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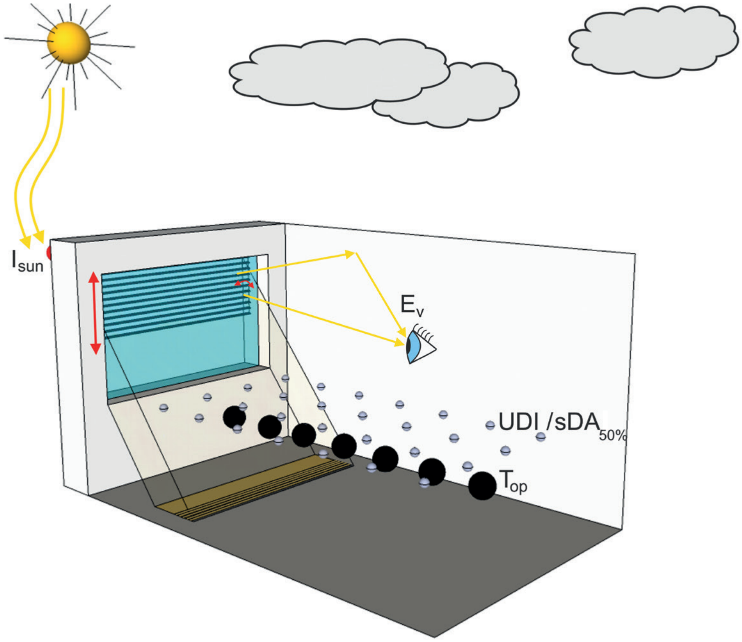

DESIGN METHODOLOGY AND CRITERIA FOR DAYLIGHT AND THERMAL COMFORT IN NEARLYZERO ENERGY OFFICE BUILDINGS IN NORDIC CLIMATE

BY
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AALBORG UNIVERSITY
DENMARK

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ENGLISH SUMMARY

The objective of this thesis was to facilitate an integrated building design process applicable to office buildings in Nordic climate with respect to thermal comfort, daylighting and energy use. The thesis is divided into three main parts.

Part I contains a literature review carried out to investigate if the present thermal comfort and daylight design practices constitute any obstacle for conducting an integrated design. Based on findings in the literature it was suggested that modelling of mean radiant temperature (MRT) should be improved by considering the location in the room, accounting for both long-wave and short-wave radiation. With respect to daylight design it was suggested that static daylight calculations should be replaced by dynamic ones and that climate-based measures should be used in the evaluation of daylight supply and glare. Examples of measures for daylight supply are given in the literature (e.g. UDI and DA). Candidates for glare might be horizontal or vertical illuminance. Additionally, it was investigated how solar shading control should be modelled, since the fenestration system and its control is a crucial link between the thermal and daylighting performance. It was suggested that shading control strategies preferably should be multivariable and incorporate variables related to interior conditions. It was proposed that the tilt angle should be considered as a control variable for shading with blinds. Furthermore, it was found that more knowledge is needed regarding user acceptance of automatic solar shading controls.

Part II describes verification of improved models of MRT and daylighting implemented into the simulation tool IDA ICE, which is one of the steps to make the integrated design method practically applicable for building designers. The new MRT model takes short-wave radiation hitting the occupant into account. The new daylight feature utilises the Radiance engine and the climate-based three-phase method, which arranges for daylight calculations to be conducted based on the same underlying boundary conditions as used in thermal comfort and energy calculations. Further, Part II describes the results from an occupant survey carried out to investigate occupants preferences with respect to use of automatically controlled venetian blinds and their sensation of glare in an office work environment. The results from the occupant survey indicated that views to the outside were an important factor for the occupants and it confirmed that the tilt angle should be incorporated as a control variable in the shading strategy. The results further indicated that there was a statistically significant correlation between both vertical eye illuminance and horizontal illuminance at the desk and the occupants' perception of glare. Based on this study, threshold of 1700 lux vertical eye illuminance at the occupant position and 1900-2100 lux horizontal at the desk was found to be reasonable for avoiding excess glare perceptions in perimeter zones.

Part II is ended with a proposal for a solar shading strategy suitable for office buildings in cold climates. The proposed strategy is based on a modified version of a control algorithm developed within the Norwegian R&D project "*Glazed facades keeping what we promise*". The strategy is improved with findings from the literature and results from the occupant survey by utilising tilt angle as a control variable as well as applying vertical illuminance of 1700 lux as activation criterion. Full-scale measurements during both winter and summer conditions along with annual simulations verified high energy, thermal comfort and visual performance; resulting in better performance than with the use of a conventional strategy where the shading is activated according to external irradiance with closed slats in activated position.

Part III comprises an overall conclusion and suggestions for future work. It is indicated that the proposed integrated design might have implications on the traditional area of responsibility among design disciplines within a building design.

DANSK RESUME

Formålet med denne afhandling var at tilrættelegge for en integreret designmetode med hensyn til termisk komfort, dagslys og energibrug, egnet for anvendelse i design af kontorbygninger i nordisk klima. Afhandlingen er delt ind i tre hoveddele.

Del I omfatter et litteraturstudie gennemføret med det formål at undersøge, om nuværende praksis for termisk komfort og dagslysdesign indeholder forhindringer i forhold til at udføre integreret design. Baseret på fund i litteraturen er der foreslået, at middelstrålingstemperaturen (MRT) bør modelleres som funktion af placering i rummet med hensyntagen til effekten af både lang- og kortbølget stråling. Med hensyn til dagslysdesign er der foreslået, at statiske dagslysberegninger bør erstattes med dynamiske for at dagslysberegninger kan gennemføres baseret på de samme rammebetingelser som benyttes i energi og termisk komfort beregninger. Der konkluderes med at klimabaserede mål bør bruges i evaluering af både dagslystilgang og blænding. Litteraturen indeholder forslag til mål for dagslystilgang (f.eks. UDI og DA), mens kandidater for blænding f.eks. kan være horisontal eller vertikal illuminans. I tillæg er det undersøgt, hvordan kontrol af solafskærmning bør modelleres i bygningsdesign, siden vinduer og deres kontrol er et vigtigt link mellem ydelsen på termisk komfort og dagslys. Det er indikeret, at kontrolstrategier for solafskærmning med fordel kan være multivariabel og benytte variabler relatert til indendørs forhold. I tillæg er der foreslået at lamelvinkelen bør implementeres som styringsvariabel, når persienner anvendes. Der påpeges desuden et behov for mere kendskab til brugernes accept for anvendelse af automatiserede solafskærmingssystemer.

Del II beskriver verifisering og implementering af forbedret MRT- og dagslysmodel i simuleringsprogrammet IDA ICE. Disse implementeringer er et tiltag for at gøre den integrerede designmetode praktisk brugbar for bygningsdesignere. Den nye MRT-model inkluderer effekten af kortbølget stråling. Den klimabaserede Radiance tre-fase metode er implementeret som ny dagslysmodell. Videre beskriver del II en brugerundersøgelse, gennemføret for at undersøge brugernes præferencer i forhold til anvendelse af automatisk kontrollerede persienner samt deres oplevelse af blænding i et kontormiljø. Resultaterne fra brugerundersøgelsen viste, at udsyn er en vigtig faktor for brugerne, og bekræftet, at lamelvinklen bør indgå som en kontrolvariabel for solskærmingen. Videre viste brugerundersøgelsen, at der var en signifikant korrelation mellem både vertikal øjenilluminans og horisontal illuminans ved arbejdsbordet og brugernes oplevelse af blænding. Baseret på dette studium blev grænseværdier på henholdsvis 1700 lux og 1900-2100 lux fundet som fornuftige for at undgå overdrevet blænding i perimeterzonen.

Del II ender ud i et forslag til kontrolstrategi for solafskærmning til brug i kontorbygninger i nordisk klima. Den foreslåede strategi er baseret på en modificeret version af en styringsalgoritme udviklet i det norske F&U projekt ”*Fasader i glass som holder hva vi lover*”. Strategien er forbedret med fund fra litteraturen og resultater fra brugerundersøgelsen, hvor lamelvinkelen benyttes som en styringsvariabel samt vertical øje illuminans med grænseverdi på 1700 lux benyttes som lukkekriterie. Fuldskalamålinger under vinter- og sommerforhold samt årssimuleringer verifiserede tilfredsstillende ydelse både med tanke på termisk og visuel komfort og energibrug, bedre ydelse end ved brug af en konventionel strategi med lukkede lameller aktiveret iht. udvendig solirradians.

Del III opsummerer en overordnet konklusion og foreslår fremtidigt arbejde. Det er indikeret, at den foreslåede integrerede designmetode kan have implikationer på den traditionelle ansvarsfordeling indenfor bygningsdesign.

ACKNOWLEDGEMENTS

This PhD project was mainly financed by stpend from the Norwegian Ministry of Education and Research and this support is greatly appreciated.

I owe a major thank to my supervisors Per Heiselberg and Ida Bryn for giving me the opportunity to carry out this project. Your support and reflections on the work throughout the long-lasting process has been priceless. Thank you both so much!

I appreciate the support of all my colleagues both at Oslo and Akershus University College of Applied Science (HiOA) and Aalborg University (AAU). Major thanks are especially directed towards Vivi Sødergaard at AAU for copy editing the journal articles as well as towards Hicham Johra, Mingzhe Liu, Jérôme Le Dréau and Rasmus Lund Jensen at AAU for their assistance and guidance throughout the planning and execution of the measurements in the Cube. Further, I'm thankful for the assistance by Silje N. Andressen and Silje Bjørkeng, master students at HiOA, for carrying out measurements in test case 1. Thanks are also due to the building owners and plant managers of the test-cases for their cooperation and help.

With respect to the occupant survey, special thanks are sent out to all the voluntary participants. Additionally, valuable advices by Ásta Logadóttir at SBi with respect to conducting an occupant survey as well as advices given in correspondence with Jens Christoffersen at Velux A/S and Jan Wienold at École Polytechnique Fédérale de Lausanne are hereby gratefully acknowledged. Further, I would like to thank Hugo Lewi Hammer at HiOA for valuable information, support and help with the statistical analysis.

I would also like to express my gratitude to Per Sahlin both for showing interest in my work and for welcoming me to an extended visit at Equa Simulation AB in November–December 2014. I'm sincerely grateful for Grigori Grozman at Equa AB who has been responsible for implementation of suggested models into IDA ICE, –I really appreciated our cooperation. Further, I would like to thank everybody at Equa Simulation AB for taking so good care of me during my stay in Stockholm.

Major thanks are also directed towards Erichsen & Horgen AS for technical, social and economic support throughout this project. I'm looking forward to be a part of this great firm and put the knowledge gained through this PhD project into practice.

At last, but not least I would like to thank my family and friends for all their support and understanding during this four and a half year. I'm looking forward to spend more time with you in the future. Søren, you deserve a special thank for holding out with me during this never-ending roller coaster journey.

FOREWORD

The work presented in this thesis has been carried out from September 2011 to March 2016 supervised by Professor Per Heiselberg at Aalborg University and Professor II Ida Bryn at Oslo and Akershus University College of Applied Science.

The aim of the PhD project was to arrange for an integrated building design with respect to thermal comfort, daylighting and energy use. The main substance of such an integrated design is for predicted thermal comfort, daylight and energy use to be based on the same underlying assumptions, as illustrated in Figure I.

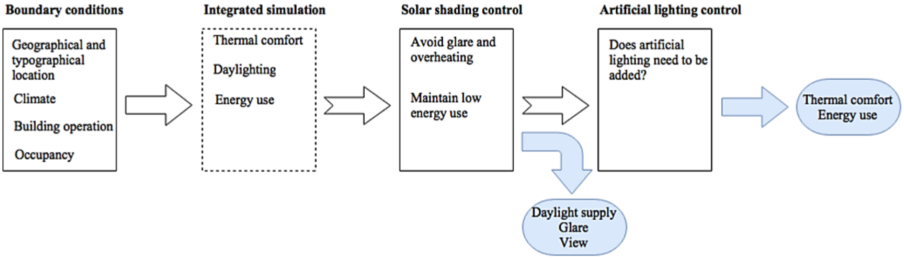


Figure I: Process of the proposed integrated design.

The work is limited mainly to focus on the calculation methods and evaluation criteria for thermal comfort and daylighting. Optimization routines for building physical properties are not considered; neither are the presence of skylights and atriums. The offered integrated design is first and foremost accommodated for office buildings in Nordic climate. Still, the proposed calculation methodology is assessed to be rather general. Nevertheless, suggested performance indices may not be adequate for buildings where the adaptive options and expectations towards the environment are significantly different than at a work station.

The work is carried out from a practical point of view where the question “Is this practical applicable in real building design?” has been an important guideline. The detail level is accordingly on a fairly superior level and the main interest has been to explore the interaction between thermal comfort, daylighting and energy use, – not the exact physiological human reaction to the thermal and visual environment.

The thesis is mainly based on a collection of six articles; see the list of publications. Parts of the papers are used directly or indirectly in the extended summary. References to the articles are given throughout the extended summary and further information is found in the appendices.

I hope you find the reading interesting. Enjoy!

LIST OF PUBLICATIONS

Journal papers

Paper I: Karlsen L., Heiselberg P. and Bryn I., *Occupant satisfaction with two blind control strategies: Slats closed and slats in cut-off position*. Solar Energy, 2015. 115(0): p. 166-179.

Paper II: Karlsen L., Heiselberg P., Bryn I., and Johra H., *Verification of simple illuminance based measures for indication of discomfort glare from windows*. Building and Environment, 2015. 92: p. 615-626.

Paper III: Karlsen L., Heiselberg P., Bryn I. and Johra H, *Solar shading control strategy for office buildings in cold climate*, Energy and Buildings, 2016 118, p. 316-328.

Conference papers

Paper IV: Karlsen, L., Grozman G., Heiselberg P. and Bryn I., *Operative temperature and thermal comfort in the sun – Implementation and verification of a model for IDA ICE*, in *Indoor Air*. 2014: Hong Kong, China.

Paper V: Karlsen, L., Heiselberg P., and Bryn I.. *Implementation of daylight as part of the integrated design of commercial buildings*. In *World Sustainable Building Conference*. 2014: Barcelona, Spain.

Paper VI: Karlsen, L., Grozman G., Heiselberg P. and Bryn I., *Integrated design of daylight, thermal comfort and energy demand with use of IDA ICE*, in *Passivhus Norden - Sustainable Cities and Buildings*. 2015: Copenhagen, Denmark.

Other publications

Bryn, I., Petersen, A. and Karlsen, L. *Tiltak mot høye temperaturer i passivhus Del II - litteraturstudie, forslag til regelverk og standarder samt videre arbeide* (In Norwegian). 2012. Author of the litterature review. *http://erichsen-horgen.no/resources/filer/publikasjoner/2012-Tiltak_mot_hoye_temperaturer_i_passivhus-Del_II.pdf*

Karlsen, L., Gedsø S., and Petersen A., *Dagslys i moderne bygg*, in *Glass & Fasade*. 2013. 03: p. 18-20. (In Norwegian)

Bryn, I., Bjørnulf A., Gedsø S., and Karlsen L., *Glass i fasader og solskjerming*. 2014. (In Norwegian). Author on the topic of daylight. *http://www.erichsen-horgen.no/resources/Utgitt-veileder-Glass-i-fasader-og-Solskjerming.pdf*

This thesis has been submitted for assessment in partial fulfillment of the PhD degree. The thesis is based on the submitted or published scientific papers and publications listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty.

TABLE OF CONTENTS

NOMENCLATURE

A_{eff}	effective radiation area	m^2
A_p	projected area	m^2
d	profile angle of the sun	°
E_h	horizontal illuminance at the desk	lux
E_v	vertical eye illuminance	lux
f_p	projected area factor	-
$F_{S\rightarrow j}$	view factor from surface j to S	-
h_c	convective heat transfer coefficient	W/m^2K
h_r	radiative heat transfer coefficient	W/m^2K
I^j_{diffuse}	diffuse radiation intensity from surface *j*	W/m^2
I^i_{direct}	direct radiation intensity of the beam from opening *i*	W/m^2
I_{sun}	total irradiation from sun	W/m^2
L_b	Luminance background	cd/m^2
L_s	luminance source	cd/m^2
s	spacing between the solar blind slats	m
t_a	air temperature	˚C
t_{op}	operative temperature	˚C
t_{mr}	mean radiant temperature	˚C
T_{mrt}	MRT of an irradiated person	K
T_{umrt}	hypothetical MRT of an unirradiated person	K
w	width of the solar blind slats	m
q_{ir}	radiant intensity	W/m^2

Greek symbols

α	solar altitude angle	°
α_{ir}	short-wave absorptance	-
$\beta_{cut-off}$	cut-off angle	°
ε_p	emittance of the subject	-
σ	Stefan-Boltzmann constant	W/m^2K^4
Ω_s	solid angle subtended by the glare source modified by Guth's position index	sr
ω_s	Solid angle subtended by the glare source	sr
γ	solar surface azimuth	°

Abbreviations

BCD	Borderline between comfort and discomfort	DF	Daylight factor
BSDF	Bidirectional scattering distribution functions	DGI	Daylight glare index
CBDM	Climate-based daylight modelling	DGP	Daylight glare probability
CBDm	Climate-based daylight metrics	MC	Monte Carlo
CGI	CIE glare index	MRT	Mean radiant temperature
CIE	Commission Internationale de l'Eclairage	PMV	Predicted mean vote
DA	Daylight autonomy	PPD	Predicted percentage dissatisfied
$sDA_{300/50\%}$	Spatial daylight autonomy 300/50%	UDI	Useful Daylight Illuminance

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Operation of buildings account for approximately 40 % of the total energy use in Europe [1]. Therefore, it is evident that the building sector needs special attention when considering national and global energy reduction in order to obtain a sustainable development. In 2002 the European Union (EU) adopted the Energy Performance of Buildings Directive (EPBD) with the purpose of increase the energy efficiency of buildings [2]. EU member states are obliged to implement the directive in their regulatory requirements. Additionally, Norway has implemented EPBD as part of the European Economic Area (EEA) [3]. A revised version of EPBD came into force in 2010, EPBD-recast. EPBD-recast require all new buildings to be nearly zero-energy buildings after 2020 [4].

Strict energy requirements, as a consequence of the EPBD, put a significant pressure on the building sector to design and construct energy efficient buildings. However, it is additionally extremely important to remember that buildings are constructed to house occupants, shelter them from the outdoor conditions and give them a healthy and comfortable environment. Use of energy is only a consequence of fulfilling this task. It is also essential to keep in mind that people spend a major part of their time indoor, –up to 90 % [5]. With respect to a working environment, it is moreover of interest to notice that research indicates correlations between indoor environment quality and occupant productivity [6-16]. Productivity is an important factor for most organisations in developed countries, since salaries of office workers are much higher than the operational costs of a building [17]. EPBD acknowledge the importance of indoor environment and states that it is not possible to fulfil the energy performance requirements by reducing the indoor comfort [4].

The façade is a determining factor for indoor environment and energy use of a building. It may, however, be a climatic challenge to design facades, especially in relation to daylight and thermal conditions due to the fact that an initiative to improve one aspect may worsen another aspect. Figure 1 gives an illustration of how daylight, thermal comfort and energy aspects influence each other in a complex manner. This indicates the need for an integrated design method in order to obtain the optimal balance of low energy use and sufficient thermal and visual comfort. It is highly agreed that use of numerical simulations are appropriate within such an integrated building design, in order to carry out multiple-view assessments and support design decisions in advance of the construction [18-20].

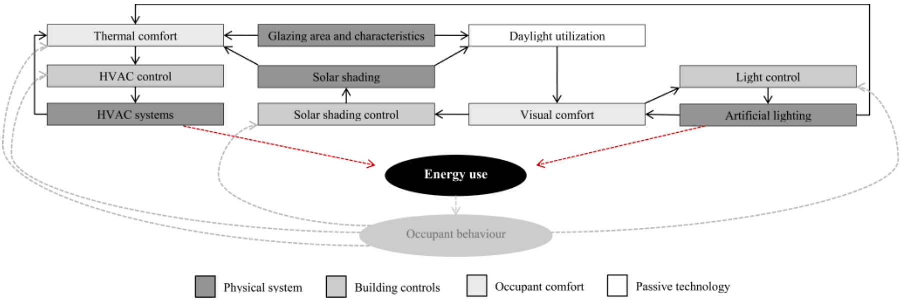


Figure 1: Interaction of daylight, thermal comfort and energy aspects within a building.

As illustrated in Figure 1, the link between thermal and lighting performance is the fenestration system. The optical and thermal properties of the fenestration system and its associated control are therefore critical factors within an integrated design [20]. During the last two decades there has been a trend towards extensively glazed facades, especially for new commercial buildings. It is a common belief that these buildings have a very high daylight supply. However, extensive daylight supply has its backside, as glare and overheating might be a huge concern. Unfortunately, the glare problems are rarely assessed in the building design, which might be a result of the lack of an internationally accepted measure to evaluate glare from windows and/or solar shadings at the present time [21, 22]. Accordingly, a very common scenario in highly glazed buildings is seeing blinds down and lights on [23, 24].

Thermal properties of glazed facades are relatively poor compared to opaque sections of the façade. A theoretical study of office buildings in Sweden consider glazed facades from an energy perspective, and illustrate that buildings with fully glazed facades are likely to consume more energy for both heating and cooling than buildings with a 30 % window-to-wall-area [25]. Besides the energy challenge of highly glazed facades, it may be challenging to obtain a satisfying thermal environment in close-range of glazed façades, due to e.g. cold or warm radiation and/or occurrence of downdraft [26, 27]. In case such phenomenon occurs, it is expected that occupants would take action to reduce or avoid discomfort by for instance turn on heating/cooling and/or activate the solar shading [23, 28, 29]. These solutions may, however, result in increased energy use for heating, cooling and artificial lighting, – higher than predicted in the project planning phase.

Artificial lighting make up for 15–30 % of the electricity consumption of office buildings in Nordic climate [30, 31]. Wise use of natural daylight in combination with intelligent control of artificial lighting can reduce the electrical use for lighting [32-36]. Moreover, due to the high luminous efficiency of diffuse daylight (≈100–130 lm/W) [37], daylight harvesting may in addition reduce the thermal gain from lighting and contribute to reduction in the cooling load. From a perspective of energy use, there is a growing need for documentation of daylight and daylight control from the early building design stage both in order to document the energy saving potential in case of daylight utilization as well as the need for solar shading to avoid glare. Yet, according to Reinhart [38] the treatment of blinds may be a major source of error for overoptimistic energy savings predictions in present daylight calculations. This is due to the fact that static daylight calculations under overcast sky still are dominating, where it is assumed that the blinds are retracted all year around [38]. Kuhn [39] suggests that treatment of blinds may be a source of error also within energy and thermal comfort design. He refers to experience of several buildings where overheating occurs, as the building designers have assumed completely closed slats for venetian blinds in activated position in their calculations, which may be unrealistic due to the occupants desire of view.

The question has arisen if the lack of realism and commonly simplifications applied in building design, in addition to the absence of consistency in the underlying assumptions in energy, thermal comfort and daylighting predictions may hinder the development of the high performing buildings we want for the future.

1.2 OBJECTIVE AND RESEARCH QUESTIONS

This PhD thesis is based on the fact that there is a lack of consistency in the building design with respect to thermal comfort, daylighting and energy use. The objective of this project is to arrange for a more holistic design process where the predicted thermal comfort, daylighting and energy use are based on the same underlying assumptions. It is further an aim to make the integrated design process practical applicable for engineers in Nordic countries within in the field of energy and indoor environment of buildings. The following research questions will be answered to support this superior aim.

