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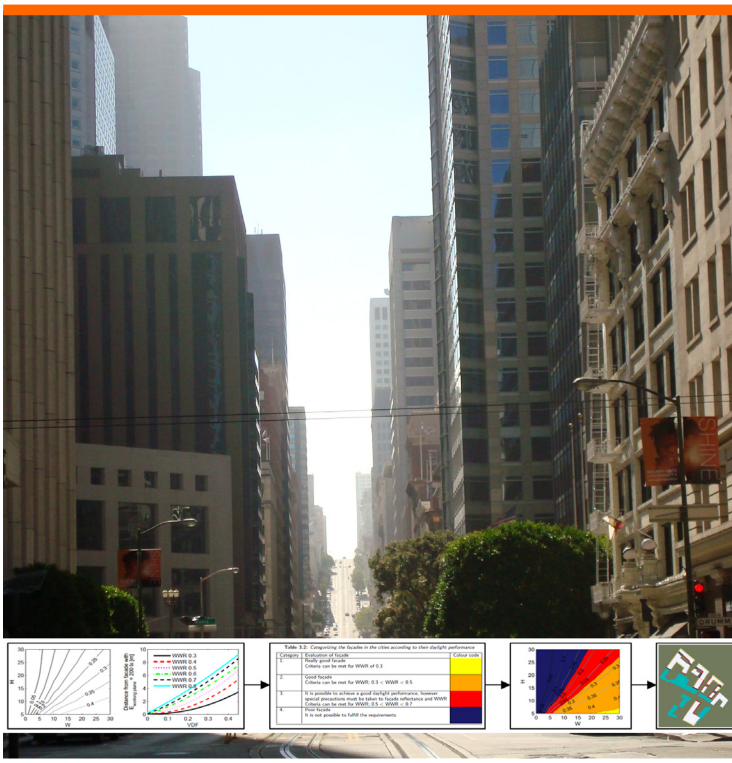
Development of a simple framework to evaluate daylight conditions in urban buildings in the early stages of design



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PhD Thesis

Department of Civil Engineering
2013

DTU Civil Engineering Report R-256 (UK)
February 2013

DTU Civil Engineering
Department of Civil Engineering

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Printed by DTU-Tryk
Department of Civil Engineering
Technical University of Denmark
ISBN: 9788778773388
ISSN: 1601-2917

Preface

This thesis is submitted as a partial fulfilment of the requirements for the Danish PhD 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 the papers which constitute the basis of the work.

Lyngby, 30th September 2012

Anne Iversen

Thesis defended: February 28th, 2013

Revised version: December 16th, 2013

There is a crack in everything. That's how the light gets in
Leonard Cohen

Acknowledgements

I wish to acknowledge the support from my supervisors and colleagues at DTU Civil Engineering. Special thanks go to associate professor Alfred Heller at DTU Civil Engineering for finding time to read through and comment on my work in the final phase of revision of this thesis.

I would like to thank my colleagues at LBNL for some inspiring months during my external stay. Special thanks go to Francis Rubinstein and his research group for giving me access to occupancy data measured in an office building in San Francisco.

Furthermore, I would like to thank the Radiance-list, for always being online and ready to answer questions. Special thanks go to Raphael Compagnon for introducing me to the path of Radiance, and to Andrew McNeil and Greg Ward for their motivating and cheerful attitude towards new Radiance users.

I would like to thank Esbensen Consultants for financially supporting a part of my PhD. Finally I would like to thank my colleagues at Esbensen who are, and have been a great contrast to academia.

Abstract

The thesis proposes a simple method to aid urban designers in the daylighting aspect of the decision-making process in the early stages of design when the outline of the city is defined. As input to this simple method, complex simulations of the urban canyon structure were made. **Paper I** reports on a study on the simplified representation of the structure of the streets and buildings in cities. From the results in this study, a simple 4-step method was developed to evaluate façades in an urban context based on daylight simulations in which the densities of the urban building layout, external surface reflectances, and façade window areas were varied. The method developed was based on a CIE overcast sky, so it did not consider the effect of building orientation, geographical location, changes of sky distribution, or the time of day on its results. In **Paper II**, climate-based daylight simulations of the urban structure were introduced. The climate-based simulations consisted of annual simulations of the daylight conditions. These simulations took into account the enormous variations in daylight illuminances during the year as well as geographical location, façade orientation and user occupancy patterns. For these simulations, the luminance distribution of the sky was described by the Perez all-weather sky-model, based on hour-by-hour input of direct and diffuse irradiance from weather data files. This meant that the weather data files used had an important impact on the simulations. In **Paper III**, the impact of different weather data sets for a given location and of the time-steps applied was therefore investigated. Occupancy patterns also have an important impact on climate-based daylight simulations. The effect of applying occupancy profiles of varying complexity was investigated in **Paper IV**. In the urban planning stage of design, you usually know very little, or nothing, about the future occupants of the building, so it is useful to know whether detailed simulations of occupancy profiles, as opposed to using simplified assumptions, would increase the value of the simulation.

The general hypothesis to be evaluated in this thesis was that:

Simple models for the early stages in the design of urban building structures can represent the complexities of daylighting without loss of important characteristics

This hypothesis was investigated through the work reported in the four papers appended. The research showed that the simple method can be expanded to include more complex aspects if the simplifications include the important parameters. To transform complex urban simulations into the simple 4-step representation, it was necessary to include simulations with i) various façade reflectances, ii) rooms located on different floors, iii) buildings with different orientations, and iv) buildings in different geographical locations. So when the right framework is set-up, the general hypothesis was confirmed. The more complex model of the urban structure used weather and occupancy data. The research showed that it made very little difference to the simulation outcome if different weather data files were applied for a given location. Furthermore, simulation with hourly mean irradiance values, as opposed to 1-min resolution, also made little difference to the simulation outcome. This means that simulating the urban structure based on hourly-mean values is sufficient. From the investigations made on the impact of occupancy profiles, it was found that applying an absence factor, as opposed to simulating the dynamic presence of occupants, also made little difference to the simulation outcome. In other words, the complex input in terms of the presence of occupants can be reduced to an absence factor.

Resumé

Nærværende Ph.d.-afhandling beskriver en simpel metode, der kan anvendes i de tidlige designfaser, hvor den første disponering af byens bygningsvoluminer fastlægges. **Artikel I** beskriver et simplificeret studie af byens gader og bygningshøjder. Fra resultaterne i denne artikel blev der udviklet en simpel 4-trins metode. Metoden baserer sig på dagslyssimuleringer af forskellige tætheder i byen, forskellige overfladereflektanser og vinduesarealer i den undersøgte façade, og metoden kan være med til at evaluere façaderne i en urban sammenhæng. Metoden var baseret på en CIE overskyet himmel og den inkluderede derfor ikke indflydelse af bygningens orientering, geografiske lokalitet eller ændringer i himmelluminanser som de forandrer sig over dagen. I **Artikel II** øgedes kompleksiteten ved at anvende klima-baserede dagslyssimuleringer. De klima-baserede dagslyssimuleringer bestod af årlige simuleringer af dagslysforholdene. Disse simuleringer tager de store variationer, der er i dagslyset over dagen, med i betragtning. Desuden tager simuleringerne højde for geografisk lokalitet, bygningens orientering samt tilstedeværelse af personer. For de klima-baserede dagslyssimuleringer var luminansfordelingen af himmelen beskrevet vha. Perez-All-weather himmel model, der baserer sig på timeværdier af den direkte og diffuse solindstråling, som er tilgængelig fra vejrdatafiler. Dette betyder, at vejrdatafilerne, der anvendes til dagslyssimuleringer er vigtige input-parametre. I **Artikel III** blev indflydelsen ved at simulere med forskellige vejrdatafiler for den samme lokalitet undersøgt. Desuden blev indflydelsen af at simulere med vejrdata med forskellig tidsskridt undersøgt. En anden vigtig parameter i klima-baserede dagslyssimuleringer er tilstedeværelsesprofiler for personerne i bygningen. Indflydelsen af at anvende tilstedeværelsesprofiler med forskellig kompleksitet blev undersøgt i **Artikel IV**. Når en plan af en by udlægges ved man oftest meget lidt, eller ingenting om de personer, der i sidste ende vil bruge bygningerne. Derfor vil det på dette stadie af designfasen være brugbar information at vide, om simuleringer med mere detaljerede tilstedeværelsesprofiler i forhold til at anvende mere simple informationer vil give bedre resultater.

Den overordnede hypotese for afhandlingen var:

Simple metoder kan gengive kompleksiteten inden for dagslysområdet i bygninger i en bymæssig sammenhæng uden at der tabes vigtige egenskaber.

Denne hypotese blev undersøgt gennem den forskning, der er beskrevet i de 4 vedhæftede artikler. Forskningen viste, at den simple metode kunne udvides til at inkludere mere komplekse aspekter, hvis simplifikationen tager højde for de vigtigste parametre. For at kunne transformere de komplekse simuleringer i bymæssige sammenhænge til 4-trins metoden vil det være nødvendigt at inkludere simuleringer med i) forskellig façade reflektanser, ii) rum placeret på forskellige etager, iii) bygninger med forskellig orientering, iv) bygninger med forskellig geografisk lokalitet. Så, svaret på den overordnede hypotese, er at, det er muligt, når man tager højde for de rigtige parametre. De undersøgte parametre til den komplekse model af byen var vejrdata og tilstedeværelsesprofiler for brugerne af bygningen. Forskningen viste at der var meget lille forskel ved at anvende forskellige vejrdata filer fra den samme lokalitet. Desuden viste resultaterne, at det også havde lille effekt på simuleringsresultatet at anvende tidsskridt baseret på gennemsnitlige timeværdier i forhold til 1-min værdier af solindstrålingen. Dette betyder, at det vil være tilstrækkeligt at anvende timeværdier i den komplekse evaluering af dagslysforholdene i bymæssige sammenhænge. Ligeledes viste undersøgelserne af tilstedeværelsesprofiler, at det havde lille indflydelse på resultatet, at simulere med varierende tilstedeværelsesprofiler i forhold til at simulere med en statisk 'tilstedeværelses'-faktor. Det betyder, at det komplekse input fra tilstedeværelsesprofiler kan reduceres til en 'tilstedeværelses'-faktor, når der evalueres på årsbasis.

Table of Contents

Additional work (not included in the thesis)

[1] Delff P., Iversen A., Madsen H., Rode C.: 'Dynamic modeling of occupancy presence using inhomogeneous Markov chains'. In press: *Energy and Buildings, 2014*

[2] 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'. Published in: *Journal of Green Buildings, 2012*, DOI: 10.3992/jgb.7.1.40

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

[4] 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).*

[5] 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*

[6] 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

This thesis is based on the following original publications, referred to in the text by their Roman numerals in bold (I-IV).

I A. Iversen, T.R. Nielsen & S.H. Svendsen:
'Illuminance level in the urban fabric and in the room'.

Published in: *Indoor and Built Environment 2011*, pp.456-463,
DOI: 10.1177/1420326X11409460

II A. Iversen, J.B. Strømann-Andersen & P.A. Sattrup:
'The impact of urban geometry and fabric on daylight availability in the building'.

Submitted to: *Building and Environment, 2012*

III A. Iversen, S. Svendsen & T.R. Nielsen:
'The effect of different weather data sets and their resolution in climate-based daylight modelling'.

Published online 9 March 2012 in: *Lighting Research & Technology*,
DOI: 10.1177/1477153512440545

IV A. Iversen, P. Delff, S. Svendsen & T. R. Nielsen:
'Simulation of annual artificial lighting demand using various occupancy profiles'.

Published online 26 September 2012 in: *Lighting Research and Technology*
DOI:10.1177/1477153512461495

1.1 Aim

New urban areas continue to be built and due to economic reasons the developer usually wants a high plot-ratio. This often leads to proposals for dense urban areas with high-rise buildings, where access to daylight is very restricted. For these areas, one way to create daylit environments is to optimize properties such as the window area, the density of the urban area, and the reflectance of the external surfaces. Daylight simulations can be made to evaluate the daylight conditions of a complex urban structure. Such simulations demand a lot of detailed input on design properties which are often not available in the early stages of the design. However, right from the beginning, it is important that the design team can make the right decisions easily, without spending a lot of time on computations. Simple tools and techniques to aid urban designers in this decision-making process are useful in optimizing the urban structure. The aim of this PhD research was to develop a simple tool that can be applied in this decision-making process in the initial stages of design.

1.2 Hypothesis

Simulation is a method for modelling complex systems. In this case, complex lighting conditions were investigated inside buildings using computer simulation. Once we have a complex system model, it is possible to develop and validate simplified models.

The hypothesis investigated in this thesis is that

Simple models for the early stages in the design of urban building structures can represent the complexities of daylighting without loss of important characteristics

This hypothesis was investigated in the work reported in the four appended papers, which will be described in greater detail in this thesis. The interconnection between the different research topics in the appended papers is visualized in Figure 1.1.

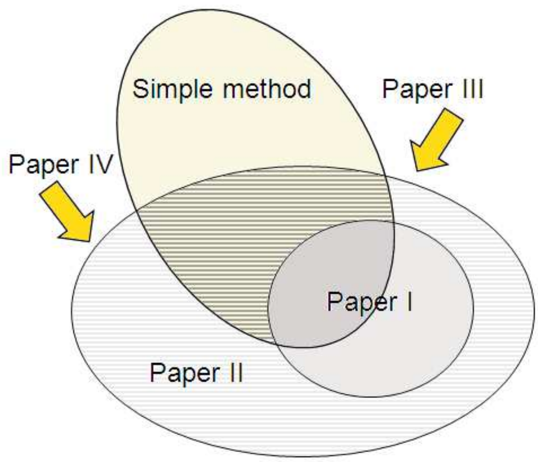


Figure 1.1: *Interplay between the different research papers*

A simple method was derived from the research described in **Paper I**, and the work for **Paper II** added further information to this method by simulating a more complex system. **Paper III** and **Paper IV** provide information on the input data used for the simulated system in **Paper II**. **Paper I** reports the study of a simplified representation of the structure of streets and buildings in urban areas. From the results in this study, a simple 4-step method was developed to evaluate façades in an urban context based on daylight simulations of different densities of the urban building layout, the reflectance of external surfaces, and the window area in the façade. The method was developed based on a CIE overcast sky, so it did not consider effect of building orientation, geographical location, changes in cloud distribution, or time of day in its results. **Paper II** describes how the limited first version of the simple method from **Paper I** was developed further to embrace the complexity of the varying solar irradiation conditions. In this paper, the complexity of the daylight simulations was increased by introducing climate-based daylight simulations to the urban structure simulation. The climate-based simulations were annual simulations of the daylight conditions. These simulations would take account of the enormous variations in daylight illuminance throughout the year as well as geographical location, façade orientation and user occupancy patterns. For these simulations the luminance distribution of the sky was described by the Perez all-weather sky model, based on hour-by-hour input of direct and diffuse irradiance from weather data files. This meant that the weather data files applied were an important factor in the input to the simulations. **Paper III** reports on work to investigate the sensitivity of the simulation results to the variety of weather data available for a given location. Another aspect was to investigate the impact of the time-steps applied, and the findings were evaluated for two additional climatic locations to test whether they could be generalized. Another important parameter in the climate-based daylight simulations was the occupancy pattern. The effect of applying occupancy profiles of varying complexity was investigated in the work for **Paper IV**. At the urban planning stage of design, one typically knows very little, or nothing, about the occupants who will use the building in the end, so it is useful to know whether detailed simulations of occupancy profiles, as opposed to using simplified assumptions, increases the value of the simulation.

1.3 Thesis outline

The thesis is structured in four main chapters. The background for the research is presented in Chapter 2, highlighting findings from the literature and aspects of lighting simulation. Chapter 3 describes the research methodology and general findings of each paper. Chapter 4 discusses the research findings, and in the final chapter, Chapter 5, overall conclusions are given based on the research findings.

1.4 Project framework

The Technical University of Denmark (DTU) was the focal point for the development of my research. The three years of PhD study extended over four years, because I was also affiliated with Esbensen Consultants as a practitioner 25% of the time. The interaction between the university and the engineering firm provided a unique opportunity to relate my research to 'real-world'-problems. My experience from Esbensen as a practitioner was the basis for the investigation of the effect of external obstructions on daylight availability inside a room. When describing the façades in an urban context, we needed a simple method that could be used in the early stages of design and relate the density of the city to the window area in the façade and the daylight factor level inside a room. This work is described in **Paper I**.

In addition to the work carried out at DTU, the project included two external research visits totalling approximately 10 months at the Lawrence Berkeley National Laboratory (LBNL). LBNL is a frontrunner in research into energy-efficient buildings with high-quality indoor climate. They have a long tradition for performing detailed simulations of building systems. On the list of programs they have developed are Window6, Optics5, COMFen and EnergyPlus. The Radiance software system for simulating daylight and light distribution in spaces was initially developed by Greg Ward, with funding from the U.S Department of Energy and the Swiss Federal Government. At the time I was there, LBNL had received new funding to further develop Radiance. So LBNL represented a unique opportunity to upgrade my skills in the world of lighting simulations with Radiance. Specifically, the visits provided the basis for using Radiance in the investigations of annual simulations applying the Three Phase Method used in **Paper III** and **Paper IV**. Furthermore, the visits provided the measured field data on the presence of occupants for the study of the development of the model for the presence of occupants in the additional Paper 1 which is not included in the thesis. This model was used in the occupancy study in **Paper IV**.

A PhD study at the Technical University of Denmark includes not only time for research. Teaching and supervising students at the university is also part of a PhD study. During my studies, I taught in the courses 'Daylight in Buildings' and 'Lighting Design in Buildings' from 2007 to 2010. During the autumn of 2010, we took the students on excursions to three different day-lit buildings in Copenhagen. The three buildings had in common that they were all libraries. However, they were built in different decades and with different restrictions on the building plot. For example, the library in Frederiksberg is located underground, so it only has access to daylight through skylights. The library in Albertslund is a retrofitted library, which clearly gave some natural restrictions to the building plot. Furthermore, several different design methods were applied to the building design. Using semi-structured interviews (Yin, 2009), we interviewed the architects responsible for the design. The students were asked to evaluate the daylight conditions in each space. The outcome from this investigation is reported in a paper accepted for publication in the Industry Corner of the Journal of Green Buildings (additional Paper 2). The main finding from this research was that daylight strategies that include spatial considerations received more positive evaluations. Furthermore, the study showed that designs aimed at achieving an even distribution of daylight with an illuminance target of 200 lx did not result in higher evaluations.

Chapter 2

Background

2.1 Why do we need to worry about daylighting and energy?

Over the years, research has identified daylight and sunlight in buildings as essential to good health and people's well-being (Webb, 2006). With the discovery of the 3rd photoreceptor in the eye by Berson *et al.* (2002), it was shown that exposure to light is directly linked to the regulation of people's circadian rhythms (van Bommel & van den Beld, 2004). Today, however, people still spend up to 90% of their time indoors (Leech *et al.*, 2002), in buildings with much less daylight than our forefathers (Loe, 2009). Building design was affected by the development of the fluorescent light tube by GE Consultants in the 1930s and the invention of air conditioning by Willis Carrier in 1902. Until then, natural light was the primary light source and dictated the shape of buildings. But the new technology made it possible to light, heat, and cool buildings at will, encouraging deeper floor plans and self-contained building units that excluded the context in which they were built in (Baker & Steemers, 2002). The use of the new technology increased the energy consumption of buildings. Today, however, a growing need to create sustainable buildings has led to increased emphasis on day-lit spaces in buildings that use lighting controls to reduce electrical energy needs. The use of daylight not only reduces the building's energy consumption, it can also make a positive contribution to the lighting quality of a space (Boubekri, 1995) and research has shown that occupants prefer daylight to artificial lighting (Boyce *et al.*, 2003; Galasiu & Veitch, 2006; Loe, 2009). The definition of a day-lit space is given in Reinhart & Wienold (2011) as a space which is primarily lit by natural light, and results in both high occupant satisfaction with the visual and thermal environment and low overall energy use for lighting, heating and cooling.

Globally, lighting consumes about 19% of the total electricity generated (IEA, 2006). The annual electricity consumption for lighting per square metre of a building varies between 20 and 50 kWh/m^2 per year (IEA, 2010). According the European Lamp Companies Federation (European Lamp Companies Federation, 2012), it is the energy consumed during lamp use that has the greatest environmental impact. In the life cycle of a lamp from production to disposal, up to 90% of the energy is consumed during the operation phase. Of course, it should be noted that the European Lamp Companies Federation has an interest in minimising the environmental impact of their production processes and of the disposal of their products. But the IEA Annex 45 (IEA, 2010) study found that the cost of an electric lighting installation typically represents 20-30% of total costs and the electricity used during operation represents around 50-60% of the total cost of the lighting system. These findings are based on lighting power densities of 15W/m^2 and 25W/m^2 as recommended by EN15193 (2007). These results might therefore be too harsh in their evaluation of the operational costs, because it is difficult to comply with the requirements for low-energy buildings with such high power densities (cf. sections 2.2 and 2.2.1). However, the message is clear: To minimize the environmental impact of a lighting system, it is important to reduce the energy consumed during operation. And, there is a lot of potential for reducing the environmental impact from lighting by cutting electricity consumption during the operation of lighting systems, which can be accomplished using existing technology.

2.2 Overall energy consumption in office buildings

The Danish Building Code specifies that the total primary energy consumption for a building must not exceed the 'energy framework' calculated by 2.2.1 and 2.2.2, where A is the heated floor area [m^2] (BR10, 2010).

The 'energy framework' is the maximum allowed energy demand for a building which includes e.g. thermal bridges, solar gains, heat recovery, lighting (non-residential buildings only) and cooling (EPBD, 2011).

$$\text{Energy framework}_{\text{residential}} = \mathbf{52.5} + \frac{\mathbf{1,650}}{\boldsymbol{A}} \qquad [\frac{\text{kWh}}{\text{m}^2}\text{per yr}] \tag{2.2.1}$$

$$\text{Energy framework}_{\text{non-residential}} = \mathbf{71.3} + \frac{\mathbf{1,650}}{\boldsymbol{A}} \qquad [\frac{\text{kWh}}{\text{m}^2}\text{per yr}] \tag{2.2.2}$$

EPBD (2011) shows that Denmark is currently the only country with defined low-energy classes. A building can be classified as Low-Energy Building Class 2015 if its energy consumption does not exceed the values calculated by Equations 2.2.3 and 2.2.4. In (BR10, 2010), it is stated that these low-energy classes are expected to become the standard minimum requirement for all new buildings in 2015.

$$\text{Low-energy class 2015}_{\text{residential}} = \mathbf{30} + \frac{\mathbf{1,000}}{\boldsymbol{A}} \qquad [\frac{\text{kWh}}{\text{m}^2}\text{per yr}] \tag{2.2.3}$$

$$\text{Low-energy class 2015}_{\text{non-residential}} = \mathbf{41} + \frac{\mathbf{1,000}}{\boldsymbol{A}} \qquad [\frac{\text{kWh}}{\text{m}^2}\text{per yr}] \tag{2.2.4}$$

Furthermore, the Danish Building Code describes Low-Energy Building Class 2020 as buildings where the energy consumption does not exceed the values given in Equations 2.2.5 and 2.2.6.

$$\text{Low-energy class 2020}_{\text{residential}} = \mathbf{20} \qquad [\frac{\text{kWh}}{\text{m}^2}\text{per yr}] \tag{2.2.5}$$

$$\text{Low-energy class 2020}_{\text{non-residential}} = \mathbf{25} \qquad [\frac{\text{kWh}}{\text{m}^2}\text{per yr}] \tag{2.2.6}$$

For both the Energy framework (Equation 2.2.1 and 2.2.2) and the Low-Energy Class 2015 (Equation 2.2.3 and 2.2.4),the consumption of electricity is multiplied by a site-to-source factor of 2.5, while heating is multiplied by 1 for the Energy framework and 0.8 for the Low-Energy Class 2015. For the Low-Energy Class 2020 requirements, the site-to-source factor for electricity is 1.8, and heating is multiplied by a factor of 0.6.

These classifications should be kept in mind when designing any building system.

2.2.1 Lighting requirements

In the European Standard EN12464-1 (2002), lighting requirements are based on 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 for 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 the presence of occupants, improving the 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 the levels of indoor horizontal illuminance desired for different work tasks. The illuminance level should be maintained from daylight, artificial light, or a combination of the two. In the European Standard EN15193 (2007), a uniform horizontal working-plane illuminance is required, which might induce over-illumination and waste of energy with illumination being provided to locations where it is not actually needed. In Denmark, the use of the Danish Standard DS700 is mandatory for specifying light in work places. This standard requires lighting levels for office work of 500 lx on the work, 200 lx in the immediate surroundings, 100 lx in remote surroundings, and 50 lx for general lighting (DS700, 2005). The approach of distinguishing between work-area and ambient lighting can allow for greater flexibility in the layout and use of the space, because the work areas do not have to relate to a ceiling array of lights. Furthermore, this approach can yield higher energy savings because high illuminance levels are only provided where needed. The work-area/ambient approach is not new. According to Loe, this approach was already in use in the early part of the 20$^{\text{th}}$ century, when electricity and equipment used for lighting was extremely expensive (Loe, 2009).

The Danish Building Code specifies a minimum luminous efficacy for light sources of 50 lm/W. There is no specific requirement for the installed lighting power density (LPD) of the lighting system, but if a building is to be low-energy, the LPD must not be too high. In the European Standard EN15193 (2007), LPD limits are set, 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 for visual comfort. The Danish Centre for Energy Savings (GoEnergi) has published an on-line list of energy-efficient lighting systems. Here the best practice system has an LPD of 3.6 W/m^2 for delivering 200 lx in an office (GoEnergi, 2011). In Table 2.1 the energy consumption for artificial lighting is calculated for a one-person office and given as the LENI (Lighting Energy Numeric Indicator) number:

$$LENI = \frac{W_{light}}{A} \tag{2.2.7}$$

Where, W_{light} is the total annual energy used for lighting [kWh/year] and A is the total useful floor area of the building [m^2].

The LENI number was established as a metric in the standard EN15193 (2007) as a means of showing the annual lighting energy per m^2 required to fulfil the lighting requirements in the building specifications. The LENI number is useful when comparing the energy performance of the same building type with different lighting systems and daylight availabilities. For the calculations in Table 2.1 an annual usage time of 2500 hours has been assumed. The annual energy consumption is calculated for different LPDs with different reduction factors for a one-person office as given in EN15193 (2007): i) manual lighting control with manual on/off switch (man), ii) 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 iii) automatic occupancy and daylight control (day).

Table 2.1: *Guidelines for installed LPDs, reduction factors and the LENI number according to EN15193 (2007), and best practice according to GoEnergi (2011)*

		LPD	Reduction factors			LENI [kWh/m^2 per year]		
		[W/m^2]	man	occ	day	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

Comparison of the calculated LENI numbers in Table 2.1 with the energy consumption requirements of the low-energy buildings (Equations 2.2.1 to 2.2.6) shows that low LPD and control of artificial lighting has to be mandatory to comply with the energy requirements. Please note that the values in Table 2.1 have not been converted to primary energy. To convert to primary energy, the LENI numbers should be multiplied by a site-to-source factor of either 2.5 or 1.8 depending on the low-energy class requirement. This means that for this simple evaluation, the best practice system (cf. Table 2.1) with manual, occupancy and daylight control, achieves up to approximately 20% of the energy consumption required in a low-energy office 2020.

A certain amount of daylight must be available for a space to be called daylit. Daylight levels of illumination will typically vary considerably over the room depth, due to distances from the window. For the artificial lighting, this means that the light needed to supplement the daylight to maintain the required illuminance level varies over the room depth. So the space needs to be subdivided into daylight zones depending on their daylight availability. In the Danish Building Code, this is formulated as a requirement in offices for zone division in the lighting system depending on activities and daylight level (BR10, 2010). To categorize a space as being well-lit, the Danish Building Regulations require that the glazing area is 10% of the heated floor area or that the daylight factor is 2% inside the room. For 2020 low-energy offices, the daylight factor has to be 3% inside the room for a room to be called daylit (BR10, 2010).

2.3 Aspects of lighting simulation

Lighting simulations are computer-based calculations aimed at predicting the lighting situation in a building under a specific daylight situation. Some programs were initially developed to aid designers in the process of determining the lighting layout, e.g. DIALux (DIALux, 2011) and Relux (Relux, 2011). Other programs were developed for simulating the daylight distribution inside a room, e.g. VELUX Daylight Visualizer (Visualizer, 2012), and for simulating both artificial light and daylight, e.g. Radiance (Larson & Shakespeare, 1998). Furthermore, some programs were developed for the purpose of creating visualizations, e.g. Mental Ray (Autodesk, 2012).

The usual inputs to the programs are information on the building and, if daylight is to be considered in the calculations, on the prevailing sky condition. A simulation algorithm calculates indoor illuminances and/or luminances based on the input. The various simulation programs differ in their complexity with regard to what input is required and in their simulation methods. At the present time, all simulation programs require detailed input data with respect to the material properties and geometric modelling of the space.

2.3.1 Algorithms for light simulation

The four prevailing algorithms used for light simulations are:

1) Direct calculation,

2) Radiosity,

3) Ray tracing, and

4) Photon mapping.

Direct calculation is used for simulating light coming directly from light sources. The light sources can be the sun or lamps. Direct calculation is typically applied in simulation programs that only take artificial lighting into account, because the algorithm excludes the diffuse contribution from e.g. the sky vault. In Europe, the most commonly used simulation programs for lighting design are Relux and DIALux. These programs are freely available for download from www.relux.ch and www.dial.de. Both programs use direct calculation to simulate the light coming from the light sources. With the implementation of RadiCal in DIALux 4, both programs also use the radiosity method to calculate the indirect light exchange between the surfaces in the room (DIALux, 2011; Relux, 2011).

The radiosity method was developed by researchers at Cornell University in 1984 and relies on the principles of energy conservation adapted from heat transfer to lighting simulation (Watt, 2000). The method is based on light exchange through view factors and assumes that all surfaces are perfectly diffuse. The method is view-independent, meaning that light exchange is calculated for every point/patch in the scene rather than just those points that can be seen from the eye (view dependent).

In addition to the above-mentioned algorithms, the Relux Suite also offers a ray tracing facility using the simulation program Radiance. The ray tracing facility is used for both visualizations and traditional room simulations. When a scene is ray-traced, the rays are traced from the view point back to the emitter. Ray tracing is thus a view dependent algorithm. The original ray tracing algorithm was developed by Whitted in 1980 (Whitted, 1980) and, in its pure form, it is a deterministic algorithm (Larson & Shakespeare, 1998), which means that the same result will be achieved for every simulation. The ray is sent towards the centre of the source every time. The original algorithm only includes perfect specular interaction (Watt, 2000). In Radiance, the ray tracing follows both the deterministic technique and a stochastic technique in which rays are sent in random directions. This allows Radiance to simulate both specular and diffuse interaction. Radiance is freely available for download from radiance-online.org and is an open source program. The program has been validated in a number of research projects (Mardaljevic, 1995; Reinhart & Herkel, 2000; Reinhart & Walkenhorst, 2001), and agreement within 10% between simulations and measurements is typical of what can be expected as good agreement (Larson & Shakespeare, 1998). Over the years, Radiance has been incorporated in a number of simulation software packages as the lighting simulation engine. Some of the programs are no longer supported, while others are still supported by the developers. Table 2.2 lists various light simulation programs that have been developed over the years. The list shows whether the programs are still supported by the developers today and whether they have a radiance-engine included. The list is not comprehensive, but is based upon the findings of the literature review by Ochoa *et al.* (2012), in which they examined the lighting simulation programs found in the English-language literature.

