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Integrated Energy Design of the Building Envelope

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PhD thesis

INTEGRATED ENERGY DESIGN OF THE BUILDING ENVELOPE

Martin Vraa Nielsen

Integrated Energy Design of the Building Envelope

Svanemærket tryksag

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Preface

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The fool wonders, the wise man asks

<div style="text-align: right">Benjamin Disraeli</div>

The intention of this thesis is to engage and contribute to the development of beautiful architecture that has energy efficiency and indoor comfort as an inherent part of the idiom.

The idea that technology alone can solve the issue is neither the point of departure for this research project nor is it the means of transportation. Thus, this project does not seek to engage in the traditional perception of Integrated Energy Design (IED) which often tend to take on a technical approach. Rather is it the belief that IED has the potential to contribute to a more holistic performance evaluation of the built environment and thereby illustrating that true architecture can amount to something greater than the sum of its individual parts – it can thrill, excite and improve the quality of life.

This thesis is submitted as part of the requirements for the Danish Ph.D. degree and is based on the scientific papers appended.

May 2012

Martin Vraa Nielsen

Acknowledgements

Abstract

This thesis describes the outcome of the PhD project Integrated energy design of the building envelope carried out through a combination of scientific dissemination reported through peer-reviewed journals and a wide range of affiliated projects involved in at an architectural firm. The research project analysed how the implementation of technical knowledge early in the building design process can quantify the effect of a building's façades on its energy efficiency and indoor climate and thereby facilitate a more qualified design development.

The project was structured in the following way: 1) the importance of integrating knowledge in the early stages of design, and how it can be done; 2) understanding the façade's typology; and 3) the complex notion of comfort.

The project touched not only on the technical capabilities and requirements governing façade design, but also the process by which it takes place. This was done by applying the methodology of Integrated Energy Design (IED) and analysing its applicability in the design of façades. A major part of the project was an actual engagement in the architectural process to test out incorporating a consciousness about energy and comfort as part of a more holistic performance evaluation.

The research project illustrates the great potential in taking passive properties into account through a geometrical optimisation inherent in the development of the architectural concept. It demonstrates that integration of technical knowledge at the early stages of design not only can qualify the geometrical processing, but also facilitate the design development of the façade. Thereby a more holistic performance optimisation can be obtained through parameters such as overall façade geometry and orientation, functional organi-

sation, room height and depth, façade layout, window geometry and transparency, design of the window aperture, etc. Through the wide range of affiliated project involved in at the architectural firm over the course of this project, this approach resulted in building designs with an energy demand at least 25% below the minimum requirements while simultaneously maintaining high-quality indoor climate and architectural quality.

One cardinal finding from the project is that by applying engineering knowledge in a supportive way in what is usually considered the realm of architects, common ground can be established. This can ensure the full utilisation of both the inherent aesthetic qualities and the potential for improvements in energy efficiency that combine to enrich the architectural concept. True architecture should represent a holistic performance evaluation and therefore be seen as the common goal for all the professional disciplines involved in the building design process. This project also illustrates the importance of understanding the interdisciplinary collaboration between engineers and architects. Contrary to the traditional notion that the building's performance is determined by the architect's first sketch on a napkin, to a great extent it is already determined by the building's context and the building programme. This places great responsibilities on the shoulders of both engineers and architects in the critical first phases of design.

Resumé

Denne afhandling beskriver produktet af ph.d.-projektet Integreret energidesign af klimaskærmen gennemført gennem en kombination af forskningsmæssig formidling gennem videnskabelige tidsskrifter og en bred vifte af projekttilknytninger ved et arkitektfirma. Forskningsprojektet analyserer hvorledes en implementering af teknisk videnskabelig viden tidligt i design processen kan kvantificere facadens effekt på bygningers energieffektivitet og indeklima for derigennem at facilitere en mere kvalificeret designudvikling.

Beskrivelsen af projektet er struktureret efter; 1) vigtigheden af metoden hvormed viden er integreret i de tidlige designfaser, 2) forståelsen af facadens typologi og 3) perceptionen af det komplekse begreb komfort.

