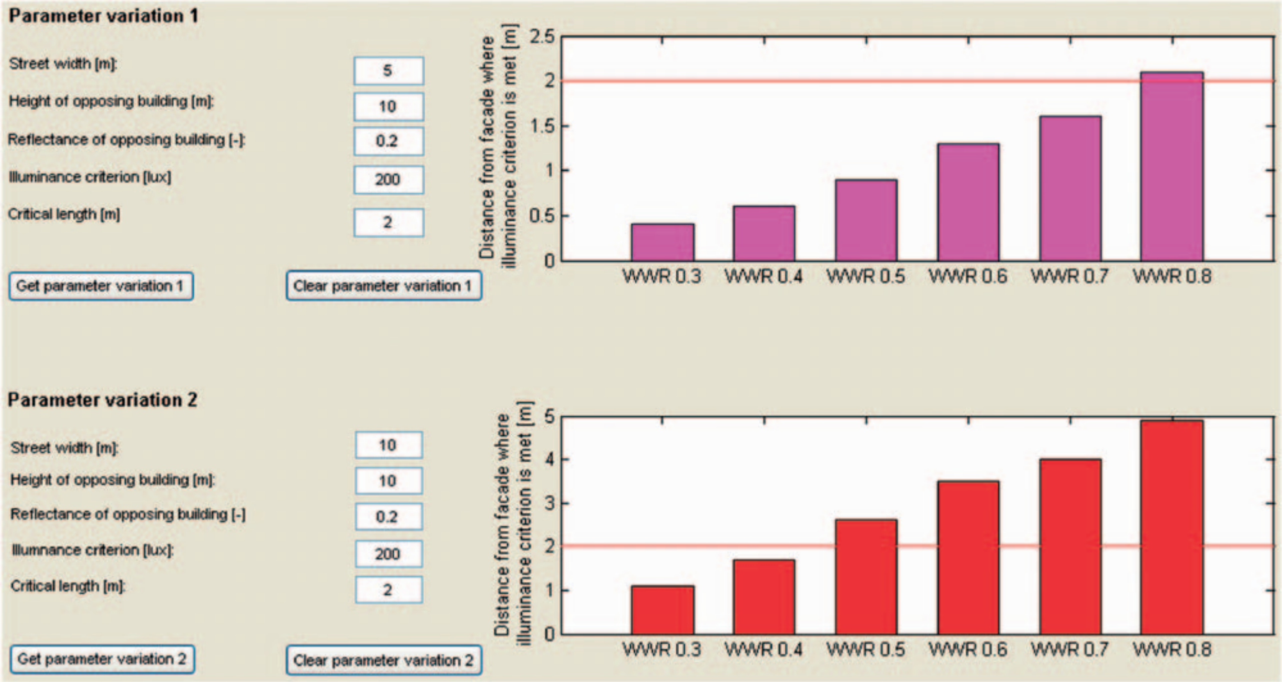


Fig. 6. Illuminance level profile through the room; comparing rooms placed on the ground floor to rooms placed on higher floors with VDF and reflectance of opposing building of 0.38 and 0.2, respectively.



Parameter variation 1

Street width [m]: 5

Height of opposing building [m]: 10

Reflectance of opposing building [-]: 0.2

Illuminance criterion [lux]: 200

Critical length [m]: 2

Parameter variation 2

Street width [m]: 10

Height of opposing building [m]: 10

Reflectance of opposing building [-]: 0.2

Illumnance criterion [lux]: 200

Critical length [m]: 2

Fig. 7. An example of an output from the tool EvUrbanplan.

applied for the entire height of the building, the daylight performance of the upper floors would be evaluated slightly conservative.

Tool – EvUrbanplan

The results show that from the VDF-isoline plot given in Figures 3(a) and 4(a) and the information provided in Figures 3(b) and 4(b), it is possible to decide the distance to and height of the opposing building and the size of the window in order to obtain satisfactory illuminance levels in the room for the ground floor, and within good agreement for the upper floors as well. A design tool has been developed to allow the application of the findings to the early stage of urban design. The tool is a simple look up function based on the results from simulations in Radiance generated for the different building configurations. The input parameters to the tool are: street width, height of opposing building, reflectance of opposing building, illuminance criterion and critical length. The illuminance criterion is the illuminance level the design will be evaluated at, and the critical length is the distance from the façade, where the design team requires the illuminance criterion to be met. For different WWRs, an output graph as illustrated in Figure 7 could be produced.

With a narrow street width of 5 m and a height of the opposing building of 10 m, a WWR of 0.8 would give an illuminance level of 200 lux on a work plane 2 m from the façade. If the street is widened to 10 m, the criteria can be met for WWR larger than 0.5.