1. How are thermal comfort and daylight modelled within building design and which evaluation criteria are used for assessment of thermal comfort and daylight quality?
    a. Do these models and evaluation criteria constitute any obstacle for conducting integrated design?
    b. Are there other models and/or evaluation criteria which may be more suitable for integrated design?
2. How should use of solar shading be accounted for within an integrated building design?
    a. What are suitable criteria for activation of solar shading for obtaining satisfying thermal and visual comfort as well as a low energy use within an office environment?
    b. What are important factors with respect to occupants' satisfaction with automatically controlled solar shadings?

1.3 THESIS OUTLINE

This thesis is divided into three parts. Part I incorporates a literature review with the aim to cover research question 1 and to a certain degree question 2. Part II describes two test cases used for verification of proposed models for thermal comfort and daylight calculations to be used within building design. Besides, it includes the methodology and results from an occupant survey carried out to indicate occupants' preferences with regard to use of solar shading and their sensation of glare in an office like work environment. Part II ends with a suggestion for solar shading control suited for Nordic climate, with the aim to cover research question 2. Part III contains an overall discussion and conclusion where the work is put in perspective.

PART I – LITERATURE REVIEW

This part presents a literature review regarding thermal comfort, daylighting and use of solar shading within building design. The intention with this chapter is to answer research question 1 and to a certain degree question 2 in order to uncover where it is appropriate to concentrate the further effort of research for this thesis.

The more I learn, the more I realize how much I don't know…
–Albert Einstein

CHAPTER 2. THERMAL COMFORT

Thermal comfort is defined as that condition of mind where the human is satisfied with the thermal environment and do not require the environment to be either warmer or colder. These comfort conditions are, however, strongly individual and it is impossible to satisfy everybody at the same time [40]. So, the goal in present building design is to satisfy as many as possible or accept a maximum percentage dissatisfied occupants. However, is this goal ambitious enough? Or should we design buildings where thermal comfort at least may be obtained at all workstations?

There are three mechanisms influencing how people perceive their own thermal comfort; physical, physiological and psychological. At the present time, two principal directions in the science of thermal comfort exist [41-43]. One direction is based on physical and physiological theories and the heat balance between the human body and its environment. The other is based on psychological theories and the assumption that people are adaptable to the thermal environment as well as it is assumed that the expectations to the thermal environment may influence the thermal perception. Sophisticated analytical, empirical and/or statistical derived models exist both within the heat balance [40, 44-46] and the adaptive thermal comfort approach [47-51]. Still, in practise operative temperature is often used as an indicator to assess thermal comfort within building design, which might be due to operative temperature requirements in various national guidelines, e.g. [52-54].

2.1 OPERATIVE TEMPERATURE

Operative temperature is defined as the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the real non uniform environment [55]. Numerically the operative temperature is the average of the air temperature (t_a) and mean radiant temperature (MRT, t_{mr}), weighted by the convective (h_c) and radiative (h_r) heat transfer coefficients respectively [56], see equation 1.

$$t_o = \frac{h_c \cdot t_a + h_r \cdot t_{mr}}{h_c + h_r} \qquad (1)$$

The MRT of a person is often rather difficult to determine [40], which might be the reason why simulation programs often apply various kinds of simplifications to establish this parameter. Typical simplifications are for instance to simplify the shape of the human body [57], calculate the MRT as the mean temperature of all the surrounding surface areas [40] or to neglect the contribution of short-wave radiation on the human body, e.g. arising from solar radiation [58, 59]. Simplifying the shape of the human body can often be justified for most realistic situations within building design, both since the posture of a person commonly is unknown as well as studies have shown that e.g. the shape of a sphere match quite well for seated persons, while it might overestimate the influence of the ceiling and floor for standing persons [57].The latter simplifications are, however, more crude and might lead to very wrong estimations of MRT of a person at a specific position. This is especially true when considering modern office buildings where it is common with open plan layouts and extensively glazed façades, whereas both long and short-wave radiation might greatly affect the occupants' thermal comfort as well as major variation in MRT throughout the room might occur. It is obvious that if the MRT is wrongly estimated this leads to wrong estimations of operative temperature which further might contribute to directly misleading results of the thermal comfort analysis.

In order to be able to predict the variation in MRT of a person as a function of the location due to long-wave radiation, it has to be calculated from surrounding surface temperatures, emmisivities of the surfaces and view factors between the surfaces and the person. Such models exist in sufficiently detailed building simulation programs, e.g. [60]. Yet, the effect of short-wave radiation on the human body in indoor spaces has received limited attention in the thermal comfort research, due to the assumption that people are shaded [61]. However, as indicated above, this assumption may not be generally valid, especially not for unshaded, highly glazed office buildings. Only more recently, a few studies have addressed the issue of solar radiation and its effect of thermal comfort [27, 62-67].

Han et al. [63] and Han and Huang [64] have used virtual thermal comfort engineering to carry out analysis to assess the influence of various parameters on the thermal comfort of an occupant in a passenger compartment of a vehicle. Both studies exemplifies that solar load might be dominant in assessment of local thermal comfort for body segments exposed to solar radiation. While the body segments blocked for sun were found to be relatively insensitive to the solar load. They report that the thermal sensation ratings increases fairly linearly with the total solar load on the driver [64]. This finding is in line with results reported by Hodder and Parsons [62] who indicate an increase of thermal sensation of one scale unit for each increase of direct radiation of around 200 W/m^2. As Han and Huang [64] point out, it is a challenge to reduce asymmetric thermal load on cabin occupants in the case of extreme solar gain, this might be a challenge in offices as well, c.f. Ref. [68].

The solar load of an indoor room is dependent on glass properties, solar incidence angle, and incident solar spectrum [69]. Utilization of solar reducing glazing has been found to improve the thermal sensation of occupants exposed to solar loads [62, 63, 70]. For such assessments it is, however, important to utilise light sources with the same spectral properties as solar radiation. This has been highlighted in an investigation by Ozeki et al. [71]; their results indicates that a solar reduction glass could reduce solar energy absorbed by a car occupant by about 15 % compared to normal green glass when considering solar radiation, while the reduction was more than 65 % with use of an infrared solar lamp.

Fanger [40] proposed a method for calculation of MRT of a person affected by high-intensity beam heating systems, see equation 2.

$$T_{mrt} = \left(T_{umrt}^{4} + \frac{f_p \alpha_{ir} q_{ir}}{\varepsilon_p \sigma}\right)^{0.25} \tag{2}$$

$$f_p = A_p / A_{eff} \tag{3}$$

Where T_{mrt} is the MRT of the irradiated person, $T_{umrt}$is the hypothetical MRT of an unirradiated person, f_p is the projected area factor, α_{ir} is the absorptance of the outer surface of the radiated person, q_{ir} is the radiant intensity, ε_p is the emittance of the subject, σ is Stephan-Boltzmann constant, A_p is the projected area and A_{eff} is the effective radiation area. In case of direct solar radiation, the sun might be considered as a high-intensity beam heating source and results from a study by Bryn and Smidsrød [72] indicate that equation 2 might be applicable to estimate the MRT of a person hit by solar radiation. Similar methods have recently been proposed and/or tested both for indoor [59, 61] and outdoor [73, 74] environments and Lyons et al. [75] refer to an expression presented by Sullivan for the sensitivity of PMV to the incident solar flux.

2.2 DISCUSSION THERMAL COMFORT

Based on findings in the literature, it is recommended that occupants' thermal comfort within building design should be evaluated as a function of the location in the room, taking the contribution of both long-wave and short-wave radiation into consideration. This is especially important when evaluating modern office buildings with large open-plan offices and/or highly glazed facades, where there might be substantial variations of thermal comfort across the room, –variations which needs to be assessed in order to ensure that thermal comfort can be obtained at all locations where it is natural to place a workstation.

The literature indicates that models have been proposed for including short-wave radiation in the calculation of MRT. Yet, there is still a lack of implementation of these models into simulation tools used in practical engineering and building design. It is believed that taking short-wave radiation into consideration in thermal comfort analysis may have implications on the predicted energy use and/or the design of the façade and the room layout, since e.g. an enlarged need for local cooling or increased use of dynamic solar shading might be discovered in the design phase as a consequence of the thermal conditions close to the façade. Improvement in the calculation of operative temperature may additionally improve the thermal comfort predictions with e.g. the PMV/PPD model and adaptive thermal comfort models, since operative temperature is included in these models.

CHAPTER 3. DAYLIGHT

Daylight is defined as the part of solar radiation which humans perceive as light [69]. The visual radiation within the electromagnetic spectrum is approximately between 380-740 nm [69]. Different reasons occur for implementations of daylight in building design, ranging from solely aesthetic to more functional purposes. Daylight may in addition have positive health effects [76-80] and Wurtman [76] states that ”*light is the most important environmental input, after food, in controlling bodily functions*”. Moreover, research has indicated that occupants usually prefer daylight as their source of illumination [81-83].

3.1 DAYLIGHT METRICS

The daylight factor (DF) is currently the most commonly used daylight metric worldwide [37, 84]. The concept has existed since the late 19th century [85] and is today incorporated into a number of national design guidelines, e.g. [52, 86]. The DF is defined as the ratio between the internal illuminance at a point in a room and the unshaded, external horizontal illuminance under a *Commission Internationale de l’Eclairage* (CIE) overcast sky [87]. The daylight factor of a room can be considered to consist of the sky component (SC), the externally reflected component (ERC) and the internally reflected component (IRC), see Figure 2.

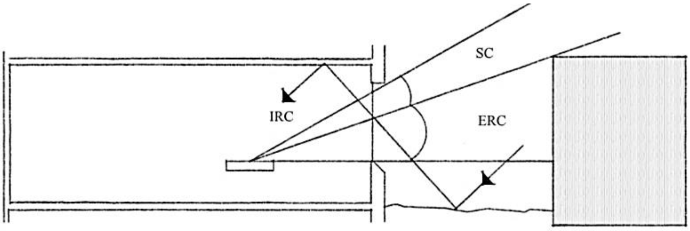


Figure 2: Visualization of the three daylight components SC, ERC and IRC.

The primary object of measuring daylight in terms of ratio rather than absolute values is to avoid the difficulty involved by the frequent fluctuations in the intensity of daylight [88]. However, in real life the daylight indoor is dynamic and influenced by the size and orientation of glazed areas, glazing characteristics, room plan, outdoor weather and the geographical and topographical location of the building [89, 90]. Therefore, as an isolated measure DF does not contribute with much information regarding the real daylight level in a room. Reinhart [87] argue that the popularity of DF probably is due to its simplicity to calculate as well as it is a well-known measure which may be easy to communicate to a design team. The lack of realism in the DF approach is, however, blamed to be one of the reasons why daylight is an under-exploited natural resource [91].

During the last decade the need for a new daylight metric to replace the DF has been expressed [84, 92-94] and effort has been put down in creating climate-based daylight metrics suitable to function as criteria for annual daylight evaluations. Climate-based daylight modelling (CBDM) uses sun and sky conditions derived from meteorological datasets [95]. Table 1 present a selection of recently developed climate-based daylight metrics (CBDm).

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

Metric	Information in the metric	Lower threshold [lux]	Upper threshold [lux]	Comment	Reference
Daylight autonomy (DA)	Percentage of occupied time when a minimum work plane illuminance can be maintained by daylight alone.	500*	-	Threshold commonly derived from standards for artificial lighting.	[96]
Useful daylight illuminance (UDI)	Percentage of work hours when daylight levels are useful for the occupants.	100	2000 ** 3000***	Thresholds derived from literature study on occupant preferences in daylit offices. Upper limit is associated with glare/overheating.	[92, 97]
DA_{con} in combination with DA_{max}	Based on the DA criteria, but softener the threshold by attribute partial credits to time steps when the daylight illuminance lies below the minimum illuminance level.	500 *	10 times the design illuminance of a space	DA_{max} indicate occurrence of direct sunlight and potentially glary conditions.	[87, 98]
Spatial daylight autonomy 300/50% ($sDA_{300/50\%}$)	Percentage of analysis area that achieves the threshold of 300 lux for 50 % of the analysis period.	300	-	Target value of *300 lux* was derived from a survey with daylight experts and building occupants in 61 day lit spaces.	[93, 99]

* The value of 500 lux is valid for offices. ** 2000 lux is derived for offices, in places where the occupants have opportunity to adjust the settings higher illuminances may be accepted [29]. *** 3000 lux has been proposed as the upper threshold in a recent publication by Mardaljevic et al. [97]

The question is then which CBDm to use? UDI and $sDA_{300/50\%}$ might be preferable, since they are developed based on occupant preferences in daylight environments. One advantage of $sDA_{300/50\%}$ is that the annual daylight level in the room can be expressed with one single number and according to the Illuminanting Engineering Society of North America (IES); $sDA_{300/50\%} \geq 55$ % has to be met in order for a space to be nominally acceptable daylit. $sDA_{300/50\%}$ has been accepted as daylight metric by the IES as part of an methodology for evaluating annual daylight in combination with the criteria that solar shadings are temporarily closed whenever more than 2 % of a space is illuminated by direct sunlight above 1000 lux [99].

Still, from an integrated design perspective, UDI seems to give more interdisciplinary information. The UDI concept is divided into four categories [97]; UDI_fell short (UDI-f, 0-100 lux) which indicates the time when required illuminance has to be maintained by artificial lighting, UDI_supplementary (UDI-s, 100-300 lux) which indicates the time when artificial lighting needs to supplement daylight to maintain required illuminance, UDI_autonomous (UDI-a, 300-3000 lux) which indicates the time when the light level can be obtained by daylight alone and UDI exceeded (UDI-e, >3000 lux) which is associated with glare or overheating and indicates the time when solar shading might be needed. Cantin and Dubois [100] suggest to replace DF by UDI in order to evade “the more the better” approach for glazing areas in buildings, which may occur when considering DF alone.

3.2 GLARE

Glare is commonly divided into two categories: disability glare and discomfort glare. According to the CIE vocabulary, disability glare makes a person unable to see certain objects in a scene, while discomfort glare produces discomfort without necessarily influencing visual performance and visibility [101]. Disability glare is rather well understood, but there is still a lack of knowledge about the underlying process for discomfort glare, especially discomfort glare from daylight [102, 103]. Fluctuation in pupil size [104], visual distraction [105] and hyperexcitability of visual neurons [106] have been suggested as mechanisms for causing discomfort glare. According to Vos [107], the present understanding of discomfort glare covers two fundamentally different phenomena which he suggests separating into discomfort and dazzling glare. Vos explains discomfort glare as disturbing lights off the line of sight interfering with the foveal vision. The disturbing lights attract the eyes and work as a distraction from the visual task. Dazzling glare, on the other hand, occurs when our eyes meet a bright field of view which makes one screw up the eyes and show avoidance rather than attraction reactions.

3.2.1 GLARE METRICS

Even if discomfort glare is a subjective sensation, several efforts have been made to predict it objectively, which have resulted in various glare indexes, e.g. CIE glare index (CGI) [108], Daylight glare index (DGI) [109], Unified glare rating (UGR) [110] and Daylight glare probability (DGP) [111]. Daylight may be more likely to give rise to glare than artificial lighting since daylight sources often are placed in vertical walls which makes them prone to be seen directly, or in the peripheral vision, while artificial lighting usually is mounted overhead. Yet, only two of the aforementioned metrics are intended for daylight glare evaluations: DGI and DGP.

Hopkinson [109] developed DGI, see equation 4, by modifying the formula for Glare Index. According to Hopkinson, discomfort glare from daylight is a direct function of both the window size and the brightness of the sky seen through it, and an inverse function of the brightness of the room interior. Even though DGI takes into account these factors, Hopkinson emphasises that high correlation between glare predictions and the actual discomfort experienced should not be expected, since discomfort glare is a complex situation with several side effects. Pleasant view was found by Hopkinson to be an important side effect which would extend the observer tolerance to discomfort, even though the view is not actually reducing the glare [109]. This result has been supported by later studies [102, 112-114].

$$DGI = 10 \cdot log_{10} 0.48 \sum_{i=1}^{n} (L_s^{1.6} \Omega_s^{0.8}) / (L_b + 0.07 \omega_s^{0.5} L_s) \tag{4}$$

Where $L_{b/s}$ is the luminance of background/source, Ω_s is the solid angle subtended by the glare source modified by Guth's position index (P) and ω_s is the solid angle subtended by the glare source. Several researchers have proposed improvements of the formula for DGI over the years, e.g. [112, 114-116]. However, as Van Den Wymelenberg [117] points out, neither of the modifications have gained wide acceptance in practical building design and, according to Van Den Wymelenberg, DGI has surpassed its useful life.

In 2003-2004 Wienold and Christoffersen [111] conducted user assessments under real daylight conditions in Denmark and Germany. The results showed poor correlations with existing glare models and revealed a need for a new glare model. They developed DGP, which is based on a combination of the existing CGI algorithm and an empirical approach, see equation 5. Wienold and Christoffersen found that the general field of luminance was not suitable as measure for the adaptation level, since the large glare sources themselves have impact on the adaptation level. They suggested using vertical eye illuminance (E_v) instead, and by implementing this measure in the DGP model a higher correlation with the user assessment was found compared to use of general field of luminance.

$$DGP = 5.87 \cdot 10^{-5} E_v + 9.18 \cdot 10^{-2} log(1 + \sum_i (L_{s,i}^2 \omega_{s,i}) / (E_v^{1.87} P_i^2) + 0.16 \tag{5}$$

Some literature recommend use of DGP in assessing discomfort glare from daylight [100, 118, 119], and multiple studies show that DGP outperforms DGI [111, 120, 121]. However, studies also indicate that DGP is not a robust glare metric [122, 123], at least not as a single measure for securing visual comfort [120, 124].

3.2.1.1 Annual glare evaluation

One major drawback with DGP, as well as most of the traditional glare metrics, is the high time-consume to carry out an annual analysis. In order to address this problem, Wienold [125] developed and validated two simplified versions of DGP: (1) DGP simplified (DGPs) based on E_v, see equation 6, and (2) enhanced simplified DGP based on E_v in combination with a simplified image. The validation generally showed good results for the enhanced simplified DGP and reasonable results for DGPs when no peak glare sources where present.

$$DGPs = 6.22 \cdot 10^{-5} E_v + 0.184 \qquad (6)$$

As the development of DGP and DGPs demonstrate, vertical illuminance at eye level might be a reasonable, simple indicator for discomfort glare applicable for annual glare evaluations. A number of other studies have also reported correlation between vertical illuminance and perceived glare by occupants [120, 126-129]. Van Den Wymelenberg and Inanici [120] conclude that establishing reliable design criteria for E_v which can be used in the design stage should lead to improved occupant satisfaction with the visual environment. Based on results from their study, a threshold for E_v should be in the range of 1000-1500 lux.

Horizontal illuminance is the variable traditionally evaluated and referred to by engineers and architects in the daylight design community, and it is commonly used as an indicator of daylight sufficiency. However, it has also been proposed as an indicator of visual discomfort [92, 99, 130]. A few recent studies have reported a reasonable relationship between the reported glare perception by occupants and horizontal illuminance [120, 131]. However, Konis [127] suggests that the relation between horizontal illuminance and subjective assessment of discomfort may be context specific related to the distance of the observer to the façade as well as interior surface reflections. This suggestion is based on the finding that occupants report visual discomfort in the core zones of a side-lit office building even when the horizontal illuminance at the workstation is low – significantly lower than 2000 lux, which was suggested as the original upper threshold of UDI.

3.3 DAYLIGHT DESIGN PRACTICE

A few surveys concerning daylight design have been conducted during the last decades [132-135]. The essential findings from these surveys are that far from all building designers conduct daylight analysis during their design and some designers carries it out infrequently depending on the problem. It is found that an extensive amount of different daylight design tools are in use, both manual and computer tools. Some frequently mentioned manual tools are; scale models, calculations based on Waldram diagrams, BRS daylight protractors and control of window area according to simple equations and diagrams. As for the mentioned simulation tools the complexity ranges from software packages based on relatively simple analytical algorithms to the more complex backward ray-tracing method. Further, results from Ref. [134] indicate that the daylight factor is one of the most frequently produced outputs from the building design daylight analysis.

In the two most recently conducted surveys, [134, 135], the major part of the participants informed that they utilise simulation tools. The strong bias towards use of simulation tools could be explained by the fact that many of the participants had been recruited through building simulations mailing lists. Still, the results indicates that computer simulations have become more included in daylight design than earlier. However, it was found that the usage was significantly higher during the design development than during schematic design. The dominant tools during the schematic design were still experience, rules of thumb and design guides. In Ref. [135], free text answers showed that a number of non-standardized, self-made rules-of-thumb were being used for a variety of design aspects.

A limited survey, carried out by two master degree students at Oslo and Akershus University College of Applied Science [136, 137], indicates similar tendencies among Norwegian building designers as suggested in the published literature, see Figure 3. A number of the participating building designers do not consider daylight in their design. Still, the major part of the questioned architects evaluates daylight, – which may be expected since daylight often is part of the architects' responsibility. Even so, it is seen that the 10 % glazing-to-floor rule, referred to in the guidance to the Norwegian building codes [52], is popular among the participating architects. This simple, static pre-accepted target has been found not to be a reliable measure to secure sufficient daylight supply within modern buildings [138].

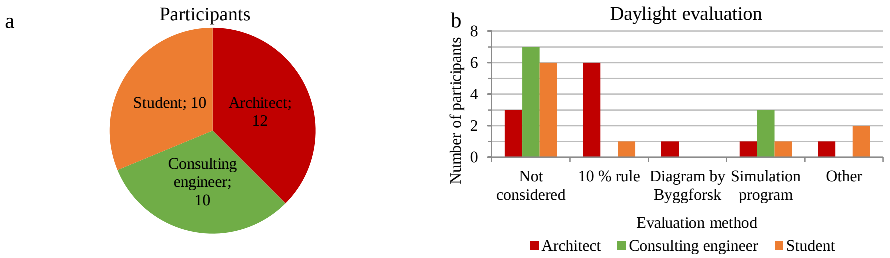


Figure 3: a) Categorization of participants responding in the limited survey regarding building design. b) Methods used for evaluation of daylight among the survey participants.

3.3.1 ANNUAL DAYLIGHT MODELLING

As indicated in the previous section, the literature gives description of an extensive amount of methods used in daylight design. However, simulation tools with annual daylight modelling features are required in order to make the previous mentioned CBDm and annual glare evaluations useable for daylight designers.

There are numerous lighting simulation programs available on the marked and most of them are based on the radiosity or ray-tracing luminance distribution approaches [139-141]. Radiance [142] is considered to be a *state-of-the-art* backward-raytracing tool and it has been highly validated [142, 143]. However, with respect to annual daylight evaluations the time consume is extensively high for running traditionally Radiance ray-tracing calculations at each time-step. Therefore, several approaches for annual daylight modelling has been suggested, see e.g. Ref. [84, 144, 145].

Reinhart and Walkenhorst [96] validated the Daysim method for annual climate-based daylight calculations earlier proposed by Reinhart and Herkel [84]. The Daysim method is based on combining a modified version of Radiance with Tregenza and Waters [146] daylight coefficients and Perez et al. [147] sky luminance distribution model. The daylight coefficient gives the contribution to the illuminance at a point in the room from a small sky segment [146], see Figure 4. The advantage of the daylight coefficient approach is that once a set of daylight coefficients are calculated it can be combined with the luminance of sky segments at arbitrary sky conditions and the sum of light contribution from each sky segment yields the corresponding indoor illuminance at the point of interest [84]. The Daysim method distinguishes between light contribution from diffuse sky, ground segments and direct sunlight and more recent refinements in the daylight coefficient approach with respect to direct sun has been proposed by Bourgeois et al. [148].