Table 2.2: *Various light simulation programs with a Radiance-engine included, showing whether the programs are supported by the developers today*

	Supported	Radiance-engine
Relux	x	x
Daysim	x	x
RadianceIES	x	x
ADELINE	-	x
Desktop Radiance	-	x
SPOT	x	x
DIVA for Rhino	x	x

The fourth algorithm listed on the previous page was photon mapping. Photon mapping was introduced by Jensen in 1995 (Watt, 2000). It is a two-pass algorithm tracing illumination paths both from the light sources and from the view point. In the first pass, photons are traced from the light sources into the scene. These photons carry flux and are caught in a data structure called a 'photon map'. In the second pass, an image is rendered using the information stored in the photon map (Dutré *et al.*, 2006). A detailed description of the photon mapping technique can be found in (Jensen, 2001). VELUX Daylight Visualizer uses photon mapping. This is a recently developed simulation program with the focus on the simulation of daylight. The program is freely available from http://viz.velux.com/. The program has been validated against CIE 171:2006 test-cases (Labayrade *et al.*, 2009). The test cases were based on work by Maamari & Fontoynont (2003) and Maamari *et al.* (2006).

2.3.2 Simulation of daylight

The amount of daylight that falls on a surface in a room depends on the geometry and choice of material on the surrounding surfaces and the luminance distribution of the sky. In their publication, CIE (CIE, 2003) has defined 15 standard types of sky ranging from heavily overcast to clear.

For the daylight calculation in DIALux, three different types of sky from the CIE publication can be used. These are the overcast sky, the clear sky and the average sky (See Figures 2.1a - 2.1c). The sky types are described in terms of the distribution of luminance. For the overcast and clear skies, DIALux applies Krochmann's zenith luminance, which corresponds to what is applied in the German Standard DIN 5034 (DIALux, 2011).

To simulate the daylight contribution in Relux, one of the following four CIE-skies can be applied: clear; overcast; intermediate, and uniformly overcast (Relux, 2011) and, as with DIALux, Krochmann's zenith luminance is applied for the luminance distribution of the sky (Doulos *et al.*, 2005).

In Velux Daylight Visualizer all of the 15 different sky types defined in (CIE, 2003) can be applied.

In Radiance, it is possible to simulate six different types of standard sky. These are the CIE clear sky (Figure 2.1b), clear sky with sun, CIE overcast sky (Figure 2.1a), CIE intermediate sky, intermediate sky with sun, and a uniform cloudy sky. The implementation of the CIE overcast sky in Radiance corresponds to CIE Sky Type 16, and follows the description of the standard overcast sky of CIE S003/E-1996 (CIE, 2003). Both the CIE overcast sky from CIE (2003), referred to as Sky Type 1, and the Sky Type 16 of CIE S003/E-1996 are valid sky types when overcast sky types are modelled (CIE, 2003). Furthermore, it is possible to simulate sky luminance distributions according to the Perez all-weather sky model (Figure 2.1d), which describes the "mean instantaneous sky luminance angular distribution patterns for all sky conditions from overcast to clear, through partly cloudy, skies" (Perez *et al.*, 1993). The conversion of irradiance into illuminance for the direct and the diffuse components is determined by the luminous efficacy models of (Perez *et al.*, 1990). To convert the luminance values into radiance integrated over the visible range of the spectrum, the luminance is divided by the white light efficacy factor of 179 lm/W (Larson & Shakespeare, 1998).

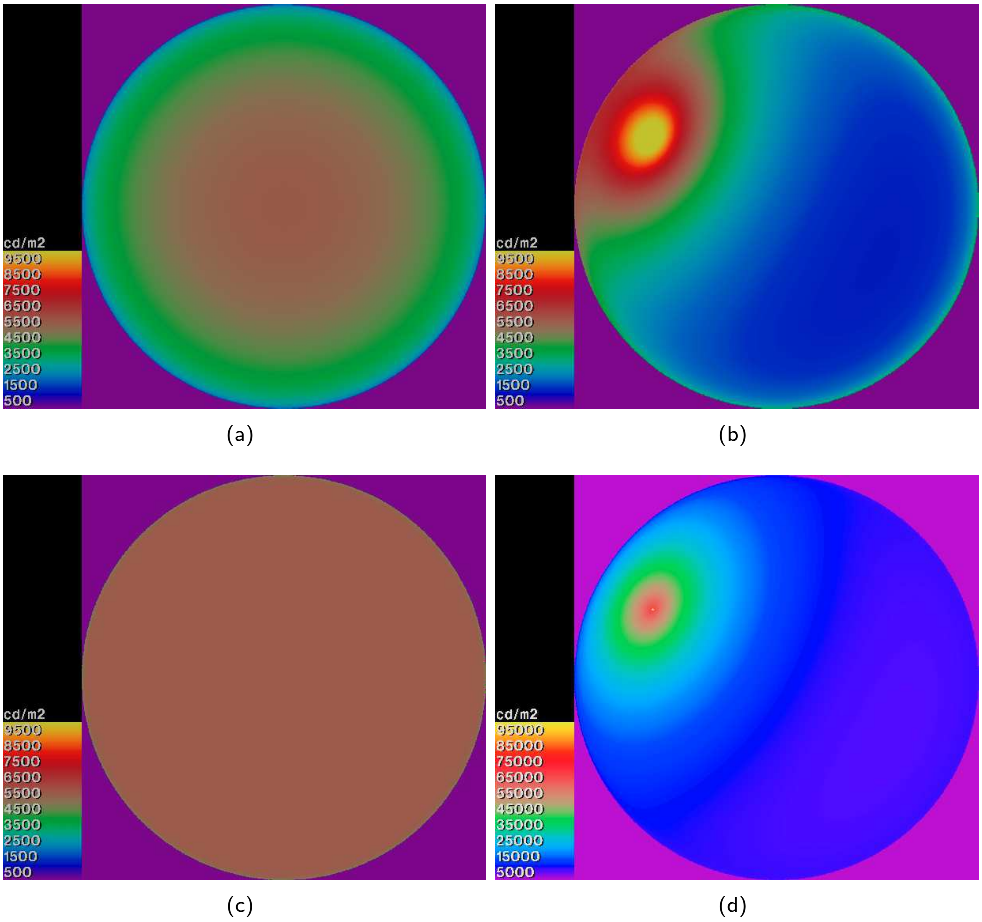


Figure 2.1: *(a) CIE overcast sky (Sky type 16), (b) CIE clear sky, (c) CIE average sky (d) Perez all-weather sky of the* 18^{th} *of June at 3 pm.*

Overcast vs. 'real sky' simulation

Daylight level is usually estimated using the conventional static daylight factor method combined with cumulative daylight distributions. Daylight factor evaluations are 'snapshot' evaluations of the daylight conditions, excluding the climate, building orientation, and direct sunlight. Over the last decade, the literature in the field of daylighting has described the shortcomings of this method (Nabil & Mardaljevic, 2005; Mardaljevic, 2006; Reinhart *et al.*, 2006; Mardaljevic *et al.*, 2009), but the daylight factor method is still the good practice evaluation method for daylight in national standards (e.g. (BR10, 2010; BS8206-2:2008, 2009)). In 2006, Mardaljevic argued that this is 'because of its simplicity rather than its capacity to describe reality' (Mardaljevic, 2006). In studies, Mardaljevic (2000) and Reinhart & Herkel (2000) demonstrated that reliable predictions based on hourly climatic data can be made using the Climate-Based Daylight Modelling principle (CBDM). In the literature, this principle is also referred to as 'annual simulations' or 'dynamic simulations' (Walkenhorst *et al.*, 2002). "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 data sets are derived from a lengthy measurement period and structured to have the same properties as the actual data, with averages and variations that are typical for the site. In this way, CBDM includes the dynamic effects of daylight described in the meteorological data, such as changes in cloud cover, variations over time, and the seasons. The CBDM approach is based on available weather data, so the weather data used as input is crucial. In **Paper III**, a description is given of the design reference year (DRY) (Jensen & Lund, 1995), the Meteonorm weather data set (MET) (Remund *et al.*, 2010), and the Energy Plus weather data set (IWEC)(ASHRAE, 2001) for the location of Copenhagen. Table 2.3 summarizes the 'characteristics' of each weather data set as to weather stations used, statistical methods applied, and the number of years the data are based on.

Table 2.3: *Summary of the 'characteristics' of each weather data set, as to weather stations used, statistical methods applied and period of years the data are based on*

Weather data set	Number of years	Weather station	Method
DRY	15 (1975-1989)	Landbohoejskolen, Taastrup	Measured hourly horizontal diffuse direct irradiance
MET	20 (1981-2000)	Technological Institute, Taastrup Lund University	Daily and hourly global irradiance values stochastically generated from monthly average values using the TAG-model (Time dependent, Autoregressive, Gaussian model) (Aguiar & Collares-Pereira, 1992). The direct and diffuse components were deduced from the global radiation using the method of Perez *et al.* (1991), in which they convert the hourly global irradiance to direct irradiance values
IWEC	18 (1982-1999)	not stated, but the maximum distance from Copenhagen was 50 km	The Kasten model (Davies & McKay, 1989) was used to calculate the hourly global solar radiation and the output was then fed into the Perez *et al.* (1992) model to extrapolate the hourly diffuse and direct irradiation

Comparison between static and dynamic daylight simulations To compare the conventional static daylight factor method with CBDM, simulations were made for the one-person office used in the research for **Paper III** and **Paper IV**. The indoor illuminance levels were simulated at two locations in the room: one at the front, 1 m from the façade; and one at the back of the room, 5 m from the façade. The geometry and photometrical properties of the room correspond to the daylight laboratory at the Danish Building Research Institute (SBi). A sketch of the test office is shown in Figure 2.2. 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 located on a plinth 7 m above ground level.

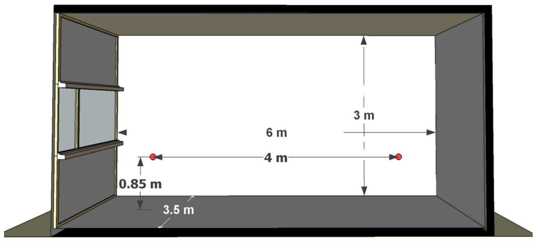


Figure 2.2: *Sketch of the simulated model*

As mentioned in the previous section, daylight factor evaluation represents the conventional way of evaluating daylight conditions in a space. An estimate of the daylight level inside the room and the energy consumption for artificial lighting can be obtained by combining the daylight factor and the external diffuse horizontal illuminance (Figure 2.3a) (Mardaljevic, 2000). The daylight factor was simulated to be 7% at the front of the room and 0.8% at the back of the room. For the simulated test office, this gave the figures for cumulative internal diffuse illuminance shown in Figure 2.3b.

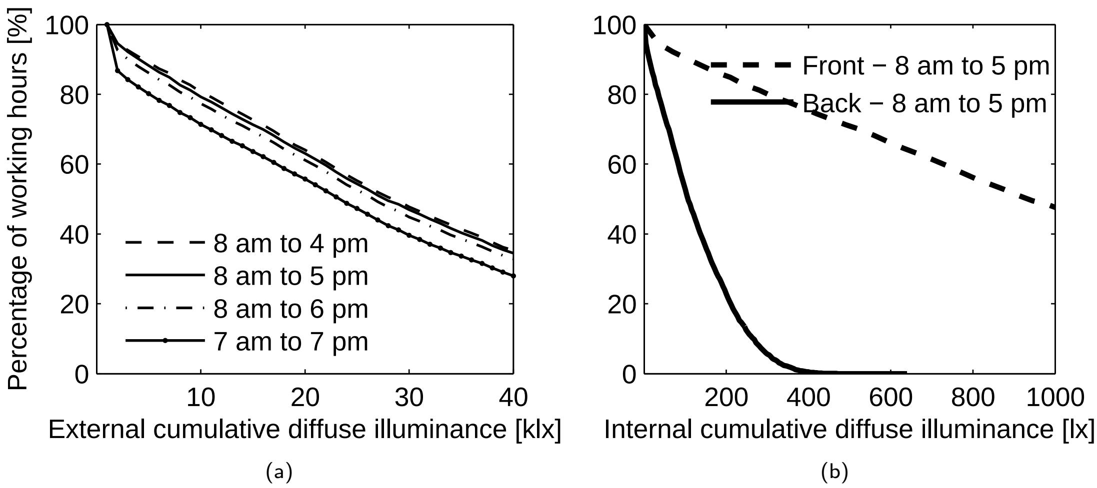


Figure 2.3: *(a) External cumulative diffuse illuminance for the location of Copenhagen at different occupied time intervals, (b) Internal diffuse illuminance at the front and at the back of the test room for the location of Copenhagen from 8 am to 5 pm.*

From the cumulative graphs, the lighting dependency (LD)(see section 3) was calculated at the front and at the back of the room. The lighting demand was calculated both for the on/off strategy, in which lights are switched on when the illuminance is below the threshold, and for the continuous dimming strategy (con), in which the light output is topped up to achieve the target illuminance level. The lighting demand of the room is then determined as the average of the lighting demand at the front and the back of the room. The calculated lighting demand of the test room, based on a static daylight factor is given in Figure 2.4, alongside the lighting demands as calculated using the CBDM approach for the same room, located in Copenhagen with northern and southern orientations.

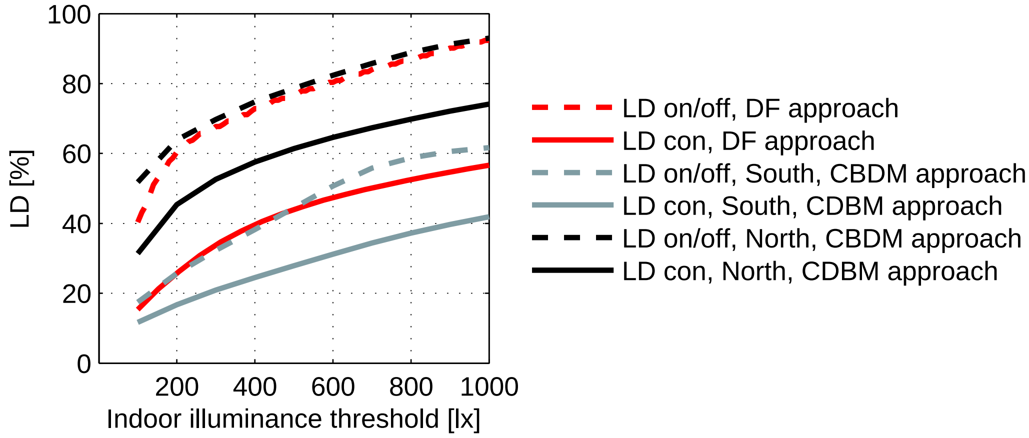


Figure 2.4: *Lighting Dependency for on/off and continuous control based on the daylight factor approach and climate-based modelling approach for northern and southern orientations*

In Mardaljevic (2000), comparisons between the cumulative illuminance obtained from the standard daylight factor approach and from the climate-based approach showed that the daylight factor approach underestimates the daylight levels inside the room for southern-oriented rooms. For rooms facing north, the situation is reversed; here the daylight factor approach overestimates the illuminance values. The results for the room studied in this research show the same trend for the southern orientation. For the northern orientation with the automatic on/off control strategy, the lighting dependency is almost the same, and with continuous control the lighting demand is 20% percentage points higher for the northern orientation compared to the southern orientation. For the southern orientation, the lighting dependency obtained with on/off control using the CBDM approach is 30% percentage points lower than when using the DF-approach, and with continuous control, the lighting dependency is 7-20% percentage points lower depending on the indoor illuminance threshold. The results are given for a situation in which no solar shading was used. So, they describe 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 that causes the occupant's discomfort, then this saving potential might be achievable. However, traditional solar shadings obstruct the entire window when occupants experience discomfort from high luminance in the field of view or high illuminance at eye level, and when these are used, the lighting dependency will increase. So, to investigate the performance of a non-trivial shading solution, more detailed simulations of the system would need to be applied.

Applying weather data in daylight simulation programmes

Applying weather data in daylight simulation programs to calculate the annual energy consumption for artificial lighting is not the common standard. In DIALux, energy performance is calculated in accordance with EN15193 (2007). To take daylight into account, DIALux applies the method outlined in Appendix C of EN15193 (2007) (DIALuxForum, 2008). Here, the daylight contribution is calculated using a daylight supply factor. This factor is obtained from rule-of-thumb daylighting guidelines. No weather data is employed directly. Monthly values can be obtained using a monthly redistribution factor, which indicates the monthly average amount of daylight available. In Relux, the ReluxEnergy module calculates the annual energy consumption for interior lighting of non-residential buildings based on EN15193 (2007) and the German standard DIN 18599-4 (Relux, 2010).

Daysim was developed specifically for annual simulation using daylight coefficients (DCs) to run annual simulations efficiently (Reinhart & Herkel, 2000). The DC approach is a method for annual simulations in which the sky is subdivided into patches whose partial contributions are computed independently (Tregenza, 1983). From the annual simulations of illuminances, it can be directly calculated how much artificial light is needed to fulfil a required illuminance threshold at the working plane.

Recently, Ward *et al.* (2011) developed a new DC method that separates the effect of the sky, window, fenestration description if included, and the view, thus creating a platform that can run annual simulations, even with complex, operable fenestration. In the literature, this method is referred to as the Three Phase Method (McNeil, 2010; Ward *et al.*, 2011). The approach uses the *rtcontrib*[1] tool in Radiance to compute coefficients for incoming and outgoing directions at the window. The Three Phase Method focuses on simulating internal light distribution with complex fenestration systems. The method is limited, in that it can only give results in terms of internal luminances/illuminances, so it cannot be applied when investigating exterior daylight conditions. For such investigations, Daysim should be applied.

With the development of Daysim and the Three Phase Method in Radiance, the question arises of what resolution is needed in the weather data used as input. The weather, by its nature, is very dynamic, and simulating with hourly mean irradiance values is a simplification. The impact of resolution of weather data on simulated daylight availability was investigated in both Walkenhorst *et al.* (2002) and Roisin *et al.* (2008). Both studies looked at the effect of simulating with data sets of one-hour resolution as opposed to a one-minute resolution, and both studies applied the modified Skartveit-Olseth method (Skartveit & Olseth, 1992) implemented in Daysim (Walkenhorst *et al.*, 2002; Reinhart, 2010) to create one-minute irradiance data from one-hourly data. In Walkenhorst *et al.* (2002), they concluded that neglecting short-term dynamics can introduce substantial errors in the simulation of the specific annual electrical energy demands for automated control strategies for artificial lighting systems. They found that consumption is underestimated by 6–18% when using hourly mean irradiance values. But the study by Roisin *et al.* (2008) found a difference of less than 1% using a threshold value of 500 lx. This question about the resolution of weather data was investigated for the research in **Paper III** and section 3.1.3.

2.3.3 The surrounding built environment

Obstructions reduce the light incident on the façade and should be considered in the daylight analysis of spaces. According to instructions given by the Danish building research institute, obstruction angles above 20^o reduce the light within the room significantly (Johnsen & Christoffersen, 2008).

For decades, focus has been given to the optimization of individual buildings and their various daylight systems, operation, and maintenance. But considering a building in isolation from the context in which it is built means ignoring the interaction between the urban environment and the building's daylight performance. Moreover, simulation models are generally 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. Yet, access to daylight is vital for the creation of social spaces, well-lit environments, and reductions in energy consumption for artificial lighting. Optimizing the urban plan in terms of daylight is therefore of major importance, because one cannot just add daylight to a lighting scene later on, in the way that, e.g. 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 back to 1189) and its later embodiment in statute law, the Prescription Act of 1832, provides that, if a window has enjoyed uninterrupted access to daylight for a twenty-year period, the right to that access has become permanent (Bryan *et al.*, 1981).

The effect of obstructions has been described in several research papers, but previous research on daylight availability has focused on solar irradiation and illuminance levels. Compagnon (2004) looked at solar irradiation on the urban fabric (roofs and façades) to assess the potential for active and passive solar heating, photovoltaic electricity production, and daylighting. Nabil & Mardaljevic (2005) also investigated irradiation on the urban fabric and used an image-based approach to generate irradiation "maps" that were derived from an hourly time-series for one year. Such maps can be used to identify façade locations with high irradiation, e.g. to assist in the positioning of photovoltaic panels. More recently, Kaempf & Robinson (2010) applied a hybrid evolutionary algorithm to optimize building and urban geometric forms for solar radiation utilization. But these studies only investigated the urban design from the point of view of external environmental impact.

However, there have been some investigations that link exterior radiation/illumination to interior daylight availability. A study by Li *et al.* (2009b) introduced the vertical daylight factor (VDF) and demonstrated that

[1]After the research for this thesis was finished, new developments in Radiance and the Three Phase Method have improved the performance of the *rtcontrib* routine, and the new Radiance routine would be *rcontrib*

daylight is significantly reduced in a heavily obstructed environment. The VDF is a measure that defines the illuminance level on a vertical external plane to the external unobstructed illuminance level under CIE overcast sky. A study of VDF predictions using Radiance simulation demonstrated that an upper obstruction at 60° reduces the daylight level by up to 85% compared to a lower obstruction at 10°. The results also indicated that reflection from the obstructive buildings can be significant in heavily obstructed environments, such as rooms on lower floor levels facing high-rise buildings. A study by Strømann-Andersen & Sattrup (2011) showed the effect of the height/width ratio (elevation of an obstruction) on the energy demand for artificial light. The effect is rather strong: for example, an obstruction with a height/width ratio of 1.0 (equal to an elevation angle of 45°) can increase the lighting energy demand by up to 85% compared to a free horizon. A study by Cantin & Dubois (2011) investigated two office spaces, with northwest and southwest orientations, located in a high-rise building in Montreal. They did not only focus on the horizontal illuminance as an evaluation parameter, but also looked at the effect of the surroundings on the daylight distribution within the room. To investigate the spatial distribution of light, they looked at 'directivity', using a scalar called the 'vector-to-scalar illuminance ratio'. The scalar, or metric, was proposed by Cuttle (2003) and expresses the ratio between all the illuminance vectors incident on a sphere and the average illuminance on the sphere. They found that the directivity across the depth of the room was more constant in the northwest-facing office than in the southwest-facing office, which was caused by the fact that the southwest-facing office received more direct sunlight in the periphery of the window, creating more variability in the space. Furthermore, the northwest-facing office faced a reflecting building façade from which reflected light bounced off sending near-horizontal light vectors into the space thereby contributing to a more even light distribution in the space.

2.3.4 Solar Shading Devices

Solar shading is an effective strategy to reduce overheating and diffuse direct sunlight, thus reducing energy consumption. Moreover, problems associated with glare and visual discomfort are inevitable when direct solar radiation is transmitted into the room. To avoid overheating and glare problems, it has been suggested that direct sunlight should not be allowed to enter office spaces (Vartiainen, 2001). Shading provision is necessary to prevent thermal and visual discomfort. Climatic conditions and daylight availability play a major role in the design and control of a shading system. The location, properties and control of the shading device have a significant impact on both daylighting and thermal performance in perimeter office spaces.

There have been a lot of studies on the effect of solar shadings on daylight availability and solar heat gains. In building simulation programs where solar heat gains are considered in the overall energy balance of the building, shading is often included as a 'shading factor' or as commonly used shading systems (e.g. in BSim). Shading is typically activated when the operative temperature indoors exceeds a certain threshold. This also usually means that solar shading is modelled as a constant factor corresponding to the shading effect required, which is thus independent of solar incidence angles (Tzempelikos & Athienitis, 2007). However, an important factor in the evaluation of the performance of such devices is their detailed optical and thermal characterization. The challenge is to evaluate those parameters in an interconnected context, because some of the characteristics have contradictory effects, e.g. increasing solar gains in winter while providing shading in summer. Furthermore, such properties are usually not described by manufacturers and there is no standard procedure for measuring them. Recent developments in the ESP-r program integrated a module allowing the input of information about state-of-the-art fenestration solutions (Frontini *et al.*, 2009). According to Kuhn (2006) and Kuhn *et al.* (2011), the standard method of evaluation, which uses only the normal incidence value of the transmittance of a fenestration system, heating demand is overestimated by up to 23% and cooling demand is underestimated by up to 99% compared to using bi-directional information.

In daylight simulations, the approach to including shading systems has been to model them explicitly or in a more simplified way in which the shading corresponds to a reduction in light transmittance. In the daylight simulation program Daysim, this latter approach is referred to as the simple blind model. This model uses a simplified model to consider the effect of a generic Venetian blind system on annual daylight availability: Daysim uses the basic Radiance scene to calculate indoor illuminances when the blinds are retracted. During times of the year when the blinds are lowered due to direct glare, Daysim simply assumes that a generic blind system blocks all direct sunlight and transmits 25% of all diffuse daylight (Reinhart, 2010). In this mode, glare is defined as when the irradiance on the working plan exceeds $50\mathrm{W/m^2}$, which is an empirically established threshold found in the PhD study of Reinhart (2001). This generic blind system corresponds to the one employed in the studies of Lee *et al.* (1998) and Vartiainen (2001).

The development of the Three Phase Method simulation approach in Radiance has made it possible to simulate with complex fenestration systems (CFS), described through their bidirectional scattering distribution function (BSDF). This development is a huge improvement in terms of both simulation time and the modelling of fenestration systems. Now the fenestration system can be described using the BSDF, which can be obtained from Window6, and measured in a goniospectrophotometer or generated with the *genBSDF* routine in Radiance (McNeil, 2010).

Tzempelikos & Athienitis (2007) is an example of a study in which the shading effect has been explored. They considered two types of shading control: (i) passive control: the roller shade remains closed during working hours to ensure privacy/reduce glare; and (ii) active automatic control: the roller shade is open when beam illuminance on the window is negligible (or beam solar radiation incident on the window is less than 20 W/m^2). For each working hour in the year during which the above condition is satisfied, the roller shade opens automatically to maximize daylight and the view to the outside (without causing glare, since there is no direct sunlight). The impact of control is clear: passive shading control results in poor daylight availability, while simple on/off (open/close) control of the shade during working hours – depending on daylighting conditions – increases annual daylight availability by 20% on average. This means that people could work for 20% more of the year without having to use electric lighting (just by using daylight).

A study by Reinhart (2005) looked at the effect of shading on the daylit zone depth. The daylit zone depth is defined as the points at which daylight autonomy was half its maximum value, meaning a daylight autonomy of 50%. Five different daylight zones in the USA and the four cardinal orientations, North, South, East and West, were simulated. The light transmittance of the window was simulated as 35% and 75%, and the illuminance threshold for daylight autonomy was simulated as both 300lx and 500lx. This led to a total of 640 different combinations. From these combinations, it was found that where there were no blinds, 85% of the simulated cases had a daylight zone depth of about 1 to 2.5 times the window-head-height. With blinds, the daylight zone depth decreased and 85% of the cases had a daylight zone depth of between 0.8 and 2 times the window-head-height.

These studies show of course that solar shading has to be included in simulations to achieve more realistic predictions of annual daylight availability. In the research for **Paper III** and **Paper IV**, solar shading was not employed. The rationale behind this was that when solar shading was employed the daylight availability would be reduced proportionally. In other words, the impact of applying different weather data sets or weather data sets with different resolutions (**Paper III**), or of various occupancy profiles (**Paper IV**), would be the same, irrespective of any use of solar shading. To support this assumption, the simple blind model in Daysim was added to the research for **Paper III**, see section 3.1.3. The research described in **Paper I** was based on CIE overcast sky conditions. In this case, it is common practice to assume that, if the shading is not static, e.g. an overhang, then it is retracted in the overcast situation.

2.3.5 Lighting Controls

The main purpose of most lighting systems is to provide illumination for the work to be done in a space. Lighting controls are installed to reduce energy consumption for artificial light and/or to provide a means of adjusting lighting conditions to ensure individual comfort and/or safety. The controls can be either discrete or continuous in that the light output of the electrical lighting system can be either switched or dimmed. Depending on the type of control, the factors that might affect how the lights are controlled include: the arrangement of furniture and partitions, the reflectance of surfaces, the direction of incoming daylight, the use of task lighting, the positions of occupants, and the location and direction of the photosensor. The three main types of control are: (i) time switches, (ii) photosensor dimming, and (iii) occupancy sensors (Boyce, 2003).

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

A photosensor is an electronic device that adjusts the light output of a lighting system depending 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 on the basis of where they are located and how their signal is used to adjust the electric lighting. The classification has two main categories, referred to as either open or closed loop. In an open-loop system, the photosensor is not affected by the lighting that it controls and there is no feedback. In a closed-loop control system, the photosensor is affected by the lighting that it controls, so there is feedback.

Some photosensors are used to control electrical lighting on basis of 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, e.g. to compensate for lamp depreciation and the effect of dirt. And others simply switch lights on at dusk and off at dawn (NLPIP, 2007).

Occupancy sensing control systems switch lights on in a space when motion is detected, and switch lights off if no motion is detected after a pre-set interval has elapsed. The literature reports interval times between 6 and 30 min (Pigg *et al.*, 1996; Guo *et al.*, 2010). Commercial buildings usually use passive infrared (PIR), 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 so common. Other systems that use video cameras or biometric identification can provide higher resolutions for occupant identification and localization, but, at the present time, these are primarily used in security and alarm applications. The various occupancy sensing control types are nicely described and summarized in the review of Guo *et al.* (2010).

The common denominator for all three types of lighting control is that they all have the potential to save energy by minimizing the electric lighting load when no one is present or an alternative light source is available. Furthermore, they are all automatic and therefore take no account of the natural behaviour of occupants.

2.3.6 Occupation

Most building simulation tools integrate the effects of occupant presence in their calculations in a very simplified way, usually considering all occupants to be present according to a fixed schedule (Hoes *et al.*, 2009; Haldi, 2010) and multiplying the number of occupants by fixed values of metabolic heat gain. The ASHRAE Research Project 1093-RP work of Abushakra *et al.* (2001) generated diversity profiles for various categories of internal gains and types of buildings. These profiles can be employed in building simulation programs, such as EnergyPlus and DOE-2, to estimate the impact of internal heat gains (from people, office equipment and lighting) on energy and cooling load calculations (Abushakra *et al.*, 2001).

In the European Standard EN15193 (2007), a dependency factor is used for the presence of occupants. This factor depends on the lighting control system applied and the degree of absence from the room or building. In Table 2.4, the absence factor determined at either building or room level is summarized for various office configurations. The absence factor reflects the fact that the 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 small zone, such as a single workstation, is vacated more frequently than a larger zone (Newsham *et al.*, 1995; Littlefair, 2006). This descriptive approach is appealing because it means that designers and engineers avoid having to deal with the dynamic behaviour of occupants and use a simple and easily applicable factor.

Table 2.4: *Absence factors for various office configurations (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

In lighting simulations, such as DIALux (DIALux, 2011)), occupants are taken into account using absence factors in accordance with the European Standard EN15193 (2007). In Relux (Relux, 2011) and Daysim (Reinhart, 2010), the default occupational patterns are the static pattern for weekdays and weekends. In Daysim, it is also possible to apply the Lightswitch-2002 model. According to Reinhart (2004), the Lightswitch-2002 model was developed on the basis of the same idea as Newsham's original model (Newsham *et al.*, 1995), i.e. to predict electric lighting use based on behavioural patterns actually observed in office buildings. At the moment, the presence of occupants in Lightswitch-2002 can be simulated using profiles with a constant presence during the occupied hours, but with arrivals and departures randomly scheduled in a time interval of 15 min around their official starting times to add realism to the model (Reinhart, 2004). Furthermore, breaks can be added to the occupancy profile depending on the length of the working day. The model was applied in whole-building simulation in the PhD thesis of Bourgeois (2005). Here, he investigated the effect on lighting demand of having a fixed occupancy profile with the lights always on compared with cases with manual control of the artificial lighting and automatic control of the artificial lighting. Not surprisingly, he found that the introduction of variable occupancy profiles to the building simulations led to reduced energy consumption for artificial lighting. From simulations, he found manual control reduced energy consumption by up to 62%, while automatic control could achieve a further reduction of 50%.