Table 1. Categorising the façades in the cities according to their daylight performance

Category	Evaluation of façade	Color code
1.	Really good façade! Criteria can be met for WWR >0.3	🟨
2.	Good façade! Criteria can be met for WWR >0.5	🟧
3.	It is possible to achieve a good daylight performance However, special precautions must be taken for façade reflectance and WWR! Criteria can be met for WWR >0.7	🟥
4.	Poor façade! It is not possible to fulfill the requirements	🟪

Based on this information, the different façades in a city according to their indoor daylight performance can be evaluated. To apply this method in practice, the designers should start by defining daylight requirements for their buildings. If the building should be analysed based on a daylight factor of 2%, the illuminance criterion would be set to 200 lux. If this illuminance level should be fulfilled in a distance of 3 m from the façade, the critical length should be set to 3 m.

Fig. 8. An application example of the EvUrbanplan tool, for planning of a new urban area.
Note: The colour mapping shown here corresponds to the daylight performance for the ground level.

The façades can then be categorised according to how well they could provide daylight to the building, based on the categories proposed in Table 1.

By going through the different street widths and building heights of a proposed urban plan, it is possible with this simple tool to point out positive urban areas and areas where the city have not been optimised daylightwise. Based on the findings, it is possible at this early stage of design to change the street widths and building heights or to specify the required reflectance for façades in narrow streets in order to fulfil the daylight requirements. Furthermore, it is possible to define the areas where building functions that does not require daylight should be located. An example of the use of the tool is seen in Figures 8 and 9.

Limitations of the EvUrbanplan Design Tool

The work presented in this paper describes a limited method and the results may only be applied by also knowing its limitations. The focus of the study was to look at the influence of the surrounding buildings on the daylight availability indoors; therefore, the interior surface properties remained fixed throughout the simulations.

1. The VDF as presented in this paper can only be applied under overcast sky conditions. So, the VDF would be a reasonable prediction for the most

Fig. 9. An application example of the EvUrbanplan tool for designing the urban fabric.
Note: The street width is 10 m, each floor has a height of 5 m and the colour mapping follows the coding in Table 1 and Figure 8.

common daylight situation in heavily clouded environments, i.e. in the Northern Europe. Within the current daylight research, the trend is to perform dynamic daylight simulations; however, this would require information on the specific building location and the results cannot be generalised as easily as with the static daylight factor calculation. It is, however, a future goal to include annual results for different locations, for different façade orientations.

2. The VDF used in this paper is for straight streets. The model does not consider rooms placed in corners of buildings or rooms facing court yards. At these locations, different results may be found.
3. The façade reflectance is simulated as an average value of the reflectance of the walls, windows, framing, etc. The advantage of using an average façade reflectance is that in the early design stage one would not know the exact design of the façade. An average value would therefore be useful to indicate the daylight performance of the urban plan. Different results may be found if the exact building design is known, and the simulations may be rerun at a later design stage to get more precise results.
4. The simulated room is placed at the ground floor in the middle of a larger building of fixed height. Changing the building height would change the amount of daylight falling on the opposing façade, and would influence the size of the redirected light. However, in this study, this effect has been evaluated as a second-order effect, as with typical average façade reflectances of 0.2 and 0.3, the redirected effect would be small.
5. The windows are simulated as façade wide window bands. Other façade configurations will give different results. The future goal is to have EvUrbanplan supporting other façade layouts than façade wide window bands.
6. The focus of this study was to look at the influence of the surrounding buildings on the daylight availability indoors, so the interior surface properties and room dimensions remained fixed throughout the simulations. Other reflectance will yield other results, i.e. lower interior reflectance will yield an overall lower daylight performance.
7. The room is simulated with a room height of 4 m. A typical room height would be 2.8 m, which could be reached with WWR of 50% (window height of 2 m and room height of 4 m). The effect of the high room height can be seen with the WWR of 60%, 70% and 80%, where 200 lux could be achieved between 7 and 9 m from the façade for the highest VDF.

Conclusion

A method based on the VDF and CIE overcast sky has been presented to aid architects and engineers on decisions regarding the urban planning which could have an effect on the daylight performance of the buildings.

A design tool, EvUrbanplan, has been developed to allow the application of the findings in this paper to the early stage of urban planning when important decisions are made on the density of the city. By simulating the street widths, building heights and reflectance of opposing buildings, the illuminance level on the façade and in the room can be evaluated, and the façades in the cities can be categorised according to their daylight performance.