Projektet berører såvel de tekniske aspekter og krav betydende for facadedesign, men ligeledes processen hvormed de er designet. Dette udføres ved at anvende metoden Integreret energidesign (IED) og analysere dens egnethed i relation til at designe facader. Således er et egentligt engagement i den arkitektoniske design proces for at teste implementeringen af en bevidsthed omkring energi og komfort som en del af en mere holistisk ydeevnebeskrivelse, en stor del af projektet.

Forskningsprojektet illustrerer at der eksisterer et stort potentiale ved at betragte de passive egenskaber i den geometriske optimering iboende udviklingen af det arkitektoniske koncept. Det demonstreres hvorledes integreringen af teknisk viden ikke blot kan kvalificere den geometriske behandling på det tidlige designstadie, men ligeledes ligge til grund for en egentlig designudvikling af facaden. Derigennem opnås en mere holistisk optimering af ydeevnen ved at betragte parametre som overordnet facadegeometri og orientering, funktionsorganisering, rumhøjde og –dybde,

vinduesåbningens design etc. Denne tilgang har gennem en lang række projekttilknytninger gennemført i løbet af dette projekt, vist sig at kunne tilvejebringe bygningsdesigns med et energibehov mindst 25 % lavere en minimumskravene og der samtidig opretholder høj indeklimamæssig og arkitektonisk kvalitet.

En afgørende konklusion for projektet er at det ved at indgå i hvad der traditionelt betragtes som arkitekters domæne, med et understøttende udgangspunkt, er muligt at etablere et fælles grundlag. Således kan potentialet i henhold til såvel æstetik som energieffektivisering udnyttes mere optimalt og derigennem kan det berige det arkitektoniske koncept. Sand arkitektur har potentialet til at repræsentere en mere holistisk evaluering af designforslaget og bør således være et fælles mål for alle fagdiscipliner involveret i bygningsdesignprocessen. Projekt illustrerer vigtigheden af en forståelse for det interdisciplinære samarbejde mellem ingeniører og arkitekter. Således er et bygningsdesigns ydeevne, modsat hvad der ofte beskrives, ikke først bestemt ved arkitektens første skitse på en serviet, men er til vid udstrækning allerede bestemt af konteksten og byggeprogrammet. Det betyder at der er placeret eksisterer et stort ansvar på skuldrende af såvel ingeniører som arkitekter i de kritiske første designfaser.

Summary of scientific papers

During the research paper a number of scientific papers have been published. This thesis mainly considers the analyses from four ISI-indexed papers (paper I, II, III and IV).

Paper I

Integrated Design - A paradigm for the design of low-energy office buildings

A case study representing an actual architectural competition implementing integrated design where both engineers and architects worked towards a mutual goal of architectural excellence, low energy consumption and a high level of indoor environment. The case study analyses the integration of technical knowledge concerning building performance in the conceptual design stage by focussing on challenges during the design process. Specific attention is given to how the engineering input is presented and how it can facilitate the design development.

Published in ASHRAE Transactions 117 (1) (2011), 230-239.

Paper II

Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight

AA quantification of dynamic solar shading's potential by using integrated simulations that took energy demand, the indoor air quality, the amount of daylight available, and visual comfort into consideration. Three types of façades were investigated (without solar shading, with fixed solar shading,

and with dynamic solar shading), and we simulated them with various window heights and orientations. Simulation results comparing the three façade alternatives showed potential for energy reduction, but great differences and conflicting tendencies were revealed when the energy needed for heating, cooling and artificial lighting were considered separately. Thus, while dynamic solar shading dramatically improved the amount of daylight available compared to fixed solar shading, it cannot always be considered the optimal choice when economics (acquisition and maintenance) or subjective factors such as aesthetics are included.

Paper III

Simulation based design development of the facade for a new university building

A simulation case study of facade design options for a new university building in Denmark. Focus was on a geometrical optimisation and utilisation of the passive properties essential in the development of the architectural concept. The main objective was to develop a façade design that efficiently could control the amount of insolation, uphold a satisfactory level of indoor environment, contribute to the reduction in energy demand and at the same time support and consolidate the architectural vision. Integrated thermal studies and daylight analyses was carried to procure design recommendations and evaluate the design proposition's effect on the daylight utilisation, the annual energy demand for heating, cooling and artificial lighting and the peak loads for heating and cooling. Simulation results show significant performance improvements through an utilisation of the passive properties and that a substantial reduction in annual energy demand, peak loads for heating and especially cooling can be obtained.