The presence or absence of occupants is one aspect of occupation; another aspect is their behaviour. To take into account the dynamic, natural behaviour of occupants, various occupancy models have been suggested, based on empirical data. Table 2.5 divides the models in two groups: 1) those that simply model the presence/absence of occupants, and 2) those that also include behaviour such as manual on/off switching of lights and the operation of blinds or intermediate activities of the occupants.

Table 2.5: *Developed occupancy models*

1	Presence/absence of occupants	Delff *et al.* (2014); Page *et al.* (2008) Richardson *et al.* (2008); Wang *et al.* (2005)
2	+ manual on/off switching of lights + intermediate activities	Reinhart (2004); Newsham *et al.* (1995); Hunt (1979) Tabak & de Vries (2010)

The behaviour of occupants and their operation of the designed building systems often cause the predicted energy consumption obtained from simulations to differ from the energy consumed in the realised buildings. Studies by e.g. Mines (1991); Branco *et al.* (2004); Emery & Kippenhan (2006), compared the predicted and realised energy consumption. These studies highlight that the differences in energy consumption result from not only the behaviour of occupants and their interaction with the building systems, but also from the final realisation of the construction and its technical installations.

Chapter 3

Methodology and results

The general hypothesis to be tested was that "*Simple models for the early stages in the design of urban building structures can represent the complexities of daylighting without loss of important characteristics*". For this evaluation, a virtual laboratory was used as the simulated built environment. The assumptions and limitations of this laboratory are outlined in the following.

The research described in this thesis was simulation-based. Radiance and Radiance/Daysim were used for the simulations. As also mentioned in section 2.3.1, these programs have been extensively validated against real measurements in various research papers, so the assumption of this thesis is that Radiance is valid for the current domain of building modelling.

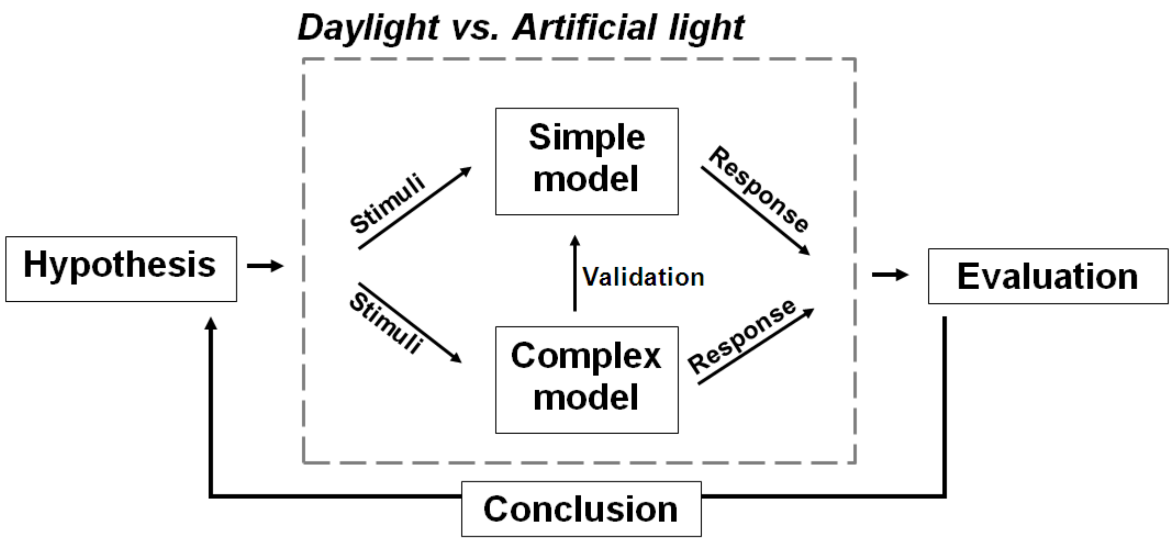


Figure 3.1: *Diagram of the methodology of the thesis*

The figure above shows how the hypothesis was tested by applying the 'tools' in the box with the broken line, followed by an evaluation based on the response from the system. The system which was the focus for the research is the daylight contribution inside an idealized room. The factors affecting the overall system can be visualized using a flow chart. A diagram of the system is shown in Figure 3.2.

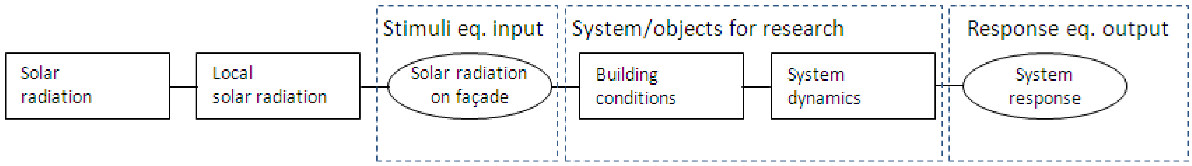


Figure 3.2: *Flow-diagram of the effects influencing the system from the solar radiation to the system response*

Solar radiation is the overall input to the system, from extra-terrestrial solar radiation outside the earth's atmosphere to global solar radiation inside the earth's atmosphere. This effect is taken into account in the sky models applied to the simulations. This research used the Perez all-weather sky model and the CIE overcast sky (cf. section 2.3.2) to describe the luminance distribution of the sky. The distribution of sky luminance depends, of course, on where you are in the world. In the literature, the prevailing sky condition for the northern hemisphere, or at least for the UK and Scandinavia, has been described as an overcast sky. However, when climate-based simulations are run, the sky is not mainly overcast, as was seen in section 2.3.2 and in the research of Mardaljevic (2000). Comparison between climate-based simulations and CIE overcast sky simulations showed that the lighting demand is underestimated for the northern orientation and overestimated for the southern orientation in CIE overcast sky simulations.

Furthermore, the time of day is a parameter that affects the simulated solar radiation. The investigated time period is during office hours. From 8 am to 5 pm for the research in **Paper II** and **Paper III**, and 7 am to 9 pm in **Paper IV**. In **Paper I**, the daylight evaluation was made under CIE overcast sky conditions, so the effect of the time of day was not considered in these investigations. However, one could say that time in this case is the moment when the sky corresponds to a 10,000lx CIE overcast standard sky.

Local solar radiation takes into account the surrounding built environment. If obstructions are present, they will block parts of the available solar radiation and thus reduce the local solar radiation. The solar radiation that hits the façade also depends on the orientation of the building: a south-oriented non-obstructed façade will receive more solar radiation than a similar north-oriented façade. Parameters such as the reflectance and distance to nearby buildings can affect the solar radiation hitting the façades of a building. In **Paper I** and **Paper II**, the influence of such surroundings was investigated with respect to both their reflectance and distance- and height of the urban canyon. In the research made for **Paper III** and **Paper IV** on daylight aspects, the scope did not include surrounding buildings, because by their nature they block a large amount of the daylight entering the interior space. And since the research described in these two papers was to investigate the effect of resolution on both weather data and occupancy profiles, the effect of the surroundings were excluded to give a clearer and more understandable picture.

Solar radiation on façade is a stimuli or input to the simulated room and is a result of the previously described factors: The **solar radiation** and the**local solar radiation**.

Building conditions refer to the parameters that affect the light distribution within the building, such as the window area, the position of the window, the shape of the room, the visible light transmission of the window system, the shading system, the reflectance of surfaces, wall thicknesses and furniture. In **Paper I** and **Paper II** the window area varied, whereas in the research made for **Paper III** and **Paper IV**, the parameters remained fixed.

System dynamics are the factors that bring dynamics into the system, such as lighting control, occupants, or solar shading, if these are controlled dynamically.

System response is the output from the system. In the research made for this thesis, the focus was the energy consumption computed on the basis of lighting demands resulting from daylight availability.

The system response cannot directly give an assessment of the phenomenon investigated. Some quantities need to be derived from which the response can be evaluated and conclusions can be drawn. These derived quantities are called metrics. A metric is defined as 'some mathematical combination of (potentially disparate) measurements and/or dimensions and/or conditions represented on a continuous scale' (Mardaljevic *et al.*, 2009).

The metrics applied for the evaluation of horizontal illuminance in this thesis are the Daylight Factor (DF), Daylight Autonomy (DA), Lighting Dependency (LD), and continuous Lighting Dependency (LD$_{con}$), and these are described in the following.

The Daylight Factor

The daylight factor is defined under CIE overcast sky conditions as the ratio of the illuminance level at an upward-facing sensor point inside a space to the level at an unobstructed external upward facing sensor point. No direct sun or clear sky is considered. If the daylight factor calculated for the different zones is combined with accumulated daylight distributions (cf. section 2.3.2), a lighting control scheme can give an estimate of the potential energy consumption for artificial lighting in a given building zone.

However, requirements based on the daylight factor evaluation are inconsistent with the time-varying natural behaviour of daylight. So, climate-based metrics have been proposed in which the daylight availability evaluation is based on illuminance levels under the multiple sky conditions found during the hours of the year when a space is occupied.

Daylight Autonomy

One such climate-based metric is Daylight Autonomy (DA), as proposed by Reinhart & Walkenhorst (2001). DA describes the percentage of occupied hours per year for which a minimum work plane illuminance threshold can be maintained by daylight alone. According to a recently published paper by Reinhart & Weissman (2012), a draft document for 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 its daylight autonomy at an illuminance threshold of 300 lx exceeds 50%. In **Paper II** the dynamic evaluations of the space is given with a daylight autonomy of 50% at a threshold of 200 lx. The 200 lx threshold was chosen on basis of the requirement in the Danish Standard (DS700, 2005) of 200 lx in the immediate surroundings.

Lighting Dependency

To link daylight availability to the lighting demand, a metric called the lighting dependency (LD) was proposed by the authors of **Paper III**. LD defines the percentage of the occupied hours per year during which artificial light has to be added to the lighting scene to maintain a minimum work plane illuminance threshold. For an on/off lighting system with photoelectric dimming, LD describes the relative energy consumption for lighting the room, excluding the energy consumption of the ballast and control system. Energy savings can therefore be read directly from the difference in LD compared to a reference case, where the lights are on all the occupied hours. LD is the reverse of Daylight Autonomy. An LD of 100% represents a case where the lights are switched on for all the occupied hours. This could be the case, for instance, in the core zone of a building, where no daylight is present and no occupancy control is applied. In the research made for **Paper III** and **Paper IV**, this case represents a reference case.

However, LD does not take into account the hours when the daylight is below the threshold value but would still contribute to the perceived visual environment and result in energy savings if a photoelectric dimming system was in use. Rogers formulated the concept of Daylight Saturation (Rogers, 2011) or Continuous Daylight Autonomy (DA$_{con}$) in which daylight levels below the threshold are credited with a relative weight depending on the ratio between the amount of available daylight (E$_{daylight}$) and the indoor threshold illuminance level (E$_{threshold}$)(Rogers, 2006). When the daylight threshold is not maintained during working hours, the artificial light contribution in an ideal photoelectric dimming system can be described by a corresponding Continuous Lighting Dependency (LD$_{con}$).

LD and LD$_{con}$ were used for the evaluations described in **Paper III** and **Paper IV**.

The metrics applied for the evaluation of the vertical illuminances on the façades in this thesis are the Vertical Daylight Factor (VDF) and the Vertical Daylight Autonomy (VDA), and these are described in the following.

Vertical Daylight Factor
The Vertical Daylight Factor (VDF) is defined under overcast sky conditions. It is defined as the amount of illuminance falling on an external vertical surface to the unobstructed horizontal illuminance level (Li *et al.*, 2009a,b). The VDF is therefore, like the daylight factor, constrained by not taking into account orientation, location, changes in sky distribution and the time of day in its evaluation.

Vertical Daylight Autonomy
A climate-based metric, Vertical Daylight Autonomy (VDA), was proposed in **Paper IV**. VDA describes the percentage of the occupied hours per year when a threshold illuminance on the façade can be maintained by daylight alone. Depending on its threshold illuminance value, the VDA can describe how often during occupied hours of the year blinds need lowering to prevent occupants experiencing glare or to exclude solar gains to prevent overheating. However, in the research made for this thesis, the aim of using the VDA metric was to visualize differences in illuminance levels on façades with northern and southern orientations. For this purpose, the VDA threshold value was set at 10,000 lx.

Table 3.1 summarizes the metrics with regard to the sky type they make use of and whether they take into account the variations in daylight that occur during the day.

Table 3.1: *Metrics used to assess daylight availability and/or lighting demand*

Metric	Sky type	Description
DF	CIE overcast	Direct sun or clear sky is not taken into account.
DA	Perez All-weather	Takes geographical location and variation in sky luminance distribution during the day into account
LD	Perez All-weather	Takes geographical location and variation in sky luminance distribution during the day into account
LD_{con}	Perez All-weather	Takes geographical location and variation in sky luminance distribution during the day into account
VDF	CIE overcast	Direct sun or clear sky is not taken into account.
VDA	Perez All-weather	Takes geographical location and variation in sky luminance distribution during the day into account

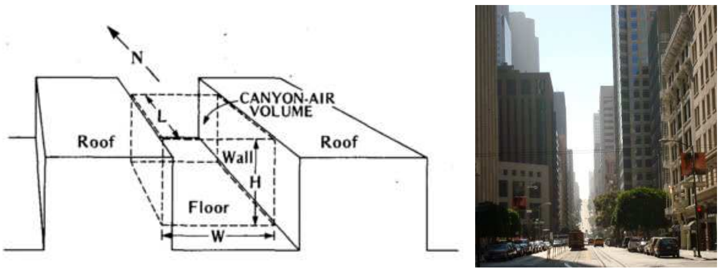
3.1 Methodology and results for the research papers

The following 4 sections outline the methodology applied for each of the research papers.

3.1.1 Paper I

The aim of the research described in **Paper I** was to set-up a simple framework to evaluate façades in an urban context with various densities of the urban building layout, surface reflectances, and window-to-wall ratios (WWR) in the façade.

The urban canyon describes a simplified representation of the structure of streets and buildings in urban areas. Nunez & Oke (1977) defined an urban canyon as consisting of the walls (H) and floor (W) between two adjacent buildings, see Figure 3.3. And a search on Wikipedia using the keyword 'Urban canyon' reveals that an urban canyon is an artefact of an urban environment similar to a natural canyon. It is manifested by streets cutting through dense blocks of structures, especially skyscrapers, that form a human built canyon (Wikipedia, 2012). The research for both **Paper I** and **Paper II** was made within these canyon boundaries.



(a) (b)

Figure 3.3: *(a) Principal sketch of an urban canyon in (Nunez & Oke, 1977), (b) An urban canyon seen from the Embarcadero down California St. in San Francisco*

Remembering the overall system shown in Figure 3.2, the research in this paper was influenced by variations in the parameters in the blocks for 'Local solar radiation' and 'Building conditions', as highlighted in Figure 3.4.

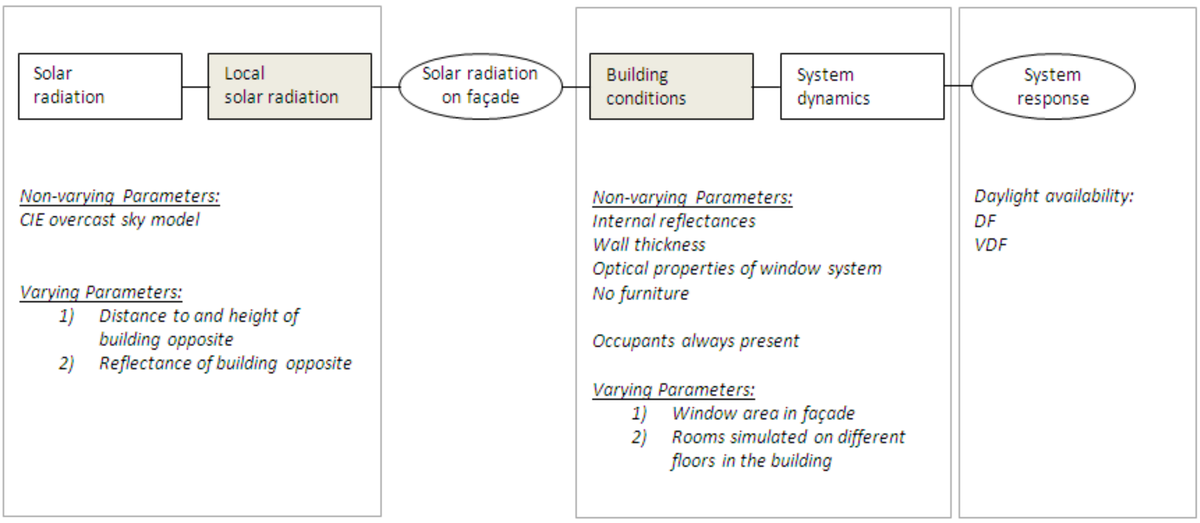


Figure 3.4: *Diagram of the parameters influencing the simulations in* **Paper I**

The following paragraphs describe the content of each block in Figure 3.4.

Solar radiation The luminance distribution of the sky was described on the basis of the 10klx CIE overcast sky description.

Local solar radiation Simulations were carried out with a building opposite of varying height (H) from 5m to 30m and with street widths (W) varying from 5m to 30m, see Figure 3.5. The reflectance of the building opposite was simulated as average diffuse reflectances of 0.2 and 0.9 for the results presented in **Paper I**. These reflectance values were chosen to represent a lower and upper limit for the reflected light expected from the building opposite. This section also presents results for a façade reflectance of 0.5, because this reflectance would in reality most likely represent the upper limit, since over time surfaces collect dirt and debris, which reduce their reflectance unless the façade is maintained in a newly built state. Moreover, a reflectance of 0.9 is very high and would only apply in the case of a very white, clean reflective surface with no windows or mirrons. The building in question with the room investigated had a fixed height of 30m, and the width of the opposing building was 100m.

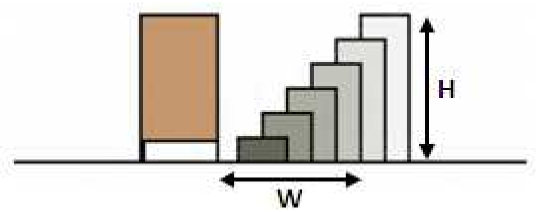


Figure 3.5: *A section of the urban canyon model showing street widths (W) from 5m to 30m and heights (H) of the building opposite from 5m to 30m.*

Building conditions A room of dimensions 20m x 15m x 4m (w x d x h) located on the ground floor in the middle of a large building with dimensions 60m x 15m x 30m (w x d x h) was simulated as a 'worst case' base, see Figure 3.6.

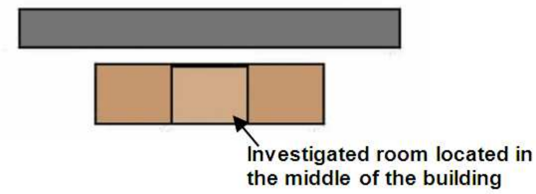


Figure 3.6: *Plan of the model, seen from above with a street width of 5m*

In the simulations presented, the room properties were fixed because the focus was on the effect of the surrounding buildings and window area on differences in daylight availability. The exterior walls were given a thickness of 0.3m to take into account a well-insulated façade. The visible light transmittance of the window was 0.72. Illuminance readings were taken in the centerline of the room at a working-plane height of 0.85 m above the floor, in accordance with values given in (Johnsen & Christoffersen, 2008). The reflectances of the interior walls, floor and ceiling were 0.7, 0.25 and 0.9, respectively. Glazing areas varied and represented 30%, 40%, 50%, 60%, 70% and 80% of the façade (WWR). Windows were simulated as a band across the whole width of the façade from 0.8m above the floor, see Figure 3.7.

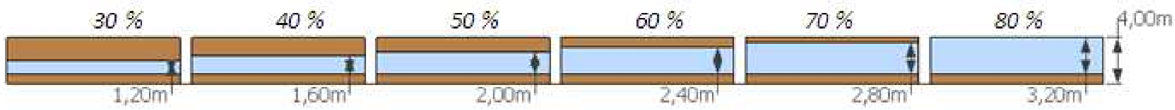


Figure 3.7: *Sketch of the façades with varying WWRs*

System dynamics No system dynamics, such as lighting control or varying occupancy load were considered, because the focus of this research was to look at the effect of the surrounding environment and varying window area in the façade on daylight availability inside the room.

System response The daylight availability inside the room was evaluated based on the Daylight Factor (DF). And the amount of daylight striking the external façade was evaluated based on the Vertical Daylight Factor (VDF).

General findings from Paper I

Urban canyon and the CIE overcast sky The paper reports on a study that combined the effect of exterior illuminance levels on façades with interior illuminance levels at the working plane. The illuminance levels on the façades were described using the Vertical Daylight Factor (VDF). The same VDF can be obtained with different street widths and opposite building heights if the reflectances of the opposite façade also differ; an example of such situations is given in Figure 3.8. Here, the same VDF can be obtained for 1) a façade reflectance of 0.9, street width $W_{r=0.9}$ of 10m and opposite building height $H_{r=0.9}$ of 25m, and 2) a façade reflectance of 0.2, street width $W_{r=0.2}$ of 20m and adjacent building height $H_{r=0.2}$ of 20m. Simulations were carried out for these two situations to test if the same VDF obtained with different opposite façade reflectances would result in the same illuminance profile inside the room.

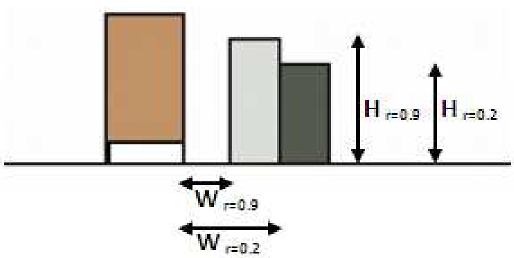


Figure 3.8: *Situations with same VDF: 1) street width of $W_{r=0.9}$ and height of opposite building $H_{r=0.9}$, and 2) street width of $W_{r=0.2}$ and height of opposite building $H_{r=0.2}$*

In the study it was found (**Paper I, Figure 5a**)) that the rooms having the same VDF obtained with different street widths (W), opposite building heights (H) and opposite façade reflectances did not result in the same illuminance profile inside the room[1]. The illuminance level in the working plane close to the window was higher with an opposite façade reflectance of 0.2, whereas the illuminance level would be higher further away from the window with an opposite façade reflectance of 0.9. This result is caused by the difference in geometry because a higher proportion of the light comes from the sky with a façade reflectance of 0.2 than with façade reflectance of 0.9. So with an opposite façade reflectance of 0.9, a higher proportion of the light comes from the building opposite due to rays bouncing off this building, so this daylight would penetrate deeper into the room. This shows that it is not possible to use VDF as a general indication of the profile of the illuminance level inside a room.

To investigate whether the illuminance profile obtained for a room on the ground floor can be applied for the entire height of the building, simulations were made for rooms on different floors to compare the illuminance profiles inside the room. This was done by simulating a room on the ground floor, the first floor, and the second floor. The building opposite also varied with heights of 5, 10 and 15m and the distance between the buildings was fixed to 10m, see Figure 3.9.

The results showed that the illuminance profile inside the room (**Paper I, Figure 6**) was different for rooms on the ground floor from rooms on higher floors. The illuminance level on the ground floor was shown to be slightly higher (2%) than on the second floor, due to light reflected from the ground. This result shows that if illuminance profiles in the room on the second floor were based on simulations made for the ground

[1] In writing up this summary an error was found in the legend to this figure in the published **Paper I**. The Figure 5a in the appended paper show results for a window-to-wall ratio of 50%, not 40% as stated in the paper. An erratum with this information has been sent to the Journal

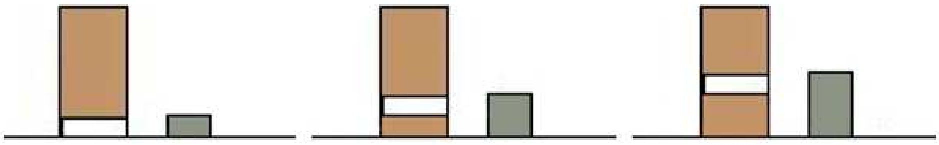


Figure 3.9: *Situation with same VDF for rooms located on different floors*

floor, the daylight performance of the upper floors would be slightly over-estimated. This finding should be kept in mind if the results obtained for the ground floor are to be applied on higher floor plans.

The previous two findings show that, in urban canyons with the same façade reflectances, it is possible to evaluate the daylight performance of the buildings based on the illuminance levels striking the façades. The importance of reflectance has therefore been added to the circle representing **Paper I** in Figure 1.1 (see Figure 3.10). This information will be used in the following, where the framework is outlined.

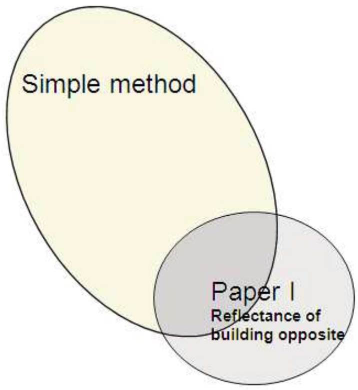
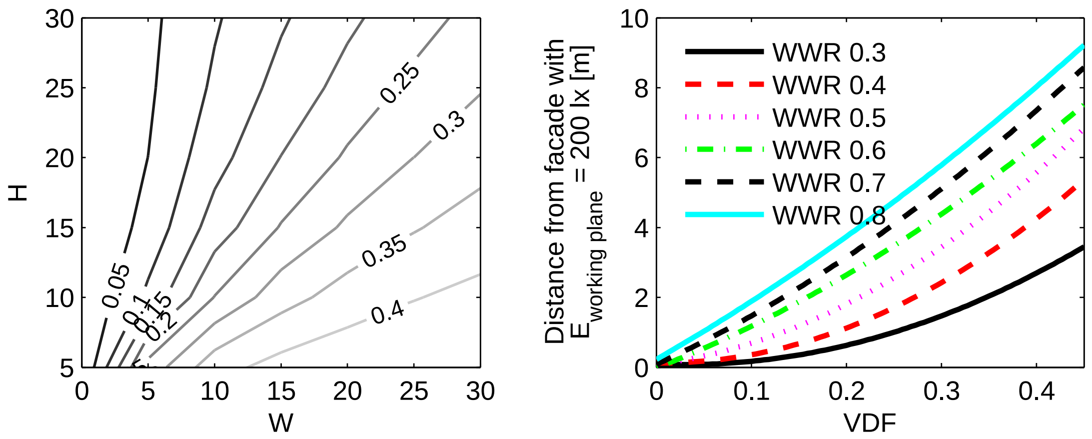


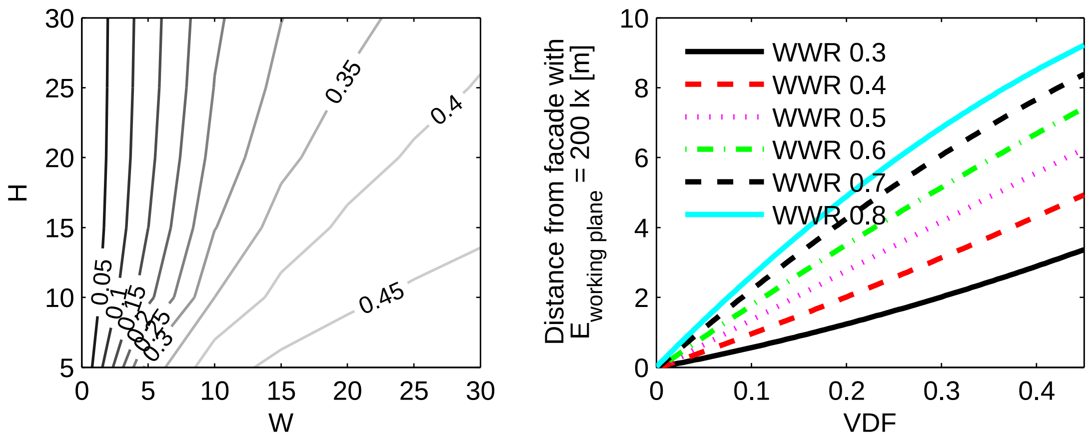
Figure 3.10: *Interplay between the simple method and* **Paper I**

Figures 3.11a and 3.12a show the VDF on the façades for different street widths (W) and building heights (H). Figures 3.11b and 3.12b show the correlation between the VDF and the distance from the façade inside the rooms, where a threshold illuminance level of 200lx was reached for different window-to-wall ratios (WWR).



(a) (b)

Figure 3.11: *Reflectance of the opposite façade is 0.2. (a) The ratio of the illuminance level on the façade to a 10klx CIE overcast sky (VDF) for different building heights (H) and distances to the building opposite (W). (b) Distance from the façade where 200lx is achieved in the work plane for different VDF levels and WWRs.*



(a) (b)

Figure 3.12: *Reflectance of opposite façade is 0.9. (a) The ratio of the illuminance level on the façade to a 10klx CIE overcast sky (VDF) for different building heights (H) and distances to the building opposite (W). (b) Distance from the façade where 200lx is achieved in the work plane for different VDF levels and WWRs.*

These figures combined with a categorization of the façades on the basis of their daylight performance constitute the framework for evaluating façades in the urban canyon. The method will be described in the following steps 1-4:

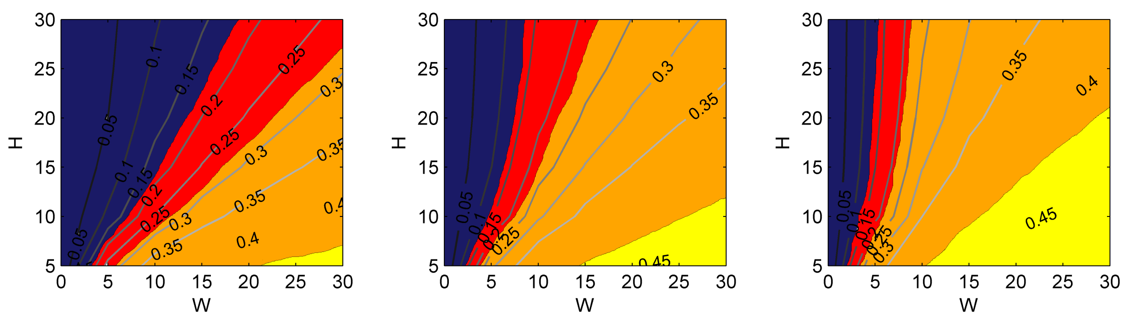
Step 1 - choosing the distance from façade where the illuminance threshold should be reached To make Figures 3.11 - Figure 3.12 operational, it was decided to look at the WWRs and VDFs for a distance of 3m from the façade. This distance is based on experience from daylight simulations and rule-of-thumb daylight penetration depths. From daylight factor figures in Johnsen & Christoffersen (2008), it was found that a daylight factor of 2% could be achieved 3m to 4m from the façade.

Step 2 - categorizing the façades Façades can be categorized on the basis of their daylight performance. A categorization has been given in Table 3.2 based on the WWR needed in the façade to attain a DF of 2% 3m from the façade.

Table 3.2: *Categorizing the façades in the cities according to their daylight performance*

Category	Evaluation of façade	Colour code
1.	Really good facade Criteria can be met for WWR of 0.3	
2.	Good façade Criteria can be met for WWR; 0.3 < WWR < 0.5	
3.	It is possible to achieve a good daylight performance, but special attention to façade reflectance and WWR is needed. Criteria can be met for WWR; 0.5 < WWR < 0.7	
4.	Poor façade It is not possible to fulfil the requirements	

Step 3 - combining categorization with height of opposite building and street widths The different window areas from 3.2 were then applied to Figures 3.11b and 3.12b, and the corresponding VDFs were found and post-processed into 3.11a and 3.12a, see Figure 3.13.