Acknowledgement

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Paper V

”Urban Daylighting: The impact of urban geometry and fabric on daylight availability in the building”

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"Urban Daylighting: The impact of urban geometry and fabric on daylight availability in the building"

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Abstract

The link between urban design and utilization of daylight in buildings is a balance between climatic factors and spatial, material and use patterns. Many studies have shown that using daylighting design strategies in buildings would result in significant savings in electricity consumption for lighting, while creating a higher quality indoor environment. Recent advances in simulation technology and methodology now allows researchers to investigate dynamic daylight distribution phenomena with much greater precision as the traditional Daylight Factor metric is supplemented by Climate Based Daylight Modeling metrics such as Daylight Autonomy.

This study combines the effect of the exterior illuminance levels on façades with the interior illuminance levels on the working plane. The aim is threefold: An attempt (1) to introduce urban daylighting to ensure energy savings and adequate daylight illuminances in individual buildings, (2) to investigate how urban geometry, facade reflectance and window-to-wall ratios affect the daylight distribution at multiple levels of buildings, and (3) to indicate the need for inclusion of urban daylighting studies in planning and the early stages of building design.

It is found that different combinations of urban geometries, façade reflectances and façade window-to-wall ratios have strong effects on daylight distribution, allowing daylight to be distributed at the lowest levels of buildings and much deeper into buildings than hitherto recognized. But the different design parameters interact in dynamic complex ways which are highly regional climate and design specific. The dynamic interaction highlights an imperative to integrate urban daylighting as a method in planning and in urban and building design.

Keywords: Urban Design, Daylight Strategies, Indoor Environment

1 Introduction

One of the most basic and fundamental questions in urban master planning and building regulations is how to secure common access to sun, light and fresh air. But for the owners of individual properties, it is often a question of getting the most of what is available. There is potential for repetitively recurring conflict between public and private interest. Solar access and the right to light remain contested territory in any society, vital as they are to health, comfort and pleasure. For decades, the focus has been geared towards optimization of the individual building and its various daylight systems, operation, and maintenance. By considering buildings isolated from the context they are built in the interaction between environment and building's daylight performance is ignored. Hereby, daylight condition in buildings and the city's urban elements become two unrelated sizes.

However, access to daylight is inevitably for creating social spaces, well-lit environments, and reduction in energy consumption for artificial lights and heating/cooling. Optimizing the urban plan in terms of daylight is therefore of major importance since daylight cannot be added to a lighting scene just like i.e. fresh air can be supplied from ventilation systems. This fact was already acknowledged by the ancient Greeks and Romans. They mandated minimum lighting standards for their cities. The British Law of Ancient Light (which dates to 1189) and its later embodiment into statute law, The Prescription Act of 1832, provided that if a window enjoyed uninterrupted access to daylight for a twenty year period, right to that access became permanent [1].

The link between urban design and the access to daylight is a complex balance between climatic factors and spatial, material and use patterns. Many studies have shown that using daylighting design strategies in buildings would result in significant savings in electricity consumption for lighting, while creating a higher quality indoor environment. However, the role that reflected light plays in dense urban spaces has received little attention, which is ironical since the denser a city; the more will the lower levels of buildings be dependent on reflected light. *Daylighting* as a design strategy has typically stopped at the exterior of a building itself, not considering in any detail the impact of urban geometry on daylight distribution nor the impact of building façade design on the daylight distribution in the urban space. This paper introduces *urban daylighting* as a design strategy for planners and architects, and investigates its effect on daylight distribution inside and outside buildings in dense urban environments using Climate Based Data Modeling (CBDM).

Figure 1: LaSalle Street Canyon. Facade reflectance approximately equal to 15% - 25%.

Figure 2: Wall Street Canyon. Facade reflectance approximately equal to 45% - 55%.

The effect of obstructions or urban geometry has been described in various research papers. Previous research on daylight availability has focused on the solar irradiation and illuminance levels on the urban fabric. Compagnon et al. (2004) looked at the solar irradiation on the urban fabric (roofs and facades) in order to assess the potential for active and passive solar heating, photovoltaic electricity production and daylighting [2]. Mardaljevic and Rylatt (2005) also looked at the irradiation on the urban fabric and used an image-based approach to generate irradiation ‘‘maps’’ that were derived from hourly time-series for 1 year [3]. The maps can be used to identify facade locations with high irradiation to aid, e.g., in positioning of photovoltaic panels. Most recently, Käempf and Robinson (2010) applied a hybrid evolutionary algorithm to optimize building and urban geometric form for solar radiation utilization [4]. These studies only investigate the urban design from external environmental impact.