Paper IV

Quantifying the effect of solar shading types and window sizes in office buildings by evaluating thermal sensibility and comfort using the adaptive approach

Presents a very detailed analysis of the indoor thermal environment under varying climate conditions and façade designs (solar shading types and window sizes) using a model that evaluates the overall thermal sensation and comfort level experienced by the occupant. The results show that direct solar radiation has a great impact on the occupant's thermal sensation and overall comfort – even resulting in overheating during winter. Thus, the performances of the various façade designs simulated in relation to the quality of the indoor thermal environment basically only differ under sunny sky conditions, whereas cloudy conditions result in very similar performances. Generally the best performing façades are the ones with dynamic solar shading and the smallest window area, but no great differences exist and there is no clearly superior façade design out of the ones simulated. These results underline the importance of performing detailed simulations very early in the design process to inform the design development of the façade.

Under review at Solar Energy.

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introduction

Introduction

The world is changing!

How we perceive, interact and engage with the world has fundamentally changed since industrialization and dramatically so in recent decades. The ever evolving globalisation, initially brought about by technical advances in transport and communication, has brought with it immense opportunities in terms of the exchange of goods, information and technology to such a degree that one is no longer a citizen of any particular country, but a global *passenger on spaceship earth*.

The fundamental alterations to the structural fabric of society have resulted in massive improvements in living standards all over the world and also entailed a broader understanding of how our actions have impacts on not only our own backyards, but also global society as a whole. The global focus on the environment and climate transformation as a consequence of the emission of greenhouse gasses and the scarcity of fossil fuels transcends national borders and interests. Merely maintaining current living standards in the industrialised countries and, even more important, underdeveloped countries understandably seeking to upgrade their standard of living to a similar level, has resulted in the consumption of natural resources spiralling out of control. Concerns about the need for oil and other fossil fuels - how they are procured and by whom - have dominated the political landscape and are becoming an increasing part of how economic and security policy is conducted at a national, European and international level. The inappropriate use of natural resources has brought about demands for global development that is more sustainable. This new notion was defined in 1987 as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland et al., 1987) and

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We are all passengers on spaceship earth

R. Buckminster Fuller

is founded on three pillars: social, environmental and economic. With people spending up to 90% of their time indoors (Leech, 2002) and the built environment being responsible for up to 40% of the total energy consumption in the EU, how buildings are constructed and upgraded plays a significant role in the development of our global society, including all three sustainability aspects.

Sustainability is very much on the agenda of the day, but seems to have been reduced to a mere spin: Green is the new black, and everything from agriculture and tourism to buildings and cars is being attributed the characteristic of sustainability. This has made the notion of sustainability blurred, indefinable and essentially unfathomable and incomprehensible. Sustainability has, and should be given the chance to have the ability to inspire and stimulate.

This project dealt with only a small part of sustainability and only part of the goal of reducing energy consumption, but since the operation of buildings constitutes a major part of our overall consumption of energy it is a relevant starting point. And when considering the energy performance of buildings, it is important to remember that the overall reason for constructing buildings is to create shelter from the outdoor environment and obtain a certain degree of comfort. So, energy efficiency affects our quality of life and cannot be reduced to a matter of adding solar cells, greening a roof, or installing the latest high-efficiency ventilation system. Energy efficiency has to become an inherent part of our buildings, substantiating and merging with an architecture that aspires to more than aesthetics. True architecture can achieve holistic performance optimisation through an integrated and interdisciplinary approach in which responsibilities fall on both engineers and architects. Architecture is not a profession or a product; it is an attitude to the world we live in. And this project set out to embrace the challenge.