(a) (b) (c)

Figure 3.13: *Categorization of the façades, with opposing façade reflectance of (a) 0.2, (b) 0.5 and (c) 0.9*

Step 4 - examining the proposed urban plan The use of Figure 3.13 in an examination of the different street widths and building heights in a proposed urban plan makes it possible to indicate positive urban areas and areas where the plan needs optimizing for daylight. The street widths and building heights could be changed, the glazing area could be adjusted, and the reflectance required for façades in narrow streets could be specified in the early stages of design to fulfil daylight requirements. It would also be possible to identify areas where building functions that do not require daylight should be located. An example of how the results can be visualized is shown in Figure 3.14.

This simple method has been applied in a number of Danish urban planning architectural competitions, in which the author has participated as a consultant from Esbensen Consultants, e.g. Køge Kyst (http://www.koegekyst.dk), Fredericia C (http://www.fredericiac.dk), and most recently Thomas B Thriges Gade in Odense C (http://www.fragadetilby.dk). When the architects were given presentations that showed that parts of their proposed urban plan had poor daylight performance, they were generally interested in optimizing their proposal by trying different street widths and building heights.

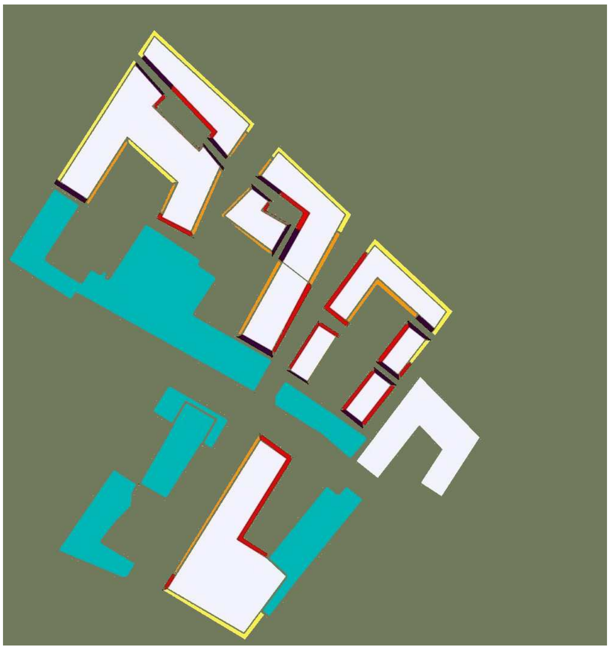


Figure 3.14: *An application example of visualizing the results for the planning of a new urban area. Note: The colour mapping shown here corresponds to the daylight performance for the ground floor.*

Recently, the BRE Trust has published the 2^{nd} edition of a guide to good practice in site layout planning for daylight and sunlight (Littlefair, 2011), which also gives a categorization of façades based on their daylight performance. Table 3.3 shows a comparison between obstruction angles for the categories in Littlefair (2011) and those in Table 3.2 for the façade reflectance of 0.2. The obstruction angles for the study in **Paper I** were for a street width of 15 m.

Table 3.3: *Categorizing urban façades according to their daylight performance. Comparison between the obstruction angles given in the BRE Trust guidelines (Littlefair, 2011) and those deduced from* **Paper I**

Category	Evaluation of façade according to Littlefair (2011)	Obstruction angle Littlefair (2011)	**Paper I**
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	$> 65^o$	$> 55^o$

Table 3.3 shows that the criteria proposed in this thesis are slightly conservative compared to the values given in the BRE guidelines. 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 inside a room (Johnsen & Christoffersen, 2008; Valbjørn *et al.*, 2000). These obstruction angles were also found to be the

limiting angles in the research for **Paper I** and in the BRE guideline by Littlefair (2011).

3.1.2 Paper II

The aim of the research described in **Paper II** was to evaluate the urban canyon under dynamic sky conditions. More specifically, the aim was to investigate the influence of orientation, external surface reflectance, and window area on daylight availability inside the simulated rooms.

So, the research for this paper went a step further than the research for **Paper I** , which focused on overcast sky simulations, by introducing annual simulations in the urban canyon. The areas of interest are the same as in **Paper I**, however, and the flow-chart (Figure 3.15) is therefore similar.

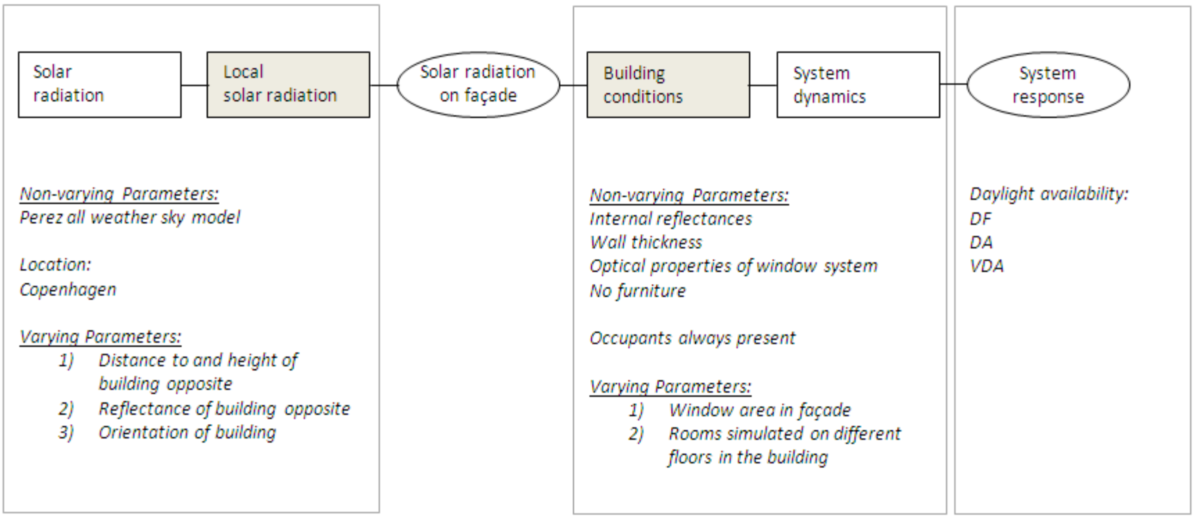


Figure 3.15: *Diagram of the parameters that affect the simulations in* **Paper II**

The following paragraphs describe each of the blocks shown above in more detail.

Solar radiation The luminance distribution of the sky was simulated as the Perez all-weather sky with hourly input data from the weather data set of the Danish Design Reference Year (DRY).

Local solar radiation Simulations were carried out with a building opposite of constant height (H) of 15m with varying street widths (W) of 7.5m, 15m and 30m, corresponding to Height/Width ratios of 2, 1 and 0.5 in the urban canyon. A diagram showing the various simulation set-ups is given in Figure 3.16.

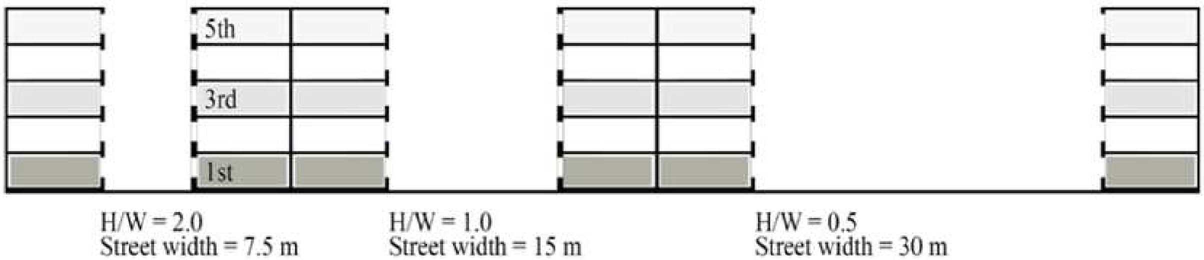


Figure 3.16: *Urban street canyon, simulation set-up*

The reflectance of the building opposite was simulated as an average diffuse reflectance of 0.25, 0.45 and 0.75. Moreover, illuminance readings were taken externally on the façades, at sensor points facing the same way as the façade for each simulation. Daylight availability was evaluated for both northern and southern orientations for each of the room typologies.

Building conditions For all the simulations, the building height was fixed at 15 m, corresponding to a building with 5 floors. Each room had inner dimensions of: height = 2.8 m, width = 6.0 m, depth = 8.0

m; see the sketch on the previous Figure 3.16. The light transmission of the window was 0.72. Rooms were simulated on the 1^{st}, 3^{rd} and 5^{th}, floors in the building. A simulation matrix was set up (see Figure 3.17) containing various window-to-wall ratios (WWRs) and façades with various average reflectances.

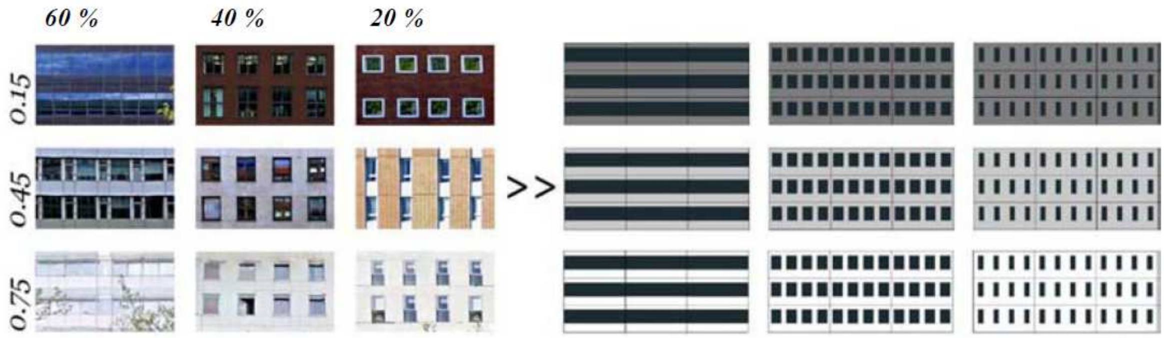


Figure 3.17: *Simulation matrix of various WWRs (20%, 40% and 60%) and average façade reflectances (0.15, 0.45 and 0.75)*

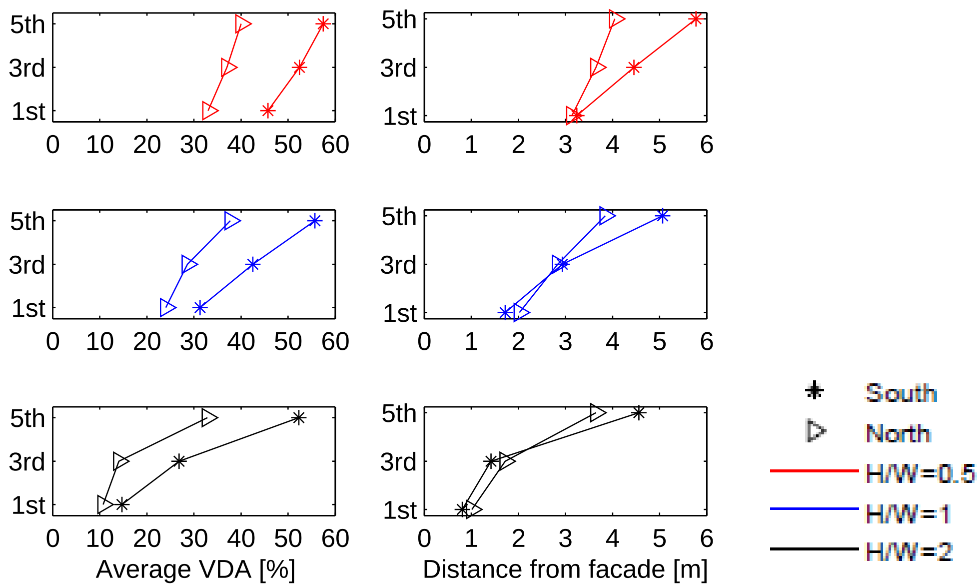
Illuminance readings were taken at upward-facing sensor points on a line through the room at work-plane height drawn from a window as close to the middle of each room as possible to avoid boundary effects.

System dynamics No system dynamics, such as lighting control or varying occupancy load, were considered because the focus of this research was to look at the effect of surrounding environment and varying window area in the façade on daylight availability inside the room.

System response The daylight availability inside the room was evaluated based on the Daylight Factor (DF) and Daylight autonomy (DA). And the amount of daylight striking the external façade was evaluated based on Vertical Daylight Autonomy (VDA).

General findings from Paper II

Urban canyon and the 'real' sky This study reports on findings where climate-based daylight simulations were applied to the urban structure. **Paper II, Figure 9** (reprinted in Figure 3.18) shows results for northern and southern orientations of the buildings with a window-to-wall ratio of 40% and façade reflectance of the opposite façade of 0.45. Figure 3.18a shows the amount of time during office hours when the illuminance threshold on the façade is above 10klux (VDA) for floors 1, 3, and 5. The VDA is taken as an average value for each floor. Figure 3.18b shows the distance from the façade inside the rooms where the illuminance levels are above 200lx during 50% of the office hours. The top figure, with red lines, corresponds to an urban canyon layout of H/W-ratio 0.5. The middle figure, with blue lines, corresponds to an urban canyon layout of H/W-ratio 1, and the lower figure, with black lines, corresponds to an urban canyon layout of H/W-ratio of 2.



(a) (b)

Figure 3.18: *WWR 40% and façade reflectance of 0.45: (a) Illuminance level on the façade, average vertical daylight autonomy (VDA) for different H/W ratios, (b) Distance from façade inside the room with DA of 50% for the different H/W ratios*

The results show, as expected, that the denser an urban area is, the smaller the difference between the illuminance level falling on the northern and southern façades for each floor level, see Figure 3.18a. This is because the denser an urban area is, the more limited the amount of direct sunlight, so it is the diffuse and inter-reflected light between the buildings that plays the most important role.

Inside the rooms (see Figure 3.18b), it can be seen that the distance from the façade to where the DA is below 50% is approximately the same for the northern and southern orientations on the lower floors. The results indicate that northern orientations are slightly better in terms of daylight availability on the lower floors. Comparing the northern façade to the southern façade for H/W ratios of 1 and 2, it can be seen that light penetrates further into the northern-oriented rooms on the 1^{st} floor and on the 1^{st} and 3^{rd} floors 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. But south-facing façades still receive more light, which is then reflected into north-facing rooms, and this increases the range at which a DA threshold of 50% is reached. With control of artificial lighting, this might have an impact on energy consumption, as seen in Strømann-Andersen & Sattrup (2011) where they found that the lowers floors in south-facing façades in dense urban context have slightly higher energy consumption for artificial lighting than those in north-facing façades.

The same finding was observed in Cantin & Dubois (2011), but they also found that reflectance from daylit south façade could create glare problems. This effect was not investigated in this paper. The results also show clearly that increasing the H/W ratio of 0.5 (street width 30 m) to 1 (street width 15 m) to 2 (street width 7.5 m) results in reduced distances from the façade with 50% DA in the ratios of 3:2:1 for the lower floor plans.

The results shown in this section describe a situation where the reflectance of the opposite façade is 0.45. **Paper II** also describes simulations with façade reflectances of 0.15 and 0.75. The results show (**Paper II, Figure 8**) that for the 1^{st} floor with windows facing north the effect of the reflectance is remarkably strong. Here, 50% DA was found at distances between 1.3m and 2.8m from the façade when the reflectance was increased from 0.15 to 0.75. In comparison the numbers for the southern façade were distances between 1.7m to 2.2m for opposite façade reflectance of 0.15 and 0.75. In urban contexts, the effect of reflection from other buildings therefore favours the lower floors in northern orientations. These results would not have been found using standard daylight factor calculations, where the effects of direct sunlight and orientation are not considered. Furthermore, these results emphasize that the design of façades in new urban areas or any new building should take into account not only the creation of an optimal solution with regard to both energy consumption and indoor environment for the building in question, but also its contribution to creating good and varied daylight conditions for neighbouring buildings.

Applying the Vertical Daylight Factor (VDF) in **Paper I** and introducing the Vertical Daylight Autonomy (VDA) in this study were both attempts to apply metrics from which information of the daylight availability inside buildings can be deduced only by exploring the external volumes of the buildings. In the investigations for **Paper I**, this led to categorization of the window area needed in the façades to achieve good daylight conditions inside the buildings. In the investigations for this paper, this aspect was not fully exploited, and future research on this topic is needed. In both papers, the metrics for the vertical façades were found not applicable when it comes to evaluating the direction of the light entering rooms in the building. This can be seen in **Paper I, Figure 5a**, where the same VDF does not lead to the same daylight penetration depth if the reflectances of the buildings opposite are different. This meant that VDFs had to be calculated for the different reflectances of the urban canyon. And in the dynamic case, this can be seen in Figure 3.18, where different VDAs can result in the same daylight penetration depth (top, 3.18), or from the middle and bottom graphs of Figure 3.18, where a higher VDA for the southern orientation does not result in a higher daylight penetration depth, compared to the northern orientation. These results are due to the direction of the reflected light from the building opposite.

Overview II To further expand the simple method from section 3.1.1 and **Paper I** to include annual evaluations of the daylight conditions in which direct sunlight is considered, it is therefore necessary to include different floors, building orientation and façade reflectances. The input needed for the 4-step method for the two approaches; CIE overcast, and annual simulations, has been added to Figure 1.1 and visualized in Figure 3.19.

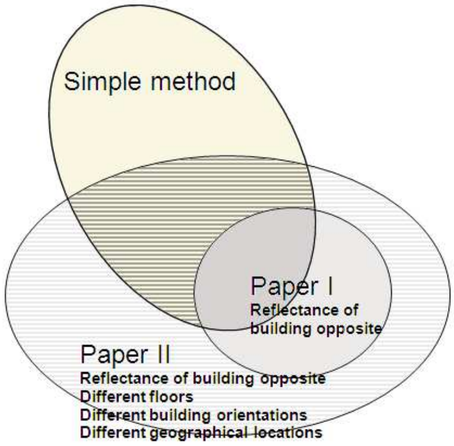


Figure 3.19: *Interplay between the simple method and* **Paper I** *and* **Paper II**

3.1.3 Paper III

One input parameter to the climate-based daylight simulations are the weather data. The aim of the research described in **Paper III** was to explore the effect of different weather data sets for a given location on simulated lighting demand. An additional aim was to investigate the influence of the resolution of weather data sets on the lighting demand.
Figure 3.20 shows the overall set-up of the system simulated for **Paper III**. Remembering the overall system shown in Figure 3.2, the research was influenced by variations in the parameters in the blocks for 'Solar radiation' and 'System dynamics' as highlighted in Figure 3.20.

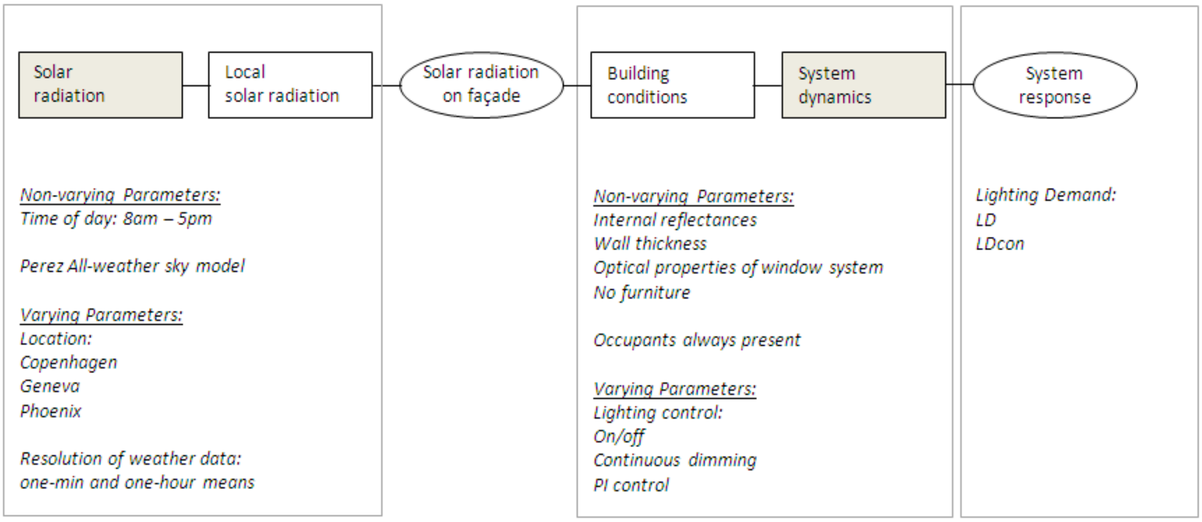


Figure 3.20: *Flow chart of the parameters that affect the simulations in* **Paper III**, *with special focus on 'Solar radiation' and the 'System dynamics'*

The following paragraphs describe each of the blocks in the above flowchart to ease the reading of the following sections of the thesis.

Solar radiation The sky simulated was the Perez All-weather sky, applying:

1. Different weather data sets for the location of Copenhagen. These were the weather data sets from the Danish Reference Year (DRY), Meteonorm (MET), and the IWEC weather data set for Copenhagen downloaded from the homepage of Energy Plus (cf. section 2.3.2).

2. Different resolutions of the weather data sets were investigated: one-hour and one-min resolution. In the research made for **Paper III** (and **Paper IV**), the weather data of one-hour mean resolution was converted to annual one-minute or two-minute irradiance values using the stochastic modified Skartveit-Olseth model implemented in Daysim (Walkenhorst *et al.*, 2002; Reinhart, 2010). For this conversion, the only required input was the data for site coordinates, elevation and hourly irradiance. Walkenhorst *et al.* (2002) investigated the non-deterministic effect of the stochastic model on the simulation outcome and they found that the impact was negligible. The relative standard deviation in the specific annual electrical energy demand for artificial lighting in ten different realizations of the model never exceeded 0.7%. So, one single realization of the model should yield sufficient simulation accuracy (Walkenhorst *et al.*, 2002).

3. Different climatic locations. To investigate the impact of resolution, the locations of Copenhagen, Geneva, and Phoenix were applied to the simulations. Phoenix was chosen because in contrast to the locations of Copenhagen and Geneva it represents a sunny climate. The location of Geneva was chosen due to the presence of this location in the study of (Walkenhorst *et al.*, 2002), but it did not prove possible to access the measured data used in their study, so the weather data file used for the simulations was the IWEC weather data file available from the Energy Plus homepage.

Local solar radiation No shading effects from the surroundings were included in these investigations, because it was the effects of weather data sets and their resolution that were in focus for this research.

Building conditions were fixed for the same reason as mentioned under **Local solar radiation**. The room simulated corresponds to the one described in section 2.3.2.

System dynamics include control of the lighting system. The occupants were assumed to be present all the time, and were therefore not considered as being a lighting control factor. The lighting was controlled as follows:

1. On/off control. If the illuminance threshold could be maintained by daylight alone, the artificial lighting was switched off. Otherwise, it was switched on at full power.

2. Continuous dimming (con). The electric lighting output was topped up to maintain a given threshold illuminance level

and

3. Continuous dimming based on the signal for every 10^{th} minute

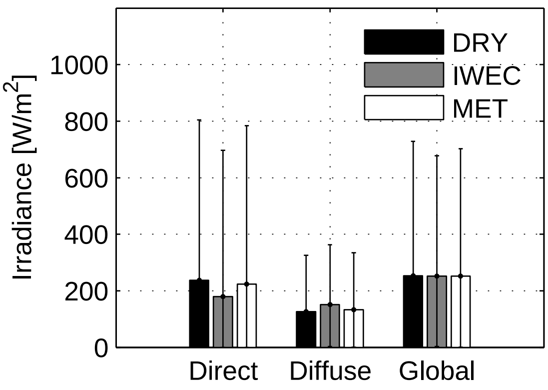
4. Continuous dimming based on the average signal for the past 10 minutes (PI-control)

The reference case against which the various scenarios were compared was one in which the lights would be on for the entire period investigated. This could be the case in the core zone of a building where no daylight is present.

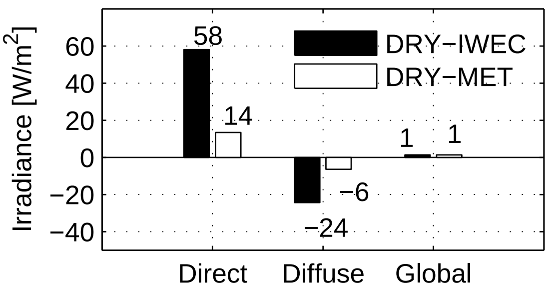
System response The lighting demand was evaluated based on lighting dependency (LD) and continuous Lighting dependency (LDcon).

General findings from Paper III

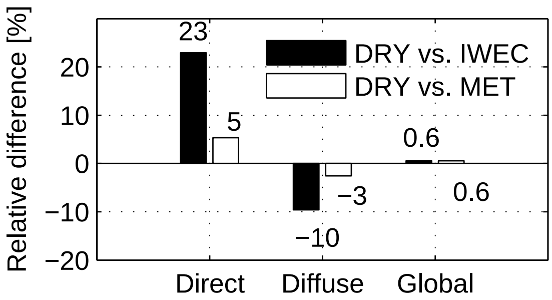
Different data-sets for the same location The following section shows a comparison between the Design Reference Year (DRY) data, the IWEC weather data file supplied from the homepage of Energy Plus (IWEC), and the weather data file provided from Meteonorm (MET) for the location of Copenhagen. The data are derived from the weather data files for the period from 8 am to 5 pm, with daylight saving time from the last Sunday in March to the last Sunday in October (March 28 to Oct 30).



(a)



(b)



(c)

Figure 3.21: *(a) Annual mean and 95% and 5% percentiles for direct normal, diffuse horizontal and global horizontal irradiance between 8 am and 5 pm, daylight saving time from the last Sunday in March to the last Sunday in October (b) Differences in direct normal, diffuse horizontal and global horizontal annual mean irradiance between DRY and IWEC and MET respectively (c) relative difference between annual mean irradiance between DRY and IWEC and DRY and MET in relation to DRY*

Figure 3.21 shows significant differences of up to 58 W/m^2 over the whole year and relative differences of up to 23% between the mean for direct normal irradiance in the DRY data compared to the IWEC file of

Energy Plus. There is more direct irradiation and less diffuse irradiation included in the DRY data than in the IWEC and the MET weather data files. There is very little difference in global irradiance. Here the relative difference between the different weather data files is 0.6%. So the question is: How do these differences affect the annual lighting demand when the different weather data sets are applied in the light simulations? This was explored in **Paper III; Figure 4**, (reprinted in Figure 3.22).

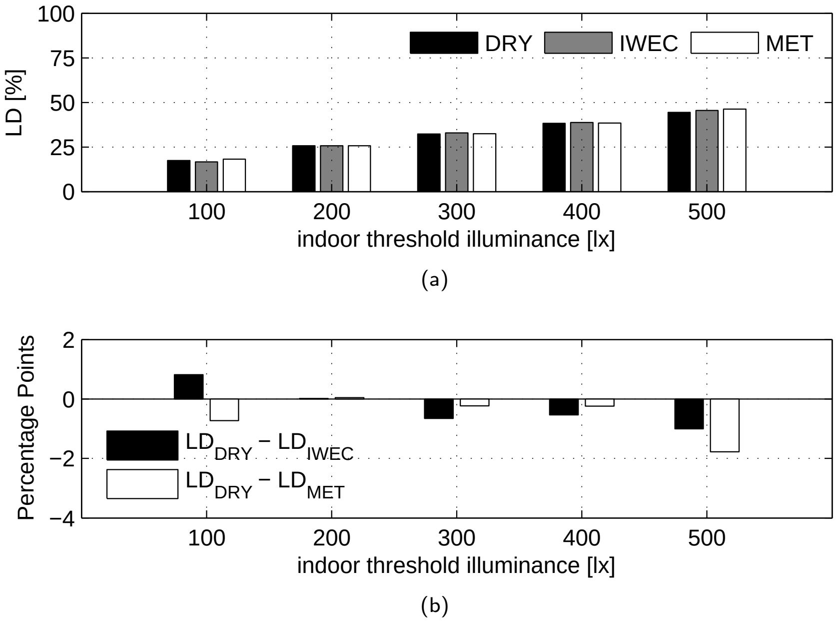


Figure 3.22: *Comparison between simulations for different weather data files for Copenhagen. (a) Predicted lighting dependencies for the sensor point at the back of the room for the daylight simulations with data from the Design Reference Year, IWEC, and Meteonorm weather data sets. Indoor threshold illuminance levels from 100 lx to 500 lx. (b) Difference in percentage points (LD_{DRY}-LD_x) for the daylight simulations*

It was found that the differences between the weather data sets had no significant effect on the annual lighting demand at the back of the room. Differences in lighting dependencies varied from -2 percentage points to approximately 1 percentage point. The reason for this very small difference can be found in the conversion from irradiance to illuminance. In Figure 3.23a, the mean external illuminance levels from 8 am to 5 pm are given for each of the different weather data sets. The illuminance levels are calculated at an unobstructed external sensor point facing upwards. The figures show that the relative difference between the different weather data sets was 1.4% and 0.3%.

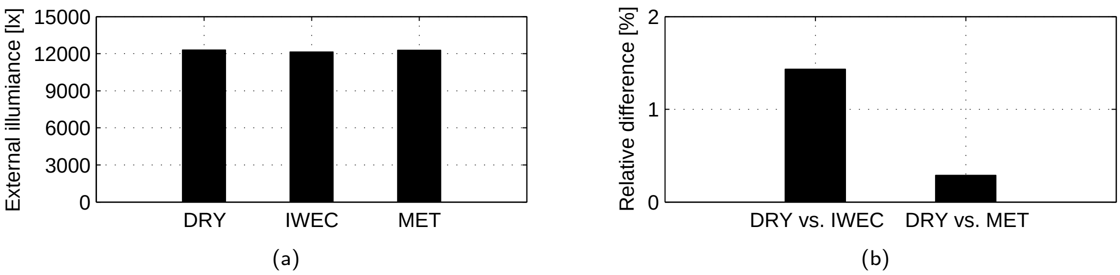
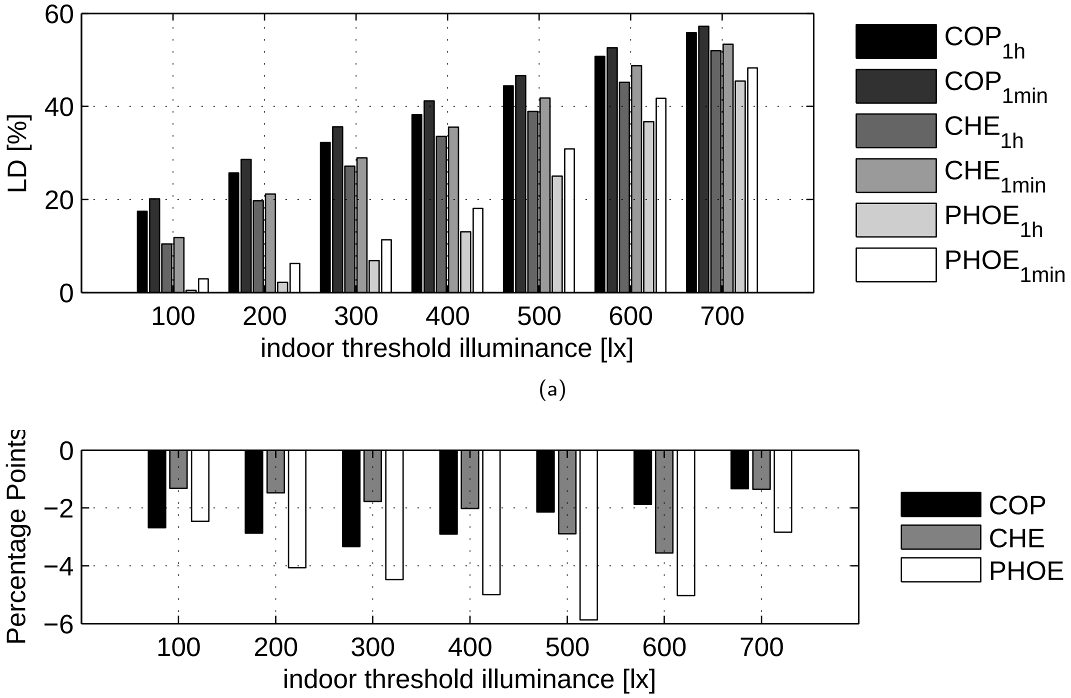


Figure 3.23: *(a) Mean values of external illuminance levels for weather data sets: DRY, IWEC and MET (b) Relative difference between simulated external mean illuminance values in DRY and IWEC, and DRY and MET weather sets*

So the differences in diffuse and direct irradiance in the weather data sets have little impact on the annual evaluation of the lighting demand, and the three weather data sets give similar results.