Nevertheless, there have been some investigations that link the exterior radiation/illumination to interior daylight availability. In studies by Li et al. (2009), they introduced the vertical daylight factor (VDF) and demonstrated that daylight is significantly reduced in a heavily obstructed environment [5,6]. A study of VDF predicted by RADIANCE simulation demonstrates that an upper obstruction at 60° compared to a lower obstruction at 10° reduce the daylight level by up to 85%. The results also indicate that the reflection of the obstructive buildings can be significant in heavily obstructed environments, such as rooms on lower floor levels facing high-rise buildings. In another study by Iversen et al. (2011), they looked at the influence of the surroundings on the daylight factor within the room followed by a categorization of the facades according to their daylight performance, with the aim being to facilitate the design process aiding to point out urban areas that are good in terms of daylight inside the buildings and areas that have a poor daylight performance [7]. In a study by Strømann-Andersen and Sattrup (2011) they showed the effect of height/width ratio (elevation of an obstruction), on the energy demand for artificial light [8]. The effect is quite strong: for example, for an obstruction with a height/width ratio 1.0 (equal to an elevation angle of 45°), the lighting energy demand in offices can be increased by up to 85% compared to free horizon.

2 Method

In this study the effect of the urban canyon on the daylight availability will be investigated. The Urban Canyon has been used in urban climatology as a principal concept for describing the basic pattern of urban space defined by two adjacent buildings and the ground plane. Apart from its metaphorical beauty, the key quality of the term is the simplicity it offers in describing a repeated pattern in the otherwise complex field of urban spaces and building forms.

The hypothesis to be tested is:

- *In dense cities the orientation of the buildings has a minor importance on the daylight availability – it is the reflected light that plays the most important role.*

- *CBDM give a more precise and spatial understanding of the daylight availability compared to calculations performed under standard CIE overcast skies*

The hypothesis will be evaluated by challenging the urban density with different Height/Width ratios, orientations and fabrics (Window-to-Wall-Ratios (WWR) and reflectance). The simulations are performed with the daylight simulation programme DAYSIM [9]. The DAYSIM/Radiance simulation parameters are given in Table 1.

Table 1: Radiance simulation parameters

Ambient bounces	Ambient Division	Ambient sampling	Ambient accuracy	Ambient resolution	Direct threshold
6	1000	64	0.1	300	0

2.1 Simulated rooms

A simulation matrix has been set up; see Figure 1, containing different Window-to-Wall-Ratios (WWR) and facades with different reflectance's (0.15, 0.45 and 0.75).

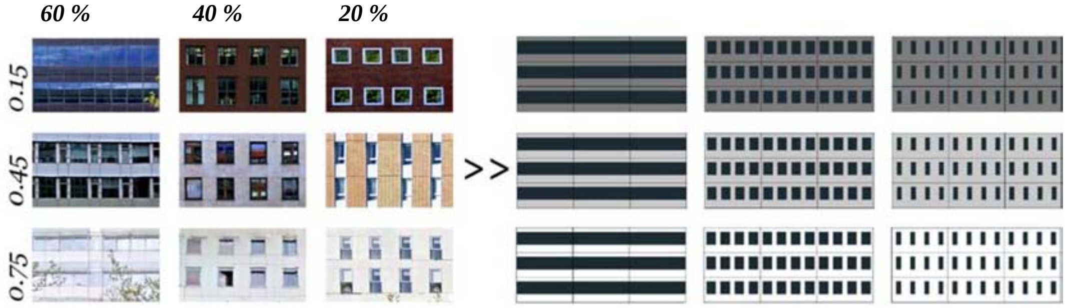


Figure 3: Simulation matrix of different WWR's (20%, 40% and 60%) and facade reflectances(0.15, 0.45 and 0.75)

For all simulations the building height is fixed to 15 m corresponding to a building with 5 floors. The simulated rooms are placed on the 1st, 3rd and 5th floor. Each room has inner dimensions of height 2.8 m, width = 6.0 m, depth = 8.0 m, see Figure 4. The light transmission of the window is 0.72. The street width varies corresponding to H/W ratios of 2.0, 1.0, and 0.5. A diagram showing the different simulation set-ups is given in Figure 4.