Concerns about the need for fossil fuels dominates the political landscape and are becoming an increasing part of how economic and security policy is conducted at international level.
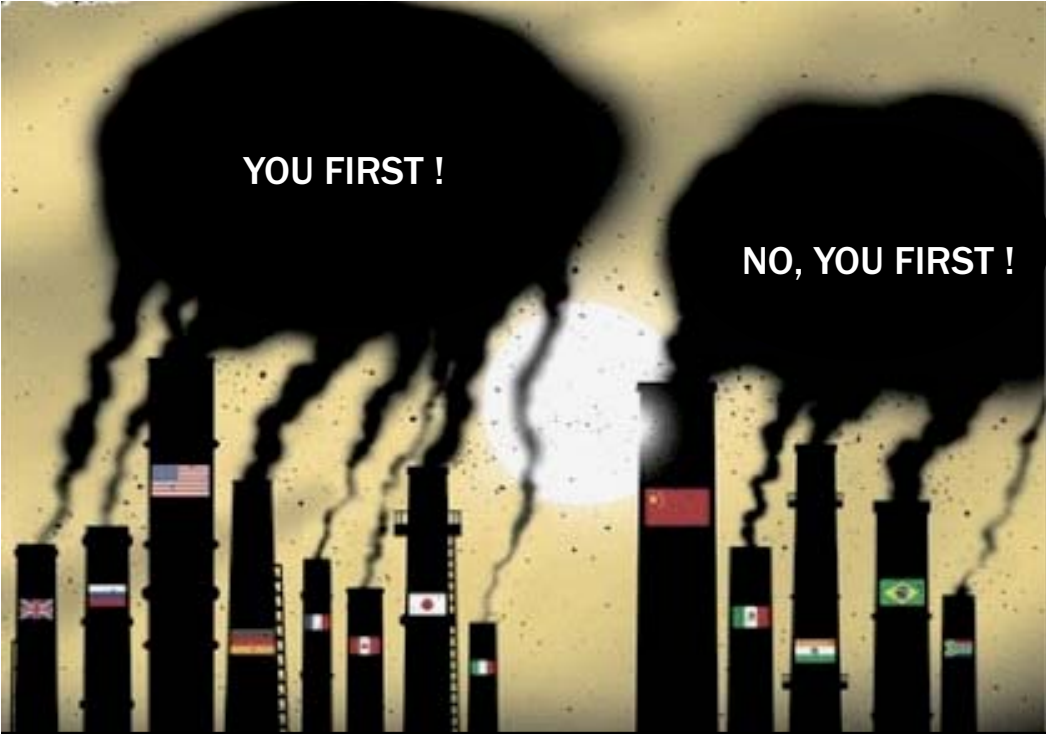
Aim & Objective

This thesis reports on three years of research aimed at investigating how the designs of energy-efficient buildings with high-quality indoor climate are developed at the conceptual level.

The thesis does not propose one single solution to this design problem - cutting the Gordian knot with the sword. Instead, the highly iterative nature of the architectural design process was investigated and analysed from the point of view that it is not necessarily something that needs to be tamed, but rather something that holds great potential when dealing with such a complex issue. For design can be regarded as a discipline rather than a science - a creative cognition conducted by not just one profession, but resulting from collaboration between several. In this thesis, Integrated Energy Design (IED) is considered as a discipline which includes a consciousness about energy efficiency and indoor climate that cannot be seen as the end goal or the full disclosure, but as a part, inherently complex in itself, of the "simple" quest for integrated design. So, the aim of this project was to provide technical input that, in combination with a wide range of other input regarding architecture, structure, fire safety etc., can enter as an equal partner in the integrated design process. The objective of this project was formulated in the following hypothesis:

Implementation of technical knowledge early in the building design process can quantify the effect of façades on the energy efficiency and indoor climate of a building and thereby facilitate a qualified design development.

As the hypothesis indicates, the project touches on not only the technical capabilities and requirements governing façade design, but also the process by which it is designed. In this way, the project enters uncharted territory by engaging in the architectural process and pursuing qualification of the reasoning behind the design and quantification of its performance from a holistic point of view. This was done by ap-

plying the methodology of IED and analysing its applicability in the design of façades.

Project framework

The overall framework for the research project was collaboration between the Technical University of Denmark (DTU) and Henning Larsen Architects A/S (HLA). Throughout the three years the project lasted, work was planned to be carried out at DTU and HLA on a 50/50 basis on average.