One-hour resolution vs. 1-minute resolution The influence of resolution of the weather data sets on the lighting dependencies for the locations of Copenhagen (COP), Geneve (CHE) and Phoenix (PHOE) showed that the lighting demand is being underestimated when applying weather data of hourly-mean resolution opposed to applying weather data of 1-min resolution, see **Paper III; Figure 5** and **Figure 6** (reprinted in Figures 3.24 and 3.25).



(a)

(b)

Figure 3.24: *Comparison between simulations using one-hour and one-minute resolution data for different climatic locations with on/off control: (a) Lighting dependencies for one-hour and one-minute resolution data for the DRY file for Copenhagen (COP), the IWEC file for Geneva (CHE), and the TMY3 file for Phoenix (PHOE); (b) Difference in percentage points in lighting dependencies for one-hour and one-minute resolution data for Copenhagen, Geneva and Phoenix, (1h-1min)*

The differences here are because simulations based on one-hour data for most working hours in the year would underestimate the lighting dependency due to spikes with high illuminances increasing the hourly mean value. With such an increased hourly mean value, the entire hour could have a sufficient level of daylight, whereas with one-minute resolution the value could be below the threshold illuminance value for some of the minutes causing lights to be switched on. However, this effect is not very visible when the reference is a lighting system that is always on. The maximum discrepancy is 6%, as shown for the location of Phoenix at an illuminance threshold of 500 lx with on/off control.

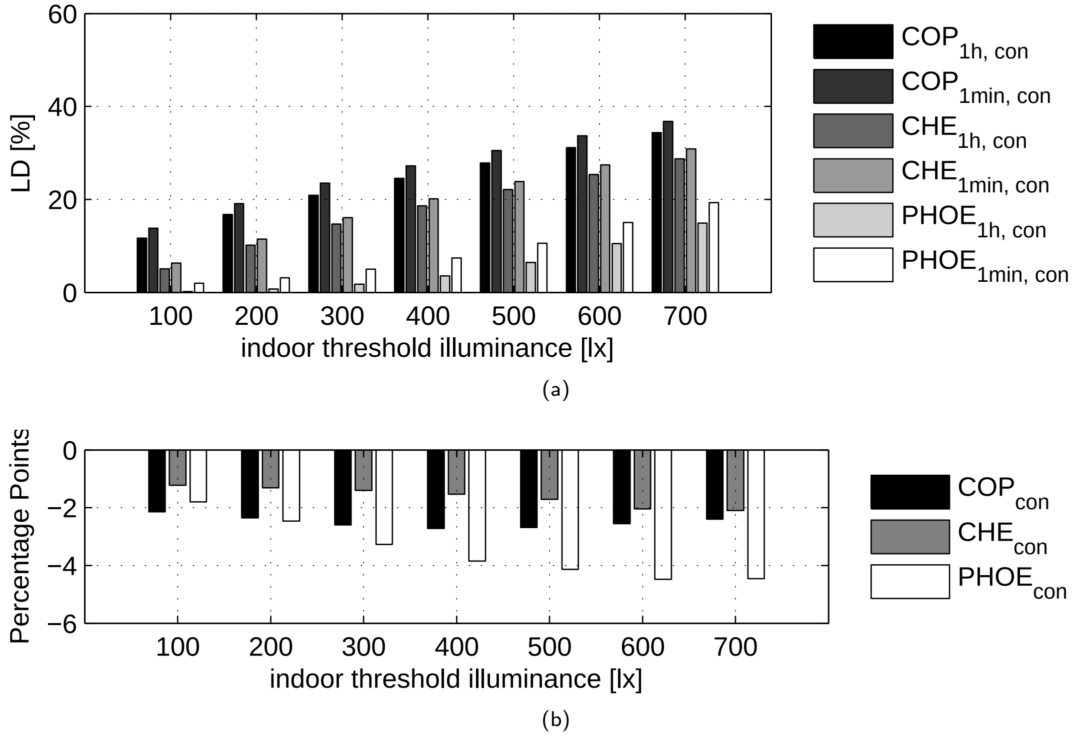


Figure 3.25: *Comparison between simulations using one-hour and one-minute resolution data for different climatic locations with continuous dimming control: (a) Lighting dependencies for one-hour and one-minute resolution data for the DRY file for Copenhagen (COP), the IWEC file for Geneva (CHE), and the TMY3 file for Phoenix (PHOE); (b) Difference in percentage points in lighting dependencies for one-hour and one-minute resolution data for Copenhagen, Geneva and Phoenix, (1h-1min)*

Figure 3.24 and Figure 3.25 show the lighting demand for simple on/off control and for continuous control. In **Paper III; Figure 7** two more control strategies were added to the comparison:

i. continuous control every 10 min, and

ii. proportional integral dimming with the response averaged over the past 10 minutes

The results showed that changing from on/off control to continuous control where the light levels were topped up resulted in reductions in lighting demand of between 5 and 20%, depending on the indoor threshold illuminance level. A negligible difference in simulated lighting dependencies was seen when simulating with continuous dimming for each time step (con), every 10^{th} minute or when using PI control with the response averaged over the past 10 min. The reason is, that when the control scheme is applied every 10^{th} minute, the lighting level will either be over- or underestimated, and over an entire year the differences will balance out.

Employment of solar shading In the research conducted for **Paper III**, no solar shading was employed. The rationale behind this was that, when solar shadings are used, the daylight availability is reduced proportionally. This means that the outcome of the effect of applying different weather data sets or weather data sets with different resolution would be the same; i.e. that there is no significant difference when simulating with different weather data sets with different resolutions. However, to fully support this conclusion, simulations were made with Daysim using the simple blind model, as described in section 2.3.4.

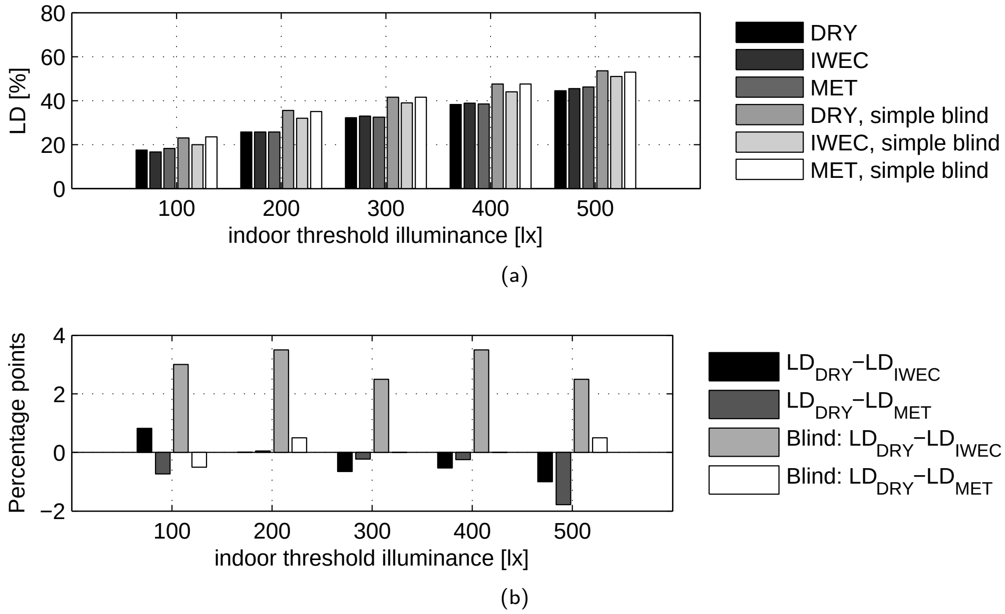


Figure 3.26: *(a) Lighting Dependencies for the different weather data sets, with and without blinds (b) Differences between weather data sets for the simulations with and without blinds*

Figure 3.26 show that there is little difference between the lighting demand obtained for the different weather data sets with and without blinds. Solar shading results in increased lighting demand, which is as expected. But, no real difference in lighting dependency is simulated with blinds for the 100lx indoor illuminance threshold. This result reflects the fact that the blind system, which excludes direct sunlight but transmits 25% of all diffuse light, lets enough daylight enter the room, so the threshold can be maintained from daylight when the sun is up. Furthermore, the results show that when blinds are included, the lighting demand is smallest for the IWEC-weather data file. This is a consequence of the way the blind system is simulated. Figure 3.21 shows that there was more diffuse irradiance included in the IWEC file than in the two other weather data files. Since the simple blind system excludes direct sunlight and transmits 25% of all diffuse light, the result is that more light enters the room when the IWEC file is used than when using the other weather data files.

Overview III The results from this section show that the weather data file used for a given location and the resolution of the weather data used have little impact on the annual evaluation of lighting demand. This means it would be sufficient for the climate-based simulations applied to the urban structure in **Paper II** to simulate with one-hour resolution weather data. This information has therefore been added to the input-arrow from **Paper III** in Figure 1.1, see Figure 3.27.

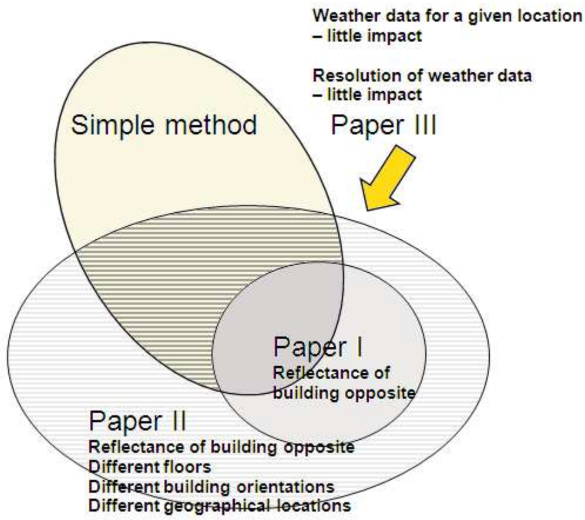


Figure 3.27: *Interplay between the simple method and* **Paper I**, **Paper II** *and* **Paper III**

3.1.4 Paper IV

The aim of the research described in **Paper IV** was to explore the effect of applying various occupancy profiles to climate-based daylight modelling.

So the research for this paper took an extra step into the building, looking at the presence of occupants. The simulations were made with different resolutions of the occupancy profile data, so the resolution of weather data varied, and the areas of focus in this research, highlighted with grey in the flow-chart in Figure 3.28 were on the blocks 'Solar radiation' and 'System dynamics'.

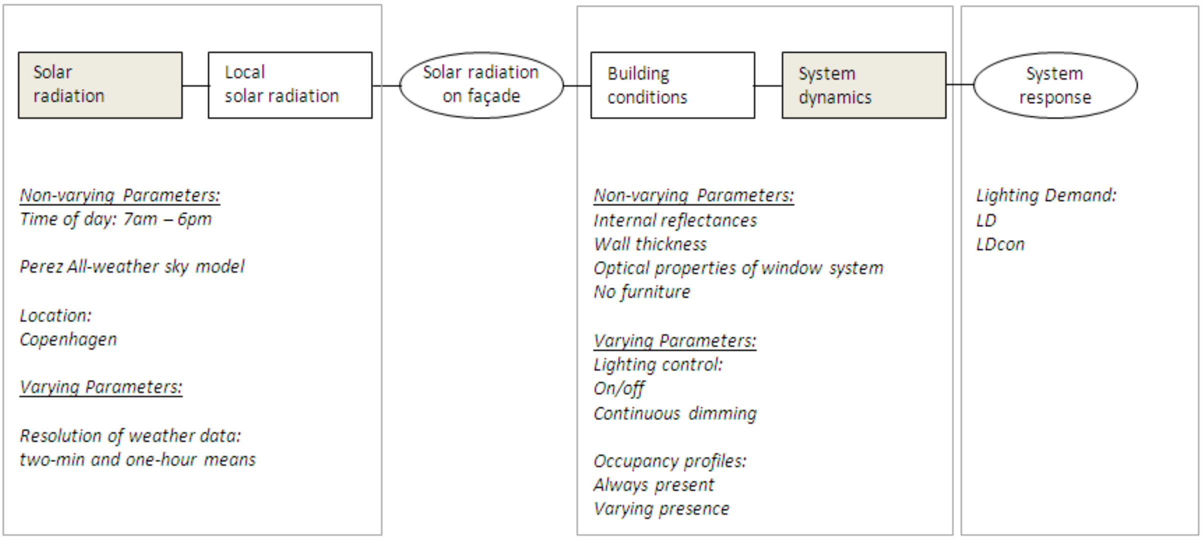


Figure 3.28: *Diagram of the parameters influencing the simulations in* **Paper IV**

The following paragraphs describe each block in the above flowchart.

Solar radiation The sky simulated was the Perez All-weather sky, applying weather data for the location of Copenhagen taken from the Design Reference Year. The weather data had one-hour resolution and 2-min resolution for the direct normal and diffuse horizontal irradiance data. The 2-min irradiance data were generated from the hourly mean values from the Design Reference Year in accordance with the modified Skartveit-Olseth method developed by Walkenhorst *et al.* (2002).

Local solar radiation No shading effect from the surroundings was included in these investigations, because the focus in this research was on the effect of the resolution of occupancy profile and weather data.

Building conditions were fixed for the same reason as mentioned under **Local solar radiation**. The room simulated corresponds to the one described in section 2.3.2, except that the indoor illuminance readings were simulated at distances of 1.5m and 4.5m from the façade, instead of 1m and 5m from the façade as in the research described in **Paper III**.

System dynamics include control of the lighting system based on the varying presence of occupants. Six different occupancy scenarios were investigated, varying from very static (occupant always present) to dynamic profiles (presence of 2 min, with absence of minimum 20 min). These are summarized in Table 3.4.

The occupancy model applied was developed by Delff *et al.* (2014) (Additional Paper 1). The model is capable of modelling the dynamic sequences of presence for a typical occupant and is based on the measured presence of occupants from an office building in San Francisco. Their paper gives a thorough description of the statistical model.

The model of the presence of one occupant is a hierarchical model. First, one of two models was selected with a given probability distribution. This resulted in either a low occupancy rate model or a high occupancy rate model. The need for two models was due to the many days when the occupancy rate was low, and Delff

Table 3.4: *The investigated occupancy scenarios(S) in* **Paper IV**

S1:	constant for weekdays and weekends - occupants are always present
S2:	based on the absence factor given in (EN15193, 2007)
S3:	based on the absence factor estimated from the occupancy model
S4:	an estimated annual mean presence, where the occupancy pattern follows the same profile each day throughout the year
S5:	an estimated 1-hour mean presence, where the occupancy pattern varied for each occupied hour throughout the year
S6:	a dynamic 2-min occupancy resolution, where the occupancy varied for each 2-min period throughout the year.

et al. found that days with a low occupancy rate and days with a high occupancy rate could not be described by the same model.

The lighting was controlled as follows:

1. On/off control. If the illuminance threshold could be maintained by daylight alone, the artificial lighting was switched off. Otherwise it was switched on at full power.

2. Continuous dimming (con). The lighting output was topped up to maintain a given threshold illuminance level

The reference case against which the different scenarios were compared was one in which the lights would be on for the entire period investigated. This could be the case in the core zone of a building where no daylight is present.

System response The output from the simulated system was lighting demand, and this was given in terms of lighting dependency (LD) or continuous lighting dependency (LDcon).

General findings from Paper IV

Absence factor vs. dynamic occupancy profile evaluated on an annual basis Figure 3.29 shows the presence of one occupant for a random day for the 6 occupancy scenarios investigated. The presence varies from 0 to 1, with one being always present.

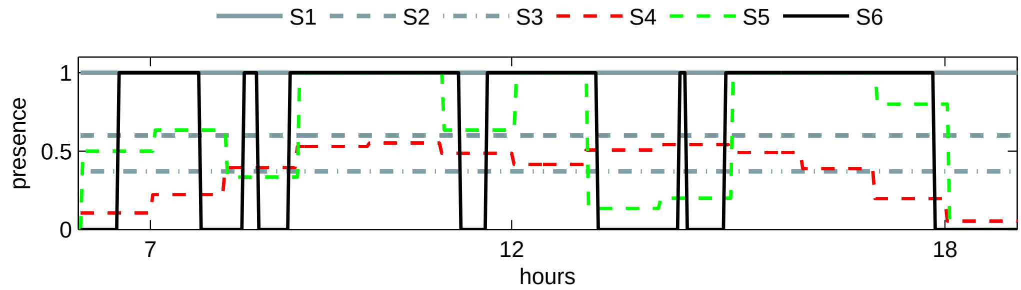


Figure 3.29: *Occupation shown for all 6 scenarios for a random day*

The occupancy profile follows the same pattern for each day for scenarios S1, S2, S3 and S4. For scenarios S5 and S6, the occupancy pattern varies for each day. To illustrate this variation, the annual profiles for these two scenarios are shown in **Paper IV, Figure 3** and **Figure 4**, reprinted in Figures 3.30 and 3.31.

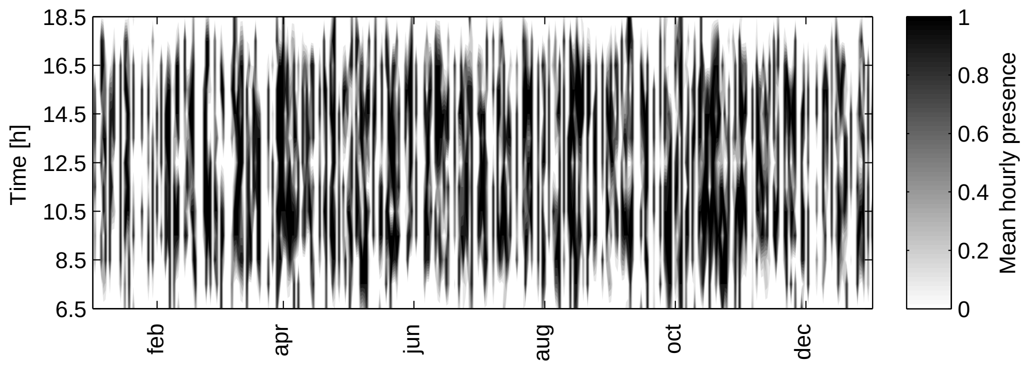


Figure 3.30: *Annual hourly mean presence (S5) for one occupant. Presence probability is shown by grey scale*

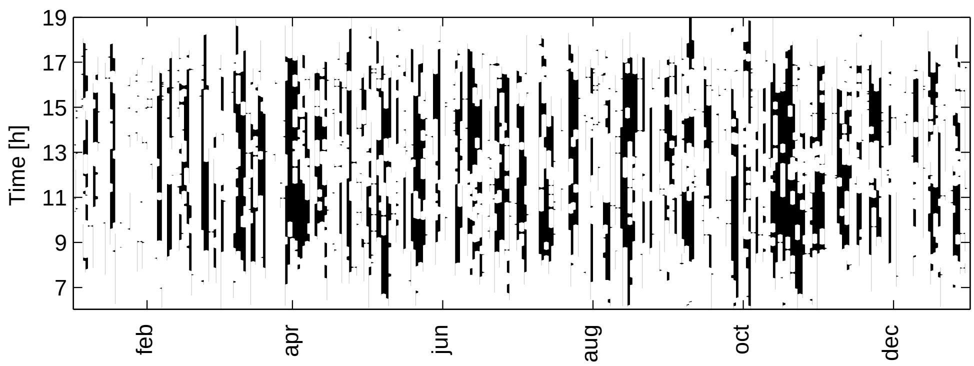
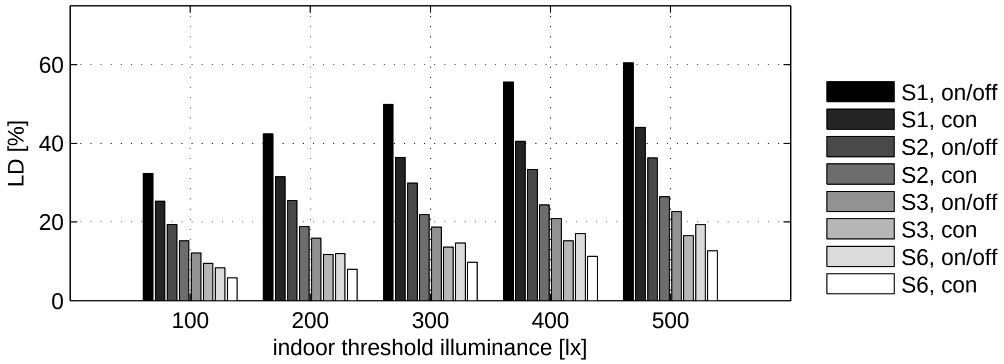


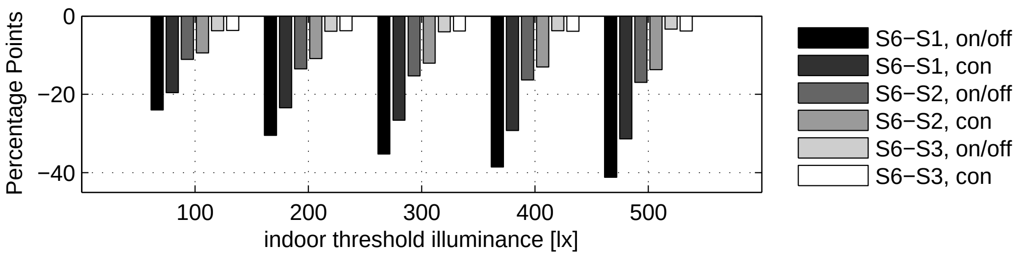
Figure 3.31: *Annual 2-min presence of one occupant (S6). Presence is shown in black*

In the research made for this thesis, these dynamics for the presence of occupants were combined with illuminance levels in the room to make it possible to evaluate the effect of the simulated occupancy profiles on the annual artificial lighting demand.

Paper IV, Figure 5 (reprinted in Figure 3.32) shows that introducing the presence of occupants in the daylight simulations, reduces the annual energy demand for lighting. The reduction in lighting demand from Scenario 1, with the occupant always present, to Scenario 6, with the lights controlled on the basis of 2-min periods of occupancy, was in the range of 24-41% depending on the indoor threshold illuminance. When the total absence factor of 0.63 (S3) was used, the energy consumption for artificial lights was overestimated by 4% compared to the dynamic occupancy profile (S6).



(a)



(b)

Figure 3.32: *(a) Lighting dependencies for on/off and continuous control of a lighting system: S1) with only daylight control, occupants always present; S2) with an absence factor of 0.40 as in EN15193 (2007); S3) absence factor of 0.63; and S6) with a dynamic 2-min occupancy profile. (b) Differences in percentage points in relation to S6.*

This result reflects the fact that when an evaluation is made on an annual basis, the occupancy model and the daylight availability will tend to converge to the same value irrespective of the data resolution. The finer dynamics, which can be seen in some of the models when simulations use a shorter time step, will be eaten up by the large number of simulation time steps, and converge to the same prediction as when more simplified methods are used. This can be exemplified by looking at **Paper IV, Figure 7** (reprinted in Figure 3.33), where large variations can be seen between different days, and Figure 3.32, where the differences vanish when the evaluation is on an annual basis. The effect of the remaining dynamic occupancy scenarios (S4-S6) showed that the artificial lighting demand differed by about 1% from that for a lighting system which was always on.

Absence factor vs. dynamic occupancy profile evaluated for a 5-day period Figure 3.33 explores the lighting demand for artificial lighting with continuous dimming for a 5-day period from January 12^{th} to January 16^{th} inclusive. The presence of occupants was simulated in terms of either an average absence factor (S3) or a dynamic 2-min occupancy model (S6).

In Figure 3.33a the presence of the occupant is indicated by the broken line. On day 3, the occupant was present the entire working day; on day 5, the occupant was present most of the working day with short

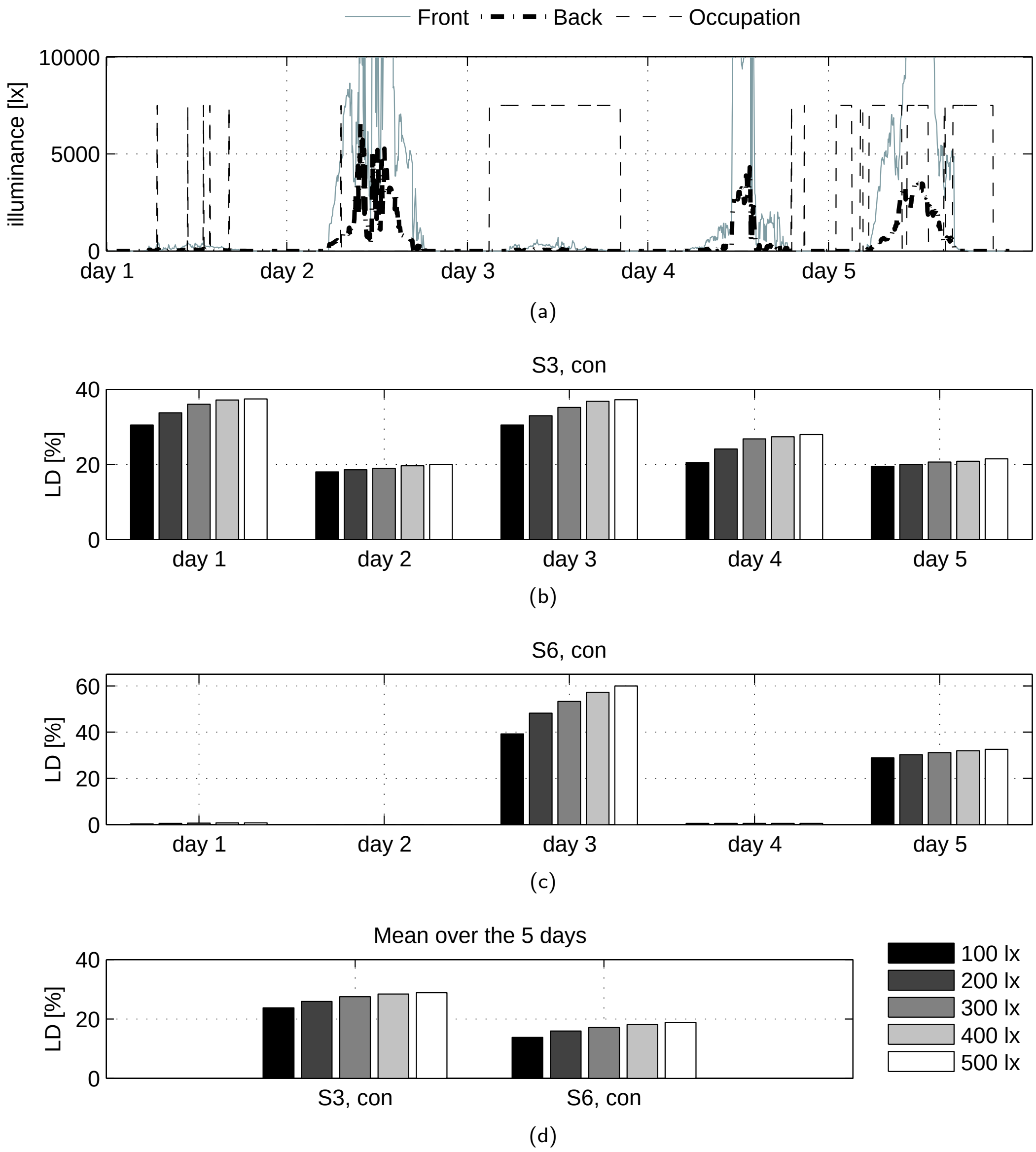


Figure 3.33: *(a) Presence of occupants and illuminance levels at the room sensor points. (b) Lighting demand at illuminance thresholds from 100-500 lx with continuous dimming (con) for each of the 5 days with occupancy based on absence factor (S3), (c) with occupancy based on the presence of occupants (S6), and d) for average lighting demand over the 5 days for the two scenarios S3 and S6.*

intervals of absence; whereas on days 1, 2 and 4, the occupant was only present for very short intervals. The illuminance levels in the working plane at the front and at the back of the room are shown with grey and black lines respectively. It can be seen that days 1 and 3 were overcast days, whereas days 2, 4 and 5 were days with direct sun. When continuous dimming of the artificial lighting was combined with the presence of occupants, either S3 or S6 resulted in the lighting demand for each day as seen in the two middle figures. The lighting demand in Figure 3.33b assumes that the occupant was present according to an absence factor of 0.63. For this scenario, the artificial lighting was switched on if the illuminance level could not be maintained by daylight alone. This is what can be seen in Figure 3.33b, where the artificial lighting is switched on every day. For the overcast days (1 and 3) the lighting demand is around 30%, whereas for the days with direct sun, the lighting demand is around 20%. For the days with direct sun, the illuminance level at the sensor points is mostly higher than the artificial lighting threshold, and the lighting demand of 20% is a result of the hours of the day with no sun, when the artificial lighting is switched on. Figure 3.33c shows the occupant present in accordance with the dynamic 2-min occupancy model. Here, the lights were only switched on when the occupant was present. So, almost no lighting demand is seen on days 1, 2 and 4, whereas a high lighting demand (40-60%) is seen for day 3. Figure 3.33d shows the average lighting demand over the 5 days. If we explore this period, it can be seen that applying an average absence factor results in 10% percentage points higher lighting demand than applying the dynamic occupancy profile.

Overview IV The results from this section show that the resolution of occupancy profiles had little impact on the annual evaluation of the lighting demand. So, to take into account the presence of occupants, it would be sufficient for the climate-based simulations applied to the urban structure in **Paper II** to apply a simple absence factor as opposed to a more complex occupancy profile. This information has therefore been added to the input-arrow from **Paper IV** in Figure 1.1, see Figure 3.34.

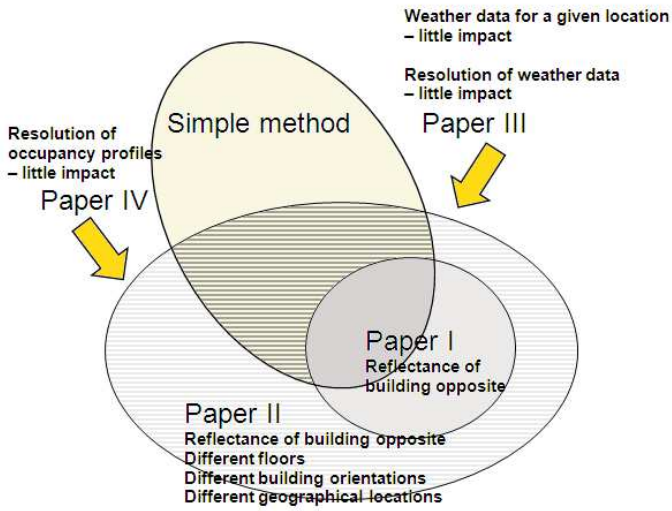


Figure 3.34: *Interplay between the simple method and* **Paper I**, **Paper II**, **Paper III** *and* **Paper IV**

Chapter 4

Discussion

The general hypothesis to be tested was that "*Simple models for the early stages in the design of urban building structures can represent the complexities of daylighting without loss of important characteristics*".