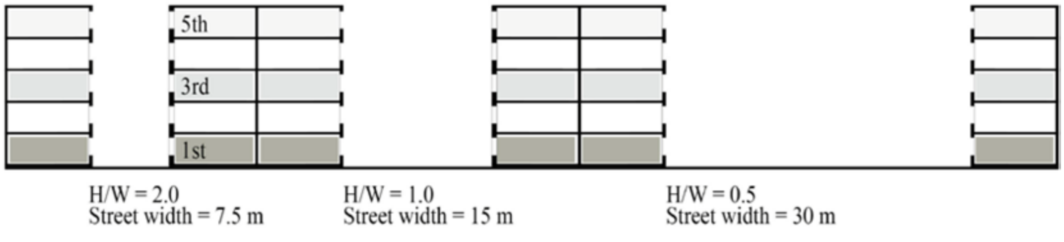


Figure 4: Urban street canyon, simulation setup

Illuminance readings are made at upward facing sensor points placed on a line in work plane height, through the room, drawn from the middle of a window placed as close to the middle of each room as possible, to avoid boundary effects influencing the results. Furthermore illuminance readings are made externally on the facades, at sensor points facing normal to the facade, for each simulation. Simulations are performed both under CIE overcast sky conditions and for each hour throughout a year with the Perez-All Weather sky model, following a daylight coefficient method [10] implemented in DAYSIM [9]. The location is Copenhagen and the weather data applied is that in the design reference year. For the different room typologies the daylight availability at different orientations (N,S,E,W) have been exploited.

2.2 Evaluation methods

2.1.1 Daylight availability within the room

The daylight availability within the room will be evaluated based on two metrics: 1) The traditional daylight factor evaluation (DF), and 2) The Daylight Autonomy metric (DA). Even though there is an ongoing debate on the shortcomings of the conventional, static daylight factor method (i.e.[11,12,13]), the good practice evaluation for daylight in national standards (i.e. [14,15]) is the daylight factor method. The daylight factor calculation evaluates the daylight conditions for one standard CIE overcast sky omitting the natural variations in daylight. According to the Danish Building Code (BR10) a workplace can be described as well-lit, if the daylight factor (DF) is minimum 2 % within the room. The 2 % DF will be the design criterion for this study.

However, the Daylight Factor ignores dynamic weather conditions since the metric does not incorporate actual climate data and sky conditions - which vary a lot depending on the real-world location. Advances in computing power now allow climate-based modeling and relatively fast calculation of daylight levels using metrics. One such system is Daylight Autonomy Metric, in which available daylight is quantified combining both direct and diffuse radiation [16]. Daylight Autonomy uses work plane illuminance as an indicator of whether there is sufficient daylight in a room so that an occupant can work by daylight alone. The DA is then defined as the percentage of the “occupied” times of the year when the minimum illuminance requirement at the sensor is met by daylight alone. For the evaluation of the DA in this study, the “occupied” time was set to 8 am to 6 pm and the minimum threshold illuminance to 200 lux. A draft document from the Daylight Metrics Committee of IESNA currently consider a point to be “daylit” if the daylight autonomy exceeds 50% of the occupied times of the year at an indoor illuminance threshold of 300 lux [17]. The DA threshold of 50 % will therefore be adopted and applied as a design criterion in this study.

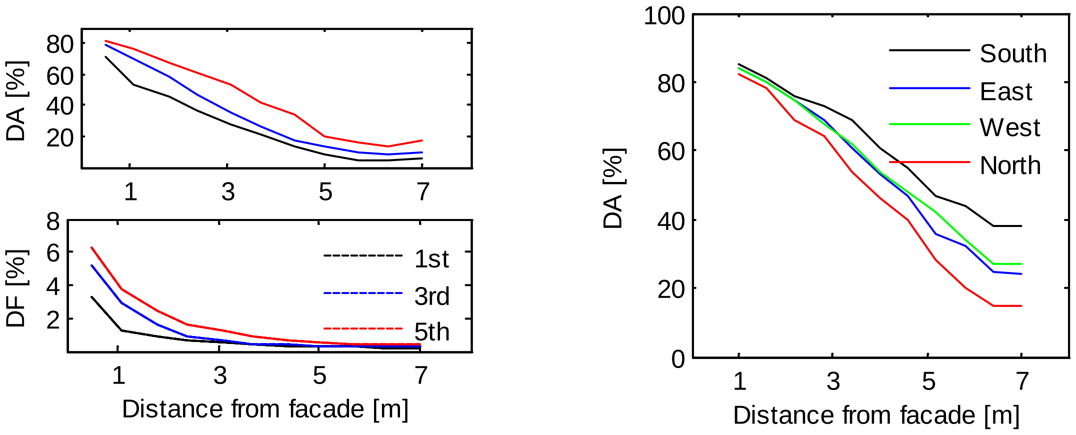
2.1.2 Daylight availability on the exterior vertical facade

The daylight availability on the façade will be evaluated based on a Vertical Daylight Autonomy (VDA). The VDA describes the percentage of the occupied hours per year when a threshold illuminance on the façade can be maintained by daylight alone. For this study the threshold value is 10.000 lux, a threshold which in its magnitude equals to the empirically found irradiance of 50 W/m^2 at which blinds are retracted [18].