Recently, the Radiance three-phase method [144] was developed, where bidirectional scattering distribution functions (BSDF) are used to describe complex fenestration systems. The theory behind the three-phase method is thoroughly described elsewhere, e.g. [144, 149], and the method is validated by McNeil and Lee [150]. Shortly, the calculation procedure is divided into three phases, see Figure 4. A Radiance ray tracing simulation generates luminous energy transfer coefficients relating (1) the luminance of sky patches to the incident light directions on the exterior side of the window, (2) the transmission through the window and (3) light from outgoing directions from the interior side of the window to desired interior points in the room. These coefficients are stored in three independent matrices; the daylight matrix, the transmission matrix and the view matrix respectively. The resultant illumination is obtained by matrix multiplication of the three phases in combination with a sky matrix that contains the average luminance of the sky patches for given times and sky conditions.

Another approach for annual daylight assessments has been proposed by Hviid et al. [145]. They combine the ray-tracing approach for incident initial light and the radiosity approach for internal daylight reflections. Further, they utilize a pre-processor to calculate the light transmission trough the glazing/shading system. Validation against Radiance showed good results for isotopic optical materials, however rather large deviations were seen for cases with complex shading systems, with relative errors up to 20 % [145]. Yet, for early design phase, the error seen might be considered satisfactory [151].

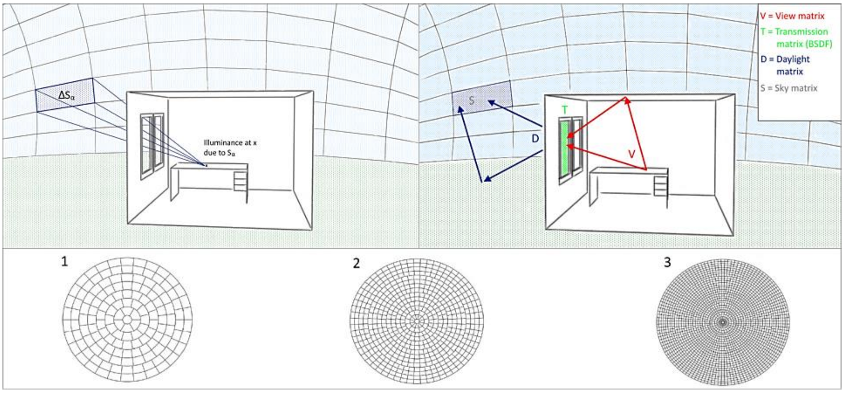


Figure 4: Principle illustration of the Daysim method (left, after[96]) and the three-phase method (right, after [152]) and the sky patch sub division according to (1) modified Tregenza-145, (2) Reinhart -581 and (3) Reinhart -2321.

3.4 DISCUSSION DAYLIGHT

In building design, a set of useful and intuitive evaluation criteria is necessary in order to correctly interpret results of performance predictions. Criteria for daylight may be used to assess if the daylight environment is satisfying, if artificial lighting needs to be added or if there is risk of glare and need for activation of solar shading. The literature reviled limitations regarding DF as daylight metric, and one thing seems certain; the time of the DF as the dominant evaluation metric for horizontal illuminance has passed. In the future, climate-based metrics should be used. It should be noted that Mardaljeveic and Christoffersen [153] have suggested a method of how to move from static to dynamic daylight evaluations by utilising a cumulative illuminance approach during a transition period.

Avoidance of glare is a request for obtaining visual comfort. From an integrated building design perspective, it would be advantageous with simple and computationally effective measures of discomfort glare from daylight that give reasonable predictions of glare on an annual basis for use in early building design when decisions regarding the façade are taken. These quantities should further be easily measurable in order to be able to validate the design as well as having the potential of being incorporated in building control strategies, e.g. of solar shading control. Candidates for such measures might be horizontal illuminance at the desk, vertical eye illuminance and more sophisticated models as DGPs or DGP enhanced simplified. However, further studies are needed to confirm their applicability.

Section 3.3 indicated that daylight evaluations not yet are a matter of course within building design and simplified and/or static calculations are still dominating among those considering daylight. Models for annual daylight calculations need to become available for building designers for annual evaluation criteria grow to be mainstream. An advantage of the three-phase method with respect to annual calculations is that different types of windows and configurations of solar shadings can be studied rather easily by only exchanging the transmission matrix in the calculation.

Table 2 compresses a preliminary proposal for a daylight design in three levels of details based on findings in the literature. Since it might be rather unrealistic at the present time to totally avoid the use of rules of thumb and simple static calculations in the early design phase to make some suggestions to the first design proposal, it is recommended to utilize the validated rule of thumb sequence proposed by Reinhart and Lo Verso [154]. Still, important features of the proposal are early implementation of simulation tools and adoption of climate-based daylight modelling, which straightens integration with thermal comfort and energy analysis.

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

Design stage	Proposed method	Evaluation metric
Initial design	Use the validated rule of thumb sequence by Reinhart and LoVerso [154] to draw up the first daylight scheme to find minimum required glazing areas; - initial assumptions regarding wall thickness, window head height, room width (*w*), mean surface reflectance (R_{mean}) and visual light transmittance (τ_{vis}) of the glazing have to be made. Use an effective simulation tool to check that the glazed areas are consistent with annual daylight requirements for UDI-a as well as for thermal comfort and energy use.	DF/UDI
Schematic design phase	Use a climate-based daylight simulation tool to verify the chosen glazed areas and glazing characteristics when use of solar shading is accounted for. In case of dynamic solar shading, use a simplified solar shading model and utilize UDI-e (3000 lux) as a threshold for activation of solar shading due to glare/ overheating. Exchange solar shading, lighting and occupancy profiles between daylight, thermal comfort and energy use predictive tools in order to achieve a model consistency for the integrated design.	UDI
Detail design phase	Keep using a climate-based daylight simulation tool, but if necessary make a more customised and product oriented simulation with respect to solar shading and installed lighting systems. Verify the daylight environmental quality with respect to useful daylight illuminance and glare.	UDI, DGPs/ DGPenhanced simplified

For an example of application of the proposed design sequence, please refer to Paper V: “*Implementation of daylight as part of the integrated design of commercial buildings*”.

CHAPTER 4. SOLAR SHADING

Tzempelikos [20] defines solar shading to be the primary link in an integrated thermal and daylighting building design, this was also indicated in Figure 1 (p.20). Accurate knowledge of blind use is therefore needed in order to improve the accuracy of predictive energy, thermal comfort and daylighting simulations.

Solar shading systems can be static or dynamic. Results from an investigation by Nielsen et al. [155] indicate that dynamic solar shading solutions function better than static ones in a Danish climate. This is true both with respect to energy demand and reduction of overheating, as well as it allows for daylight supply and view to the outside when there is no need for solar shading. Winther [156] and Liu [157] also confirm improved building performance by applying dynamic solar shading on different buildings in Denmark; they claim that use of intelligent dynamic facades are essential in achieving the high building performance required in the future.

4.1 CONTROL OF DYNAMIC SOLAR SHADING

From an energy point of view, automatic control should be applied on dynamic solar shading in office buildings, since research shows that users of the building do not tend to manually change the solar shading position for the short-term events in the outdoor weather conditions and the blind rate of change for manually systems is commonly rather low [158-162]. Still, a number of researchers have studied occupants’ manual interactions with solar shadings and tried to correlate it with physical variables in order to develop control strategies suitable for implementation in simulation programs or as a basis for automatic control strategies [162-166].

Solar irradiance is a simple and common parameter used in solar shading control [158, 159, 167-170]. Van Den Wymelenberg [159] finds evidence in reviewed literature of a solar irradiance based blind control predictor used as a proxy for occupants’ interactions with window blinds. However, the literature suggests that there is a wide disparity among the irradiance values to use, ranging from approximately 100-450 W/m^2, and a variety of locations to detect the irradiance [159]. When trying to find the correlation between solar radiation and the occupants’ interactions with solar shading, it would be preferable to assess the transmitted solar radiation which is the condition experienced by occupants. However, as O’Brien et al. [158] report, a significant part of the studies in the literature only considers external conditions, probably since it is easier to measure.

Another relatively common control parameter for solar shading is indoor temperature [169, 171-173]. Van Moeseke et al. [169] found that strategies based on both the external irradiance and the internal temperatures were more efficient to balance comfort and energy savings compared to strategies based on either of these parameters alone. Use of the combined criteria ensures better utilization of solar gains for heating during winter and may limit the time of closed mode and, thereby, increase the visual contact with the exterior as well as inlet of daylight [169].

A number of researchers indicate that glare commonly is the main factor driving shading activation, e.g. [158, 162, 174-176]. In order to provide sufficient glare-free daylight, Chan and Tzempelikos [177] suggest controlling the solar shading according to Daylight Glare Probability, either continuously controlled using real-time simulations or pre-calculated correlations between transmitted illuminance and DGP. Yun et al. [178] and Hoffmann et al. [179] also consider DGP as a control criterion within office buildings. However, Yun et al. conclude that this metric is impractical for calculation in real scenes and suggest implementing vertical eye illuminance as a control criterion instead. Other researchers have also suggested control of vertical illuminance for achieving visual comfort, e.g. [120, 180].

Based on a comprehensive literature review, Galasiu and Veitch [181] found that limited amount of research has focused on occupants' acceptance, preference or satisfaction with automatic solar shading systems. There has been some indication in the literature concerning occupants dissatisfaction or lack of preference with automatically controlled shadings [162, 182, 183] and evidence that occupants may switch off the automatic mode [162, 176]. It has also been given examples of studies where the occupants thought the solar shading operated at the wrong times [24, 184]. High occurrence of overrule actions of automatic solar shading systems has additionally been reported [167, 176, 185], which may imply that the occupants are dissatisfied with the automatic control. However, results from a recent Dutch pilot study carried out to investigate the user satisfaction and interaction with automated dynamic facades, did not find any clear link between automated facade operation and a high risk for disturbance and discomfort [185]. Furthermore, results from an older pilot study by Vine et al. [186] generally indicated high level of acceptance by users regarding an automated blind and lighting system, especially when they had the ability to overrule the systems. Similar results are reported by Meerbeek et al. [176] who suggests that it is not the actual control mode that influences the comfort of office workers, but rather the experienced level of control.

Beside function as glare control and avoidance of overheating, solar shading systems might additionally have some insulating properties for reducing the heat loss through windows in cold climate [171, 187-189]. The Norwegian R&D project "*Glazed facades keeping what we promise*" (FG project) evaluates different functions of solar shadings both with respect to daylight, thermal comfort and energy use. One of the outcomes from the FG project is a control algorithm which utilises a combination of internal and external solar shading [189], see Figure 5. The motivation for utilising both internal and external shading is that solar radiation can be very beneficial during heating season in cold climate, while it might still be need for a glare control. Glare is, however, only indicated by vertical external solar irradiation on the façade (I_{sun}) within this control, see Figure 5.

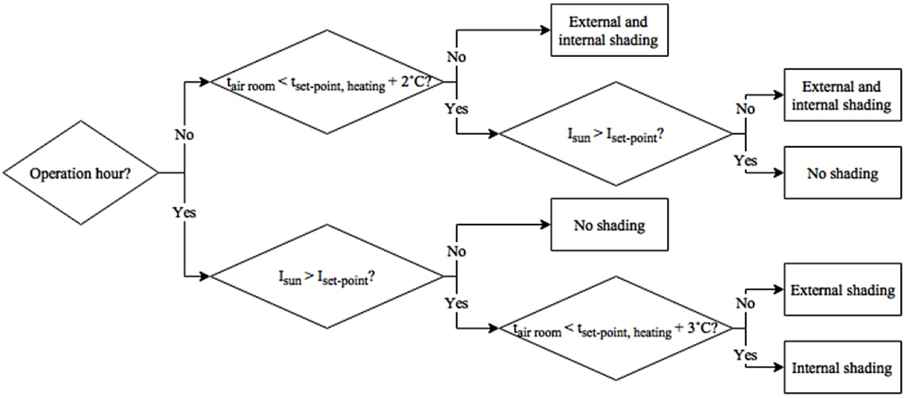


Figure 5: Solar shading control algorithm developed within the FG project [189].

4.2 DISCUSSION SOLAR SHADING

The literature indicates that solar radiation is the most commonly used parameter associated with solar shading activation. However, use of externally measured irradiance on the rooftop or vertical on the façade might not necessarily reflect the interior conditions, and use of such measures within an automatic control strategy might activate the solar shading at wrong times according to occupants' wishes. During occupied hours, the solar shading should be controlled to maintain occupant comfort and trigger parameters for activation should if possible be associated to interior conditions, e.g. indoor temperature and transmitted solar radiation.

Since solar shadings may have several functions, multivariable control strategies might be preferable. The control strategy proposed within the FG-project seems promising. Still, improvements might be needed, especially with respect to indication of glare. Moreover, instead of only identifying the shading as open or closed, the slat angle should additionally be a variable of consideration for blinds, since it might have significant impact on the daylight illuminance in the room. The latter was also noticed by Inkarojrit [162].

At last, user acceptance of automated systems may be crucial for its successful implementation within buildings. Still, solar shading control strategies are often proposed without verifying its acceptance by occupants in a working environment. More studies are needed to gain knowledge of occupants' preferences regarding automatic shading controls.

CONCLUDING REMARKS PART I

Neither of the evaluation criteria for thermal comfort referred to in the literature constitute any obstacle for conducting integrated design. Still, the literature reveals a need for improvement of the calculation of operative temperature by considering the location in the room, accounting for both long-wave and short-wave radiation.

With respect to daylight design and evaluations, it is evident that the present design practice actually constitutes an obstacle for conducting integrated design. Therefore, it is a prominent need for a paradigm shift from static calculations and use of e.g. $DF/\overline{DF}$ as evaluation criteria, towards dynamic assessment of the daylight environment both with respect to daylight supply and glare.

Regarding solar shading control it is indicated that multivariable control strategies might be preferable in order to fulfil various functions of the solar shading. Additionally, it is suggested that closing criteria should be associated to interior conditions during occupied time, when the solar shading ought to be controlled to maintain occupant comfort. For blind based solar shading it is pointed out that the tilt angle should be considered as a control variable, since the slat position might have significant influence on the visual environment. Also, more information regarding user acceptance of automatic controls is needed.

Based on findings in the literature it is assessed as appropriate to concentrate the further effort of research for this thesis on the following, in order to obtain a methodology for an integrated design with associated evaluation criteria:

- Verify and implement a model for MRT which include the contribution from short-wave radiation into a simulation tool in use by building designers in Nordic countries.
- Verify and implement the three-phase daylight model within a simulation tool in use by building designers in Nordic countries. This will make it practical feasible for building designers to conduct climate-based daylight evaluations and complete the daylight analysis based on the same underlying assumptions as used in thermal simulations with respect to e.g. climate data, operational time and use of solar shading.
- Investigate occupants' acceptance with automatically controlled solar shading strategies.
- Investigate the suitability of simple illuminance based measures for use as indication of glare.
- Propose an improved solar shading control strategy for office buildings in Nordic climate based on the findings from the literature and results from the above mentioned investigations.

PART II – EXPERIMENTAL WORK AND ANALYSIS

This part describes two test cases used to carry out full-scale measurements for verification of models for improved calculation of thermal comfort and daylighting implemented into the simulation program IDA ICE. It should be noted that the model implementation is completed by Grigori Grozman at Equa Simulations AB.

Further, this part includes the methodology and results from an occupant survey carried out to investigate occupants preferences with respect to use of solar shading and their sensation of glare in an office like work environment.

The part is ended with a suggestion for solar shading control suited for cold Nordic climate, based on the control strategy proposed within the FG-project, with the aim to cover research question 2.

Make things as simple as possible, but not simpler
–Albert Einstein

CHAPTER 5. TEST CASES

This chapter presents a description of two test cases used for full-scale measurements to verify models for improved calculation of thermal comfort and daylighting, based on findings in Part I. It closes by describing the procedure of an occupant survey carried out in test case 2 to investigate occupants’ satisfaction with two automatically controlled solar shading strategies and the correlation between occupants’ response of glare and simple illuminance based measures.

5.1 TEST CASE 1 – TEAM OFFICE OSLO

Test case 1 is a team office located in Oslo (latitude 59°57'N, longitude 10°45'E). The team office has the dimensions 3.6 × 7.5 m and is situated at the corner of the 16th floor with one partly obstructed façade oriented 57° east of south and one unobstructed façade oriented 33° west of south, see Figure 6a. The opaque part of the external facades has a U-value of 0.18 W/m^{2}K. The south-east and south-west facades contain one and three windows respectively of 2.7 m^2 each, where three of the windows have some fins as external shading, see Figure 6b. All four windows are double-glazed, with a low-*e* coating and argon filling with the properties: direct solar transmission of 0.24, g-value of 0.27, visible light transmission at normal incidence of 0.50 and U-value of 1.1 W/m^{2}K.

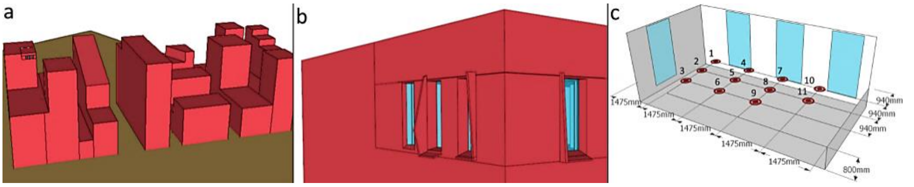


Figure 6: Illustration of the team office located in Oslo, Norway, with its surrounding obstacles (a), external vertical fins (b) and room layout and measurement locations (c).

The reflectivity of the internal surfaces was approximated by measurements with an illuminance meter (basic accuracy ± 4 %). Table 3 summarises the visible reflectance of the internal surfaces and their colour.

Table 3: Reflectance and color of the internal surfaces of the team office in Oslo.

Surface	Reflectance	Colour
Walls	0.76	White
Floor	0.25	Brown
Ceiling	0.88	White

5.1.1 CONTROL OF INDOOR ENVIRONEMENT

The office is equipped with mechanical ventilation, chill beam cooling and water based heating by radiators operated according to Table 4.

Table 4: Set points for the HVAC systems in the test room and overview of the average internal gains during the experimental periods.

VAV-ventilation		2-3.5 l/s m^2 / 0.8 l/s m^2 (temp control)
Set point heating		20.3 ˚C (period 1), 21.8 ˚C (period 2)
Set point cooling		21.5 ˚C (period 1), 23.3 ˚C (period 2)
Internal gains	Light	12 W/m^2
	Equipment	9 W/m^2
	People	6 W/m^2

5.1.2 MEASUREMENTS

5.1.2.1 Measurement period

The measurements were conducted over two periods in 2013 of approximately one week each, one week in mid-March (period 1) and one week in end of April (period 2). The observed sky conditions during these periods are summarised in Table 5. As can be seen, in total nine days with clear or partly clear sky were recorded.

Table 5: Observed sky conditions during the experimental periods.

Date	Sky conditions	Date	Sky conditions
12.03.2013	Clear sky	20.03.2013	Overcast sky
13.03.2013	Clear sky	21.03.2013	Clear sky
14.03.2013	Clear sky	17.04.2013	Partly clear sky
15.03.2013	Clouded	18.04.2013	Clouded
16.03.2013	Clouded	19.04.2013	Clouded
17.03.2013	Clouded	22.04.2013	Partly clear sky
18.03.2013	Clear sky/ partly clear sky	23.04.2013	Partly clear sky
19.03.2013	Clouded	24.04.2013	Partly clear sky

5.1.2.2 Indoor environment

The level of detail in the indoor measurements were chosen in order to capture the daylighting and thermal variations existing in the room, while at the same time keeping it at a detail level which might be reasonable within a building design.

Operative temperatures were measured by use of 40 mm black and grey globe thermometers (accuracy ± 0.1 K) at position 1, 3, 4 and 6 in Figure 6c. The short-wave radiation absorption was approximated to 0.80 and 0.95 for the grey and black globes respectively. Room air temperature was recorded in the corner of the room in order to avoid influence of direct solar radiation. Additionally indoor environmental conditions were measured using a Thermal Comfort Data logger (Innova 1221) for position 7; see Figure 6, in order to make sure that the indoor environment was within acceptable ranges for thermal comfort assessments. Innova 1221 consist of a collection of instruments and transducers measuring air velocity, humidity, air temperature, operative temperature and plane radiant temperature. Data were collected every 5 min for all the indoor measurements.

Indoor horizontal illuminance at the work plane was monitored with eleven illuminance sensors located on a grid across the room, 0.80 m above the floor, see Figure 6c. The sensors were cosine corrected, connected to an Extech SDL400 or Testo 545 illuminance meter with a basic accuracy of ± 4 % and ± 5 % respectively.

5.1.2.3 Weather data

Climatic data of hourly global radiation was collected from the BioForsk database [190] for the location of Ås, which is situated approximately 30 kilometres south-east of the experimental location. The global radiation was divided into direct normal and diffuse horizontal radiation by use of the Skartveit-Olseth model [191]. The climatic data of air temperature, relative humidity, wind velocity and wind direction was collected from Eklima database [192] for the location of Oslo.

5.2 TEST CASE 2 – THE CUBE

The Cube (latitude 57°3'N, longitude 9°55'E) is a test facility at Aalborg University. The test facility has previously been used by Kalyanova [193] to investigate double-skin façades, by Winther [156] and Liu [157] to explore intelligent glazed facades and by Le Dréau [194] to investigate radiant and air-based heating and cooling systems. The set-up from Le Dréau has been kept and extended for the present survey. The following sections will give a short description of the test facility, for further details see Ref. [194] Part II and Ref. [157] Chapter 4.

5.2.1 CONSTRUCTIONS

The Cube has a south-oriented experimental room, 2.76 m × 3.6 m × 2.70 m. The experimental room consists of an insulated wooden construction covered internally by 110-160 mm expanded polystyrene (EPS). In order to increase the thermal mass of the room, panels composed of 30 mm extruded polystyrene and 13 mm plaster have been glued to the walls [194] and a 50 mm thick concrete tile floor has been added. Additionally, it is equipped with a few office furniture and equipment.

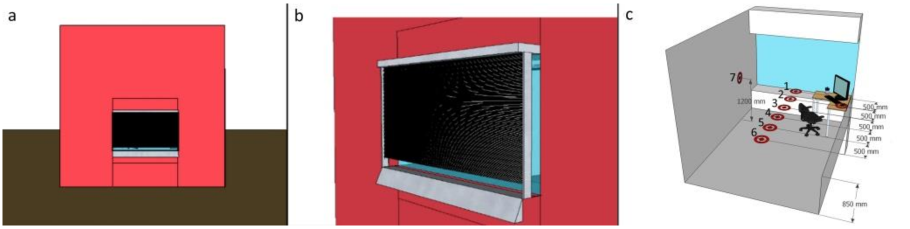


Figure 7: Illustration of the Cube located in Aalborg, Denmark. (a)South façade, (b) external solar shading) and (c) room layout and measurement locations of illuminance.

Le Dréau [194] measured the infiltration between the test room and the outdoor to be less than 0.3 L/sm^2_{floor} at 50 Pa. A ventilated guarded zone surrounds all the enclosures of the experimental room, except the south façade, in order to minimize heat transfer through the construction.

The south façade of the experimental room is equipped with a double layer glazing (2.76 m × 1.60 m) that constitutes the major part of the boundary towards the exterior, see Figure 7. The window is equipped with both an internal and external diffuse white 65 mm convex venetian blind with 60 mm spacing between the slats. Table 6 summarises thermal and optical properties for the window system.

Table 6: Glazing and shading properties at reference conditions according to ISO 15099 [195] for various configurations.

Glazing/ shading configuration	Tilt angle [˚]	U-value	g-value	Solar transmittance	Visible transmittance
Glazing	-	1.23	0.36	0.31	0.65
Glazing w/external shading	15	1.12	0.29	0.22	0.49
	80	1.05	0.04	0.01	0.02
Glazing w/internal shading	15	1.14	0.34	0.23	0.52
	80	1.09	0.26	0.02	0.06
Glazing w/external and internal shading	80	0.94	0.02	0	0

The reflectivity of the internal surfaces has been determined using a spectrometer (250 to 2500 nm). Table 7 summarises the visible reflectance of the internal surfaces and their colour.