The thesis proposes a simple method to aid urban designers on the daylighting aspect of the decision-making process in the early stages of design when the outline of the city is defined. To validate this simple method, more complex simulations of the urban canyon structure were made. Throughout this thesis, Figure 1.1, showing the overall interplay in the introduction section, was extended with the findings from each paper. This leads to Figure 4.1.

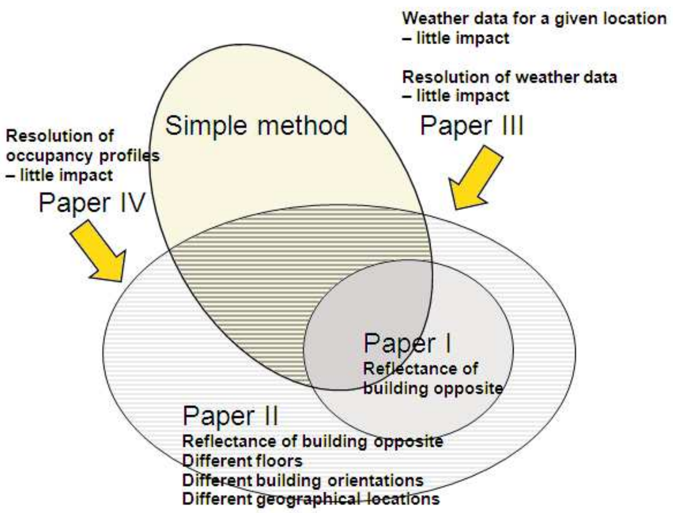


Figure 4.1: *Interplay between the simple method and* **Paper I***,* **Paper II***,* **Paper III** *and* **Paper IV**

A simple method was derived from the research described in **Paper I**. By looking at street widths and the heights of buildings opposite, it was possible to get information on the window area needed in the façades to attain a daylight factor of 2% 3m from the façade. In this research, it was found that the framework could be applied for different façade reflectances. **Paper II** added information to this method by introducing climate-based daylight modelling to the simulated system. Here it was found, that to extend the simple method from **Paper I**, it would also be necessary to have data for rooms located on different floors, rooms facing different orientations, and rooms placed at different geographical locations. The research described in **Paper II** gave initial results, and the full extension to expand the simple method was not made. Expanding the simple method to include dynamic results will be a topic for future simulation-based research. As input to this research, it was useful to know whether any of the weather data sets available could be used for the simulations. The results from **Paper III** showed that there is very little difference in simulating with different weather data sets for a given location. It is also useful to know whether the one-hour resolution that most weather data sets are structured in would give valid estimates. In the research for **Paper III**, it was found that simulating with one-hour resolution as opposed to one-minute resolution would give reliable results, when evaluating for a whole year. Another important input for climate-based daylight modelling is the presence of occupants. The research in **Paper IV** explored the effect of simulating with absence factors as opposed to simulating with various different dynamic occupancy profiles throughout the year. It was found that the absence factor was an adequate measure of the presence of occupants in the simulations.

The following sections discuss the various results in more detail.

4.1 Simple method - Application

As mentioned in section 3.1.1, the simple 4-step method has been applied in a number of Danish urban planning and architectural competitions in which the author has participated as a consultant from Esbensen Consultants, e.g. Køge Kyst (http://www.koegekyst.dk), Fredericia C (http://www.fredericiac.dk), and most recently Thomas B Thriges Gade in Odense C (http://www.fragadetilby.dk). It was the general experience that when the architects were given presentations showing that parts of their proposed urban plan had poor daylight performance, they were interested in optimizing their proposal by trying different street widths and building heights.

Expanding the method to include annual simulations makes the evaluation more realistic because both direct and diffuse radiation is considered. Annual simulations make it possible to get information on the artificial lighting demand inside rooms. Furthermore, it will be possible to indicate the floors and building orientations in the urban structure, where solar shadings should be included. One aspect which might be important when playing with the façade reflectance of the building opposite is the evaluation of glare (see the following section 4.2). With annual simulations, this evaluation can also be made for the inside of rooms.

However, both methods, CIE overcast sky and annual simulation, have their legitimacy. The simple method based on the CIE overcast sky represents evaluations made according to the criteria outlined in most national standards e.g. (BR10, 2010; BS8206-2:2008, 2009), whereas the extended method, including annual simulations, describes more detailed simulations and possibly future daylight requirements which buildings must meet.

4.2 Simple method - Limitations

If the framework outlined in section 3.1.1 is to be used in the development of an urban plan, the limitations of this model also need to be known. The method was developed based on a CIE overcast sky, so no effects of building orientation or geographical location were considered. The framework relies on the principle of the urban canyon, which means that rooms in corners of buildings or rooms facing court yards are not included in these investigations. At these locations, different results might be found. Furthermore, the results given in the vertical daylight factor figures with colour-overlay (Figure 3.13) are based on windows that span the entire width of the building. This means that side effects from having smaller windows are not included in these results. For future research, the results could be expanded to include other room typologies and make the framework even more general.

In the research done for **Paper I** and **Paper II**, the daylight evaluations were made on the basis of horizontal illuminance. However, when it came to the effect of obstructing façades and playing with the façade reflectances, it was found that reflected light has an important role in the daylight penetration depth. This reflected light may cause discomfort for the occupants in the room, especially if the opposing building is highly reflective. This effect has not been studied in this research, and future studies on this topic would be highly relevant. A study by Cantin & Dubois (2011) did include some of this effect. In their study, a northwest-facing office had a high-rise building opposite. For this orientation they found that under sunny sky conditions the light distribution was more uneven for this office than for a southwest-facing office, a fact caused by the reflected light bouncing off the building opposite. However, in general, they found that the light distribution in the northwest-facing room was more even than that in a southwest-facing office due to the reflected light.

4.3 What matters?

4.3.1 Weather data files and resolution of weather data

As mentioned in section 2.3.2 and **Paper III**, 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 lengthy measurement period and structured to have the same properties as the measured data, with averages and variations that are typical for the site. It is therefore straightforward to assume that the type of weather data sets available will have an insignificant effect on daylight simulations to estimate the annual energy performance for artificial lighting. For the practitioner working in the field of daylighting, this would mean that he or she will obtain the same result irrespective of the weather data applied. However, as also described in section 2.3.2, weather data are not obtained from the exact same measurement period and location, and the statistical procedures to derive the data are not identical. Yet each of the methods has been validated and should result in validated results. For building simulation in Denmark, the practitioner would typically use the Design Reference Year (DRY) for Copenhagen as input weather data file. However, programs such as Daysim, DIVA for Rhino, or Virtual Environment, all require the .epw file format, which is the standard format for the Energy Plus weather data files. This thesis investigated the IWEC weather data file, which is a .epw file. The .epw file format is structured differently from the DRY. For the practitioner, it is therefore useful to know that an annual simulation will come to acceptable results, irrespective of the type of weather data file used. The results showed no difference in the lighting demand at a general lighting level of 200 lx, as prescribed in Danish Standard DS700 (DS700, 2005) (Figure 3.22). The energy consumption for artificial lighting will therefore yield the same result irrespective of the type of weather data used for the calculations.

When simple solar shading included in Daysim was applied to the simulations, the IWEC weather data file performed better (by 2-3 percentage points) in terms of daylight than the weather data files from Meteonorm or DRY. This difference is related to the weather data files; more diffuse irradiance is included in the IWEC file than in the two other weather data files (see Figure 3.26). The simple blind system excludes direct sunlight and transmits 25% of all diffuse light. This has the effect that more light enters the room when the IWEC file is used than when applying the other weather data files.

Simulations with one-hour resolution data as opposed to one-minute resolution give conservative estimates of energy consumption for artificial lighting, because the lighting dependency is underestimated, resulting in decreased lighting demand. However, the difference in lighting demand is not very much - in the range of 1 to 6%. It is surprising that the short-term dynamics of the daylight available do not have a greater impact on the difference in continuous lighting dependencies between simulations with one-hour and one-minute data resolution. One would have assumed that simulations with one-hour data for most working hours in the year would underestimate the lighting dependency to a higher degree due to spikes with high illuminances increasing the hourly mean value. With such an increased hourly mean value, the hour as a whole might have a sufficient daylight level, while the estimation with one-minute resolution might fall below the threshold illuminance value for some time steps causing lights to be switched on. However, this effect is not that visible when the reference is a lighting system that is always on. The maximum discrepancy is 6 percentage points, seen for the location of Phoenix at an illuminance threshold of 500 lx (see Figure 3.24). For the location of Copenhagen, little is gained when moving from one-hour to one-minute data in the weather data sets. Differences in percentage points compared to a system that is always on were in the range of 2 to 3% (see Figure 3.24 and Figure 3.25).

As mentioned in section 3.1.3, the non-deterministic effect of the stochastic Skartveit-Olseth model on the simulation outcome is negligible. The relative standard deviation in the specific annual electrical energy demand for artificial lighting resulting from ten different realizations of the model was found never to exceed 0.7% (Walkenhorst *et al.*, 2002). The discrepancies found in this study were greater than 0.7%, which implies that differences in the weather data and not differences in the stochastic model were being simulated. Walkenhorst *et al.* (2002) also compared lighting electricity consumption in simulations using measured irradiances from one-hour and one-minute data sets and found that consumption is underestimated by 6-18% with one-hour irradiance values. The discrepancies found in this study are smaller, which suggests that, with the current data and models available, simulations using one-minute resolution do not behave as dynamically as expected. As pointed out in Reinhart's PhD thesis (2001), the amount of intra-hour variation in the modified Skartveit-Olseth model is less pronounced than in reality because the model is stochastic. While differences between measured and simulated values may be substantial for a single day, the differences tend to even out over a period with a greater number of hours (Reinhart, 2001). In the development of the IWEC files, the Skartveit-Olseth model was discarded, because the model seemed to be tuned to European conditions and had not undergone extensive testing in other locations (ASHRAE, 2001). So to take account of the true dynamic behaviour of the sky, better models and/or measured irradiance data with a finer resolution than hourly will be needed.

4.3.2 Daylight factor vs Climate-Based-Daylight Modelling

In Mardaljevic (2000), comparisons between the cumulative illuminance obtained from the standard daylight factor approach and from the climate-based approach showed that the daylight factor approach underestimates the daylight levels inside the room for southern-orientated rooms. For rooms facing north, the situation is reversed; here the daylight factor approach overestimates the illuminance values. The results for the room studied in this research show the same trend for the southern orientation. For the northern orientation, with the automatic on/off control strategy, the lighting dependencies are almost the same, and with continuous control the climate based lighting dependencies are 20% percentage points higher for the northern orientation than for the southern orientation. For the southern orientation the lighting dependencies obtained with on/off control from the CBDM approach are 30 percentage points lower than from the DF-approach, and with continuous control the lighting dependencies are 7-20 percentage points lower depending on the indoor illuminance threshold. This means that building orientation should of course be included when going from CIE overcast sky simulations to Climate-Based-Daylight Modelling.

Another aspect of the differences between CIE overcast sky evaluation and climate-based-daylight modelling can be seen in **Paper II**. The study for **Paper II** showed that in dynamic simulations of urban contexts the effect of reflection from other buildings favours the lower floors in northern orientations. These results would not have been found using standard daylight factor calculations, where the effects of direct sunlight and orientation are not considered. Furthermore, these results emphasize that the design of façades in new urban areas or in any new building should take into account not only the creation of an optimal solution with regard to both energy consumption and indoor environment for the building in question, but also its contribution to creating good and varied daylight conditions for neighbouring buildings.

4.3.3 Lighting control; on/off, continuous dimming, occupancy control

The results show that introducing on/off control or continuous daylight control in the perimeter areas of a daylit building (Figure 3.32, Scenario 1, and Figure 3.24) reduces the energy consumption by up to 70%-80% compared to a reference case where the lights are always on, as might be the case, for example, in the core building zone. The addition of automatic occupancy sensing control reduces energy consumption by another 40-60% depending on the type of control applied (Figure 3.32, Scenarios 2, 3 and 6). These reductions in artificial lighting demand were also reported in the PhD study of Bourgeois (2005). Here, he demonstrated that 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%, and a further 50% when automatic control is used.

The lighting controls were assumed to switch on/off or to top up the lighting to reach exactly the target illuminance. This control type is of course an idealized control. In practice, the control sensor is not usually located in the working plane, where it can be damaged or covered up, but externally or on the ceiling. This can lead to discrepancies between the working plane illuminance and the response of the sensor and the photoelectric control. Poor maintenance and calibration can lead to additional differences between predicted and actual operation.

4.3.4 Resolution of occupancy profiles

The presence of occupants, their behaviour, etc. are parameters permeated by randomness but they are often simulated in a deterministic way. In the early stages of design, you typically know very little about the people who will use the building, and in most cases you know nothing, but will have to assume 'standard persons'. In EN15193 (2007) such 'standard persons' are assumed present in terms of an absence factor. According to EN15193 (2007), the absence factor for the one-person office investigated in the research described in Paper IV, is 0.4. However, nothing is stated in EN15193 (2007) as to how the figures were obtained. One would assume that they are based on empirical data and represent standard situations. The question that arises therefore is whether it would be sufficient to apply such a standard person to the Climate-Based-Daylight Modelling as opposed to applying a more dynamic 'natural' occupancy profile, when the lights are controlled according to the presence of occupants.

The research described in **Paper IV** showed that no real difference is observed in the lighting dependency of an office with automatic control of the lights based on daylight and occupancy when Climate-Based Daylight Modelling is applied and the lighting demand is evaluated on the basis of an average occupancy profile with the same distribution every day of the year, as opposed to using a more dynamic occupancy profile of hourly resolution or 2-min resolution of occupancy with a minimum of 20 min absence. This means that, if the control of artificial lights based on occupancy and daylight level is automatic, the same occupancy pattern for every day of the year applied with hourly resolution will yield accurate estimations of the artificial lighting demand. Furthermore, the research described in **Paper IV** showed that multiplying the annual daylight availability by an absence factor, corresponding to the mean presence from the dynamic simulations only overestimates the lighting demand by 4%. This result suggests that in the early stages of design, when detailed information on the use of the building is unknown, it could be sufficient to simply multiply by an absence factor for the occupants. The question then is: What is the right multiplication factor? As mentioned previously, EN15193 (2007) prescribes an absence factor of 0.4 for the one-person office simulated in **Paper IV**. Applying this factor as opposed to applying the absence factor of 0.63 found in the office building in San Francisco of course results in a higher energy demand. Research shows that occupants typically spend 25-50% of their workday away from their workspace, e.g. (Maniccia *et al.*, 1999; Wang *et al.*, 2005). This suggests that the input parameter in terms of occupation could be characterized by a probability density function, or a range, e.g. an absence factor ranging from 0.25 to 0.60 depending on the type of building and occupant. The input data, used to assess building energy performance, are always affected by uncertainties coming from different sources. In the end, simulations will always be a theoretical representation of the status and operation of a building. They cannot perfectly replicate the real dynamics that govern the energy use: For example, the actual climate can vary from the meteorological data available, and the systems may not work exactly as expected from the curves of load operation. Above all, the energy performance can be affected by the actual behaviour of the building's occupants. Every building design is based on assumptions about how the building will be used, but when the building is realized, it may be used in different ways than its designer assumed or planned, affecting the validity of results.

If the aim of a simulation is to investigate the finer dynamics of a lighting system, a solar shading control, or a ventilation system, detailed knowledge about the presence of occupants is important and useful for the design of the systems. The limitation in using the annual mean presence of occupants is that the annual mean profile does not include peak loads. This might induce simulation errors when the energy demand for the systems is to be predicted, because the number of occupants in a zone affects for instance the zone's cooling and ventilation load, which determines the amount of conditioned air to be delivered to that zone to maintain thermal comfort and air quality. For an artificial lighting system, the dynamics of each occupant in a zone is of relevance when exploring the potential and control of occupant-specified lighting, as in the studies by Wen & Agogino (2011a,b). They investigated a lighting system containing individually controllable wireless ballasts with closed control loops for occupant-specified lighting. This meant that each occupant's personal and often diverse preferences in terms of illuminance level could be met. For the research described in **Paper IV**, the artificial lighting was measured in two zones to maintain a given horizontal illuminance threshold for the entire space. For the occupancy-based control, the artificial lighting responded to one occupancy profile. However, to fully exploit the potential of dynamic occupancy profiles, one topic for future research will be to extend the simulations and controls with occupant-specified lighting.

Chapter 5

Conclusions

Simulation is a method for modelling/imitating complex systems. In this case, the aim was to investigate light conditions inside buildings using computer simulation as a complex system. Once you have a complex system model, it is possible to develop and validate simplified models.

The hypothesis to be investigated in this thesis was that

Simple models for the early stages in the design of urban building structures can represent the complexities of daylighting without loss of important characteristics

This hypothesis was investigated in the work reported in the four appended papers. A simple 4-step method was derived from the research described in **Paper I** on the basis of daylight simulations of an urban building structure under overcast sky conditions. By looking at street widths and heights of buildings opposite, it was possible get information on the window area needed in the façades to attain a daylight factor of 2% 3m from the façade. In this research, it was found that the framework could be applied for different façade reflectances. The simple 4-step method is visualized in Figure 5.1.

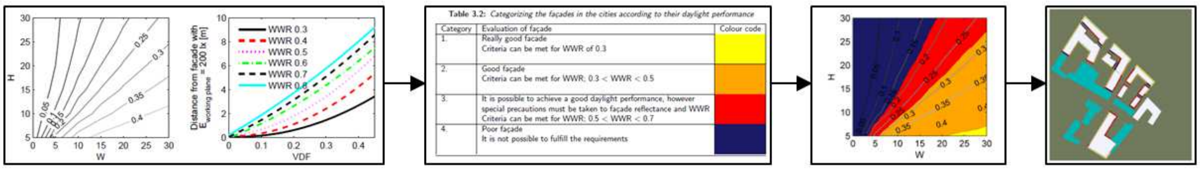


Figure 5.1: *Figures showing the principles of the simple 4 step method*

The limitations of this simple model are that it does not include building orientation and daily variations in luminance distribution of the sky because it uses the CIE overcast sky model. These limitations are overcome in the investigations in the research described in **Paper II**, **Paper III** and **Paper IV**, where the sky simulated was the time-varying Perez All-weather sky with input from weather data files. However, due to time limitations, it was not possible to implement the annual simulations in the simple method. This will therefore be a topic for future research.

From the research described in **Paper II**, it was found that the simple 4-step method can be extended to include climate-based-daylight modelling. In order to transform the complex urban simulations into the simple 4 step representation, it will be necessary to include simulations with

i) different façade reflectances,

ii) rooms located on different floors,

iii) buildings having different orientations, and

iv) buildings placed at different geographical locations.

So the general hypothesis that "*Simple models for the early stages in the design of urban building structures can represent the complexities of daylighting without loss of important characteristics*" is confirmed, if the simplification is used with caution includes the important parameters, such as those outlined in i)-iv).

The research for **Paper III** showed that if different weather data files were applied for a given location it had very little impact on the simulation outcome. This applies when the weather data sets were obtained from very similar time periods and developed from equal algorithms and standards. This means the weather data sets will have equal characteristics, and the evaluations will be more or less similar.

Furthermore, the research showed that simulations with one-hour resolution data as opposed to one-minute resolution data give conservative estimates of energy consumption for artificial lighting, because lighting dependency is underestimated, resulting in decreased lighting demand. However, the difference in lighting demand is not very much - in the range of 1 to 6%. This means that running the complex evaluation of the urban structure based on one-hour resolution values would be sufficient in the initial stages of design.

The research described in **Paper IV** showed that no real difference is observed in the lighting demand of an office with automatic control of the lights based on daylight and occupancy when Climate-Based Daylight Modelling is applied and the lighting demand is evaluated on the basis of an average occupancy profile with the same distribution for every day of the year as opposed to using a more dynamic occupancy profile of one-hour resolution or 2-min resolution of occupancy with a minimum of 20 min absence. This means that, if the control of artificial lights based on occupancy and daylight level is automatic, the same occupancy pattern for every day of the year applied with hourly resolution will yield accurate estimations of the artificial lighting demand. Furthermore, the research described in **Paper IV** showed that multiplying the annual daylight availability by an absence factor, corresponding to the mean presence from the dynamic simulations only overestimates the lighting demand by 4%. This result suggests that in the early stages of design when detailed information on the use of the building is unknown, it could be sufficient to simply multiply by an absence factor for the occupants.

5.1 Outlook

One topic not included in the investigations in this research is the light distribution inside the room. Previous research has indicated that the evaluation of glare should be considered when working with the reflectances of the buildings opposite. This evaluation could be made from the vertical eye illuminance in accordance with the daylight glare probability index developed by (Wienold & Christoffersen, 2006). Furthermore, the inclusion of shading systems should be simulated. This could be done in terms of the simple shading model included in the daylight simulation program Daysim.

This research only focused on the visible part of daylight as input to the building system. The focus was only on looking at the effects on the annual artificial lighting demand. However, an important aspect of daylight is also the solar radiation, and the effect it has on the building's heating and cooling demand. This issue was not a focus point for this research. However, to have a complete evaluation of building structures in urban areas, the related energy demand for heating/cooling the building should also be included.

The figure from the introduction showing the interplay between the different papers could then be expanded to include information on input from applying solar shadings, on output in terms of lighting quality, and information on the building's energy consumption for heating and cooling.

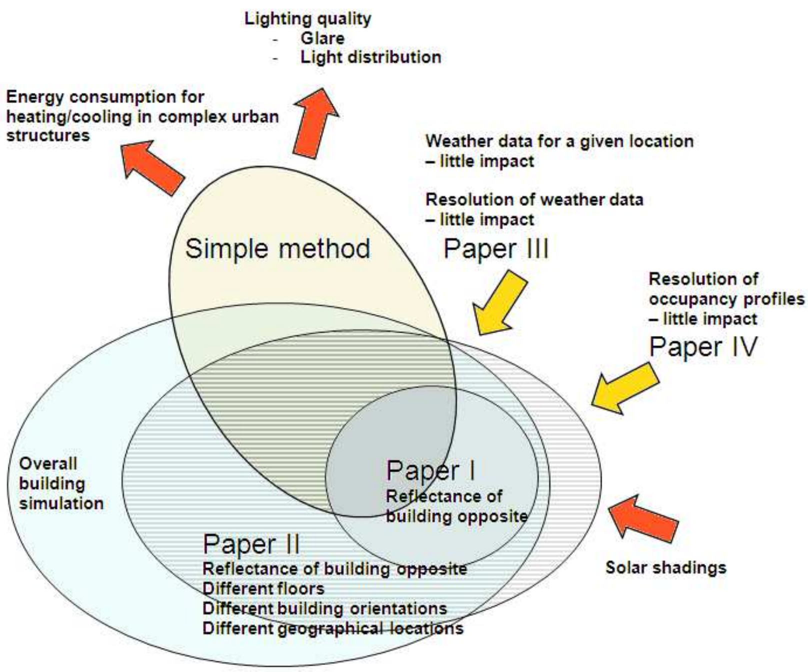


Figure 5.2: *Interplay between the research papers, and additional information, marked with red arrows, to obtain the entire picture*

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Nomenclature

A	Area	$[m^2]$
F	Factor	$[-]$
H	Height	$[m]$
r	Reflectance	$[-]$
S	Scenario	$[-]$
W	Width	$[m]$

Index

A	absence	$-$
con	continuous	$-$
Day	daylight	$-$
$floor$	floor	$-$
Man	manual	$-$
Occ	occupancy	$-$
on/off	on/off	$-$
PI	proportional integral dimming	$-$
$wall$	wall	$-$

Abbreviations

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

Part II

Appended papers

Paper I

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

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

Published in: *Indoor and Built Environment 2011, pp.456-463, DOI: 10.1177/1420326X11409460*

Original Paper

Indoor and Built Environment

Indoor Built Environ 2011;20;4:456–463

Accepted: March 11, 2011

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

DOI: 10.1177/1420326X11409460
Accessible online at http://ibe.sagepub.com
Figures 2 to 7 appear in colour online

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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).

$$\mathrm{VDF} = \frac{E_s + E_{rb} + E_{rg}}{E_h} \tag{1}$$

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 $20\,\mathrm{m} \times 15\,\mathrm{m} \times 4\,\mathrm{m}$ ($w \times d \times h$) placed on the ground in the middle of a larger building with dimensions $60\,\mathrm{m} \times 15\,\mathrm{m} \times 30\,\mathrm{m}$ ($w \times d \times h$) 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

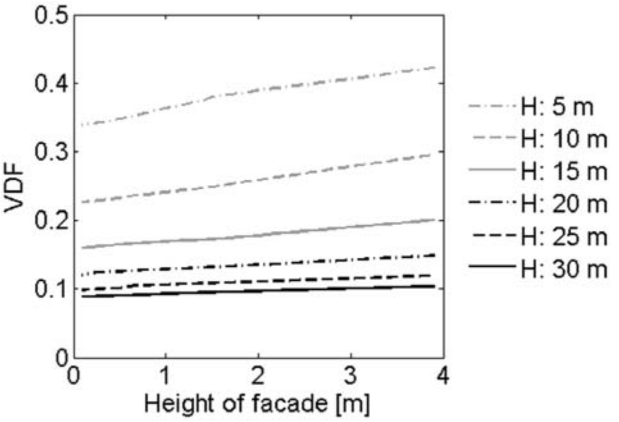

Fig. 1. (a) Plan of the model, seen from above with a street width of 5 m and (b) section of the model showing street widths from 5 to 30 m and heights of opposing building from 5 to 30 m.

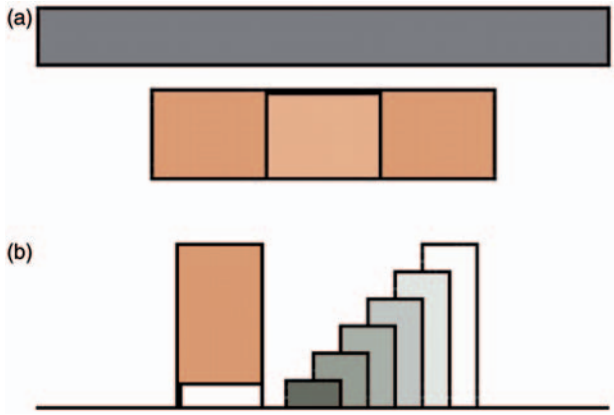

Fig. 2. Illuminance on façade in the entire height of the ground floor for a case with street width of 10 m, façade reflectance of 0.2 and different heights (H) of the opposing building.

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

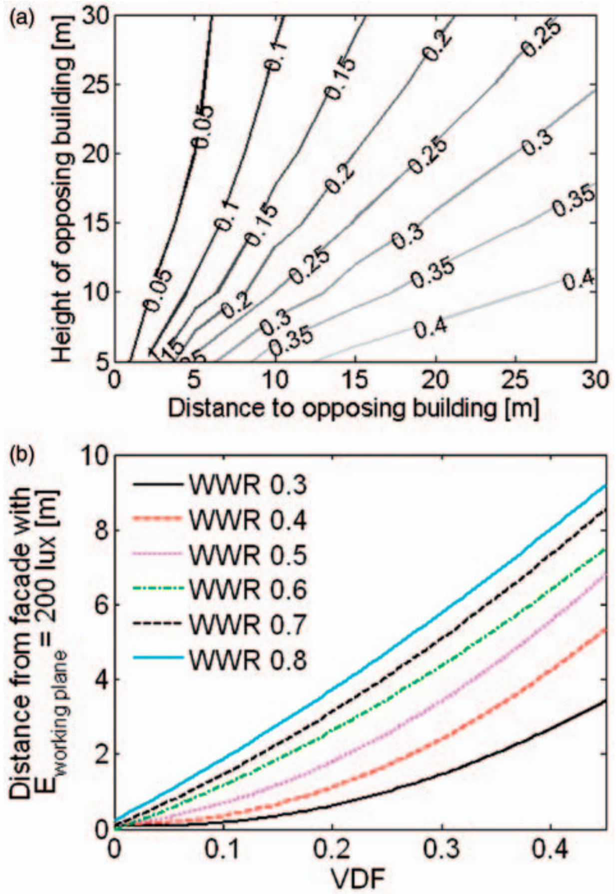

Fig. 3. Reflectance of opposing façade is 0.2. (a) The ratio of the illuminance level on the façade to a 10 klux CIE overcast sky (VDF) for different building heights and distance to opposing building. (B) Distance from the façade where 200 lux is achieved on the work plane for different VDF levels.

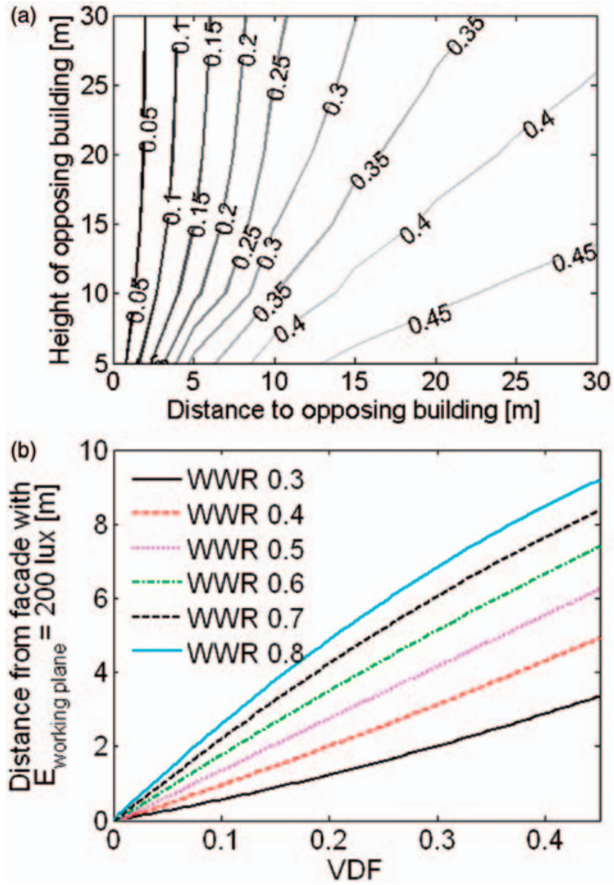

Fig. 4. Reflectance of opposing façade is 0.9. (a) The ratio of the illuminance level on the façade to a 10 klux CIE overcast sky (VDF) for different building heights and distance to opposing building. (b) Distance from the façade where 200 lux is achieved on the work plane for different VDF levels.