3 Results and Discussion

3.1 Influence of moving vertically in the building

When moving vertically in a building obstructed by an opposing building the amount of available daylight increase with higher floor level, because more light enters the space when a higher proportion of the sky is visible from that space . This applies of course both for the daylight autonomy and for the daylight factor, see Figure 5a.



a) b)

Figure 5: Northern orientation, street level of 15 m (H/W = 1) and WWR of 40%. a) Daylight distribution through the room for different floor plans (1st, 3rd and 5th) for both Daylight Autonomy and Daylight Factor and b) orientations for the 5th floor.

The influence of orientation is depicted for the 5th floor, in Figure 5b, as expected the southern orientation has a higher DA, whereas the northern orientation is the lower bound. For the 1st and 3rd floor the difference in daylight autonomy observed is not that remarkably, due to the buildings obstructing for the amount of sky visible, resulting in the light entering the room primarily being diffuse and reflected daylight. This will be explored further in the proceeding sections.

3.2 Influence of window-to-wall ratio

On Figure 6 the distance from facade with daylight autonomy below 50 % is seen for different WWR's at different floor plans. Not surprising, higher WWR result in more daylight entering the space. For the 1st floor no difference is observed at WWR of 20 %. However at WWR of 40 % and 60 % the southern orientation has the shortest DA penetration depth. When comparing the East/West orientation for the 5th floor it can be seen that slightly more light enters the space for the western orientation. This is a result of the climatic conditions, when the cloud cover in the afternoons is smaller compared to the mornings.

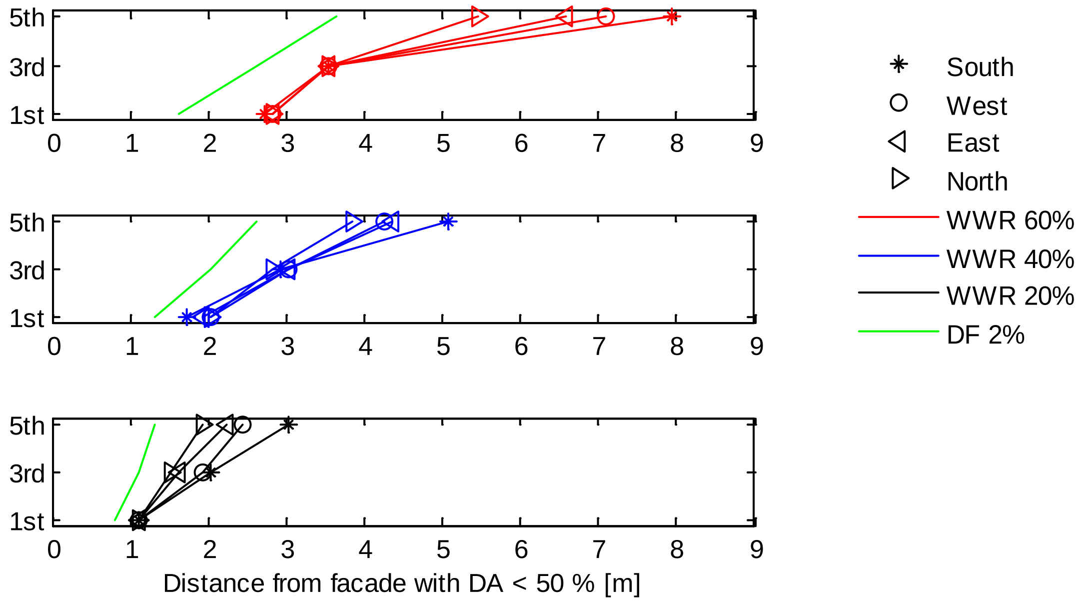


Figure 6: Distance from facade with DA below 50 % for street widths of 15 m, WWR varies from, 20 %, 40 % to 60 %. External reflectance 0.45.

The plotted DF-values give a spatial and intuitively feeling in terms of the shading effect when moving vertically in the building. The daylight factors decrease the lower floor level, due to higher proportion of the sky being obstructed. When comparing the different DF results for the different WWR simulations, the intuitively feeling of more light entering a space with higher WWR can directly be read in the increment in DF values. However the daylight factor cannot tell whether the building is orientated north, south, east or west.

3.3 Influence of opposing facade reflectance

On Figure 7 the daylight autonomy through the room is depicted for different facade reflectances for the northern and southern orientation for the H/W of 1 and for the 5th floor. As expected the increments in reflectance increase the daylight penetration depth within the room, both for northern and southern orientation.