Table 7: Reflectance and colour of the internal surfaces in the Cube.

Surface	Reflectance	Colour
Walls	0.73	White
Floor	0.32	Grey
Ceiling	0.94	White

5.2.2 CONTROL OF INDOOR ENVIRONMENT

Table 8 gives an overview of how the indoor environment and the internal gains are controlled in the Cube during the experiments.

Table 8: Overview of indoor environment and internal gains control in the Cube.

Category		Quantity	Comments and measurements accuracy
Internal gains	Occupants	1 thermal manikin (8-18 every day)	Manikin controlled to maintain a skin temperature of 34 ˚C. Heat the manikin ± 1 % [194, 196]. Control the skin temperature ± 0.2 K [194, 196]. (not used during occupant survey)
	Lighting	Fluorescent ceiling light. Max 60 W (8-18 every day).	Artificial lighting is added if daylight alone cannot supply minimum 300 lux at the horizontal work plane 1.5 m into the room. Artificial lighting is controlled to maintain 500 lux at the work plane according to the dimming characteristics given in Figure 9. Illuminances are measured with cosine corrected Hagner SD1/SD2 detectors connected to a Hagner MCA-1600 Multi-Channel Amplifier with a basic accuracy of ± 3 %. Power use for artificial lighting is recorded with Norma D5255S power analyser, basic accuracy ± 0.2 %.
Ventilation	Supply air (CAV)	2.6 l/(s m^2) (8-18 every day) 1.6 l/(s m^2) (rest of the time)	Air flow calculated based on pressure differences over an orifice plate before the inlet fan, ± 7.5 % [194].
Temperature control	Heating	Electrical heater, capacity of 1200 W.	Heating power recorded with Norma D5255S power analyser, basic accuracy ± 0.2 %.
	Cooling	Active chilled beam, capacity of approx. 500 W.	Cooling power calculated as a function of water flow rate (± 0.9 L/h [194]) and temperature difference between the forward and return water flow (± 0.057 K, Pt-500 temperature sensors [194]). Heating and cooling is controlled according to air temperature measured by a silver-coated type K thermocouples (± 0.1˚C) protected by a mechanically ventilated silver-shield, see Ref. [197].
Solar shading control	Illuminance	-	A vertical illuminance sensor placed at the east sidewall 1.2 m into the room at height 1.2 m above the floor is used in combination with the correlation equation given in Figure 8 as an approximation of vertical eye illuminance at the occupant position in order to indicate occurrence of glare.
	Temperature	-	Same sensor as used for room temperature control.
	Irradiance	-	CMP21 pyranometer placed exterior next to the glazing, see Figure 10 (accuracy ± 3 % [194]).

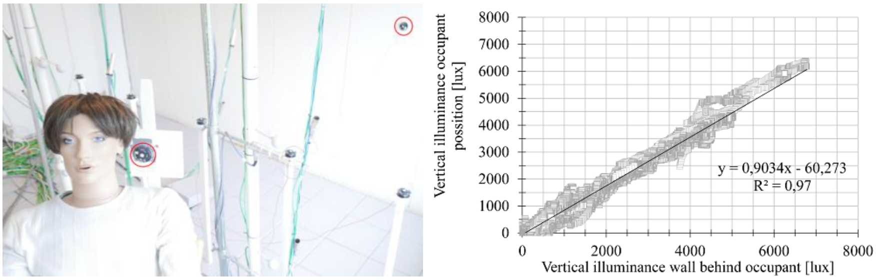


Figure 8: Left: Photo of the location of the two sensors, indicated by red circles. Right: Correlation between vertical eye illuminance at occupant position and vertical illuminance at the sensor location at the east sidewall.

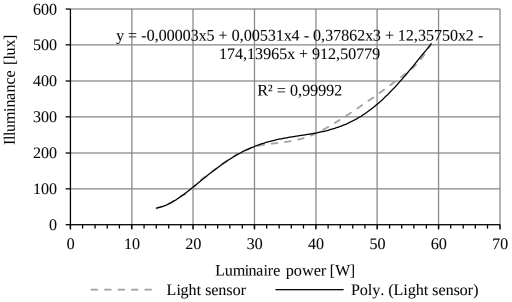


Figure 9: Dimming characteristics of the luminaire in the Cube.

5.2.3 MEASUREMENTS

5.2.3.1 Indoor environment

Indoor horizontal illuminance at the work plane was monitored with six illuminance sensors in the centre line of the room, 0.85 m above the floor, and one sensor placed at the work desk. Additionally an illuminance sensor was placed vertically on a wood stand close to the test subject in order to measure the vertical illuminance at the eye level, and one illuminance sensor was placed vertically on the east wall behind the work station at a height 1.2 m, see the location of the sensors in Figure 8 and Figure 10. All sensors were cosine corrected SD1/SD2 detectors connected to a Hagner MCA-1600 Multi-Channel Amplifier (basic accuracy ± 3 %).

Operative temperature was measured with grey globe thermometers (d≈40 mm), air temperature was measured with silver-coated type K thermocouples (accuracy ± 0.1˚C) protected by a mechanically ventilated silver-shield, and air velocity was measured with hot-sphere anemometers. These measurements were carried out for three, five and four positions in the room respectively at four heights for each position (0.1 m, 0.6 m, 1.1 m and 1.7 m) confirming to recommended measurement height for a seated and standing person according to ISO 7726 [198], see Figure 10.

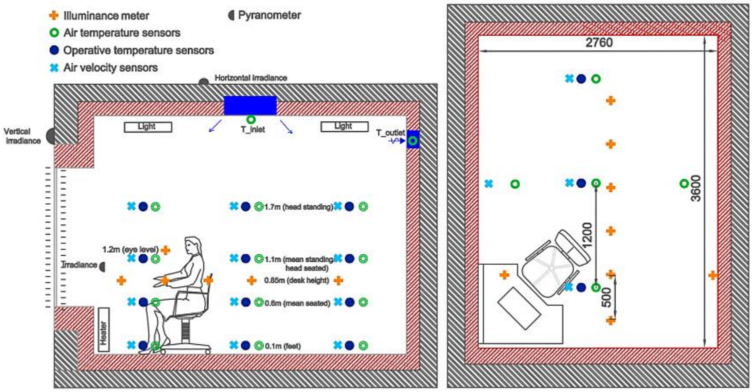


Figure 10: Placement of sensors in the experimental room in the Cube.

5.2.3.2 Weather data

Vertical irradiance was measured on the facade before and after the glazing by use of two CMP21 pyranometers (accuracy ± 3 % [194]). An additional CMP22 pyranometer was placed horizontally on the roof top of the experimental room in order to record the global radiation. The fraction of direct normal and diffuse horizontal radiation was calculated by use of the Skartveit-Olseth model [191].

Outdoor air temperature was measured with a silver-coated type K thermocouple (accuracy ± 0.1˚C) shielded from direct solar radiation, placed at the north façade of the Cube. Data of wind velocity and relative humidity of the outdoor air was collected from the Danish Meteorological Institute [199] for the location of Aalborg Airport, approximately 13 km north-west of the experiment location.

5.3 EXPERIMENTAL SET-UP OCCUPANT SURVEY

Part I indicated the importance of understanding occupants' requirements with respect to solar shading operation and apply realistic solar shading control strategies in the building performance predictions. Additionally, it was pointed out a need for computationally effective measures of discomfort glare from daylight for use in annual visual comfort analysis and in predictions of need for solar shading.

This section present the procedure of an occupant survey carried out to investigate occupants' satisfaction with two blind control strategies and to explore the suitability of simple and easily measurable quantities like vertical eye illuminance and horizontal illuminance at a desk or the model of DGPs as indicators of glare. The occupant survey is restricted to focus on the indoor environment close to the occupants' position, which in the present case is close to a window in the experimental room in the Cube, see Figure 10.

5.3.1 PARTICIPANTS

Forty-six subjects took part in the study, taking place in May–June 2014. The participants were mainly university students, researchers or office workers in the age range 20-62 years old, see Table 9. The subjects were instructed to wear vision corrected lenses or glasses if these were normally worn in office work situations.

Table 9: Overview of number of usable responses, sex distribution and age of the participants in the investigation of solar shading control strategy and glare.

Investigation	Total number of usable responses	Male	Female	Age		
				Mean	Median	SD
Solar shading control	40	22	18	28.7	26	8.3
Glare	44	26	18	28.5	26	8.1

5.3.2 INTRODUCTION TO THE TEST AND TEST FACILITY

In order to reduce biases caused by the test persons having or not having experience with the test room from previous visits, the test subjects conducted a pre-test up to 10 days before the main test. In the pre-test, the subjects were thoroughly introduced to the test and the test room, they got familiar with the concepts of glare and thermal comfort and the scales they would use in the test to rate the glare sensation and thermal comfort. Additionally, they answered some personal questions regarding gender, age and occupation. The pre-test lasted for approximately 20-30 minutes.

During both the pre-test and the main test, the subjects were facing diagonally towards the window (45˚). The subjects had the opportunity to adjust the height of the office chair, but they were instructed not to adjust the computer screen in order to secure the same pre-set viewing direction for all test subjects.

5.3.3 SOLAR SHADING CONTROL

The main test was a repeated measures design where all subjects were exposed to both blind strategies illustrated in Figure 11. Yet, the solar shading was only activated if needed, according to the criteria given in the solar shading strategies.

The simple control strategy simulate how solar shading commonly is treated in building design, while the detailed strategy is a modified version of the control algorithm developed in the FG-project for occupied hours, presented in Figure 5. The main modifications were to replace solar irradiance with vertical interior illuminance at eye level as indication of glare and to add the slat angle as a control variable. In activated state, the slats are tilted according to the estimated cut-off angle, i.e. the angle where direct solar radiation is prevented while maximum view contact to the exterior is provided. However, the minimum tilt angle of the slats was set to 15° in order to avoid negative cut-off angles in situations with large solar altitude angles and thereby avoid view to the sky and high risk of glare [200]. The cut-off angle was calculated according to equation 7 [201]. Where d is the profile angle of the sun, s is the spacing between the slats, w is the width of the slats, α is the solar altitude angle and γ is the solar surface azimuth. When activated, the whole window is shaded by the blind and all the slats have the same angle position.

$$\beta_{cut-off} = \sin^{-1}(\cos(d) \cdot s/w) - d \tag{7}$$

$$d = \tan^{-1}[\tan\alpha / \cos(\gamma)] \tag{8}$$

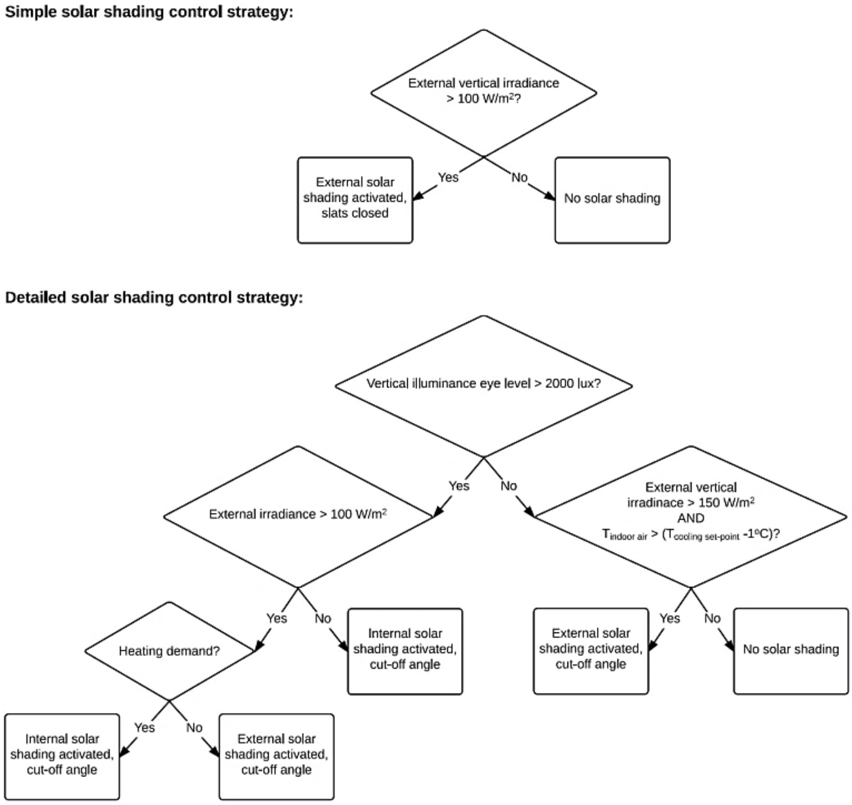


Figure 11: Schematic illustration of the simple and detailed control strategy.

5.3.4 QUESTIONNAIRE AND TEST PROCEDURE

Test subjects were asked for their subjective feedback with respect to thermal and visual comfort by completing a web-based questionnaire constructed in Surve Xact [202]. The basic questions and surveying procedure given by Christoffersen and Wienold [203] were adopted. This procedure entails that the occupants perform different visual tasks like reading from a paper, reading on a computer screen and writing on a computer while their performance is recorded.

Conducting the assigned tasks and answering the questionnaire took approximately one hour for each solar shading control strategy, see Figure 12. After completing the two tests, the participants were asked which control strategy they preferred, with the options “First control strategy”, “Second control strategy” and “No preferences”. They also had the opportunity to provide supplementary comments regarding their choice. The order of exposure to the different solar shading strategies was randomised and balanced between the test subjects and time of day.

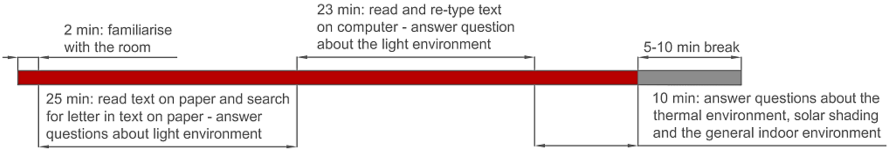


Figure 12: Time schedule for conducting the test.

5.3.5 DATA ANALYSIS

The occupants’ responses of the visual and thermal environment were combined with physical measurements. Measured illuminance were averaged over the 15-20 last minutes before the occupants answered questions regarding the light environment, while measured temperatures were averaged over the 30 last minutes before questions regarding the thermal environment were answered. Statistical data analysis was performed using R i386 version 3.1.1 [204].

5.3.5.1 Data analysis solar shading control preference

In comparison of indoor environmental conditions and participants’ responses between the two control strategies, a paired t-test was used. Normality was checked for all comparisons by use of normal probability plots. An unpaired t-test was used for comparison of two groups where pairing was not practical or purposeful. Where data was considered to be far from normally distributed, it was analysed initially by use of non-parametric statistical tests, e.g. Wilcoxon rank sum test. The significance of association between categorical variables was tested with the Fisher exact test in combination with Monte Carlo (MC) simulations.

5.3.5.2 Data analysis glare indication

Occupants' response of glare from the two solar shading strategies were mixed together and a reasonable illuminance range which frequently occurs in an office environment is thereby represented in the data.

5.3.5.2.1 Vertical and horizontal illuminance

Logistic regression was used to evaluate the correlation between vertical eye illuminance or horizontal illuminance at the desk and the perceived glare. For such analysis, the response variable of glare was assumed to be a binominal response, i.e. disturbed or not disturbed by glare. The four-point glare scale was, therefore, simplified to a binary form; *imperceptible* and *noticeable* were regarded as "not disturbed" while *disturbed* and *intolerable* were regarded as "disturbed".

AIC and BIC were used to compare the non-nested logistic regression models, the p-value of the Wald chi-square test was used to indicate the strength of evidence that there is some association between the predictor variables and the perceived glare. The overall performance of the logistic regression models were evaluated with Nagelkerke's pseudo R^2 [205] and Brier score [206], while the c-statistic was used to indicate the discriminative ability of the logistic regression model. The reader should be aware that rather low pseudo R^2 is common for logistic regressions.

5.3.5.2.2 DGPs

DGPs is based on the probability of whether a person is disturbed by glare. With this approach the glare scale is also reduced to a binominal response – "disturbed" and "not disturbed" – similar to the division for the logistic regression. The probability was established by grouping equal sample sizes of responses and evaluating the percentage of subjects disturbed in each of these groups. The total available responses of glare were 144 for the current study.

This study uses two approaches of grouping; one analogue approach to the one used by Wienold and Christoffersen where the group sizes are as large as practical in order to avoid significant sensitivity depending on the grouping while, at the same time, having a sufficient amount of groups, and another approach according to the recommendations of Hirning et al. [122] where the group size was $\sqrt{m}$, where m is the total number of observations being analysed.

For further information regarding the occupant survey, please consult Paper I: "*Occupant satisfaction with two blind control strategies: Slats closed and slats in cut-off position*" (DOI: http://dx.doi.org/10.1016/j.solener.2015.02.031) and Paper II: "*Verification of simple illuminance based measures for indication of discomfort glare from windows*" (DOI: http://dx.doi.org/10.1016/j.buildenv.2015.05.040)

CHAPTER 6. IMPLEMENTATION AND VERIFICATION OF NEW MODELS IN IDA ICE

A finding from Part I was that calculation of operative temperature within simulation programs should be improved by implementing the effect of short-wave radiation hitting the occupant. Additionally, it was suggested that annual daylight models needs to be implemented in user-friendly integrated simulation tools in order to make climate-based daylight evaluations practical useable for building designers.

IDA Indoor Climate and Energy (IDA ICE) [60] is a Swedish developed simulation tool for simulation of thermal comfort, indoor air quality and energy use in buildings. The program has gained popularity among building designers in the Nordic countries during the last decade, which makes it suitable for implementation of improved models for thermal comfort and daylight evaluations. This chapter describes implementation and verification of new models into IDA ICE. It should be noted that these model implementations are only potential and not released in any commercial product yet.

6.1 IMPROVED MRT MODEL IN IDA ICE

In the present zone model in IDA ICE the MRT of a person at a specific position is calculated based on surface temperatures and view factors between the zone surfaces and an infinitely small cube. This means that only the long-wave radiation is considered in the MRT model. A new zone model has been developed for IDA ICE which includes a new MRT model with the ability to account for the effect of shortwave radiation in the room. This section briefly describes the new MRT model and focus on its verification against full-scale measurements.

The new zone model developed in IDA ICE has the ability to predict air stratification and flow elements. Measurements are collected on a fine regular grid. The occupants are modelled as infinitely small spheres. The MRT for a point S is calculated according to equation 9, –based on equation 2 proposed by Fanger [40].

$$T_{\mathrm{mrt}}^{S} = \sqrt[4]{\sum_{j=1}^{N} F_{S\rightarrow j}\, T_j^4 \ + \frac{\alpha}{\sigma}\sum_{j=1}^{N} F_{S\rightarrow j}\, I_{\mathrm{diffuse}}^{j} + \frac{\alpha_{ir}}{\sigma}\sum_{i=1}^{M} C_{irr}^{i}\, f_p I_{\mathrm{direct}}^{i}} \qquad (9)$$

Where T_{j} is the temperature of surface j, $F_{S\rightarrow j}$ is the view factor from surface j to S, N is the number of surfaces in the thermal zone, α_{ir} is the short wave absorptance at the surface of S, σ is Stefan-Boltzmann constant, f_p is the projected area factor of point S in the direction of the sun beam, I_{diffuse}^{j} is the diffuse radiation intensity from surface j, M is the number of openings, C_{irr}^{i} is an irradiation coefficient which is equal 1 if point S is irradiated by the direct solar beam from opening i and 0 otherwise and I_{direct}^{i} is the direct radiation intensity of the beam from opening i. IDA ICE does not support the possibility of beams from several openings to hit a point, hence only one C_{irr}^{i} equals 1 and the rest are 0. The operative temperature is further assumed to be the mean of MRT and the room air temperature, which is sufficient for relative air velocities below 0.2 m/s [56].

6.1.1 VERIFICATION OF THE NEW IMPLEMENTED MRT MODEL

A verification of the model implementation is carried out by comparing simulation results with full-scale measurements in the team office in Oslo, described in section 5.1. Figure 13 shows a scatterplot for the comparison of the simulated and measured data of position 1, 4 and 7 for the hours of 8-18 for days with clear sky conditions according to Table 5. A high correlation can be seen for all the positions which indicate that the new MRT model has been implemented successfully in IDA ICE and can be used to predict the operative temperature at the specific positions with a reasonable accuracy. The total relative mean bias error of these data is 0.01 % and the total relative root mean square error which considers error compensation due to opposite sign differences is 0.17 % which is in highly acceptable ranges.

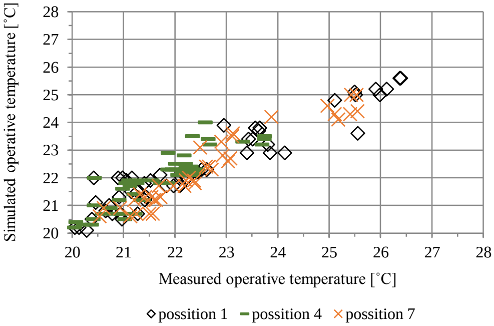


Figure 13: Comparison of simulated T_{op}^{S} with the new zone model in IDA ICE and measured T_{op}^{S} for position 1, 4 and 7. Total observations n=147, correlation coefficient R=0.95 (position 1), R=0.89 (position 4) and R=0.96 (position 7).

Figure 14 shows a comparison of predicted operative temperature with the old and the new zone model in IDA ICE of position 1 for 14th of March 2013. With the old zone model it is obvious that the short-wave radiation is neglected since the simulated operative temperatures correspond well with the average measured operative temperature in the shade.

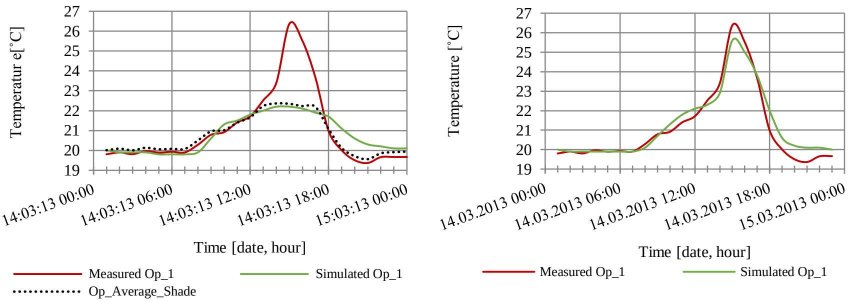


Figure 14: Comparison of measured and simulated operative temperature for position 1. Left: old zone model IDA ICE 4.5, right: new zone model

The measured drops in temperature after a day with clear sky conditions can be explained by the fact that the temperature sensor controlling the HVAC systems is placed on a concrete pile in the south-east corner in front of the room. In the late afternoon this pile is hit by solar radiation and heated up. This affects the readings of the temperature sensor and the feedback to the HVAC controller do not reveal the actual required heating load.

6.1.2 CONCLUSION NEW MRT MODEL IN IDA ICE

The results reported indicate that the new MRT model in IDA ICE contribute to considerable improvements in prediction of thermal comfort of persons affected by direct solar radiation. This prediction may further have implications on the predicted energy use and/or the design of the façade and the room layout, since e.g. an enlarged need for local cooling or increased use of dynamic solar shading might be discovered in the design phase as a consequence of the thermal conditions close to the façade, especially in case of large glass facades. It is expected that use of the new MRT model may contribute to increased focus on direct solar transmission of glazing and shading systems, since it might be seen that the only way to reduce the effect of short-wave radiation is to block or redirect it away from the occupants.