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

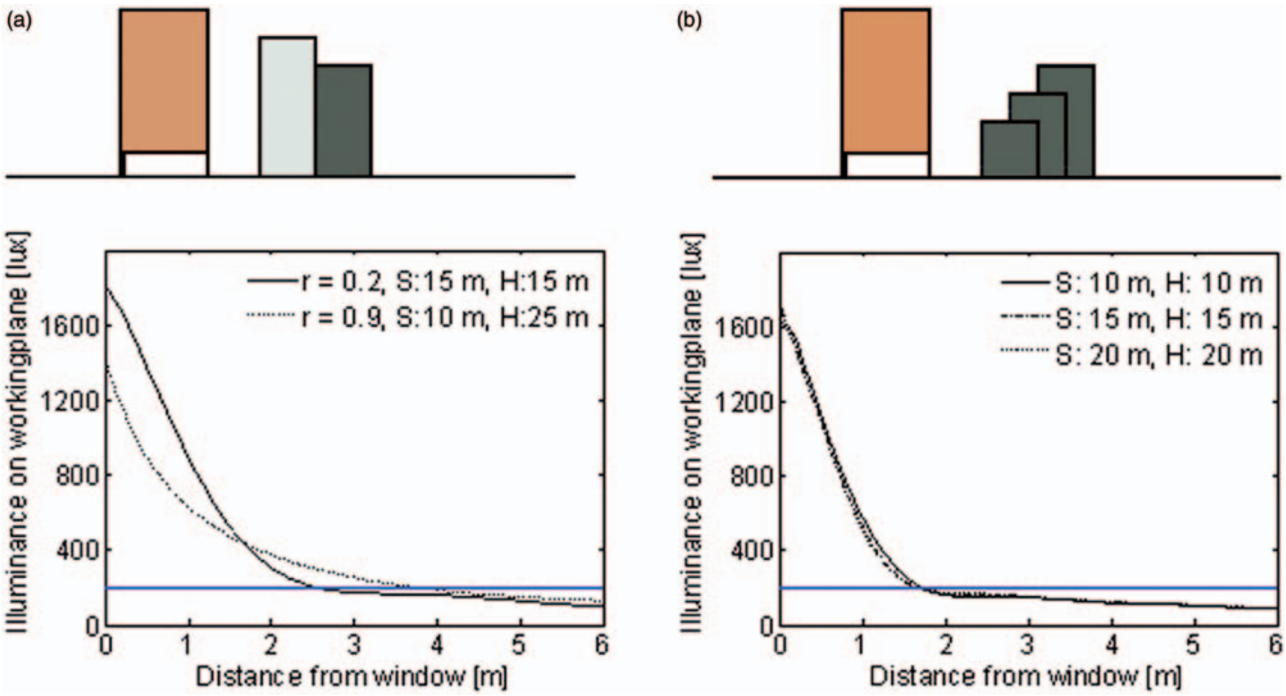

Fig. 5. Illuminance levels through the room with the same VDF (0.25) and WWR (0.4). (a) Different façade reflectances (*r*) of opposing building with street width (*S*) and height of opposing building (*H*). (b) Same façade reflectance, $r = 0.2$, with street width (*S*) and height of opposing building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

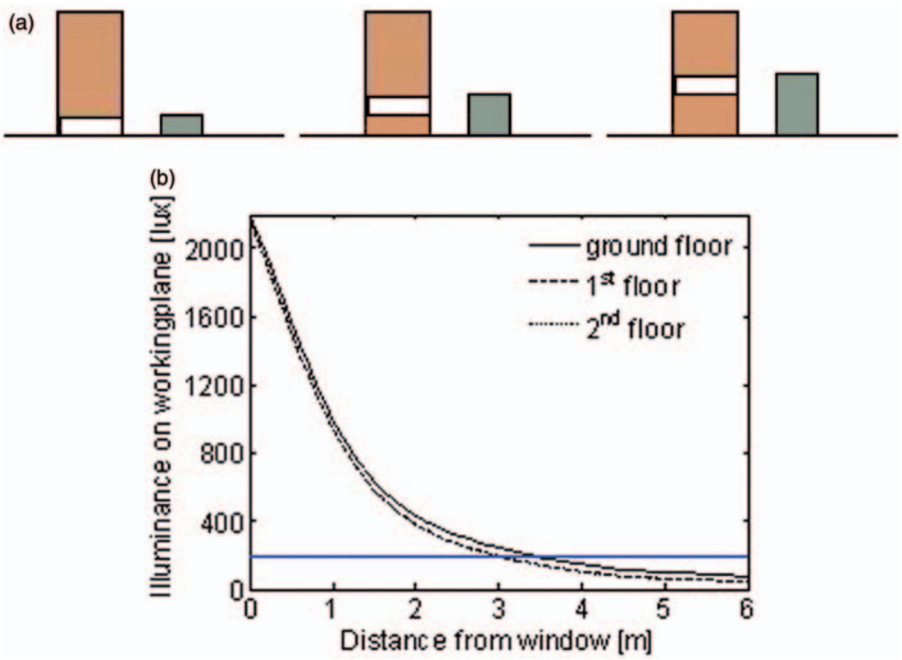

Fig. 6. Illuminance level profile through the room; comparing rooms placed on the ground floor to rooms placed on higher floors with VDF and reflectance of opposing building of 0.38 and 0.2, respectively.

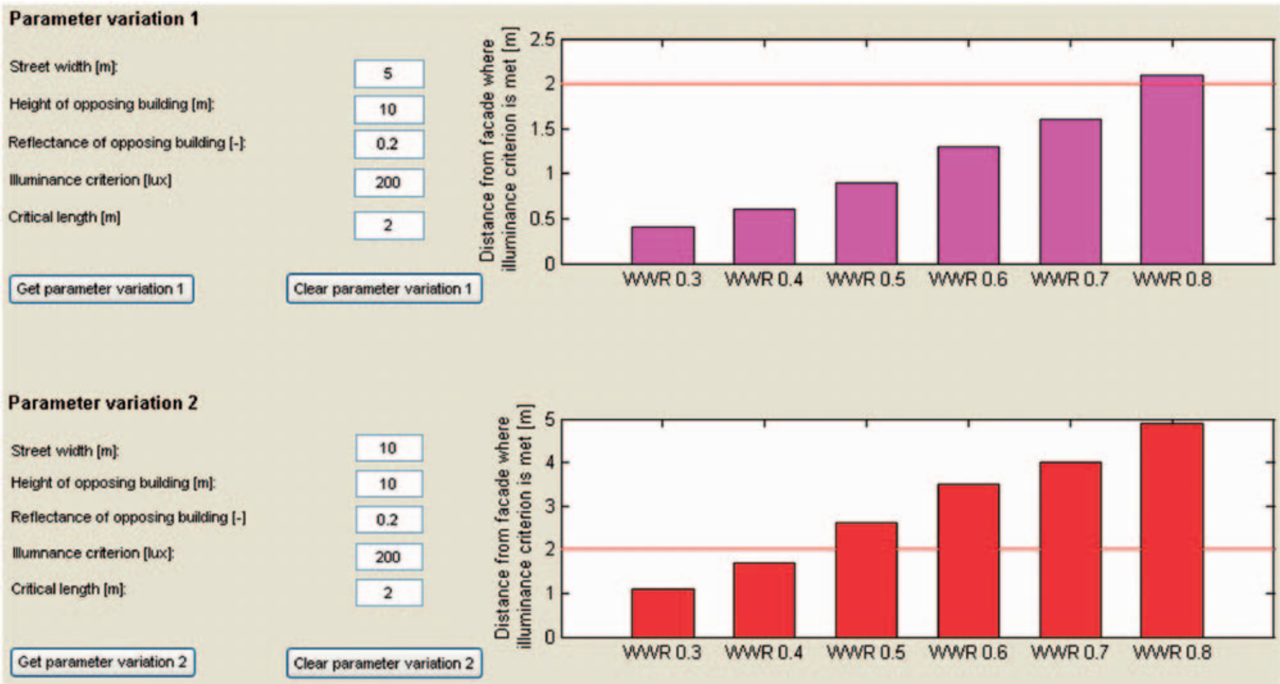

Fig. 7. An example of an output from the tool EvUrbanplan.

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

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	

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.

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.

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.

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

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

This work was partially supported by Esbensen Consultants A/S.

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Paper II

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

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Submitted to: *Building and Environment*

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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).

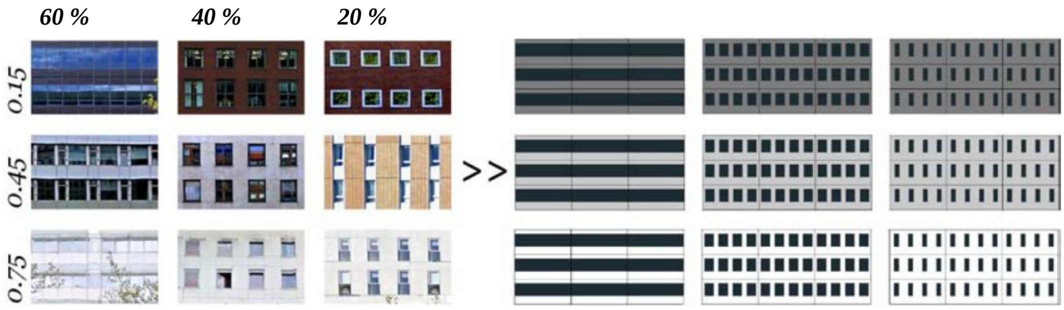


Figure 3: Simulation matrix of different WWR's (20%, 40% and 60%) and facade reflectances(0.15, 0.45 and 0.75)

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.

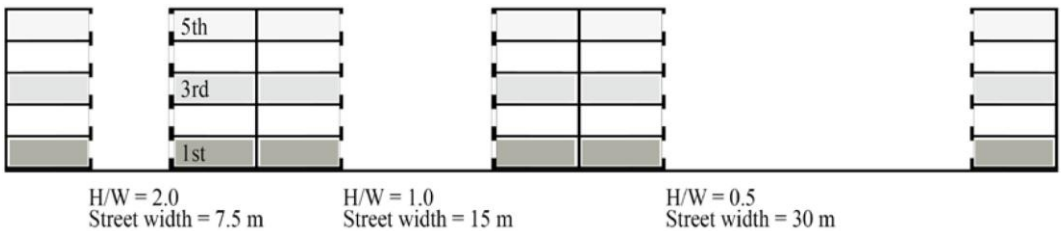


Figure 4: Urban street canyon, simulation setup

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.

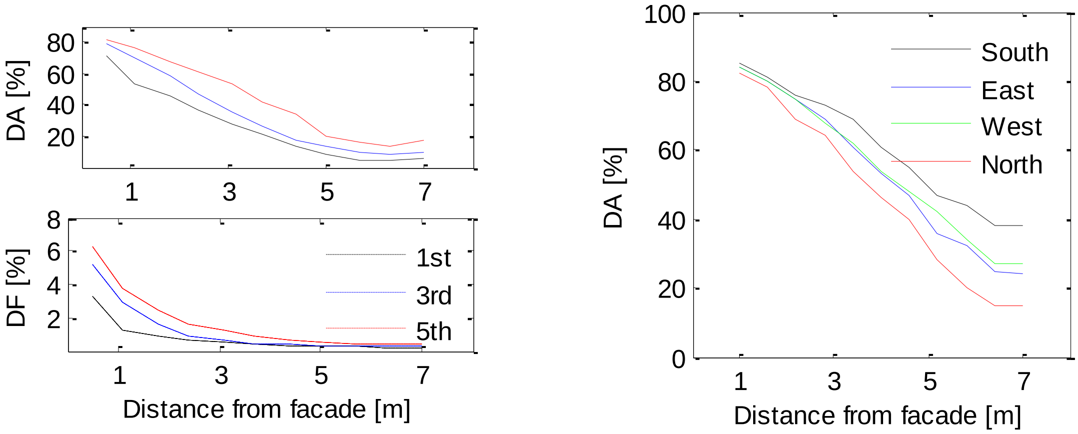
2.1.2 Daylight availability on the exterior vertical facade

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.

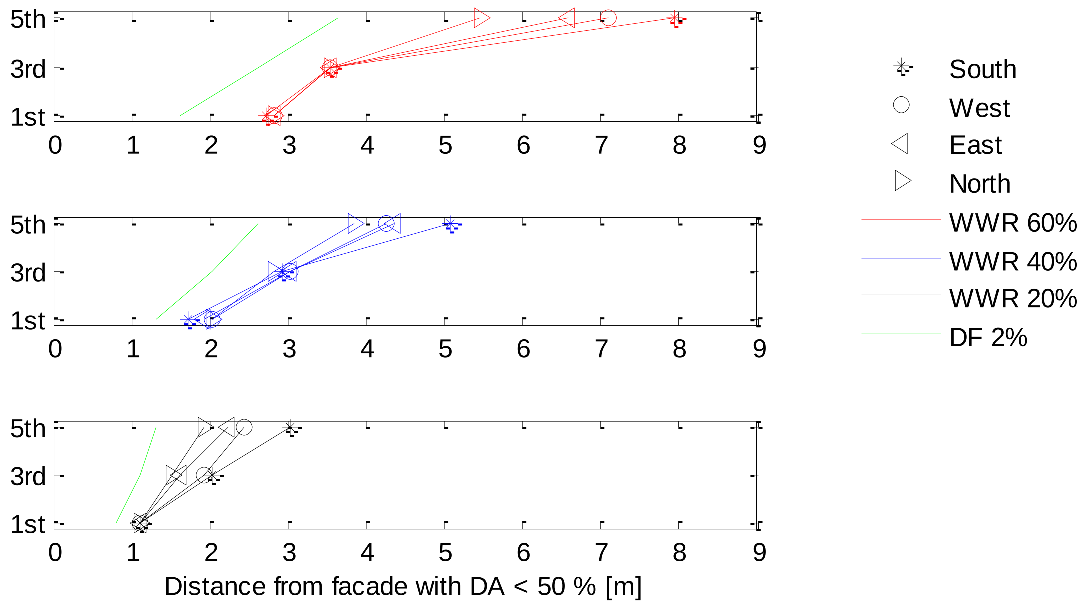


Figure 6: Distance from facade with DA below 50 % for street widths of 15 m, WWR varies from, 20 %, 40 % to 60 %. External reflectance 0.45.

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.

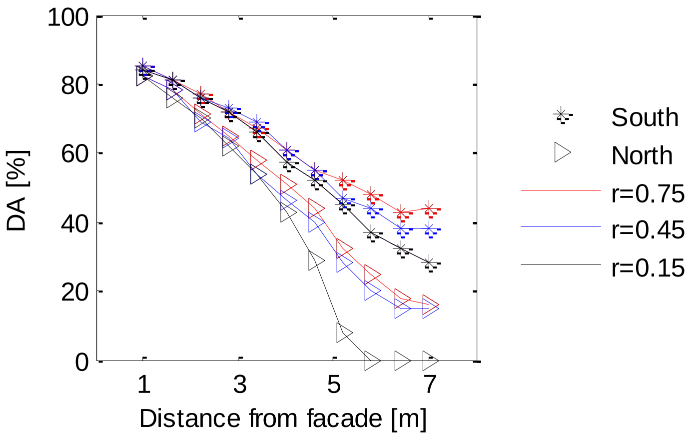


Figure 7: Daylight Autonomieson the 5th floor, through the room for north and south orientation and different reflectance's of the opposing building. H/W ratio of 1 and .WWR of 40%.

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.

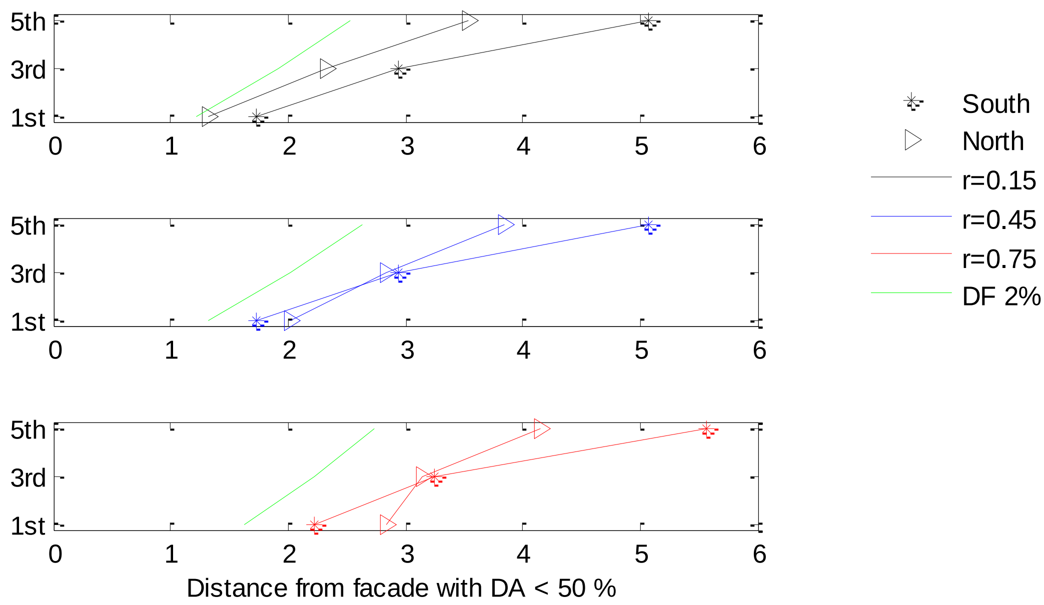


Figure 8: Distance from the facade with DA below 50 % as a function of floor level (1st, 3rd and 5th floor), H/W ratio of 1, WWR of 40%, and three different façade reflectance's. The green line show the distance from façade with DF of 2 %.

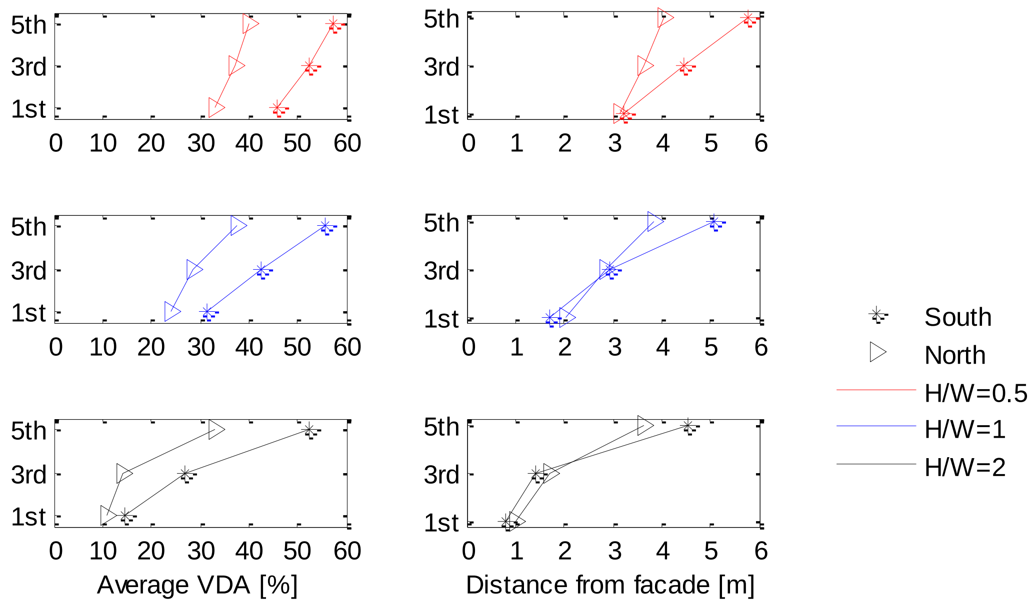
A very visible trend from
Figure 8 is that for the windows facing the northern orientation the influence of the reflectance is remarkably for the 1st floor. Here the reflected light increases the DA of 50 % from 1.3 m to 2.8 m from the facade. For the control of artificial lights this might have an impact on the energy consump-

tion, 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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Paper III

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

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Published in: *Lighting Research & Technology, 2013*

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:

$$LD_{room} = \frac{LD_{front} + LD_{back}}{2} \qquad (2.3)$$

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 %.

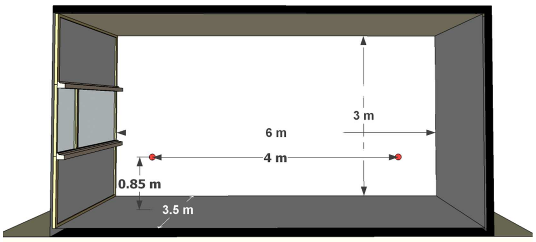

Figure 1 Sketch of the simulated model

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 %.

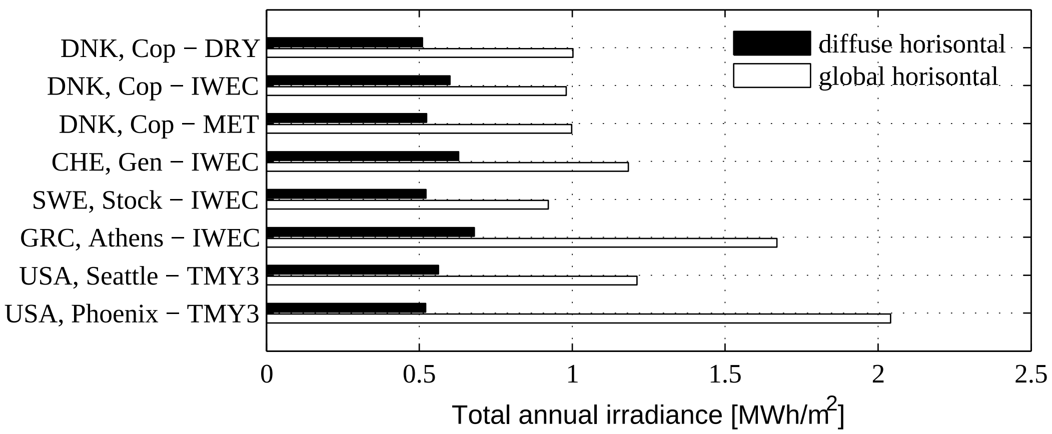

Figure 2 Total annual horizontal diffuse and global irradiance at different locations

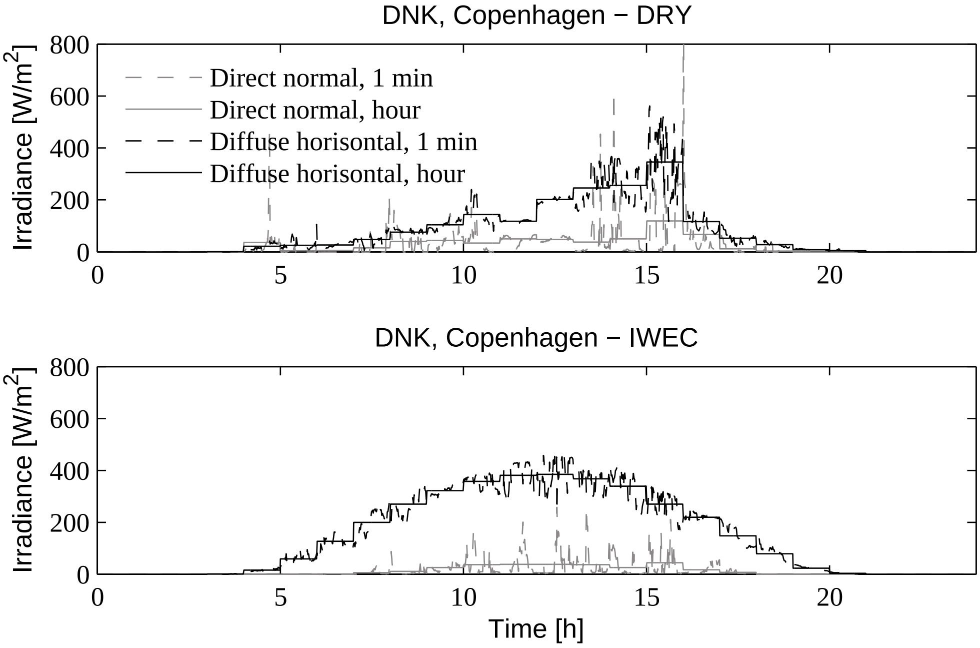

Figure 3 Horizontal diffuse and direct normal irradiance for the DRY and IWEC weather data at the location of Copenhagen on June 18th

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

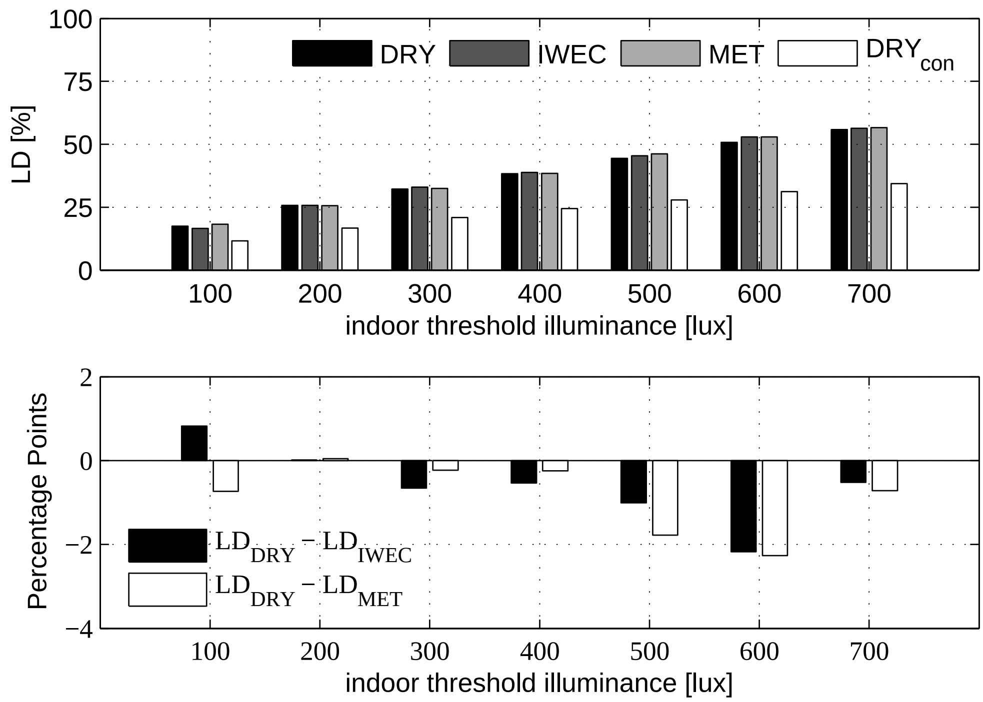

Figure 4 Comparison between hourly simulations for different weather data files for Copenhagen. Upper panel: Predicted lighting dependencies for the sensor point in the back of the room for the daylight simulations with hourly means from the Design Reference Year, IWEC, and Meteonorm weather data sets. 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

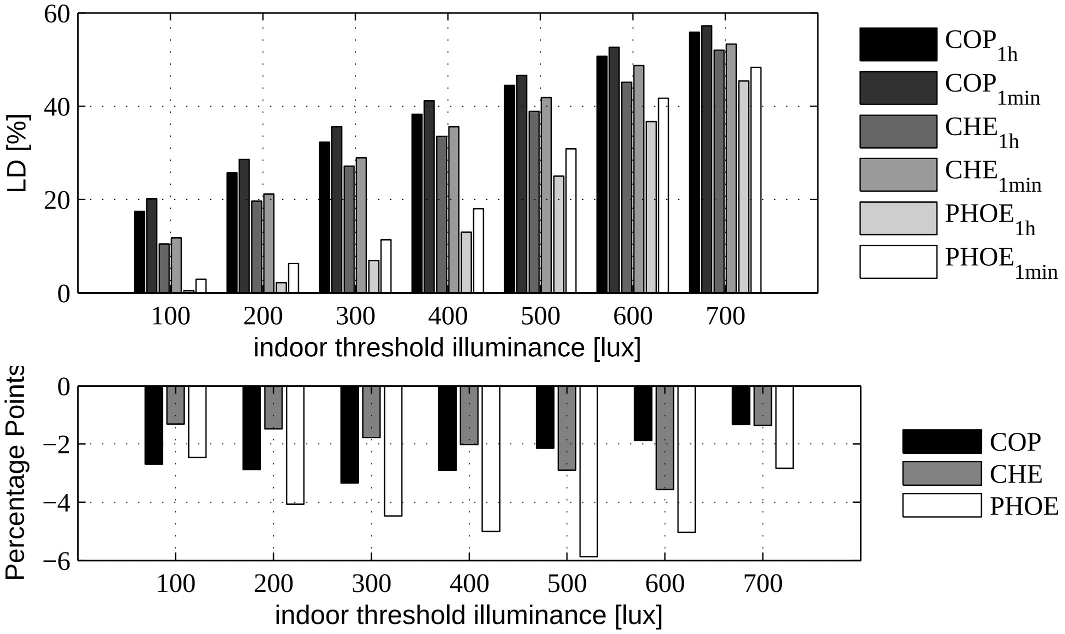

Figure 5 Comparison between hourly and one minute simulations for different climatic locations with on/off control. Upper panel: Lighting dependencies for hourly means and one minute data for the DRY file of Copenhagen (COP), the IWEC file for Geneva (CHE) and the TMY3 file for Phoenix (PHOE), Lower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

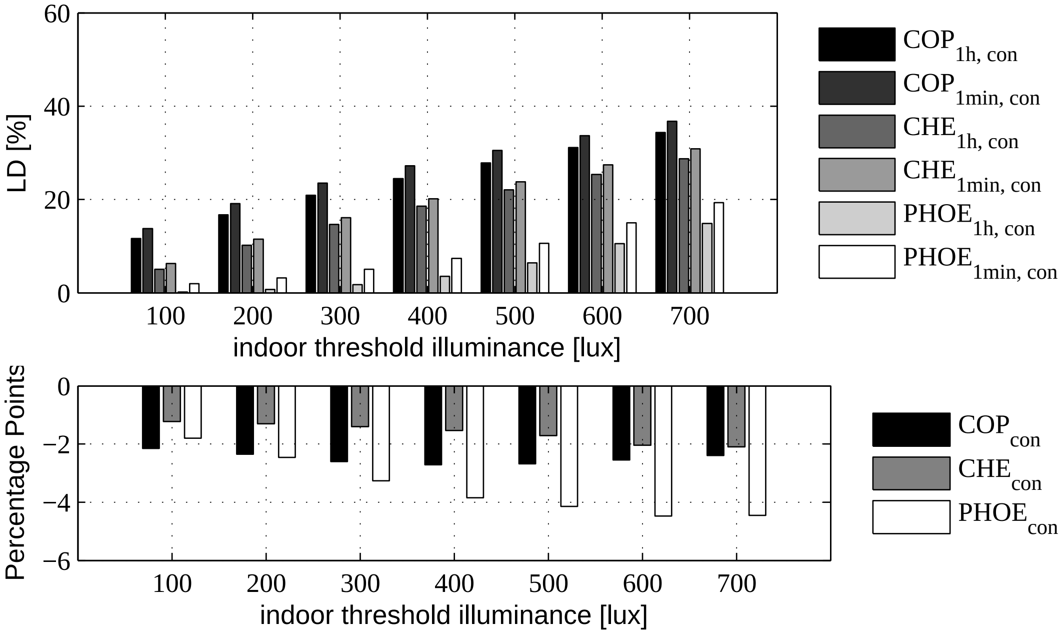

Figure 6 Comparison between hourly and one minute simulations for different climatic locations with continuous dimming control. Upper panel: Lighting dependencies for hourly means and one minute data for the DRY file of Copenhagen (COP), the IWEC file for Geneva (CHE) and the TMY3 file for Phoenix (PHOE).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

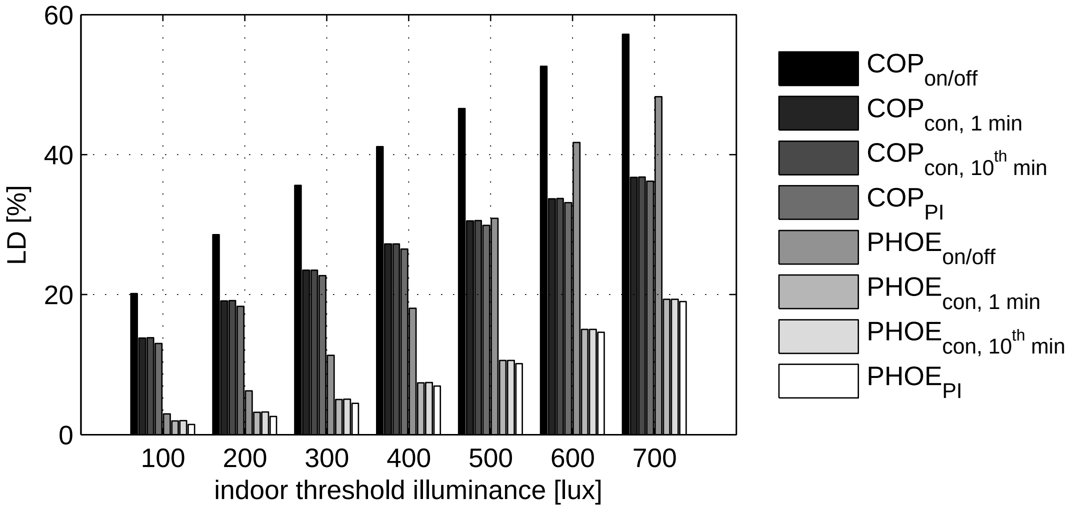

Figure 7 Lighting dependencies for weather data of one minute resolution with different control schemes for the location of Copenhagen and Phoenix

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.