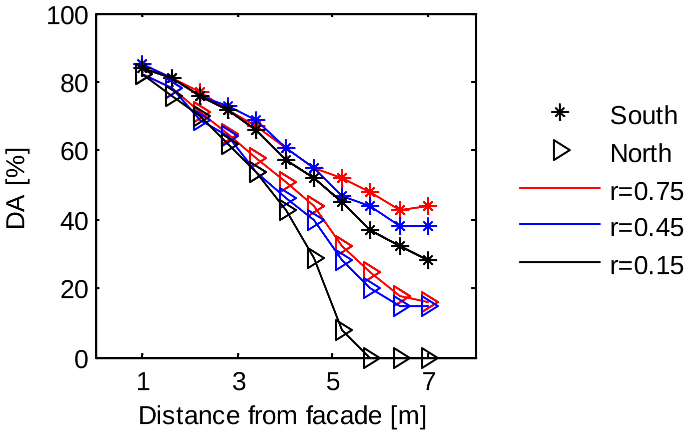


Figure 7: Daylight Autonomieson the 5th floor, through the room for north and south orientation and different reflectance's of the opposing building. H/W ratio of 1 and .WWR of 40%.

However Figure 7 describes a space located in the 5th floor in an urban canyon of H/W 1. When looking at the other floor plans in this typology, the DA on the 1st and 3rd floor increases for the northern orientation, and comes to the same level or even higher than for the southern orientation, see Figure 8.

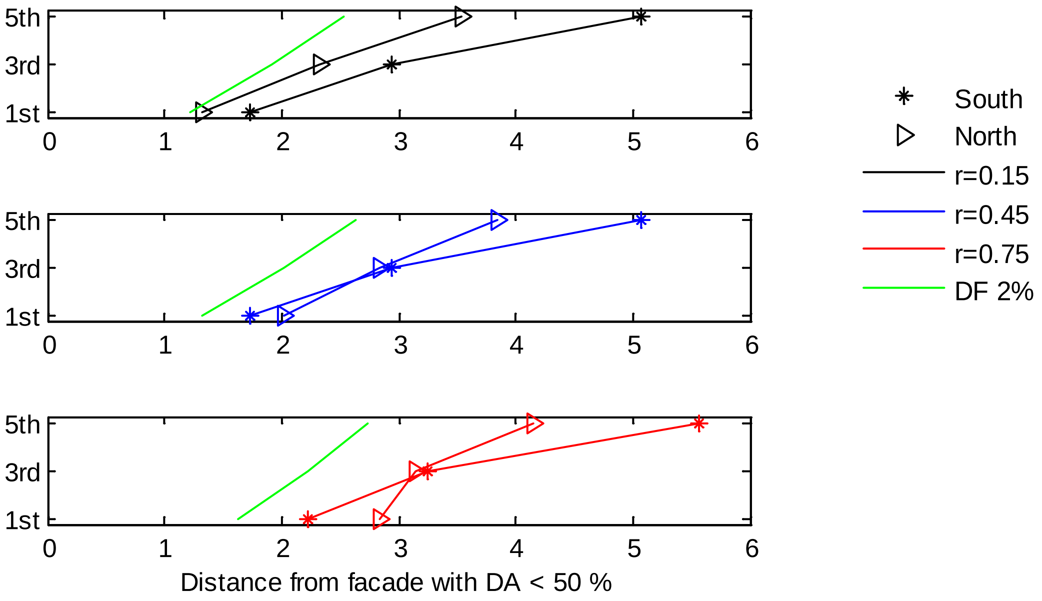


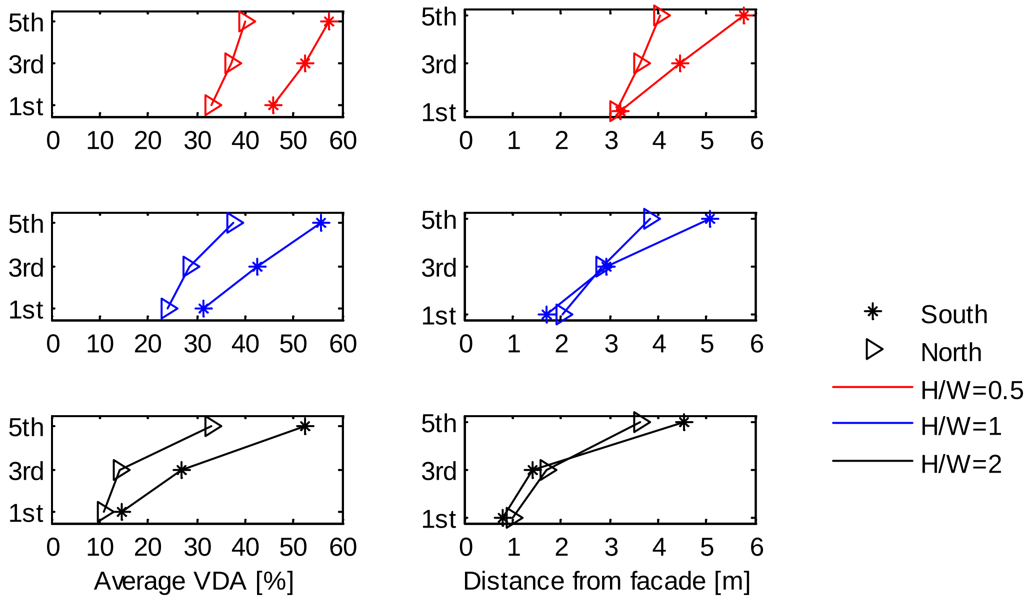
Figure 8: Distance from the facade with DA below 50 % as a function of floor level (1st, 3rd and 5th floor), H/W ratio of 1, WWR of 40%, and three different façade reflectance's. The green line show the distance from façade with DF of 2 %.