One of the limitations of the new MRT model at the present time is that it is assumed that the whole body is irradiated if the point in question is irradiated. Further studies should be done to see if the model can be used for situations where only parts of the human body are irradiated.

For more information, please refer to Paper IV: “*Operative temperature and thermal comfort in the sun – Implementation and verification of a model for IDA ICE”*

6.2 IMPROVED DAYLIGHT MODEL IN IDA ICE

This section presents work regarding the implementation and verification of a new daylight model in IDA ICE. The climate-based three-phase method in Radiance has been implemented in IDA ICE. A pre-processor convert the IDA ICE model to Radiance geometry and a post-processor import the Radiance simulation results. Within IDA ICE, the user can choose between three sky division schemes with increasing accuracy, see Figure 4 (p. 36). The user can also choose among three levels of calculation accuracy with pre-defined Radiance parameters or they may set the Radiance parameters themselves.

A major advantage of the three-phase method is that different types of windows and configurations of solar shadings can be studied rather easily by only exchange the transmission matrix in the calculation. These matrices may be generated by use of Window 7 [207], which uses a Klems angle basis of of 145 × 145 hemispherical luminous coefficients defined by paired incident and outgoing angles to the fenestration system [208]. An important approximation in the Klems BSDF approach is that the optical properties of the layers in the fenestration system are spatially averaged over a suitably-sized area [208].

6.2.1 VERIFICATION OF THE DAYLIGH MODEL IMPLEMENTATION

Figure 15 compares measured and simulated daylight conditions in the team-office in Oslo on a sunny day in March 2013 for two representative locations. Some diversity is seen, especially before and after the sensors are hit by direct sun. These differences may be explained by simplifications used in the three phase model, both the sky patch approximation which extends the sun disc over a larger area than the exact sun position and the low resolution Klems BSDF basis for the incident and outgoing angles to the fenestration system. Yet, the results indicate that the geometry and external shading elements are treated correctly in the pre-processor and contribute to reliable daylight predictions.

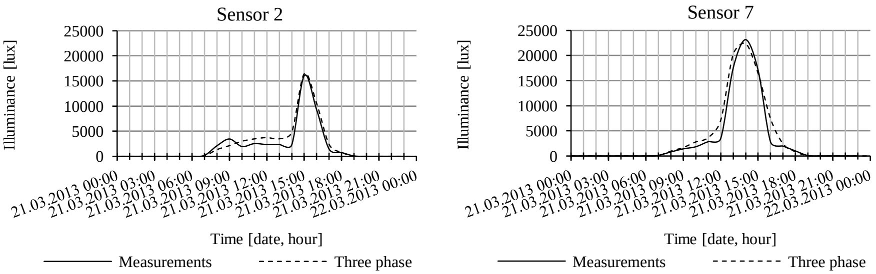


Figure 15: Comparison of measurements and simulations for two positions in the team office located in Oslo for a sunny day 21.03.2013.

Figure 16 present some representative comparisons of measurements and simulations of daylight conditions in the Cube, Aalborg, for two sunny days in July, one day without solar shading (Figure 16 a-b) and one day with the venetian blind activated with a tilt angle of approximately 75˚ (Figure 16 c-d). On an overall basis, the simulations reproduce well the measurements for a variety of locations within the room. However, some severe deviations are seen for sensor 1 when the solar shading is deactivated and for sensor 2 in the morning and in the afternoon when the solar shading is activated. For the former case it can again be explained by the fact that low resolution Klems BSDF division is utilised. In this certain case, the sensor is in reality just avoiding being hit by the sun, while in the simulation the sun patch is expanding a bit lager which makes the sensor location to be within the sun patch, see Figure 17. The deviation seen for sensor 2 can be explained by the fact that the external venetian blind is installed with a distance to the façade of approximately 20 cm. As a consequence, a light stripe is penetrating into the room through the openings that occur at the edge of the window, see Figure 18. This phenomenon is not captured by the three-phase method where the optical properties are spatially averaged over a suitably-sized area in the BSDF.

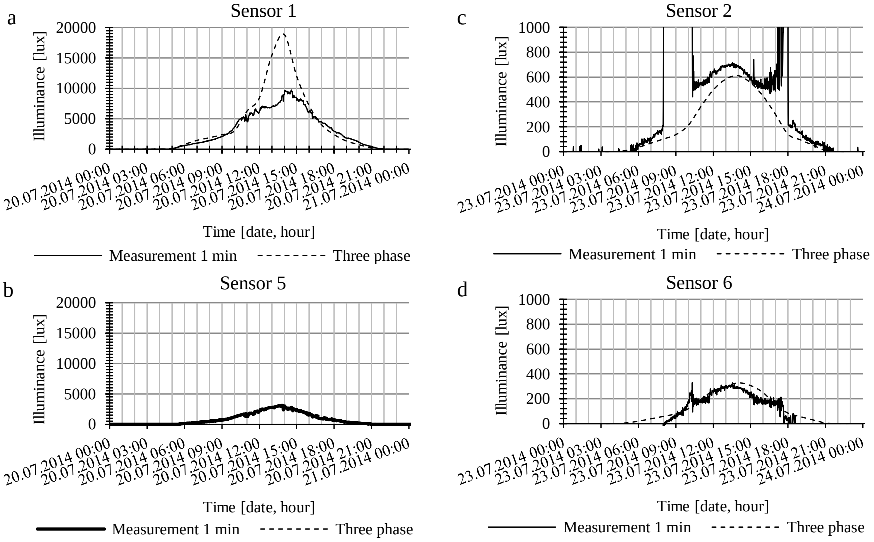


Figure 16: Comparison measurements and simulations in the experimental room in Aalborg for a sunny day without shading (a-b) and a sunny day with activated solar shading (c-d).

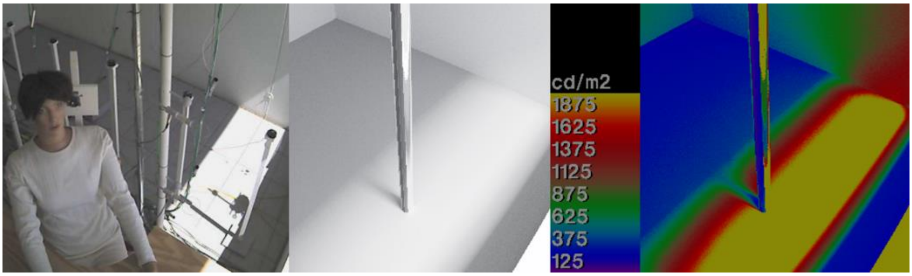


Figure 17: Photo inside the experiment room at 13. 30, 20.07.2014 and rendering from Radiance at the same time showing that the in the simulation the energy passing through the window is dispersed to a greater extent than what is the case in reality.

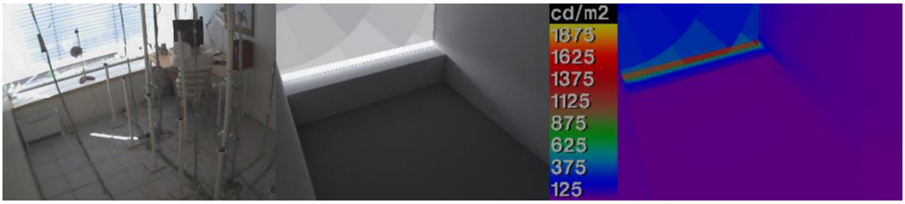


Figure 18: Photo of the experiment room at 09.30, 23.07.2014 and rendering from Radiance showing that the light stripe penetrating into the room is not detected in the simulation.

6.2.2 CONCLUSION NEW DAYLIGHT MODEL IN IDA ICE

The comparison between measurements and simulations show promising results and indicate that the coupling between IDA ICE and Radiance is working satisfactory. The deviations seen between measurements and simulations are most likely caused by model approximations as the sky patch approximation, subdivision of the fenestration system according to the Klems basis and the Klems BSDF function approximation which treats spatially inhomogeneous systems as homogeneous layers. Due to these model simplifications deviations might occur when considering specific points. However, when evaluating the daylight sufficiency in a room on an overall basis and over a sufficient time period, these small, local and time dependent deviations might have minor importance. This is especially true for an integrated design where the main goal is to predict how the fenestration characteristics influence visual and thermal comfort and the consequences it has on the energy use as well as to predict the need for use of solar shading to avoid glare and overheating. The designer should, however, be aware of the limitations associated with the three phase model.

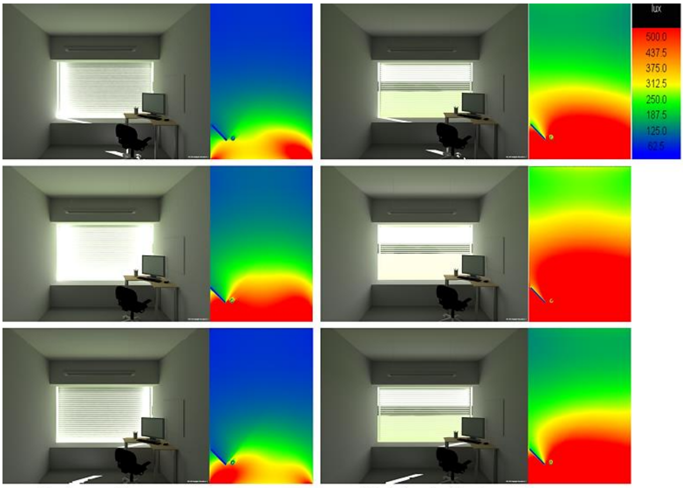
For further reading and an example of application of the new daylight model within an integrated design, please refer to Paper VI: “*Integrated design of daylight, thermal comfort and energy demand with use of IDA ICE*”

CHAPTER 7. OCCUPANTS SATISFACTION WITH TWO BLIND CONTROL STRATEGIES

This chapter present the results of the occupant survey described in Chapter 5 with respect to occupants' satisfaction with the two blind control strategies illustrated in Figure 11 (p. 55): slats closed and slats in cut-off position.

7.1 LIGHT AND THERMAL ENVIRONMENT

Within the temperature ranges occurring in the test room, the occupants did not report significant differences in perceived thermal comfort between the two control strategies. It is therefore presumed that the small differences occurring in the thermal environment did not affect the test subjects' perceived visual comfort. Figure 19 gives an example of how the light conditions might vary throughout a sunny day for each of the control strategies. The figure clearly shows that both the access to daylight and view to the exterior are better for the detailed strategy.



Simple control strategy

Detailed control strategy

Figure 19: Rendering of the luminance (perspective) and illuminance (horizontal plane 0.85m above floor) in the test room for the two solar shading control strategies with use of Velux Daylight Visualizer [209] for sunny sky conditions on May 21st at 09.00 AM (upper row), 12.00 AM(middle row) and 03.00 PM (lower row).

7.2 COMFORT AND PREFERENCES

A concern regarding use of automatically controlled solar shading systems is the acceptance by occupants. Robust control strategies should limit the number of overrules actions. When the test subjects were asked if they felt that the blinds needed to be changed to maintain a comfortable work place, surprisingly similar responses were given during the two control strategies and a considerable part of the participants required change, see Figure 20. However, the reason for wanting to change the blinds, cf. Figure 21 (a and b), significantly depends on the control strategy (Fisher exact test, p=0.04). As anticipated, the dominant reasons for wanting to change the blinds during the simple control were particularly to provide better view to the outside as well as wanting more light into the room and to the desk. Reasons for wanting to change the blinds during the detailed control strategy were more mixed. There are still some test subjects wanting more light into the room and better view to the outside, but now noticeable more changes would regard the request for less glare and less light into the room.

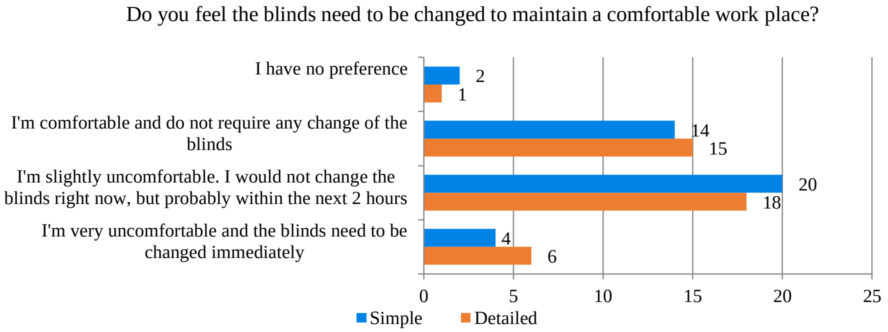


Figure 20: Reported preference for change of blinds for the simple and detailed control strategy in order to maintain a comfortable work place.

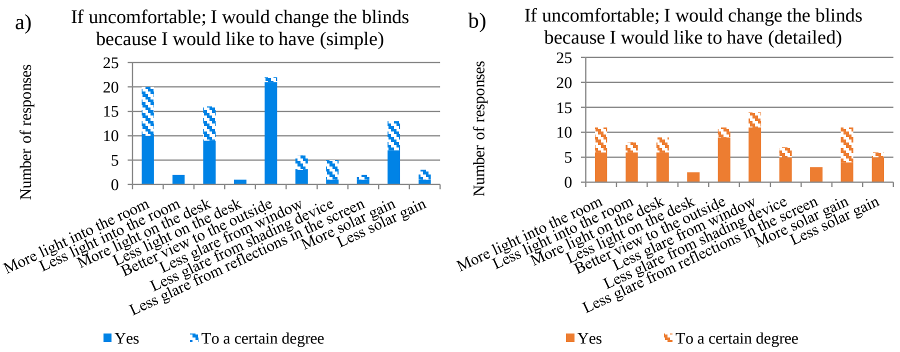


Figure 21: Reported reasons for changing the blinds during the simple (a) and detailed control strategy (b). Participants could check as many explainary factors as they wanted.

Several studies have reported that having personal control over the physical workspace leads to higher satisfaction with the indoor environment and increased occupant comfort [185, 210]. The importance of personal control is supported by the responses in this study, see Figure 22.

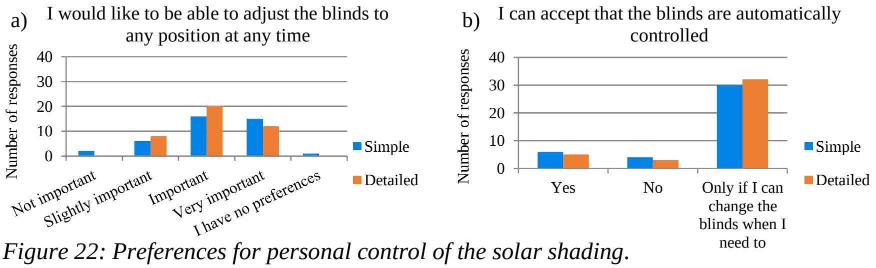


Figure 22: Preferences for personal control of the solar shading.

7.3 PREFERRED SOLAR SHADING CONTROL STRATEGY

After completing the test under each control strategy, the test subjects were asked about which control strategy they would prefer in their daily office work. Three participants selected the option “No preference”, see Figure 23a. Their supplementary comments were interpreted as them not liking either of the control strategies. However, what is more interesting is to assess if the detailed control strategy is significantly more popular than the simple control strategy. An exact binomial test suggests that there is a significantly higher probability that the detailed control strategy is preferred than the simple control strategy (p=0.02).

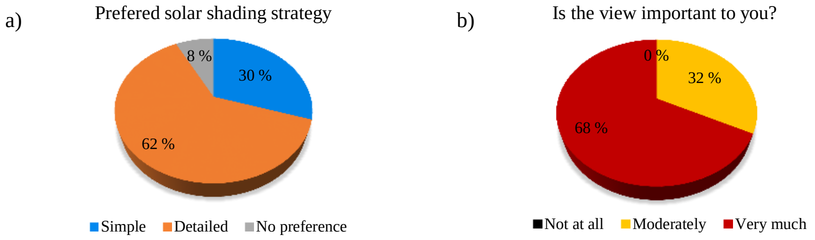


Figure 23: a) Reported preferred solar shading control strategy. b) Reported subjective importance of view.

One of the variables of interest to inspect, in order to see if it may contribute to predict the choice of control strategy, is the test subjects’ rating of importance of view. In this study the participants report higher disturbance by glare during the detailed control strategy than the simple control strategy, the detailed control strategy is nevertheless more preferred. This might be correlated to the phenomenon that the participants might tolerate some disturbance due to glare as long as they have access to view to the outside. Supplementary comments also gives strong indications that view to the outside influences the choice. Figure 23b illustrates that all test subjects rated view to be either moderately or very important. The majority of the subjects rating the view as very important prefer the detailed control strategy. However, a Fisher exact test suggests that the dependence between choice of preferred control strategy and rated importance of view is just outside the range of being categorized as statistically significant (MC=1e+08 replicates, p=0.06).

Due to differences in the outdoor weather conditions and time of day when the different tests were completed, there were some variations in the indoor conditions which the test subjects were exposed to; especially for the detailed control strategy. Figure 24(a and c) gives box-plots for the horizontal and vertical illuminance with respect to the preferred control strategy for the paper task and computer task during the detailed control strategy. Horizontal and vertical illuminance conditions are significantly higher during the detailed control strategy for those test subjects preferring the simple control strategy than for those preferring the detailed control strategy (t-test, p=2.6e-04 and p=0.01). Figure 24(b and d) illustrates the response of satisfaction with the light environment. An Exact Wilcoxon rank sum test suggests that the test subjects preferring the detailed control strategy report a significantly higher satisfaction with the light environment both for the paper task and the computer task during the detailed control strategy than those preferring the simple control strategy (p=0.03 and p=3.0e-03).

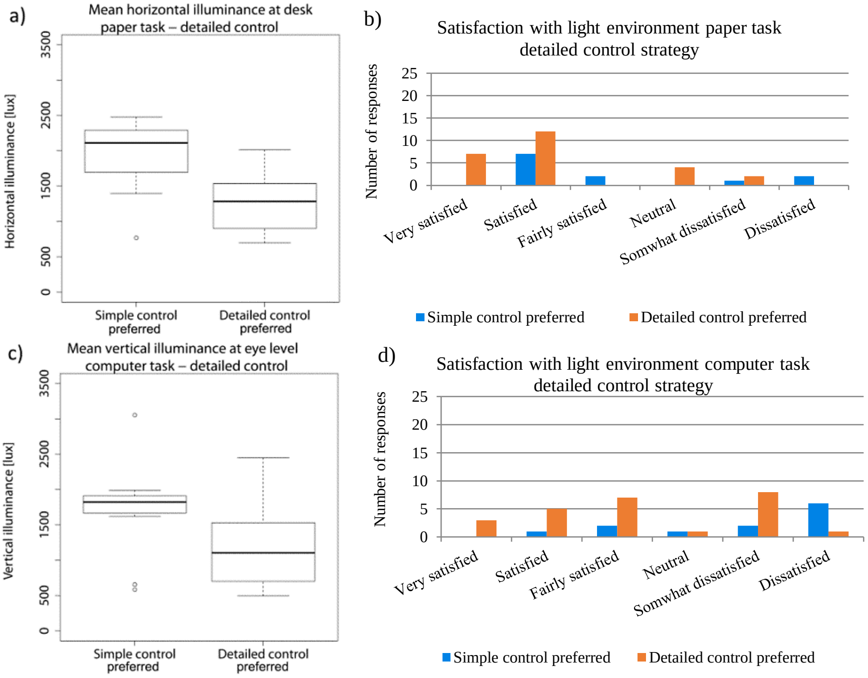


Figure 24: a) Box-plot of mean horizontal illuinance when doing paper work. b) Satisfaction with light environment when doing paper task. c) Box-plot of mean vertical illuinance when doing computer work. d) Satisfaction with light environment when doing computer work. All figures refer to response during the detailed control strategy.

These last comparisons and findings indicate that there might be space for improvement of the detailed control strategy in order to obtain higher acceptance by the occupants. The box-plots for vertical illuminance (see Figure 24c) reveal that illuminance levels above the set point of 2000 lux occur at several occasions even if the solar shading was activated. One improvement might be to make the control tilt the slats to an angle larger than the cut-off angle or 15˚ if the set point for vertical illuminance is still exceeded after activation [177, 211]. For practical implementations, careful consideration of the frequency of the movement must be considered for such strategy. Based on the box-plot for vertical illuminances during computer work (see Figure 24c), another improvement in the detailed control strategy might be to lower the set point of the vertical illuminance.

7.4 CONCLUSION

Comments by the participants in this study strongly suggest that view to the outside influenced the choice of preferred control strategy. The results further indicate that a cut-off strategy is not sufficient to avoid glare, even though a lower limit of the slat angle of 15˚ was set for the current case. Insufficiency of cut-off angles to avoid glare has earlier been reported in simulation studies [177, 211]. It is recommended that glare analysis should be incorporated into building design to a greater extent than what is common practice today. This should though be done in combination with daylight supply and view assessment in order to avoid recommending solar shading products or strategies that totally block the view contact to the exterior, since this study indicate that a certain amount of glare might be accepted by the occupants as long as view to the outside is available.

On an overall basis the results implies that the simplified treatment of blinds with a constant g-value corresponding to closed slats commonly used in building design might be insufficient when the aim is to make realistic building performance predictions. Therefore, it is recommended that building designers consider realistic control strategies, utilizes the slat angle as a control variable and apply building simulation tools which incorporate models that take angular properties of solar shading devices into account in a physical acceptable manner.

With respect to development of solar shading strategies, it is recommended that further effort is put into finding optimal set points for activation of the solar shading and for controlling the tilt angle of the blinds in order to obtain a robust control strategy with limited overrule actions.

For further reading, please consult Paper I: “*Occupant satisfaction with two blind control strategies: Slats closed and slats in cut-off position*” (DOI: http://dx.doi.org/10.1016/j.solener.2015.02.031)

CHAPTER 8. SIMPLE MEASURES FOR INDICATION OF DISCOMFORT GLARE FROM WINDOWS

In this chapter, the subjects' glare rating within the occupant survey is compared with measures of vertical eye illuminance, horizontal illuminance at the desk and predictions with DGPs. This is done in order to investigate if these measures are suitable to utilise within building design as an indication of glare.

8.1 VERTICAL EYE ILLUMINANCE

Figure 25 shows the ordered results of vertical eye illuminance colour-coded by the reported response of perceived glare for the present study. The dotted line in the graph markes the turnover point at E_v>1700 lux for where the responses in this study indicate that it is more likely to be disturbed by glare than not being disturbed by glare when assessing the glare response as an binominal response. This turnover point is higher than that reported by Van Den Wymelenberg and Inanici [120] of 1250 lux; however, their turnover point represents the change from "most perferred" to "just uncomfortable" scenes, wheras the turnover point in this study represents the change from imperceptible or noticable glare to disturbing or intolerable glare.

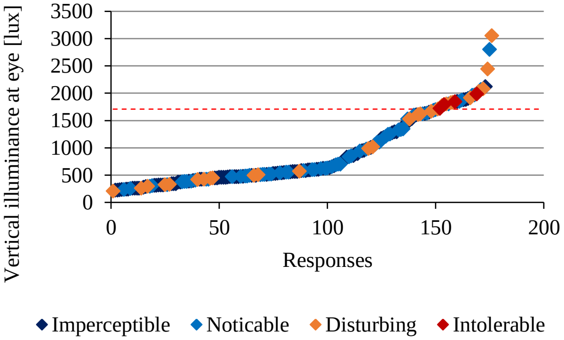


Figure 25: Results ordered according to vertical eye illuminance (E_v) and colour-coded by response to perceived glare. The dotted line represents the turnover point where it is more likely to be disturbed by glare than not to be disturbed by glare at values above this.