Funding

The work was supported by the Technical University of Denmark and Esbensen Consultants A/S.

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Paper IV

"Simulation of annual artificial lighting demand using various occupancy profiles"

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Published in *Lighting Research and Technology, 2013*

Simulation of annual artificial lighting demand using various occupancy profiles

Abstract

The research was to investigate the effect on artificial lighting demand of applying occupancy models of various resolutions to Climate-Based Daylight Modelling. The lighting demand was evaluated for a building zone with the occupant always present, with occupancy corresponding to absence factors, based on an estimated annual mean occupancy, based on estimated 1-hour mean occupancy, and based on 2-min occupancy intervals. The results showed little difference in the annual artificial lighting demand when the same occupancy profile was used every day, as opposed to when profiles were used where occupancy varied every day. Furthermore, the results showed that annual artificial lighting demand was evaluated slightly conservatively when a mean absence factor was applied as opposed to using dynamic occupancy profiles.

1. Introduction

According the European Lamp Companies Federation[1], it is the energy consumed during lamp use that causes the greatest environmental impact. In the life cycle of a lamp from production to disposal, up to 90% of the energy is consumed during the operation phase. As a remark to this, it should be noted that the European Lamp Companies Federation has an interest in minimising the environmental impact of their production processes and of the disposal of their products. However, still, the message is clear; to minimize the environmental impact of a lighting system, it is important to reduce the energy consumed during operation.

The most efficient way to keep down the electricity use of artificial lighting is to control the use of the lights based on the presence of occupants and combine this with photoelectric dimming[2-5]. Research shows that occupants typically spend 25–50% of their workday away from their workspace[2,6,7] and that the switching on of lights based on the presence of occupants can be considered as a varying dynamic incidence because occupants do not arrive in buildings or leave buildings at fixed times. To take the dynamic, natural behaviour of occupants into account, various occupancy models have been suggested based on empirical data[6,7,8-12]. These can be grouped into models that solely describe the presence/absence of occupants[6,7,8,10] and models that also include behaviour in the form of probabilities for the manual switching on/off of lights and the operation of blinds[12-14] or other intervention by the occupants[9].

All the occupancy models presented in these papers[6,7,9-12] focus on modelling the arrival and departure of occupants in office buildings or homes. The models of Wang *et al*.[6] and Richardson *et al*.[10] are occupancy models developed as first order Markov chains. Wang *et al*.'s data fit very well with the exponential distribution when individual offices and vacant intervals are observed, but their exponential model was not validated for occupied intervals. In the study by Page *et al*.[7], they tried to overcome this limitation by modelling the occupancy as an inhomogeneous Markov chain and introducing a mobility parameter. This parameter gives an idea of how much people move in and out of a zone by correlating the desire to be at work with the desire to go home. The model developed in Delff *et al*.[8] proposed a new way of estimating occupancy by fitting the 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 Wang *et al*.[6] by being capable of modelling both the presence and absence of occupants without introducing a mobility parameter as suggested by Page *et al.*[7]. Other studies have sought to capture the dynamic sequences of each occupant. The original LIGHTSWITCH model developed by Newsham *et al*.[11] was intended to capture these dynamics. This operates with three different probability profiles: 1) arrival probability, 2) departure probability and 3) a probability of temporary absence peaking at noon. However, Reinhart (PhD thesis, 2001)[15] found that the model did not conform to measured data.

Despite the development of dynamic occupancy models, the most common way of taking the presence of occupants into account in building simulation is to have a static profile for weekends and weekdays[16,17]. In lighting simulations, such as DIALux[18], occupants are taken into account using absence factors in accordance with the European Standard EN15193 (2007)[5]. In Relux[19] and Daysim[13,20], the default occupational patterns are the static pattern for weekdays and weekends. In Daysim, it is also possible to apply the Lightswitch-2002 model. According to Reinhart (2004)[13], the Lightswitch-2002 model was developed based on the same idea as Newsham's original model, i.e. to predict electric lighting use based on behavioural patterns actually observed in office buildings. At the moment, the presence of occupants in Lightswitch-2002 can be simulated using profiles with a constant presence during the occupied hours, but with arrivals and departures randomly scheduled in a time interval of 15 min around their official starting times to add realism to the model[13]. Furthermore, breaks can be added to the occupancy profile depending on the length of the working day. The model was applied in whole building simulation in the PhD thesis of Bourgeois (2005)[14]. Here he investigated the effect on lighting demand of having a fixed occupancy profile with the lights always on compared with cases with manual control of the artificial lighting and automatic control of the artificial lighting. Not surprisingly, he found that the introduction of variable occupancy profiles to the building simulations led to reduced energy consumption for artificial lighting. From simulations, he found manual control reduced energy consumption by up to 62%, while automatic control could achieve a further reduction of 50%. Although the occupancy model in Lightswitch-2002 has some randomness in its routine, the model is not capable of modelling the dynamic sequences of occupants throughout a year. The development of the dynamic occupancy model by Delff *et al.*[8] opens up an opportunity to evaluate the effect of the resolution of occupancy patterns on simulated artificial lighting demand. Resolution is important when using simulation programs, because simulation time increases with resolution. So the lowest resolution which still yields a correct result is of interest when evaluating the performance of a space on an annual basis. In this study the effect on artificial lighting demand was investigated by applying occupancy models of various resolutions to Climate-Based Daylight Modelling (CBDM). This was done by running annual simulations in RADIANCE and combining the illuminance levels used with various occupancy patterns and artificial lighting control.

2. Method

2.1 Annual simulation procedure

The simulations for daylight and artificial light availability were carried out using RADIANCE[21]. A daylight coefficient approach was applied in accordance with the three-phase method, which provides reliable and fast dynamic indoor illuminance simulations[22-24]. The sky simulated was the Perez all-weather sky discretised using the Reinhart division scheme subdivided into 2306 patches. The RADIANCE routine gendaylit created the sky based on the Perez all-weather model. However, gendaylit failed to produce the right output for some time steps at dusk and dawn. At these times, the illuminance was set to zero, assuming that it was night time. The illuminances obtained from Radiance were post-processed in matlab, where the data were corrected for daylight-saving time. The office hours from 6 am to 7 pm were investigated.

All calculations were carried out based on hourly and 2-minute direct normal and diffuse horizontal irradiance data. The 2-min irradiance data were generated from the hourly mean values from the Design Reference Year, DRY, for Copenhagen in accordance with the modified Skartveit-Olseth method developed by Walkenhorst *et al.*[25]. Iversen *et al.*[26] found that simulations of hourly means were just as good at estimating the daylight availability as simulations using a finer resolution generated from the modified Skartveith-Olseth method. However, in this study the dynamic behaviour of the occupants present was to be taken into account in the control systems for the artificial lighting, which is why the timestep-resolution was also set to be finer than hourly resolution.

2.2 Simulated room

In the present study, the indoor illuminance was simulated at two locations in the south-orientated room: one at the front, 1.5 m from the façade, and one at the back of the room, 4.5 m from the façade. Figure 1 shows a sketch of the test office. The reflectances *(r)* of the surfaces in the room were: r_{wall} = 0.62, $r_{ceiling}$ = 0.88 and r_{floor} = 0.11. The light transmission of the window system was 72%.

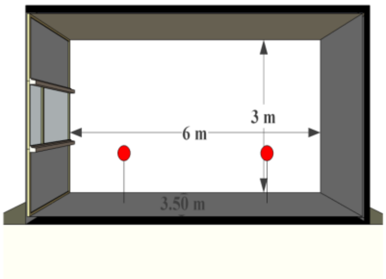


Figure 1 Sketch of the simulated room. Red dots indicate the location of sensor points

2.3 Scenarios

As Mardaljevic *et al*.[27] say, it is important that the designer does not only evaluate the performance of a building based on its predicted occupied period, because then opportunities to improve the daylight potential of the building might be missed. So the reference case for the simulation was an evaluation of daylight performance of a space with occupants present during the entire simulation period, followed by evaluations with dynamic occupancy models. In this way, the reference case represents a 'worst-case' scenario in terms of occupancy and energy consumption, because the occupant is always present. Furthermore, the artificial lighting demand was evaluated for 6 different scenarios (S) in a building zone where the occupancy profile was:
S1: constant for weekdays and weekends – occupants are always present

S2: based on the absence factor given in EN15193 (2007)[5]
S3: based on the absence factor estimated from the occupancy model
S4: an estimated annual mean presence, where the occupancy pattern follows the same profile each day throughout the year
S5: an estimated 1-hour mean presence, where the occupancy pattern varied for each occupied hour throughout the year
S6: a dynamic 2-min occupancy resolution, where the occupancy varied for each 2-min period throughout the year.

2.4 Metrics

The evaluation of lighting demand was based on lighting dependency (LD). LD defines the percentage of the occupied hours per year when electrical light was added to the lighting scene to maintain a minimum work plane illuminance threshold[26]. An LD of 100% represents a case where the lights are switched on for the entire working hours. This could be the case, for example, in the core zone of a building, where no daylight is present and no occupancy control is applied.

A continuous lighting dependency (LDcon) was also applied, where illuminance levels below the threshold value were included with a relative weight. [26]

The artificial lighting was measured in two zones – one at the front of the room and one at the back of the room. The total lighting demand of the room was then given as the average of the lighting dependency at the sensor points.

2.5 Statistical model

The occupancy model applied in this study was developed by Delff *et al*.[8]. The model is capable of modelling the dynamic sequences of presence for a typical occupant, and is based on the measured presence of occupants from an office building in San Francisco. Their paper gives a thorough description of the statistical model.

The model of the presence of one occupant is a hierarchical model. First, one of two models was selected with a given probability distribution. This resulted in either a low occupancy rate model or a high occupancy rate model. The need for two models was due to the many days when the occupancy rate was low, and Delff *et al*.[8] found that days with a low and days with a high occupancy rate could not be described by the same model.

The model is based on Markov chains. A Markov chain is a time series that meets the Markov condition that conditioned on the present state, the future is independent of the past[28]. If the transition probability matrix is constant, the Markov chain is said to be homogeneous. However, to model the time-varying presence of occupants, an inhomogeneous Markov chain (X_n) was used. Let n be a discrete time stamp, then the transition probabilities were introduced as:

$$p_{00}(n) := P(X_{n+1} = 0 | X_n = 0) \quad (1)$$
$$p_{11}(n) := P(X_{n+1} = 1 | X_n = 1) \quad (2)$$

where
$p_{10}(n) + p_{11}(n) = 1$ and $p_{01}(n) + p_{00}(n) = 1$ apply for each n

The varying transition probabilities, P_{00} and P_{11}, were fitted with generalised linear models with logit as the link function[29], this means:

$$logit(P_{00}) = \log\left(\frac{P_{00}(n)}{1-P_{00}(n)}\right) = Z_{0,n}\theta_0 \quad (3)$$
$$logit(P_{11}) = \log\left(\frac{P_{11}(n)}{1-P_{11}(n)}\right) = Z_{1,n}\theta_1 \quad (4)$$

$Z_{0,n}$ and $Z_{1,n}$ are the n'th rows of the design matrices Z_0 and Z_1, and they are given by:

$$Z_{0,n} = (1, B_{0,1}(u(n)), \dots, B_{0,Q}(u(n)), \Lambda_n) \quad (5)$$
$$Z_{1,n} = (1, B_{1,1}(u(n)), \dots, B_{1,Q}(u(n)), \Lambda_n) \quad (6)$$

Let $u(n)$ denote the time on the day for each point n, then $B_1(u(n)), \dots, B_Q(u(n))$ are the values of the Q basis splines at the point n. The splines are piece-wise third order polynomials.
Λ_n denotes exponential smoothing, which was added to the model. The exponential smoothing is given by:

$$\Lambda_n = \lambda X_n + (1-\lambda)\Lambda_{n-1}, \qquad \lambda \epsilon [0, 1] \quad (7)$$

The exponential smoothing improved the description of the dynamics of the sequences for each occupant. The exponential smoothing gives feedback to the transmission of probabilities. One could say that the filter represents a measure for how much an occupant worked in the recent past. If the occupant worked a lot, it is more likely that he/she will continue working.

3. Results

The first part presents an overview of the modelled presence of occupants, based on the statistical model described in the previous section. The second part presents the results of the lighting dependencies when the occupancy patterns are applied to the dynamic daylight simulations.

3.1 Modelled occupancy patterns

For the simulated period from 6 am to 7 pm, the total absence factor (F_A) in the modelled occupancy profiles was 0.63. The estimated annual mean presence and the confidence interval are shown in Figure 2.

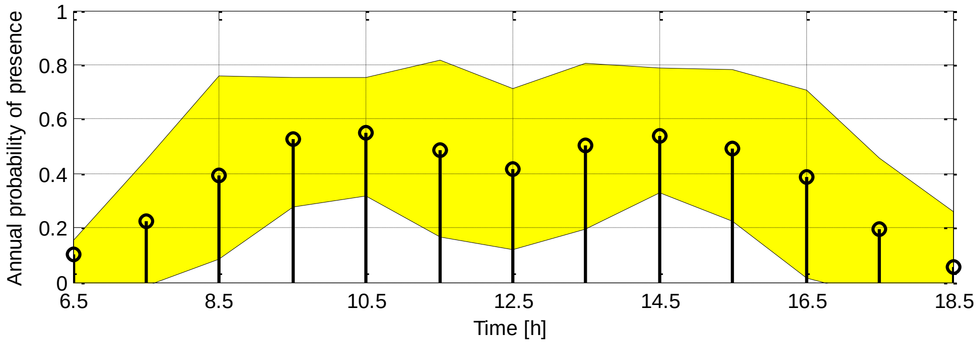


Figure 2 Estimated annual mean presence (S4) and confidence interval for 4 different occupants.

When the annual mean presence is applied in the daylight simulation, the occupancy profile is the same for every day of the year. However, in reality, the presence of occupants varies. Figure 3 shows the annual time-series for the hourly occupancy means for one occupant. A value of 1 indicates that the occupant is present for the entire hour, while 0 indicates that the occupant is absent during that specific hour. A value of 0.8 means that the occupant is present 80% of that hour.

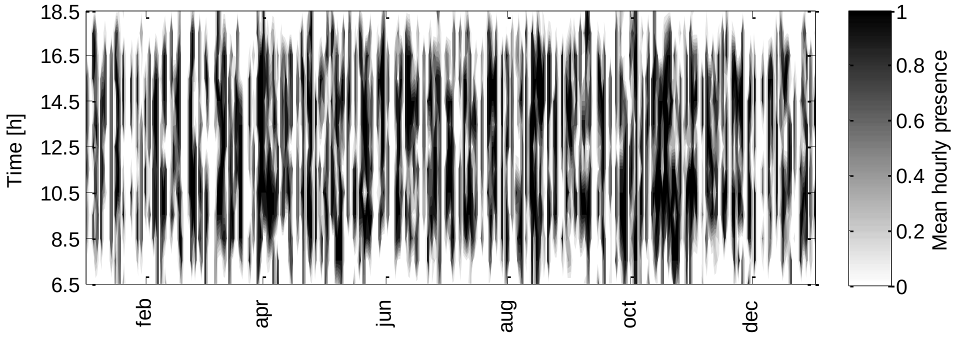


Figure 3 Annual hourly mean presence (S5) for one occupant

The output from the occupancy model can show the presence of occupants with a 2-min resolution. Figure 7 shows occupancy profiles for an entire year for one occupant. The black areas represent the presence of the occupant in the 2-min interval.

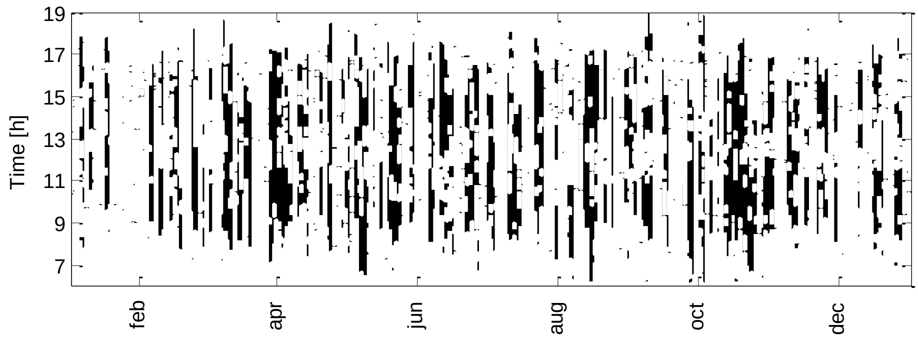


Figure 4 Annual 2-min presence of one occupant (S6). Presence is shown in black

3.2 Annual lighting dependencies and occupancy patterns

Figure 5 shows the annual artificial lighting demand for four scenarios: S1, S2, S3 and S6 (cf. 2.3) with automatic control (on/off) of the artificial lighting when the illuminance threshold is reached and continuous dimming (con) of the artificial lighting system.

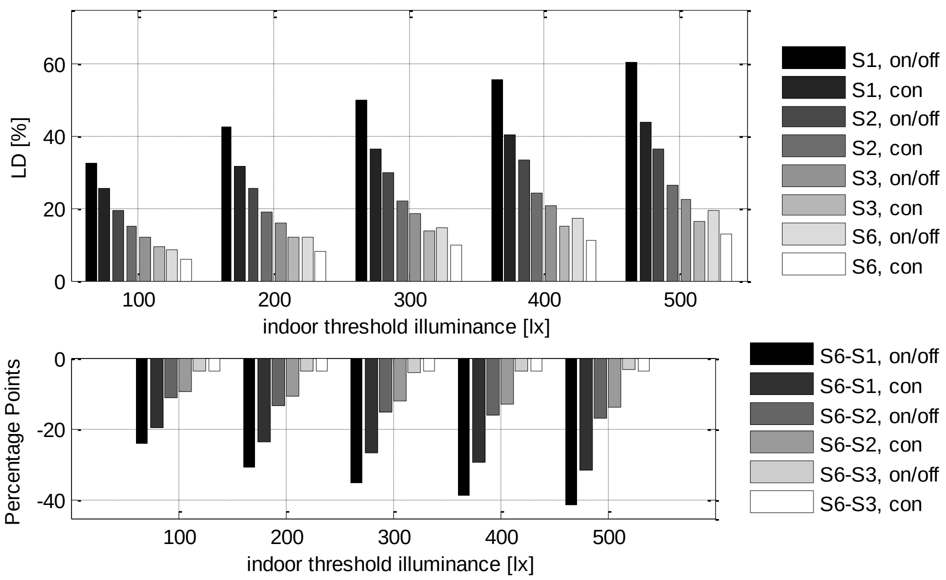


Figure 5 Upper panel: Lighting dependencies for on/off and continuous control of a lighting system: S1) with only daylight control, occupants always present; S2) with an absence factor of 0.40 as in EN15193 (2007)[6]; S3) absence factor of 0.63; and S6) with a dynamic 2-min occupancy profile. Lower panel: Difference in percentage points in relation to S6.

Not surprisingly, the lighting dependencies decreased when the presence of occupants was introduced in the daylight simulations. The reduction in lighting demand from Scenario 1, with the occupant always present, to Scenario 6, with the lights controlled on the basis of 2-min periods of occupancy, was in the range of 24–41% depending on the indoor threshold illuminance.
Applying the total absence factor of 0.63 (S3) overestimated the energy consumption for artificial lights by 4% compared to the dynamic occupancy profile (S6).

Figure 6 shows the lighting dependencies for the dynamic simulations when the 2-min resolution (S6) and hourly mean resolution (S5) are applied in terms of both occupancy profiles and weather data, as well as for a case where the occupancy profile was the annual mean (S4) and the weather data were of hourly mean resolution.
The differences in artificial lighting demand for the 3 scenarios were in the range of 1% (Figure 6, Lower panel) compared to that for a lighting system which was always on.

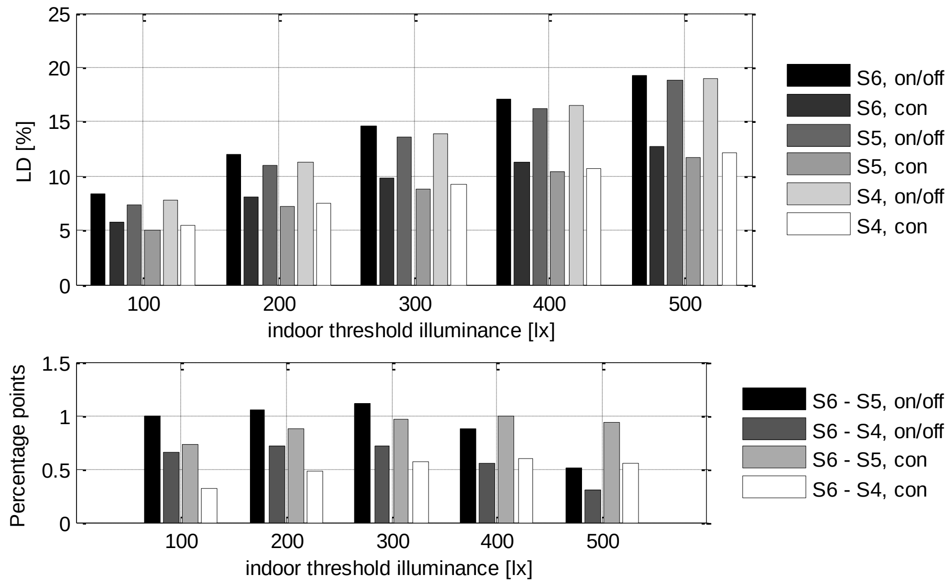
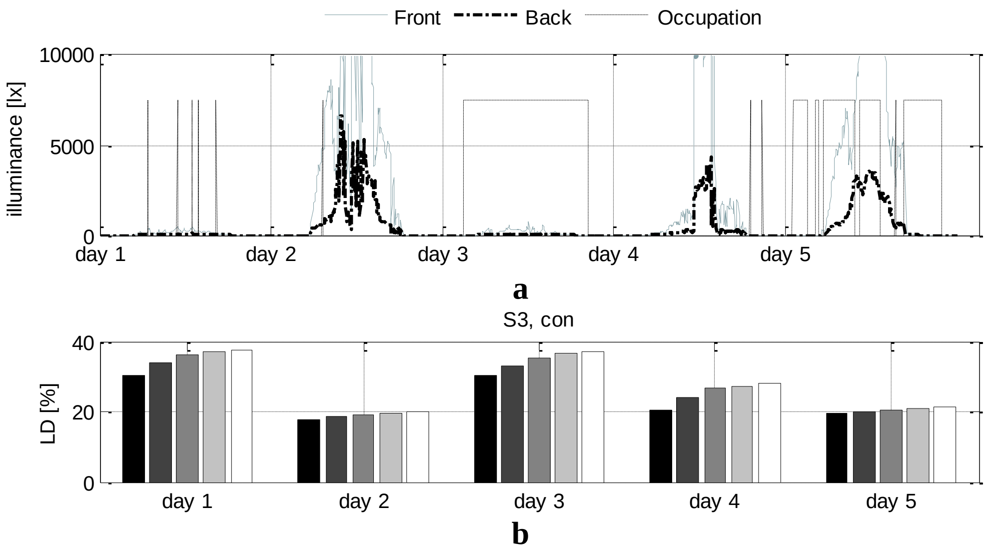


Figure 6 Upper panel: Lighting dependencies for the dynamic simulations when resolutions of 2-min (S6), hourly mean (S5), and annual mean (S4) are applied to occupancy profiles. Lower panel: The differences in percentage points for 2-min resolution and hourly mean and annual mean occupancy.

3.3 Energy demand for 5 days in January

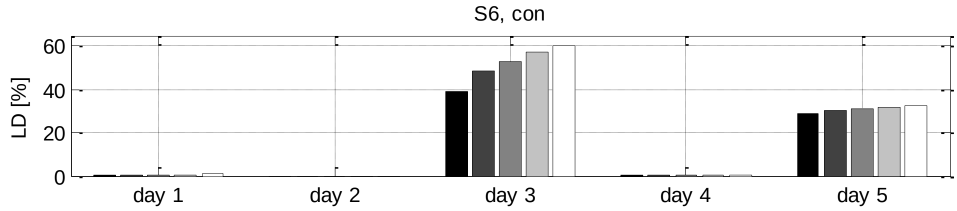
Figure 7 explores the lighting demand for artificial lighting with continuous dimming for a 5-day period from January 12th to January 16th inclusive. The presence of occupants was simulated in terms of either an average absence factor (S3) or a dynamic 2-min occupancy model (S6).

In Figure 7a, the presence of the occupant is indicated by the green line. On Day 3, the occupant was present the entire working day; on Day 5, the occupant was present most of the working day with short intervals of absence; whereas on Days 1, 2 and 4, the occupant was only present for very short intervals. The illuminance levels in the working plane at the front and at the back of the room are shown with black and red lines respectively. It can be seen that Days 1 and 3 were overcast days, whereas Days 2, 4 and 5 were days with direct sun. When continuous dimming of the artificial lighting was combined with the presence of occupants, either S3 or S6 resulted in the lighting demand for each day as seen in the two middle figures. The lighting demand in Figure 7b assumes that the occupant was present according to an absence factor of 0.63. For this scenario the artificial lighting was switched on if the illuminance level could not be maintained by daylight alone. This is what can be seen in Figure 7b, where the artificial lighting is switched on every day. For the overcast days (1 and 3) the lighting demand is around 30%, whereas for the days with direct sun, the lighting demand is around 20%. For the days with direct sun, the illuminance level at the sensor points is mostly higher than the artificial lighting threshold, and the lighting demand of 20% is a result of the hours of the day with no sun, when the artificial lighting is switched on. Figure 7c shows the occupant present in accordance with the dynamic 2-min occupancy model. Here, the lights were only switched on when the occupant was present. So, almost no lighting demand is seen on Days 1, 2 and 4, whereas a high lighting demand (40-60%) is seen for day 3. Figure 7d shows the average lighting demand over the 5 days. If we explore this period, it can be seen that applying an average absence factor results in 10% higher lighting demand than applying the dynamic occupancy profile.

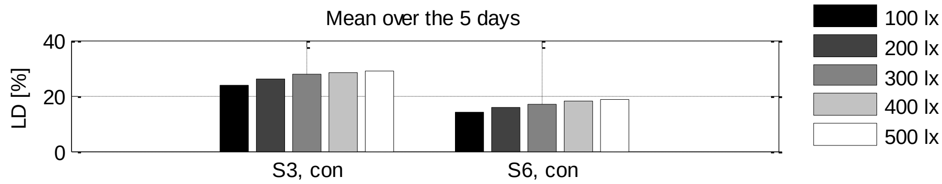


a

b



c



d

Figure 7 a) Presence of occupants and illuminance levels at the room sensor points. b) Lighting demand at illuminance thresholds from 100–500 lx with continuous dimming (con) for each of the 5 days with occupancy based on absence factor (S3), c) with occupancy based on the presence of occupants (S6), and d) for average lighting demand over the 5 days for the two scenarios S3 and S6.

4. Discussion

This study showed that no real difference is observed in the lighting dependency of an office with automatic control of the lights based on daylight and occupancy when Climate-Based Daylight Modelling is applied and the lighting demand is evaluated on the basis of an average occupancy profile with the same distribution for every day of the year as opposed to using a more dynamic occupancy profile of hourly resolution or 2-min resolution of occupancy with a minimum of 20 min absence (Figure 6).
This means that, if the control of artificial lights based on occupancy and daylight level is automatic, the same occupancy pattern for every day of the year applied with hourly resolution will yield accurate estimations of the artificial lighting demand.

The lighting demand is overestimated by 4% if an average absence factor is applied (Figure 5, comparing Scenarios 3 and 4), and the evaluation of the saving potential is therefore slightly conservative. This result reflects the fact that when an evaluation is made on an annual basis, the occupancy model and the daylight availability will tend to converge to the same value independent of the data resolution. The finer dynamics which can be seen in some of the models, e.g. when simulations use a shorter time step, will be eaten up, by the large number of simulation time steps, and converge to the same prediction as when more simplified methods are used. This can be exemplified by looking at Figure 7, where large variations can be seen between different days, and Figure 6, where the differences vanish when the evaluation is on an annual basis.

If the aim of a simulation is to investigate the finer dynamics of a lighting system, a solar shading control, or a ventilation system, detailed knowledge about the presence of occupants is important and useful for the design of the systems. The limitation in using the annual mean presence of occupants is that the annual mean profile does not include peak loads. This might induce simulation errors when the energy demand for the systems is to be predicted because the number of occupants in a zone affects for instance the zone's cooling and ventilation load, which determines the amount of conditioned air to be delivered to that zone to maintain thermal comfort and air quality. For an artificial lighting system, the dynamics of each occupant in a zone is of relevance when exploring the potential and control of occupant-specified lighting, as in the study by Wen *et al.*[30,31]. They investigated a lighting system containing wireless individually controllable ballasts with closed control loops for occupant-specified lighting. This meant that each occupant's personal and often diverse preference in terms of illuminance level could be met. In this study, the artificial lighting was measured in two zones to maintain a given horizontal illuminance threshold for the entire space. For the occupancy-based control, the artificial lighting responded to one occupancy profile. However, to fully exploit the potential of dynamic occupancy profiles, one topic for future research will be to extend the simulations and controls applied for the research in this paper with occupant-specified lighting.

This study used simple immediate on/off control of the artificial light or continuous dimming depending on daylight availability and the presence of occupants. More sophisticated control, such as introducing inertia to the lighting systems as delays, or dimming the lights before they switch off, could be investigated and might give different results. It should be stressed that the dynamic occupancy profiles used here did not include absences 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 be measurements that record presence alone. This would mean that shorter absences, like going for a coffee, would have been included.

Not surprisingly, the results show that introducing on/off or continuous daylight control in the perimeter areas of a day-lit building (Figure 5, Scenario 1) reduces the energy consumption by up to 70% compared to a reference case where the lights are always on, as could be the case, for example, in the core building zone. The addition of automatic occupancy sensing control reduces energy consumption by another 25–50% depending on the indoor threshold illuminance level (Figure 5, Scenarios 3 and 4). These reductions in artificial lighting demand were also reported in the PhD study of Bourgeois (2005)[14]. Here he demonstrated that 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%, a figure which is reduced by another 50% when automatic control is used.

5. Conclusion

The key finding from this study was that no real difference in the simulated annual artificial lighting demand was observed when the same occupancy profile was used for every day of the year as opposed to a dynamic occupancy profile, where the probability of presence varied for each day. Furthermore, it was found that the annual artificial lighting demand was evaluated slightly conservatively (4% higher) when the mean absence factor of a measured building was used as opposed to applying dynamic occupancy profiles estimated for the same building. This means that the use of an average absence factor will yield accurate results for the evaluation of annual artificial lighting demand based on the presence of occupants and automatic on/off or continuous control of the artificial lights.

Funding

The work was supported by the Technical University of Denmark and Esbensen Consultants A/S.

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The thesis proposes a simple framework to aid urban designers in the daylighting aspect of the decision-making process in the early stages of design when the outline of the city is defined.
The research showed that it is sufficient to simulate the annual daylight availability based on hourly-mean irradiance values opposed to applying 1-min resolution. From the investigations made on the impact of occupancy profiles, it was found that applying an absence factor, as opposed to simulating the dynamic presence of occupants, also made little difference to the annual simulation outcome.

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ISBN: 9788778773388
ISSN: 1601-2917