A very visible trend from Figure 8 is that for the windows facing the northern orientation the influence of the reflectance is remarkably for the 1st floor. Here the reflected light increases the DA of 50 % from 1.3 m to 2.8 m from the facade. For the control of artificial lights this might have an impact on the energy consumption, which is what is seen in [8], where they found that south-facing buildings in urban context have higher energy consumption for artificial light compared to north-facing buildings.

The green line show the distance from the facade where the daylight factor is 2 %. Compared to the distance from the facade where DA of 50 % is maintained the 2 % DF categorically underestimates the day lit area in the space compared to applying the dynamic metric. The daylight factor is higher with increased facade reflectance; however the impact is 1.2 m to 1.6 m for the first floor and facade reflectance of 0.15 and 0.75 respectively.

3.4 Influence of changing Height/Width ratio

The results show that the denser a city is the smaller is the difference between the illuminance levels falling on the facades for each floor level, see Figure 9a.



a) b)

Figure 9: a) VDF and average VDA on the facade for northern and southern orientation. For WWR of 40% and different H/W-ratios, b) Diatsnce from the façade with DA below 50 %, for WWR of 40% and different H/W ratios.

Furthermore, when moving from the external to the internal, see Figure 9b, the distance from the façade, where the DA is below 50 %, approximates each other the lower floor level. In dense cities the orientation of the buildings therefore has a minor importance on the difference in daylight availability. However, the results indicate that there is a preference for the northern orientations in terms of daylight availability at the lower floor plans. For H/W ratio of 1 and H/W ratio of 2 the light penetrates deeper into the room for the northern façade on the 1st floor and 3rd floor respectively. This is a consequence of the direct part of the daylight being reduced when the H/W ratio decreases, because a smaller amount of the sky is visible from the lower floor plans. For the dynamic simulations this has the effect that a higher proportion of the reflected light bounces of the southern façade, and then falls into the northern oriented rooms. Hereby the limit at which a DA threshold of 50 % is reached increases.

4 Conclusions

In dense cities the orientation of the buildings has a minor importance on the daylight availability. However, the results indicate that there is a preference for the northern orientations in terms of daylight availability at the lower floor plans. Using finishes of high reflectivity on the opaque part of the street facades increased the daylight penetration depth for the lower floor plan.

As a result highly glazed and dark facades reduce the urban daylight potential by ‘privatizing’ the daylight resource, leaving less for neighboring buildings. Bright facades can improve daylight availability considerably at the deepest levels of the urban canyon, decreasing the dependency on artificial lighting, but attention must be given to visual comfort and glare when using this strategy. Facade mounted solar heating and PV systems should also be considered in terms of their effect on the urban daylight potential, as dark colors will affect reflectivity. It can be concluded that building facades have high influence on the comfort conditions in both the urban space and on neighboring buildings which should be considered in urban design and in building evaluations.

The DF-values give a spatial and intuitively feeling in terms of the shading effect when moving vertically in a building. The daylight factors decrease on the lower floor level, due to higher proportion of the sky being obstructed. When comparing the different DF results for the different simulations when varying WWR, facade reflectance or H/W-ratios, the intuitively feeling of more light entering a space can directly be read from the increment in DF values. However the daylight factor cannot tell for whether the building is orientated north, south, east or west.

When evaluating the daylit area from the 2 % DF criterion and the 50 % DA criterion recently proposed by IESNA LM, the daylight factor evaluation categorically underestimates the daylit area in the space compared to applying the dynamic DA metric. Integration of climate based daylight procedures should be considered essential in environmental performance evaluation.

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