It might seems like a contradiction that subjects report glare at low illuminance levels; however, it is important to remember that contrast-based glare might be a considerable concern in low light environments [122, 212]. One of the limitations with vertical eye illuminance as an indicator of glare is that it can never account for contrast-based glare, unless the contrast itself contributes to a significant increase in the vertical illuminance [131, 212]. It should be noted that all responses of disturbing glare in the low illuminance range are reported under the simple solar shading control strategy when the lamellas are fully closed. As mentioned in section 6.2.1, a vertical stripe of light from the side of the solar shading and a horizontal stripe of light at the bottom of the solar shading occurred in closed position. When the lamellas are closed, the luminance ratio between the vertical/horizontal light stripe and the surrounding surfaces might be significant, especially for sunny weather conditions (see Figure 26), and the light stripes might act as a distraction to the occupants' eyes away from the central vision.

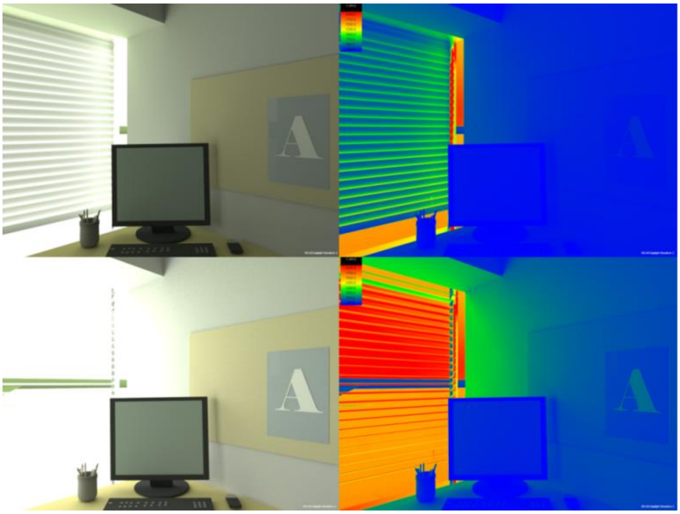


Figure 26: Rendering of the luminance in the test room for the two solar shading control strategies, upper row = simple, lower row = detailed. Luminance values are given with a false color scale where red indicates values equal to or above 2000 cd/m^2. The rendering is done in Velux Daylight Visualizer [209] for sunny sky conditions on May 21st at 10AM.

Table 10 gives a summary of statistical measures for the logistic regression model with E_v as a predictor variable. The resulting p-value from the Wald test suggests that E_v is connected to the probability of being disturbed by glare in a statistically significant way. Computing the chi square difference between the model with only an intercept and the model where E_v is added gives us a p-value of 7.74 e-5, suggesting that only adding E_v significantly improve the prediction of disturbance by glare. Further, the c-statistic of the model indicates that the model has an acceptable but rather weak discriminative ability. The lack of explanatory power of the model might be attributed to limited data as well as to a restricted number of occupants reporting disturbance by glare in the present study.

Table 10: Statistical measures for the logistic models with E_v and E_h as predictor variables.

	α	β	AIC	BIC	Nag.'s pseudo R^2	Brier score	c-statistic	p-value predictor variable	p-value likelihood ratio test
E_v	-2.71	0.001	155.28	161.62	0.14	0.13	0.66	1.17 e-4	7.74 e-5
E_h	-3.28	0.001	150.60	156.94	0.18	0.13	0.67	1.24 e-5	6.62 e-6

8.2 HORIZONTAL ILLUMINANCE AT THE DESK

Figure 27 shows the ordered results of horizontal illuminance at the desk colour-coded by the reported response of perceived glare and it is seen that the horizontal illuminance is generally higher than the vertical illuminance under the test conditions. This graphic reveils three preliminary thresholds: if E_h < 1900 lux, it is likely that the occupants are not disturbed by glare; if 1900 lux < E_h < 2100 lux, the probability of being desturbed/not disturbed by glare is equal; while if E_h > 2100 lux, it is likely that the occupants are disturbed by glare. This upper threshold corresponds well with the the original threshold of UDI-e of 2000 lux [92].

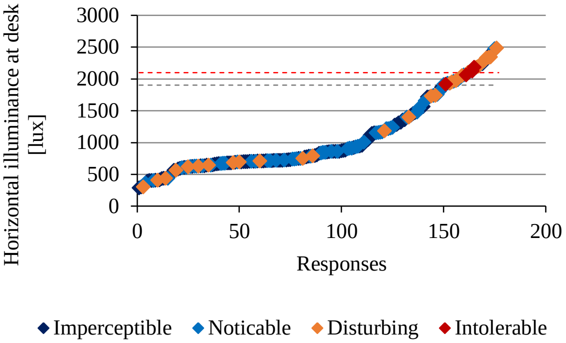


Figure 27: Results ordered according to horizontal illuminance (E_h) and colour-coded by response to perceived glare. The dotted lines show the bounded BCD, where the upper line represents the turnover point where it is more likely to be disturbed by glare than not be disturbed by glare at values above this.

Table 10 also presents statistical measures for the logistic regression model for E_h as a predictor of glare. Similar to what was seen for vertical illuminance, the resulting p-value for E_h from the logistic regression (p=1.24e-5) suggests that E_h is connected to the probability of being disturbed by glare in a statistically significant way. Conducting a likelihood ratio test between the model with only an intercept and the model where E_h is added results in a p-value of 6.62e-6, suggesting that only adding E_h significantly improves the prediction of disturbance by glare. Similar to what was seen for E_v, the c-statistic of the logistic regression model suggests that the model with E_h also has an acceptable but rather weak discriminative ability.

Comparing the AIC, BIC and R^2 presented in Table 10 for the two logistic models gives indications that the logistic regression model with E_h performs slightly better than the logistic regression model with E_v in this study. However, the difference of BIC between the models is <6 which, according to Raftery [213], only gives a positive but not statistically strong evidence that the logistic model for E_h performs better than the logistic model for E_v. The same Brier score of 0.13 for the two models also indicates similar overall performance of the models.

It should be emphasised that use of horizontal illuminance as an indication of glare might be position dependent as suggested by Konis [127] as well as having the same limitation as E_v of not being able to adequately represent contrast-based glare environments. Additionally, as Wienold [131] points out, horizontal illuminance cannot take the spatial light distribution into account.

8.3 DGPs

Figure 28 shows the comparison of the percentage of persons disturbed by glare for the observed data and the predictions according to DGPs for both of the grouping of the data described in section 5.3.5.2.2. The dotted lines indicate the confidence interval for the regression lines of the observed data from the current study. The coefficients of determination are 0.77 (24 responses) and 0.65 (12 responses), and this might support the argument by Hirning et al. [122] suggesting that the group division by Wienold and Christoffersen [111] over determine the correlation.

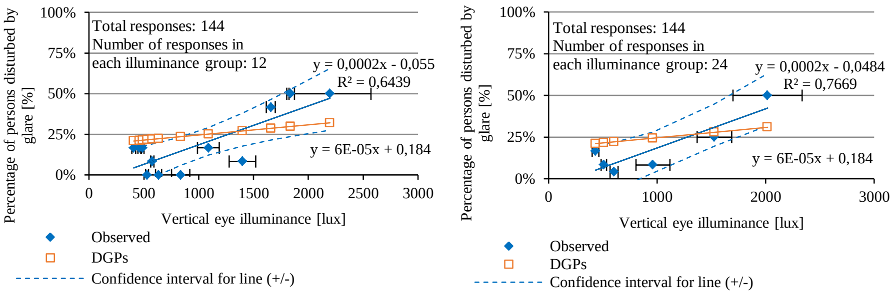


Figure 28: The daylight glare probability as a function of vertical illuminance at the position of the subject's eyes (EV) both for the observed data in the current survey and for the predictions based on DGPs according to two group divisions. The dotted lines represent the confidence intervals for the regression lines of the observed data.

When comparing the reported glare sensation in this study with the predictions done according to DGPs, the regression lines for the observed data have steeper slopes than the ones for DGPs for both groupings. It seems like the participants in the present study are more tolerant to low illuminance levels than what is predicted with DGPs, whereas they are more sensitive to illuminances higher than approximately

1400-1500 lux than predictions with DGPs indicate. This observation is confirmed by an analysis of variance, which suggests that there are statistically significant differences both between the intercept (p=0.015 (group of 24 responses), p=1.7e-3 (group of 12 responses)) and the slope (p=0.029 (group of 24 responses), p=5.0e-3 (group of 12 responses)) of the lines for the observed data and the line for the prediction according to DGPs. It should be noted that the illuminance levels in the present study are generally lower than most of the levels reported in the study by Wienold and Christoffersen [111], which might be an explanatory factor for the differences seen. However, the tendency of being more sensitive to relatively high vertical illuminance levels then the DGPs predict are also supported by the studies by Van Den Wymelenberg and Inanici [120] and Konis [127], who predicts 50 % of the occupants to be disturbed by glare at E_v of 1250 lux and 1600 lux respectively.

8.4 CONCLUSION

Similar to earlier reported research, large individual variations were seen in the occupants' assessment of glare. This strongly suggests that the users should have the opportunity to control or overrule the glare control within an office environment in order to be able to maintain an acceptable visual environment.

The results from this study confirm that there is a statistically significant correlation between both vertical eye illuminance and horizontal illuminance at the desk and the occupants' perception of glare in a perimeter zone office environment. This finding is promising as it supports that such simple measures might be applied in annual analysis in the building design in order to obtain a design basis which arranges for satisfying visual comfort. Based on the result from this study, 1700 lux vertical eye illuminance at the occupant position and 1900-2100 lux horizontal at the desk seem like reasonable thresholds for avoiding excess glare perceptions in perimeter zones. However, as neither vertical nor horizontal illuminance can represent contrast-based glare, especially under low-light environment, more detailed analysis is needed in case of low-light dominating environments.

This study was not able to reproduce the results of Wienold and Christoffersen [111] with respect to DGPs. The observed response indicate that the participants in the present study were more tolerant to low illuminance levels and more sensitive to high illuminance levels than the DGPs model would predict. The idea of being able to predict the percentage of people being disturbed by glare is advantageous as it may allow differentiating between different levels of quality of a design as proposed by Wienold [131] and it also addresses the participant variability to glare.

For further reading, please consult Paper II: "*Verification of simple illuminance based measures for indication of discomfort glare from windows*" (DOI: http://dx.doi.org/10.1016/j.buildenv.2015.05.040)

CHAPTER 9. SOLAR SHADING CONTROL STRATEGY

The objective of the study presented in this chapter is to continue the work conducted within the FG project (see Figure 5 p. 41) by extending the control algorithm with factors relating to glare, daylight sufficiency and view based on findings in the literature and results from the occupant survey reported in Chapter 7 and Chapter 8. This is done in order to obtain a realistic control strategy that balances the aspects of indoor environmental performance and energy demand for office buildings in cold climate. Full-scale measurements in the Cube will be used to verify the control strategy performance.

9.1 CONTROL ALGORITHM

The control strategy is divided into two main parts: work hours and outside work hours. During the work hours, the main goal is to obtain occupant comfort. In this mode the control strategy focuses on avoiding glare and overheating while also, when possible, ensuring satisfactory daylight supply and view to the outside by utilizing the estimated cut-off angle of the slats in activated state. An improvement of the control strategy applied in the occupant survey is that the tilt angle is step-wised increased in case the cut-off angle is insufficient in avoiding glare. Additionally, the set-point of vertical eye illuminance, which is used as an indication of glare, is adjusted to 1700 lux based on findings from Chapter 8.

Outside work hours, energy saving is the main focus, and the solar shading is utilized both as an insulating layer during cold periods as well as a protecting shield against excessive unwanted solar gains during cooling-dominated periods.

9.2 SIMULATION MODEL

A simulation model of the Cube is constructed within IDA ICE [60] according to the description of the test case given in section 5.2. The analysis uses the detailed zone model with the new improved operative temperature model that includes the effect of direct solar radiation, verified in Chapter 6.

The detailed window model in IDA ICE is applied in the simulation where the thermal window and shading performance are modelled according to ISO 15099:2003 [195]. The daylight contribution from the window opening is calculated with the new daylight features in IDA ICE, also verified in Chapter 6.

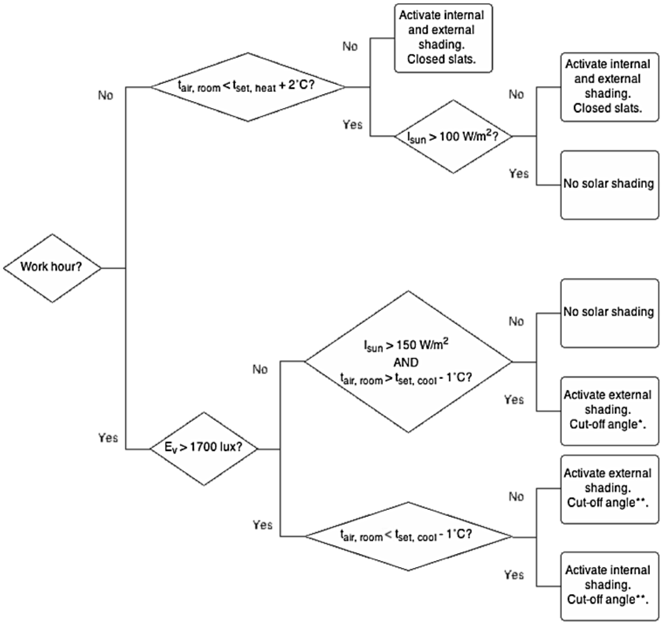


*Figure 29: Optimized control strategy with respect to visual and thermal comfort and energy use. * Cut-off angle, minimum tilt angle of 15˚. ** Cut-off angle, minimum tilt angle of 15˚ and stepwise increase of 10˚ until* E_v *< 1700 lux.* $t_{air,\ room}$ *is room air temperature (˚C),* $t_{set,\ heat/cool}$ *is set-point temperature for heating/cooling,* E_v *is vertical eye illuminance and* I_{sun} *is vertical external solar irradiation.*

9.3 VERIFICATION OF SHADING CONTROL PERFORMANCE

In order to verify the performance of the control strategy for heating and cooling seasons, measurements in the Cube were conducted during July 2014 and January 2015 and compared with simulation results. Due to a relatively warm period in Aalborg in January 2015, the set-points for heating and cooling were set to 32 ˚C and 35 ˚C respectively in order to trigger a heating demand, for the cooling season it was fixed to 21 ˚C and 25 ˚C respectively.

Figure 30(a) compares measured and simulated heating power during 17.01.2015–23.01.2015 for which the proposed optimized shading control is applied. Additionally, the figure illustrates by use of simulations how the heating demand would have been with only external solar shading and without night shading. The simulation results reproduce the measurements rather well and the coefficient of determination (R^2) is equal to 0.94, see Figure 29(b). Some severe deviations occur at certain situations during daytime where the simulation underdetermines the heating demand. The reason for this is mainly the differences in measured and modelled vertical irradiances at the façade and can be attributed the inaccuracy of the Skartvet-Olseth model under intermediate sky conditions.

Based on the simulation results, it is further evident that use of solar shading as insulating layers outside work hours may have a certain energy saving potential in cold climates during the heating season. Additionally, using internal solar shading as glare protection and letting heat enter the room during periods with a heating demand contributes to reduce energy for heating at daytime, see 17.01.2015.

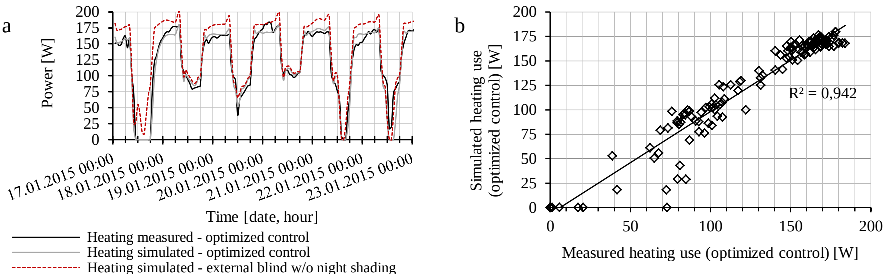


Figure 30: a) Comparison of measured and simulated heating uses during the period of 17.01.2015-23.01.2015. b) Correlation between measured and simulated heating uses under the proposed optimized control strategy.

Figure 31 illustrates the resulting chill beam cooling power for the measurements and simulations during the period of 25.07.2014–30.07.2014. Figure 31(a) compares measured and simulated cooling power for a situation to which the proposed optimized shading control is applied. Additionally, the figure illustrates by use of simulations how the cooling demand would have been if only internal solar shading were applied. Similar to the heating comparisons, the simulation results reproduce the measurements rather well with a coefficient of determination (R^2) of 0.94; see Figure 31(b). It should also be pointed out that the simulation results are within the measurement accuracy level at all times during the analysed period (±0.9 L/h flow meters and ±0.057 K Pt-500 temperature sensors).

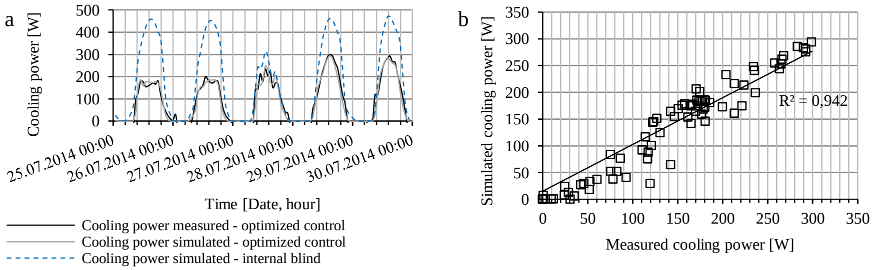


Figure 31: a) Comparison of measured and simulated cooling use during the period of 25.07.2014-30.07.2014. b) Correlation between measured and simulated cooling use under the proposed optimized control strategy.

Comparison of air temperatures and operative temperatures at the occupant position also shows that the simulations are capable of reproducing the measurements with a reasonable level of accuracy for both heating and cooling seasons, see Table 11.

Table 11: Mean bias errors, mean absolute errors and root mean square error of the simulated air and operative temperatures for winter and summer performances in the Cube.

	MBE [˚C]		MAE [˚C]		RMSE [˚C]	
	T_{air}	T_{op}	T_{air}	T_{op}	T_{air}	T_{op}
Winter performance	-0.04	0	0.06	0.10	0.19	0.20
Summer performance	0.08	-0.04	0.11	0.17	0.15	0.20

9.4 ANNUAL PERFORMANCE SOLAR SHADING CONTROL

The previous section illustrate that IDA ICE is able to reproduce both heating and cooling season situations with reasonable accuracy and that the simulation model is well calibrated, which makes it interesting to expand the investigation and explore the annual performance of the control strategy at different geographical locations. The expanded investigation considers the locations Aalborg (57°3'N, 9°55'E), Oslo (59°57'N, 10°45'E) and Røros (62°34'N, 11°23'E).

The construction of the simulation model is kept unaltered from the investigation in the previous sections, while Table 12 summarises the HVAC set-points as well as internal gains used in the annual simulations.

Table 12: Set-points for HVAC systems and overview of internal gains in annual analysis.

Category		Input value
Set-point heating/cooling		21˚C / 25˚C (15.Sep.-15.May) 19˚C / 25˚C (15.May-15.Sep.)
Internal gains	Occupants	1 occupant (7-19 weekdays) Activity level: 1 met Clothing level: 0.85 ± 0.25 clo
	Equipment	50 W (7-19 weekdays)
	Lighting	Max 60 W, controlled to maintain 500 lux at the work plane according to the dimming characteristics given in Figure 9 (7-19 weekdays).
Ventilation	Supply air (CAV)	2.6 $l/(s\ m^2)$ (7-19 weekdays) 1.6 $l/(s\ m^2)$ (rest of the time)
	Supply air temperature	Outdoor compensated (18 ˚C at -20 ˚C, 16 ˚C at 25 ˚C)
	Heat exchanger	80 %

In order to evaluate the annual performance of the control strategy in Figure 29, it is necessary to compare it to some reference. In this case the reference is chosen to be a simple control strategy commonly used in building design annotated *Control 100 W/m^2 external*, as well as the annual performance when there is no shading in use as references. Additionally, it is assessed how the annual performance of the proposed control strategy would be with either only internal or external solar shading. Table 13 summarises a short description of the investigated solar shading controls.

Table 13: Overview of the simulated solar shading controls.

Solar shading control	Description of solar shading control
Optimized control	According to the control algorithm in Figure 29.
Detailed control external	According to the control algorithm in Figure 29, but only with use of external shading.
Detailed control internal	According to the control algorithm in Figure 29, but only with use of internal shading.
Control 100 W/m^2 external	The solar shading is activated when the external vertical irradiance at the façade exceeds 100 W/m^2. In activated position the slats are closed with a slat angle of 80°, in practice totally closed.
No solar shading	No solar shading applied.

9.4.1 RESULTS AND DISCUSSION – ANNUAL PERFORMANCE

Figure 32–Figure 34 present results of the annual performance of the solar shading control strategies outlined in Table 13 with respect to energy use and indoor environment for the locations of Aalborg, Oslo and Røros. Since identical venetian blinds are used both for internal and external shading, there are only neglect able differences in the daylight results for the optimized control, detailed control external and detailed control internal. These results are, therefore, presented together under the label ‘optimized/detailed control’.

It is apparent that the optimized solar shading control strategy or the detailed control strategy with only external shading is the best compromise between energy use and indoor environment for all three considered locations. This is the control strategy with the lowest net energy demand, a thermal comfort within acceptable ranges as well as a highly acceptable daylight sufficiency with $DA_{300\_50\%}$ of 100 % at all three locations. With this control strategy, the solar shading is activated for 61 %, 40 % and 45 % of the occupied time for the location of Aalborg, Oslo and Røros respectively. During this time, the slat angle is less than 45° during significant parts of the time, which gives a certain contact to the outside, see Table 14. It should be noted that there are times when the vertical eye illuminance at the occupant position exceeds 1700 lux even for this control strategy, which indicates that there is not an ideal correlation between vertical illuminance at the sensor placement and the occupant position at all times. This illustrates the challenge with sensor placement. Additionally it proves the importance of arranging for manual override of the solar shading, maybe along with flexibility of the occupants’ viewing direction in order for the occupant to be able to obtain an acceptable visual work environment at all times; strategies which have been pointed out in earlier studies [118, 185, 210].

Table 14: Summary of percentage of occupied time with activated solar shading and the percentage of time with activated solar shading with slat angle <45°. For Control 100 W/m^2 the tilt angle is fixed at 80° in activated mode.

	Percentage of occupied time with solar shading activated		Percentage of time in activated mode with slat angle <45°	
	Optimized control	Control 100 W/m^2	Optimized control	Control 100 W/m^2
Aalborg	61	57	72	N/A
Oslo	40	57	84	N/A
Røros	45	60	88	N/A

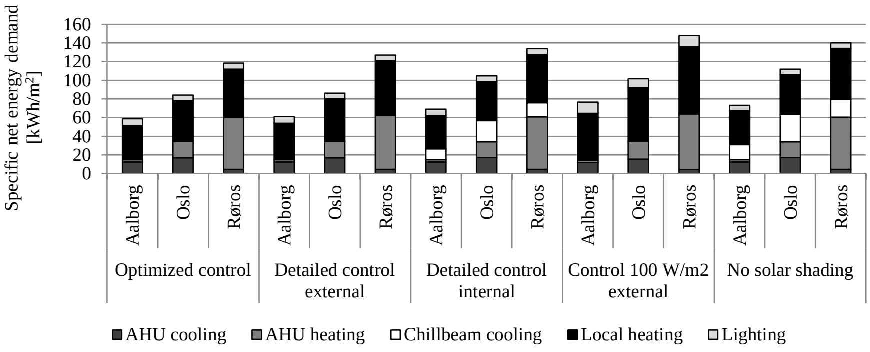


Figure 32: Comparison of annual energy demand for heating, cooling and lighting for different solar shading controls for the location of Aalborg, Oslo and Røros.

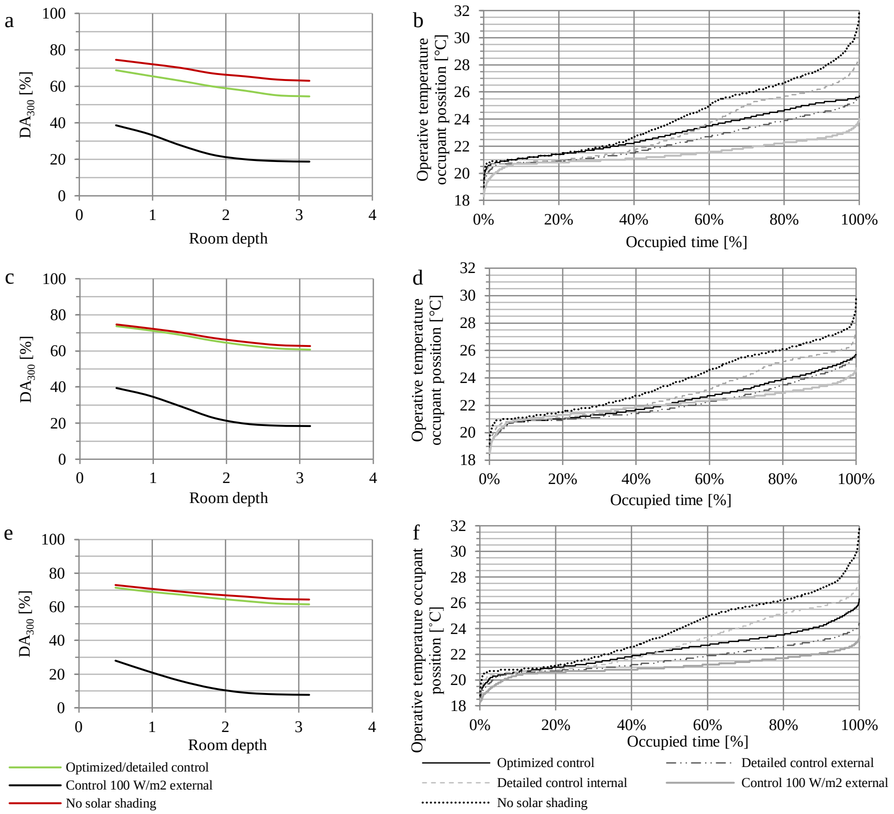


Figure 33: Room centerline distribution of daylight autonomy 300 lux for the different solar shading control strategies for the location of Aalborg (a), Oslo (c) and Røros (e). Duration curves of the operative temperature with inclusion of direct sun at the occupant position for the different solar shading control strategies for the location of Aalborg (b), Oslo (d) and Røros (f).

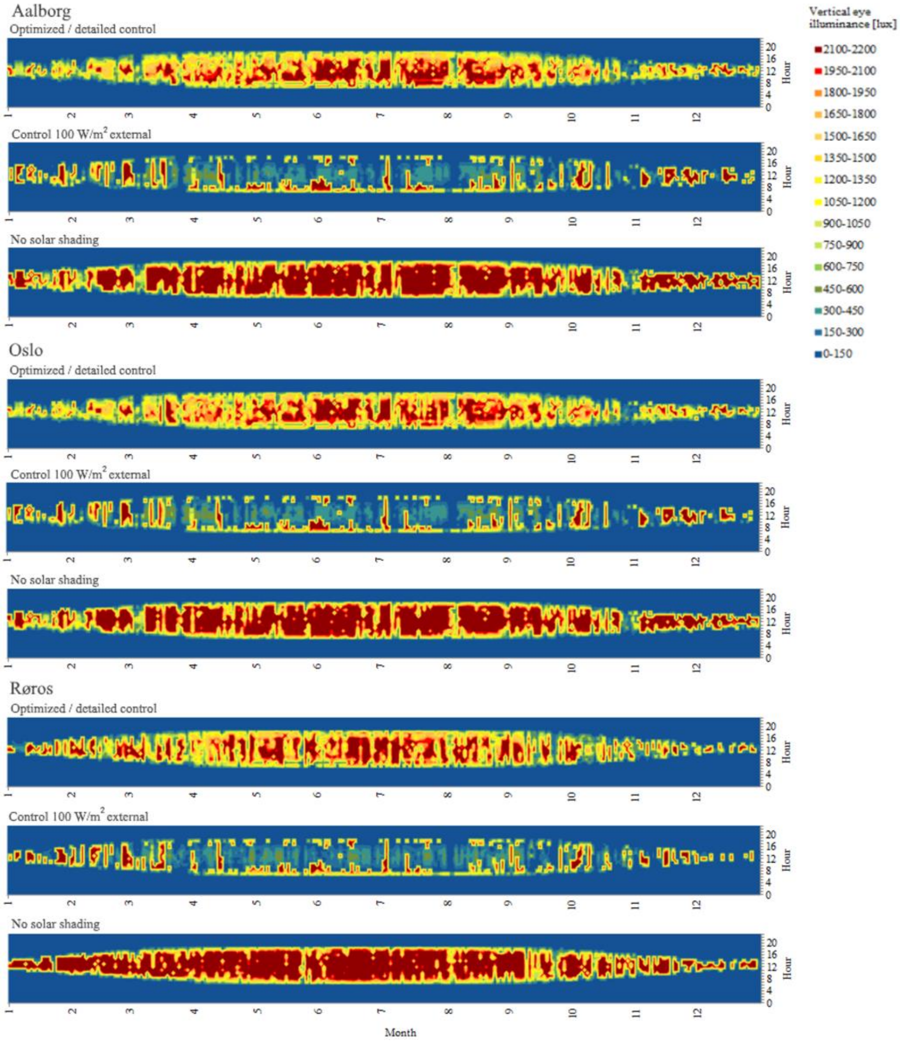


Figure 34: Analysis of the annual E_v at the occupant position with a view direction towards the south-west corner of the room according to Figure 7*c (p. 50). The dark red areas indicate hours with an E_v level above 2100 lx.*

9.5 CONCLUSION

Full-scale measurements showed promising performance of the proposed solar shading control strategy for both winter and summer conditions. Generally, the investigation exemplifies the importance of doing integrated evaluations of energy use and thermal and visual comfort when making decisions regarding solar shading control strategies. The results of the annual performance illustrated that the proposed control strategy would be the best compromise between energy use and indoor environmental performance. Still, for moderate cold climates, like Aalborg and Oslo, the application of the proposed control strategy with only external shading might be the preferred alternative since investment cost of two sets of solar shading with automatic control might be unprofitable when considering the lifetime of the components. As for more extreme cold climates, the energy and indoor environmental performance analyses should be accompanied with a cost-benefit analysis when making decisions of installing only external or a combination of external and internal solar shading systems.

Further, sensor placement for vertical illuminance might be a challenge since there is no ideal correlation between illuminance at two positions in the room at all times during a year. Even with activated solar shading and controlled tilt angle to avoid vertical illuminance >1700 lux at the sensor placement, the vertical eye illuminance at the occupant position might exceed this threshold which could be associated with a risk of glare. Still, it is assessed that the solar shading performance is acceptable since the results from the occupant survey reported in Chapter 7 indicates that a certain amount of glare might be accepted by the occupants as long as there is a view to the outside. However, users should have the opportunity to overrule the automatic glare control within an office environment or have the flexibility to change viewing direction in order to be able to maintain an acceptable visual environment at all times.

For further reading, please consult Paper III: “*Solar shading control strategy for office buildings in cold climate”*
(DOI: http://dx.doi.org/10.1016/j.enbuild.2016.03.014)

PART III – CONCLUSION AND FUTURE WORK

This part contains an overall discussion and conclusion of the thesis where the work is put in perspective. The part is ended off with a suggestion for future work based on findings and knowledge gained through this project.

> *The whole of science is nothing more than a refinement of everyday thinking.*
>
> *–Albert Einstein*

CHAPTER 10. CONCLUSION

This PhD thesis was based on the fact that there is a lack of consistency in the building design with respect to thermal comfort, daylighting and energy use. Consequently, the objective of this project was to arrange for a more holistic design process where the predicted thermal comfort, daylighting and energy use are based on the same underlying assumptions. Further, it was an aim to make such integrated design method practical applicable for building designers in Nordic countries.

First out was to investigate if the approaches used to model and evaluate thermal comfort and daylight within present building design constituted any obstacles for conducting an integrated design. In practical design, operative temperature is the most commonly applied evaluation criteria and it was assessed that its use doesn’t represent a hinder for conducting integrated design. Even though, studies reported in the literature indicated need for improvement of the modelling of MRT. Through the last decades a common simplification within practical engineering has been to model MRT as the mean temperature of all the surrounding surface areas. However, based on findings in the literature, it was suggested to model MRT as a function of the location in the room accounting for contribution of both long and short-wave radiation, see Figure 35 Such level of detail is required in design of modern office buildings, where both use of extensively glazed facades and deep room layouts are rather dominating on which significant local differences in the thermal environment might occur. Within this thesis it was confirmed that a model proposed by Fanger for calculation of MRT of a person affected by a high intensity radiation heating source can be used for assessing the effect of solar radiation. Further, it was verified that the model is successfully implemented in the simulation tool IDA ICE.

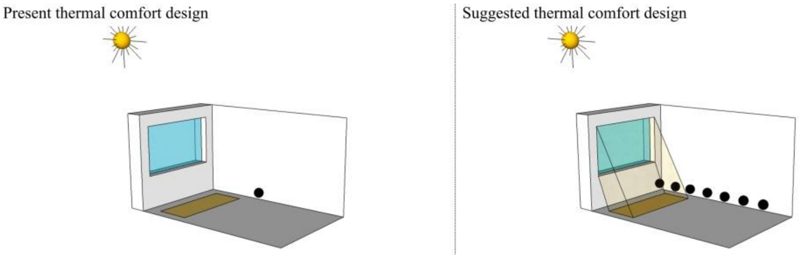


Figure 35: Illustration of how thermal comfort usually is modelled and evaluated in present building design (left) and a suggestion of how it should be done in the future (right).

Regarding daylight design, results from the literature review indicated that the static daylight calculations and widespread evaluations according to $DF/\overline{DF}$ along with lack of glare evaluations actually represented obstacles with respect to achieving an integrated design. Based on findings in the literature it was suggested that the DF

should be replaced with climate-based daylight metrics for assessment of daylight supply. Moreover, it was implied that annual glare evaluations are required within visual comfort assessments and predicted need of solar shading activation, see Figure 36. A few climate-based daylight models were identified in the literature. The three-phase model was implemented in IDA ICE, due to its advantage of efficiently consider various fenestration configurations. Successful implementation was verified by comparison of simulations and full-scale measurements.

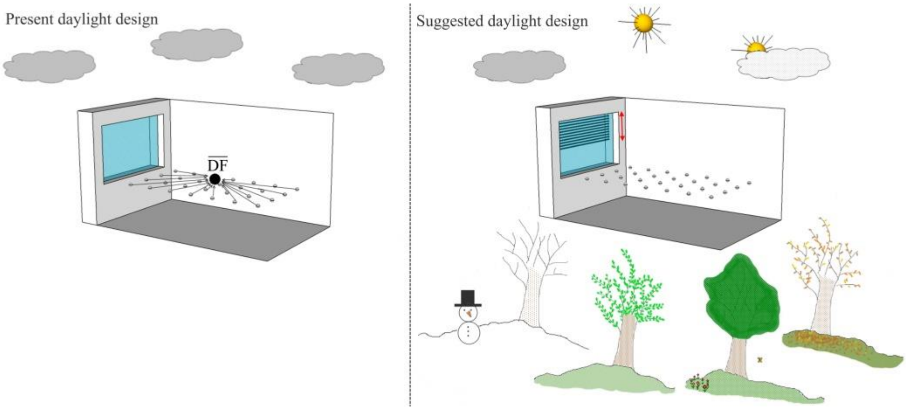


Figure 36: Illustration of how daylight usually is statically modelled and evaluated in present building design (left) and a suggestion of how it should be done dynamically with consideration of e.g. solar shading, climate and location in the future (right).

Secondly, it was of interest to investigate how use of solar shading should be accounted for within an integrated building design, since the fenestration system and its control was identified as a crucial link between thermal and daylighting performance. The literature indicated that simple shading control strategies based on externally measured solar radiation commonly are utilised in building design and operation. Additionally, it was found that the blind slat angle generally is ignored in studies treating venetian blinds and that the blind position only is considered as open or closed. Based on findings in the literature, it was suggested to use multi-variable control strategies in order to fulfil various functions of the solar shading, use variables associated with interior conditions as activation criteria to maintain occupant comfort as well as consider the blind slat angle as a control variable.

A multivariable solar shading control algorithm proposed through the Norwegian R&D FG-project was modified by implementing blind slat angle as a control variable. Additionally, interior vertical eye illuminance replaced external vertical solar irradiation as a parameter for indication of glare. The modified part of the control strategy (detailed control) for occupied hours were tested in an occupant survey together with a control strategy simulating how solar shading commonly is treated in present building design with slats closed in activated position (simple control), see Figure 37. Results from the occupant survey suggested that significantly more of the test subjects in the survey preferred the detailed control strategy, even though it was associated with higher occurrence of glare than the simple control. The finding further indicated that view to the outside was an important factor for occupants comfort. Based on these results, the modified solar shading control was further improved and its performance was verified by full-scale measurements at heating and cooling seasons along with annual simulations. The simulation results exemplified the importance of doing integrated evaluations when making decisions regarding solar shading control strategies, which support the value of the proposed framework for integrated design.

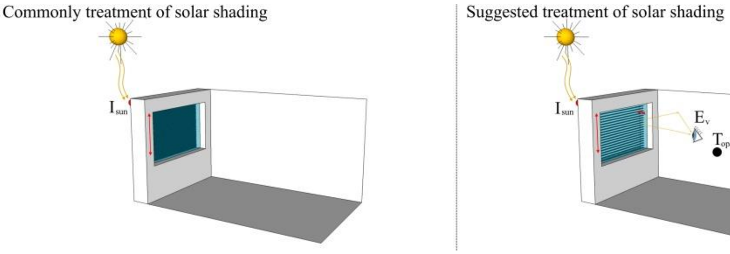


Figure 37: Illustration of how solar shading control usually is modelled in present building design (left) and a suggestion of how it should be done in the future (right).

Table 15 summarizes suggested criteria for thermal and visual comfort evaluations within an integrated design. With respect to the daylight evaluation, the listed criteria are a renewed proposal compared to those presented in Table 2 (p. 37). Since the time when the initial proposal for implementation of daylight as part of the integrated design was developed, researchers have reported results that strengthen the evidence towards using $sDA_{300/50\%}$ as annual daylight criteria [214, 215]. Additionally, the Education Funding Agency (EFA) in UK now requires use of climate based daylight design when designing schools, either UDI or DA [216]. Further, $sDA_{300/50\%}$ has been implemented in the certification system LEED v4, which has extended its application. With respect to glare evaluations, results from the occupant survey reported in this thesis confirm that there is a statistically significant correlation between both vertical eye illuminance and horizontal illuminance at the desk and the occupants' perception of glare in a perimeter zone office. These findings support that horizontal illuminance at the desk might be an applicable indicator of glare for perimeter office environments, especially for use in early building design. While vertical illuminance, which possess the ability of taking the spatial light distribution into account, might be favourable at a later design stage when the location of the occupant is decided as well as for incorporation as control parameter for building control strategies. Further, evaluation of view has been added as a parameter for assessment of visual comfort, since results from the occupant survey suggest that view might be an important factor for occupants comfort.

Table 15: Suggested thermal and visual evaluation criteria for an integrated design.

Design stage	Thermal comfort	Daylight supply	View	Glare
Initial design	$T_{op, sun}$	(DF)/ $sDA_{300/50\%}$ / UDI	Percentage of occupied time with closed solar shading.	2000 lux at the horizontal work plane.
Schematic design	$T_{op, sun}$	$sDA_{300/50\%}$ / UDI	Percentage of occupied time with closed solar shading.	2000 lux at the horizontal work plane.
Detail design	$T_{op, sun}$	$sDA_{300/50\%}$/ UDI	Percentage of occupied time with closed solar shading, plus indication of time when a certain amount of view through the slats are maintained.	1700 lux vertical eye illuminance. More detailed assessments for low light environments.

10.1 PRACTICAL IMPLICATIONS

By utilising the proposed integrated design method with associated evaluation criteria, the designer might experience that predicted energy use may be higher than predictions done with conventional methods. In a practical design world where fulfilments of energy requirements are high on the agenda, this is of course not an incentive for conducting such integrated design. However, the motivation for using the suggested integrated approach should be that it reflects the building performance more realistically and one can make design decisions and building optimizations rooted on a more information based foundation.

In present building design, architects usually have the responsibility of daylight design while the engineers commonly have the commitment towards thermal comfort and energy use of the building. The suggested integrated design presented in this thesis may have consequences on this traditional distribution of area of responsibility. The proposed design is founded on the principle that the predicted energy use and thermal and visual comfort are based on the same underlying assumptions, e.g. with respect to climate data as well as use of solar shading, artificial lighting and heating/cooling. It is therefore highly recommended that an integrated simulation tool is utilised throughout the design to secure such agreement in the boundary conditions. Subsequently, it will be natural if the responsibility of energy use, thermal comfort and daylighting is gathered at one design discipline. Due to the physical complexity and required need for numerical simulations it would be expected that the responsibility rest with the engineer. This, however, require a great commitment towards cooperation between the design disciplines from the very beginning of the design, since the aesthetic expression and design of the façade will be the determining factor for the energy and indoor environmental performance of the building. The proposed design framework therefore implicates an interdisciplinary, collaborative design process.

10.2 RESEARCH CONTRIBUTION TO ACADEMIA AND INDUSTRY

The findings reported in this thesis have generated contribution both to academia and the industry. A list of the contributions is given in the following:

Contribution to academia

A number of contributions to academia have been generated along the road of establishing a framework which arrange for a more holistic design process regarding the predicted energy use and thermal and visual comfort.

- Findings support that short-wave radiation should be incorporated in calculation of MRT in view of the fact that this might improve the prediction of thermal comfort, especially close to glazed facades where solar loads might be dominating.
- Results from the occupant survey confirmed that there was a statistically significant correlation between both vertical eye illuminance and horizontal illuminance at the desk and the occupants’ perception of glare in a perimeter zone office environment. This finding is promising as it supports that such simple measures might be applied in annual analysis in the building design in order to obtain a design basis which arranges for satisfying visual comfort. Based on results from the occupant survey, 1700 lux vertical eye illuminance at the occupant position and 1900-2100 lux horizontal at the desk seem like reasonable thresholds for avoiding excess glare perceptions in perimeter zones. These thresholds are in comparable ranges to earlier findings [92, 120, 127].
- Findings from the occupant survey support that view is an important factor in a working environment and that occupants may tolerate a certain degree of glare as long as view is present. The quality of view was not investigated and more research should be carried out in this area as well as evaluation criteria for view should be established. As a minimum at the present time, it is suggested that the percentage of occupied time with activated solar shading should be reported as an inverse indication of view, in agreement with recommendations by Reinhart and Wienold [119].

Contribution to industry

The main contribution to the industry is the verification of improved models implemented in IDA ICE. The value of the models and its output is illustrated in simulation cases presented in Chapter 6/Paper III and in Paper VI. If these verified models are released in a commercial product of IDA ICE in the future, the proposed integrated design methodology will be practical applicable and easily available for building designers in Nordic countries.

Additionally, results reported in this thesis gives advices that can be put into practical use:

- Due to the dynamic nature of daylight, it should be modelled in a dynamic manner. Use of simple calculations like the 10 % rule and use of the static DF should be avoided when the aim is to get a realistic picture of the daylight conditions.
- Glare analysis should be incorporated into building design to a greater extent than what is common practice today. This should though be done in combination with daylight supply and view assessment in order to avoid recommending solar shading products or strategies that totally block the view contact to the exterior, since this study indicate that a certain amount of glare might be accepted by the occupants as long as view to the outside is available.
- Results from the occupant survey strengthen the proof that occupants should have some personal control over the physical workspace, especially with respect to the glare control since large variations were seen in the occupants’ assessment of glare. It is important that the designers arrange for such control possibilities.
- The solar shading control strategy presented in Chapter 9/Paper III that balances the aspects of thermal and visual indoor environmental performance and energy demand can be used in practical design and building operation.

CHAPTER 11. FUTURE WORK

The research presented in this thesis has resulted in a number of conclusions and minor suggestions applicable for academia and the industry. However, it is evident that future research should be carried out to further support some of these findings. Additionally, some of the results obtained through this thesis have barely touched some area of interest which also needs more attention in future research.

11.1 VIEW

Results from the occupant survey presented in this thesis indicate that view to the outside is an essential factor for occupants in a working environment and that view was a decisive factor for the occupants' preference of solar shading control. At the present time, there is no standardized method to assess view; however, proposals have recently been given, e.g. [131, 217]. It is recommended that proposed models should be verified and possibly improved in order to take the influence of view on occupant comfort into account in building design.

11.2 SIMPLE ANNUAL GLARE EVALUATIONS

The results presented in Chapter 8 confirmed that there was a statistically significant correlation between both vertical eye illuminance and horizontal illuminance at the desk and the occupants' perception of glare in a perimeter zone office environment. The results are restricted to office environments where the occupant is facing diagonally towards the window. Position and view direction dependency is an issue which should be investigated further in the future.

The occupant survey was not able to reproduce the results of Wienold and Christoffersen [111] with respect to DGPs. The observed response indicated that the participants in the study in the Cube were more tolerant to low illuminance levels and more sensitive to high illuminance levels than the DGPs model would predict. The idea of being able to predict the percentage of people being disturbed by glare is advantageous as it may allow differentiating between different levels of quality of a design, as proposed by Wienold [131], as well as it addresses the participant variability to glare. However, more and larger scale studies are needed to either confirm the suitability of the DGPs model or to confirm the findings in the present study that suggest that the DGPs equation should be renewed.

11.3 SENSOR PLACEMENT

Sensor placement for vertical illuminance might be a challenge since there is no ideal correlation between illuminance at two positions in the room at all times during a year. The simulation study in Chapter 9 showed that even with activated solar shading and controlled tilt angle to avoid vertical illuminance >1700 lux at the sensor placement, the vertical eye illuminance at the occupant position might exceed this threshold which could be associated with a risk of glare. Further research should be accomplished to investigate optimal sensor placement and maybe assess if different correlations for different times of the year may result in better control of the daylight environment.

11.4 OPERATIVE TEMPERATURE IN THE SUN

Due to a number of limitations, the new MRT model implemented into IDA ICE might at the present time only be used as a rough indication of how an occupant hit by the sun experience the thermal radiation; it is for instance assumed that the whole body is irradiated if the point in question is irradiated and the human body is approximated as a sphere. Further studies should be done to assess if a more detailed model is needed.

When accounting for short-wave radiation on the human body, assumptions have to be made regarding the absorptivity of the clothing. In the studies reported in this thesis absorption of 0.7-0.8 is assumed, corresponding to a grey outer surface. Further investigations are needed to suggest suitable values for this parameter.

11.5 DAYLIGHT MODELLING

Chapter 6 indicated that there are some limitations associated with the three-phase method, especially with respect to distribution of direct solar light in a room. A more detailed model exists, the five-phase method. However, this model is also more time consuming to execute. Studies are needed to assess if higher accuracy in the annual daylight modelling is needed within an integrated design.

11.6 DAYLIGHT REQUIREMENTS IN BUILDING REGULATIONS

This thesis has illustrated that the static daylight targets given in the guidance to the Norwegian building regulations not necessarily result in well daylit buildings. As Reinhart and Wienold [119] point out, effort should be put into making code authorities understand that use of climate-based daylight modelling might lead to better daylit buildings and that this might have positive effects on the comfort and health of building occupants.

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APPENDICES

Appendix I. Paper I

Please consult:

Karlsen L., Heiselberg P. and Bryn I., *Occupant satisfaction with two blind control strategies: Slats closed and slats in cut-off position*. Solar Energy, 2015. 115(0): p. 166-179. DOI: http://dx.doi.org/10.1016/j.solener.2015.02.031

Appendix II. Paper II

Please consult:

Karlsen L., Heiselberg P., Bryn I., and Johra H., *Verification of simple illuminance based measures for indication of discomfort glare from windows*. Building and Environment, 2015. 92: p. 615-626. DOI: http://dx.doi.org/10.1016/j.buildenv.2015.05.040

Appendix III. Paper III

Please consult:

Karlsen L., Heiselberg P., Bryn I. and Johra H, *Solar shading control strategy for office buildings in cold climate*, Energy and Buildings, 2016 118, p. 316-328. DOI: http://dx.doi.org/10.1016/j.enbuild.2016.03.014

Appendix IV. Paper IV

Karlsen, L., Grozman G., Heiselberg P. and Bryn I., *Operative temperature and thermal comfort in the sun – Implementation and verification of a model for IDA ICE*, in *Indoor Air*. 2014: Hong Kong, China.

Operative Temperature and Thermal Comfort in the Sun – Implementation and Verification of a Model for IDA ICE

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Keywords: IDA ICE, operative temperature, thermal comfort, solar radiation

SUMMARY

This paper focuses on the implementation and verification of a new mean radiant temperature (MRT) model for IDA Indoor Climate and Energy (IDA ICE). The new feature of the model is that it includes the effect of shortwave radiation in the room and contributes to a more comprehensive prediction of operative temperature, e.g. of a person exposed to direct sun light. The verification of the model is carried out by comparing simulation results with full-scale measurements of a team office located in Oslo (59N10E). The measurements were conducted during mid-March and April 2013. The results indicate that the new MRT model might contribute to considerable improvements in prediction of thermal comfort of persons affected by direct solar radiation. This may further have implications on the predicted energy use and design of the façade, since e.g. an enlarged need for local cooling or use of dynamic solar shading might be discovered.

INTRODUCTION

Thermal comfort is an important aspect of the indoor environment. According to the heat balance approach, thermal comfort is influenced by six parameters; air temperature, mean radiant temperature (MRT), air velocity, relative humidity, metabolic rate and the thermal resistance of clothing. Among these parameters the mean radiant temperature of a person is often the most difficult to determine (Fanger, 1970), which might be the reason why simulation programs often apply various kinds of simplifications to establish this parameter. A crude typical simplification is to neglect the contribution of short-wave radiation on the human body, e.g. arising from solar radiation. This might lead to very wrong estimations of MRT of a person, especially in modern non-residential buildings which commonly have extensive amount of glazing in the façade whereas direct solar radiation might greatly affect the occupants.

In practise operative temperature is often used as an indicator to assess thermal comfort. Operative temperature is defined as the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the real nonuniform environment (Rizzo et al., 2004). Numerically the operative temperature is the average of the air temperature and mean radiant temperature, weighted by the convective and radiative heat transfer coefficients respectively (Fanger, 2006). It is obvious that if the MRT is wrongly estimated this leads to wrong estimations of operative temperature which further might contribute to directly misleading results for the thermal comfort analysis.

Fanger (1970) proposed a method for calculation of MRT of a person affected by high-intensity beam heating systems. In case of direct solar radiation, the sun might be considered as a high-intensity beam heating system. According to Fanger the hypothetical MRT of an unirradiated person, the projected area factor, the radiant intensity and the absorptance of the outer surface of the radiated person must be found to determine the MRT of the irradiated person. Similar methods have recently been proposed and/or tested both for indoor (Hiller et al., 2010; La Gennusa et al., 2007) and outdoor (Huang et al., 2012; Thorsson et al., 2007) environments. Yet, there is still a lack of implementation of these methods into simulation tools used in practical engineering and building design.

IDA Indoor Climate and Energy (IDA ICE) is a tool for simulation of thermal comfort, indoor air quality and energy consumption in buildings. In the present zone model in IDA ICE the MRT of a person at a specific position is calculated based on surface temperatures of the zone surfaces and view factors between the zone surfaces and an infinitely small cube. This means that only the long-wave radiation is considered in the MRT model and it does not e.g. account for the contribution of direct solar radiation on the human body. A new zone model has been developed for IDA ICE which includes a new MRT model with the ability to account for the effect of shortwave radiation in the room and contribute to a more comprehensive prediction of operative temperature. This study briefly describes the new MRT model and focus on its verification against full-scale measurements.

METHODOLOGIES

Operative temperature model in IDA ICE

The new zone model developed in IDA ICE has the ability to predict air stratification and flow elements. Measurements are collected on a fine regular grid. This paper focuses on the implementation and validation of a MRT model on this grid. The MRT for a point S is calculated according to equation 1.

$$T^S_{\mathrm{mrt}} = \sqrt[4]{\sum_{j=1}^{N} F_{S\to j}\, T_j^4 + \frac{\alpha}{\sigma}\sum_{j=1}^{N} F_{S\to j}\, I^j_{\mathrm{diffuse}} + \frac{\alpha}{\sigma}\sum_{i=1}^{M} C^i_{irr}\, f_p I^i_{\mathrm{direct}}} \tag{1}$$

Where T_{j} is the temperature of surface j, $\mathrm{F}_{\mathrm{S}\to\mathrm{j}}$ is the view factor from surface j to S, N is the number of surfaces in the thermal zone, α is the short wave absorptance at the surface of S, σ is Stefan-Boltzmann constant, f_{p} is the projected area factor of point S in the direction of the sun beam, I^j_{diffuse} is the diffuse radiation intensity from surface j, M is the number of openings, $\mathrm{C}^{\mathrm{i}}_{\mathrm{irr}}$ is an irradiation coefficient which is equal 1 if point S is irradiated by the direct solar beam from opening i and 0 otherwise and I^i_{direct} is the direct radiation intensity of the beam from opening i. IDA ICE does not support the possibility of beams from several openings to hit a point, hence only one $\mathrm{C}^{\mathrm{i}}_{\mathrm{irr}}$ equals 1 and the rest are 0. The operative temperature is further assumed to be the mean of MRT and the room air temperature, see equation 2, which is sufficient for relative air velocities below 0.2 m/s (Fanger, 2006). Where T^S_{op} is the operative temperature at point S and T^S_{air} is the air temperature at point S.

$$T^S_{op} = \frac{T^S_{mrt} + T^S_{air}}{2} \tag{2}$$

Though equation (1) may seem simple and straight forward, it is a non-trivial task to calculate all the input parameters, such as surface temperatures, short-wave radiation form openings and diffuse (multiply reflected) short-wave radiation balance in the zone. IDA ICE suits for such a calculation since it already contains the entire boundary information. However, equation (1) is a simplification in many ways. Firstly, it assumes all the surfaces and openings are uniform in all their properties. That is, each surface has uniform temperature and reflectance; radiation intensity from an opening is uniformly distributed over the beam; a surface reflects incoming short-wave radiation uniformly from its entire area. Also, all the direct short-wave radiation becomes diffuse when it hits a surface. Secondly, the occupants are modelled as infinitely small spheres. That means, for instance, that they do not obstruct each other or absorb any radiation energy. Also, the beam from an opening either hits the occupant or not, it cannot hit a part of the occupant's body. Thirdly, the surface of the occupant is assumed to have the same absorptivity as emissivity. These parameters are assumed to cancel each other out and are hence not part of equation (1).

Test case and experimental set-up

The verification of the new MRT model in IDA ICE is carried out by comparing simulation results with full-scale measurements. Full-scale measurements were taken in a team office located in Oslo (latitude 59N, longitude 10E). The office has the dimensions 3.6 ^{x} 7.5 m and is situated at the corner of the 16th floor with one partly obstructed façade oriented 57° east of south and one unobstructed façade oriented 33° west of south, see Figure **1**. The south-east and south-west facades contain one and three windows respectively of 2.7 m^2 each where three of the windows have some fins as external shading, see Figure **1**. All four windows are double-glazed, with a low emissivity coating and Argon filling with the properties: direct solar transmission=0.24, g-value=0.27, visible light transmittance=50 % and U-value= 1.1W/m^{2}K. Internal vertical louvers are installed in the office, but these are not activated during the experiments. The office is equipped with mechanical ventilation, child beam cooling and water based heating by radiators operated according to Table 1.

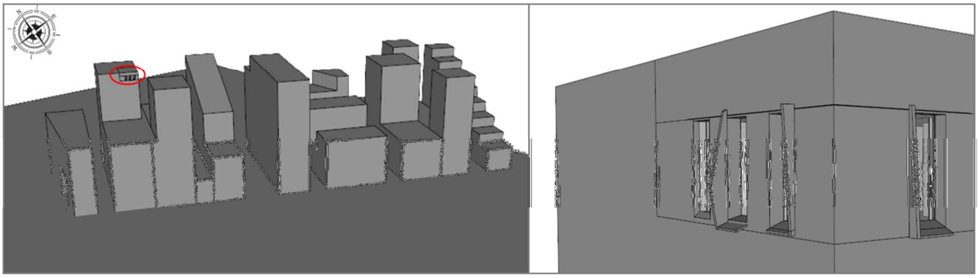

Figure 1: Illustration of the location of the test case and its façade.

Table 1: Set points for the HVAC systems in the test room and overview of the average internal gains during the experimental periods.

VAV-ventilation		2-3.5 l/s m^2 / 0.8 l/s m^2
Set point heating		20.3 ˚C (period 1), 21.8 ˚C (period 2)
Set point cooling		21.5 ˚C (period 1), 23.3 ˚C (period 2)
Internal gains	Light	12 W/m^2
	Equipment	9 W/m^2
	People	6 W/m^2

The measurements were conducted over two periods of approximately one week each in 2013, one week in mid-March (period 1) and one week in end of April (period 2). The observed sky conditions during these periods are summarised in Table 2. As can be seen, in total nine days with clear or partly clear sky were recorded.

Table 2: Observed sky conditions during the experimental periods.

Date	Sky conditions	Date	Sky conditions
12.03.2013	Clear sky	20.03.2013	Overcast sky
13.03.2013	Clear sky	21.03.2013	Clear sky
14.03.2013	Clear sky	17.04.2013	Partly clear sky
15.03.2013	Clouded	18.04.2013	Clouded
16.03.2013	Clouded	19.04.2013	Clouded
17.03.2013	Clouded	22.04.2013	Partly clear sky
18.03.2013	Clear sky/ partly clear sky	23.04.2013	Partly clear sky
19.03.2013	Clouded	24.04.2013	Partly clear sky

Operative temperatures were measured by use of 40 mm black and grey globe thermometers in four positions in the room, position 1, 3, 4 and 6 in Figure 2. The globes where positioned both in the front and in the back of the room in order to have measurements both in the sun and in the shade, see Figure 2. Room air temperature was recorded in the corner of the room in order to avoid influence of direct solar radiation, and the air temperature was assumed to be uniform for the whole room. Additionally indoor environmental conditions were measured using a Thermal Comfort Data logger (Innova 1221) for position 7; see Figure 2, in order to make sure that the indoor environment was within acceptable ranges for thermal comfort assessments. Innova 1221 consist of a collection of instruments and transducers measuring air velocity, humidity, air temperature, operative temperature with an ellipsoid sensor and plane radiant temperature. Data were collected every 5 min for all the indoor measurements.

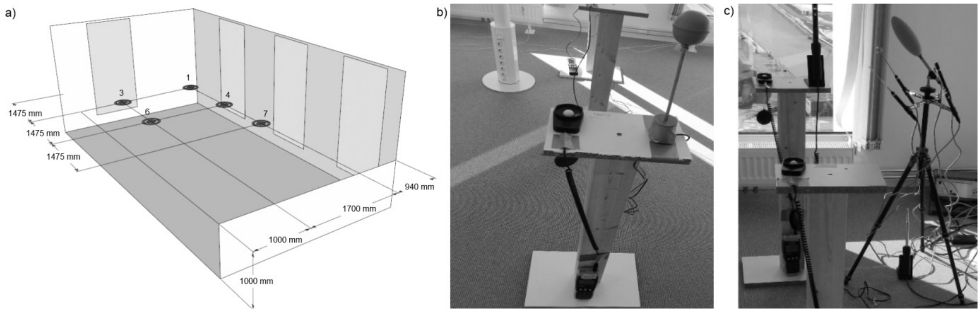

Figure 2: a) Illustration of placement of the globe thermometers for measurements of operative temperature. b) and c) Photo of the measurement setup; globe thermometer (b) and the Innova Thermal Comfort Data logger (c) (photo: Silje Bjørkeng).

According to ISO 7726 (ISO1998) the standard globe thermometer corresponds to a black globe with a diameter of 150 mm and with a thermometer with its bulb in the centre of the sphere. Smaller globes are used here since lower thermal inertia allows the measurements to respond quickly to changes in e.g. solar radiation. According to a study by Simone et al. (2007) globe thermometers with a diameter between 0.03 and 0.05 m might be sufficient to represent the operative temperature of a person in moderate indoor thermal environments, which is in line with recommendations by Humphreys (1977). The study by Simone et al. (2007) also confirms that the colour of the sensor significantly affect the temperature readings when exposed to short-wave radiation. This is a result of different short-wave absorptance coefficient for different colours, while the colour is not important when only exposed to long-wave infrared radiation (Simone et al., 2007). For the experiments in the present study, the absorption of short-wave radiation is approximated to 0.80 and 0.95 for the grey and black globes respectively.

Climatic data of hourly global radiation was collected from the BioForsk database (BioForsk) for the location of Ås which is situated approximately 30 kilometres south-east of the experimental location. The global radiation was divided into direct normal and diffuse horizontal radiation by use of the Skartveit-Olseth model (Skartveit et al., 1998). The climatic data of air temperature, relative humidity, wind velocity and wind direction was collected from Eklima database (Norwegian Metrological Institute) for the location of Blindern, Oslo.

A model of the test case has been made according to the above description and simulations are conducted with a beta version of IDA ICE with the new zone model implemented.

RESULTS AND DISCUSSION

Figure **3** shows the results for outdoor air temperature and a comparison of measured and simulated operative temperature during the two experimental periods for position 1. These results are representative for the measurements taken in the front row of the office.

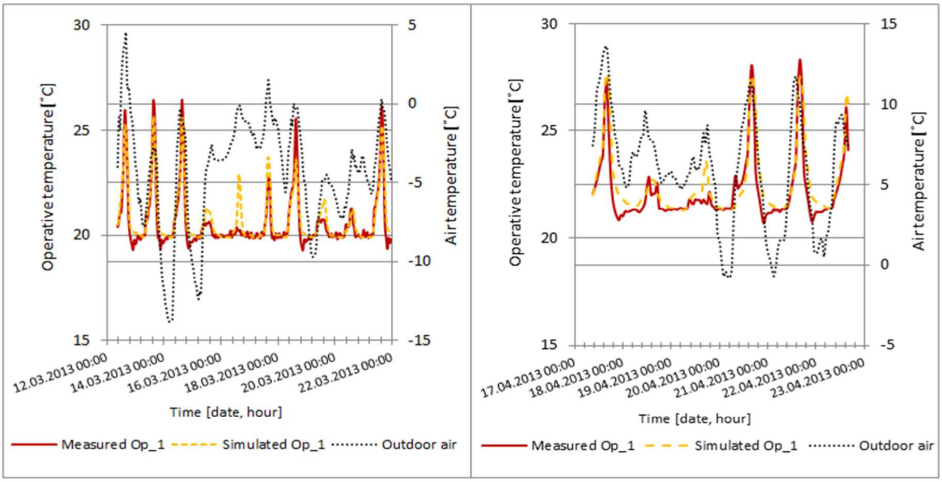

Figure 3: Presentation of outdoor air temperature and a comparison of measured and simulated operative temperatures for position 1 during the two experimental periods.

The measured drops in temperature after a day with clear sky conditions, which also is visualised in Figure 5, can be explained by the fact that the temperature sensor controlling the HVAC systems is placed on a concrete pile in the south-east corner in front of the room. In the late afternoon this pile is hit by solar radiation and heated up. This affects the readings of the temperature sensor and the feedback to the HVAC controller do not reveal the actual required heating load.

For sunny days the measured and simulated results correspond relatively well apart from the deviations explained above. Generally the simulated results are a little lower than the measurements for the peaks in the middle of the day. One explanation might be that the short-wave absorption coefficient for the grey globes has been underestimated. Larger discrepancies are seen for days with clouded sky conditions. This might be contributed incorrect prediction of direct and diffuse solar radiation from the sky arising from inaccuracy in the Skartveit-Olseth diffuse fraction model for sky conditions not corresponding to totally clear or totally overcast. The deviation might in addition stem from differences in sky conditions at the experimental location in Oslo and the location for measured global radiation in Ås. In order to reduce uncertainty from the diffuse fraction model to affect the results, only days with clear sky conditions is consider in the further analysis.

Figure 4 shows a scatterplot for the comparison of the simulated and measured data of position 1, 4 and 7 for the hours of 8-18 for days with clear sky conditions according to Table **2**. A high correlation can be seen for all the positions which indicate that the new MRT model has been implemented successfully in IDA ICE and can be used to predict the operative temperature at the specific positions with a reasonable accuracy. The total relative mean bias error of these data is 0.01 % and the total relative root mean square error which considers error compensation due to opposite sign differences is 0.17 % which both is in highly acceptable ranges.

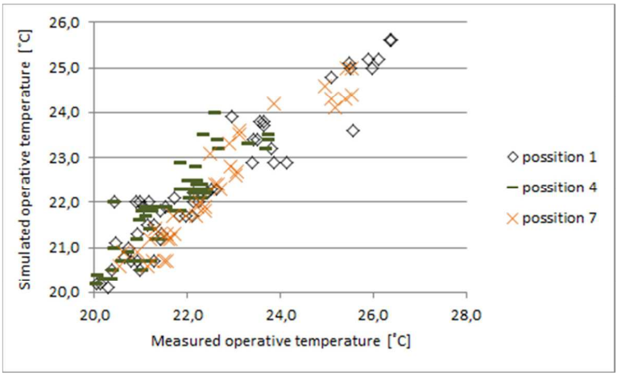

Figure 4: Comparison of simulated $\mathbf{T_{op}^{S}}$ with the new zone model in IDA ICE and measured $\mathbf{T_{op}^{S}}$ for position 1, 4 and 7. Total observations n=147, correlation coefficient R=0.95 (position 1), R=0.89 (position 4) and R=0.96 (position 7).

The results in Figure 3 showed that even for cold winter days there might be a risk of overheating in the perimeter zone on sunny days when solar shading is not applied. This problem would not have been discovered with use of a model which didn't consider the effect of short-wave radiation on the operative temperature. Figure 5 shows a comparison of predicted operative temperature with the old and the new zone model in IDA ICE of position 1 for 14th of March 2013. With the old zone model it is obvious that the short-wave radiation is neglected since the simulated operative temperatures correspond well with the average measured operative temperature in the shade. The result illustrates that the new MRT model in IDA ICE might contribute to considerable improvements of prediction of thermal comfort of persons affected by direct solar radiation.

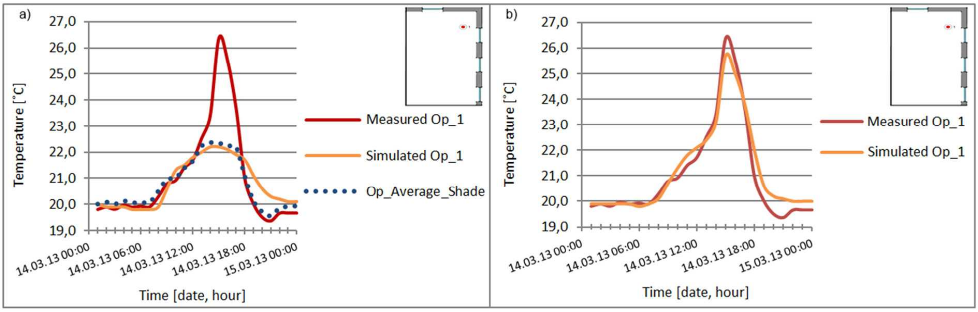

Figure 5: Comparison of measured and simulated operative temperature for position 1. Left: old zone model IDA ICE 4.5, right: new zone model.

It is also interesting to notice that depending on the position in the room occupants may experience significantly different thermal conditions for a considerable part of the working day during clear sky conditions. These differences are now very apparent with use of the new MRT model. It is likely that occupants close to the façade will either activate the solar shading for several hours or adjust the cooling/heating to obtain satisfying thermal comfort. The first alternative will block the view, reduce the daylight and perhaps contribute to unsatisfying visual conditions especially in the back of the room. This will most certainly also lead to a higher demand of artificial lighting. The other alternative will have consequences for the energy use of heating and cooling.

CONCLUSIONS

The results reported in this paper indicate that the new MRT model in IDA ICE contribute to considerable improvements in prediction of thermal comfort of persons affected by direct solar radiation. This prediction may further have implications on the predicted energy use and/or the design of the façade and the room layout, since e.g. an enlarged need for local cooling or increased use of dynamic solar shading might be discovered in the design phase as a consequence of the thermal conditions close to the façade, especially in case of large glass facades. Therewithal it might be found that in case of deep rooms it can be difficult to obtain satisfying indoor conditions both in the front and back of the room simultaneously, which might lead to reassessments of room layouts. It is also expected that use of the new MRT model may contribute to increased focus of the direct solar transmission of glazing and shading systems since it might be seen that the only way to efficiently reduce the effect of short-wave radiation on thermal comfort will be to block it or redirect it away from the occupants.

One of the limitations of the new MRT model at the present time is that it is assumed that the whole body is irradiated if the point in question is irradiated. Further studies should be done to see if the model can be used for situations where only parts of the human body are irradiated.

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Appendix V. Paper V

Please consult:

Karlsen, L., Heiselberg P., and Bryn I.. *Implementation of daylight as part of the integrated design of commercial buildings*. In *World Sustainable Building Conference*. 2014: Barcelona, Spain. (Session 81 http://www.gbce.es/archivos/ckfinderfiles/WSB14/CreatingNewResources_volume3.pdf)

Appendix VI. Paper VI

Please consult:

Karlsen, L., Grozman G., Heiselberg P. and Bryn I., *Integrated design of daylight, thermal comfort and energy demand with use of IDA ICE*, in *Passivhus Norden - Sustainable Cities and Buildings*. 2015: Copenhagen, Denmark. (Paper 083 http://passivhus.dk/7phn/)

SUMMARY

The objective of this PhD thesis was to arrange for an integrated building design with respect to thermal comfort, daylighting and energy use, applicable for office buildings in Nordic climate. In order to achieve this, it is suggested that modelling of mean radiant temperature (MRT) should be improved by considering the location in the room, accounting for both long and short-wave radiation and that daylighting should be modelled in a dynamic manner. Full-scale measurements have been conducted to verify improved models for MRT and climate-based daylighting and their implementation into the simulation tool IDA ICE.

Furthermore, the control of solar shading is given attention, since it is a crucial link between the thermal and daylighting performance. The thesis presents results of an occupant survey with 46 subjects, which was carried out to investigate occupants' preferences towards automatically controlled venetian blinds and their sensation of glare in a work environment. The results indicate that view to the outside was important for the occupants' satisfaction. Moreover, a correlation between both vertical eye illuminance and horizontal illuminance at the desk and the occupants' perception of glare was indicated. Based on these results and findings in the literature, a shading strategy was proposed. Its performance is verified by full-scale measurements and annual simulations.

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