The project aimed to consider how integrated energy design is and can be carried out "in reality" with the building envelope as the focal point. DTU was the starting point for the development of the research project, while the connection with HLA and its wide range of affiliated projects provided an optimal test-bed for the hypothesis. The interaction between the university and an architectural firm provided a unique opportunity to practise applied research in the very early stages of building design – a stage that is currently almost always in the hands of architects.

The office of Henning Larsen Architects A/S in Copenhagen, Denmark.

Experiences from the work at HLA influenced and were used to calibrate the overall research project throughout the process. The architectural company's collaboration, both national and global, with a wide range of engineering and consultancy firms provided the opportunity to observe and engage in the practices of these companies. The very varied nature of their projects and locations helped to broaden the perspective of the research project and put the design development of sustainable buildings (with a focus on energy efficiency and high-quality indoor climate) into not only a European, but a global context.

In addition to the work carried out at DTU and HLA, the project included two external research visits totalling approximately 6 months, at the Center for the Built Environment (CBE) at the University of California's architectural department in Berkeley. The CBE works closely with the Lawrence Berkeley National Laboratory, and both are front-runners in research into energy-efficient buildings with high-quality indoor climate, but they also pay great attention to the design process through which such buildings are developed and constructed. The CBE has a board of advisors from a wide range of industrial partners who constantly feed the definition of the research area and also implement its outcomes. So the CBE represented a unique opportunity for an upgrade in the interdisciplinary field of architecture and building physics. Specifically, the visits provided the basis for an investigation of the adaptive approach to evaluating comfort (see Paper III, Appendix A).

Research methodology

The research project sought to combine the *rational and analytic* approach, with its origins in the engineering and technical aspects of the research area, with the more *argumentative* approach of architecture and planning. The thesis covers work carried out at both the university and the architectural firm, as well as how it was connected. To fully encompass the broad spectrum that the research project operates in, it is structured along three tracks:

> 1. **Knowledge** - integration of technical input in the early stages of building design

> 2. **Typology** - the functional properties of the façade

> 3. **Comfort** - occupant comfort and its role in energy efficiency

Knowledge addresses the building design process with the focus on its conceptual stages. These are analysed through the experience obtained from projects and the development of an approach and a method by which design projects could be developed and optimized. The work includes a description of the need for an integrated approach, the development of IED, the affiliated projects involved in at HLA, the development of a presentation methodology, differences in dissemination, and how it all interconnects.

Typology is a look at the function of the building envelope, more specifically the façade, its elements, and how the performance requirements are met, especially in relation to aesthetics, energy efficiency and indoor climate. Analyses focus on the fenestration system because it represents often contradictory wishes for the façade and is a very dominant factor in the early stages of design in terms of all the performance parameters.

Comfort deals with the occupant's perception of the indoor environment and seeks to go beyond the traditional evaluation of indoor climate according to European standards, by applying a broader perspective. Here the adaptive approach to comfort is considered because it links the occupant and his perception of comfort to the actual situation, including the transient character of the environment. Analyses focus on the effect of the façade on the thermal indoor environment based upon analyses carried out in the typology section.

The research methodology provided a framework for representing a series of different perspectives for examining the main hypothesis. The project was investigative in nature and sought to merge analyses considering energy efficiency and indoor climate with the architectural concept in the early conceptual design stages. The success of the project should be measured on its ability to improve, quantify and facilitate the design development of building façades that support a more holistic performance evaluation.

The project was investigative in nature to challenge traditional thought patterns and steer clear of "business as usual".

Structure of thesis

This thesis covers work carried out at both the university and the architectural firm, as well as how it was connected, and follows the investigative nature of the research project. The objective of the thesis is to place the articles that constitute the traditional scientific basis of the project into a broader context, including both the technical possibilities and requirements governing façade design and the process by which it is designed. So the thesis also includes and highlights the importance of the general *knowledge upgrade* needed to perform IED, with descriptions and analyses as a significant part of the project, but which are hardly mentioned in the scientific articles.

The structure of the thesis is greatly influenced by the overall project and follows the three steps described in the section on research methodology. The structure of the thesis does not necessarily represent the chronological course of the project, but more a hierarchy in the sense that the implementation of technical knowledge is essential for integrated design and is the common thread throughout the project. With this point of departure, the thesis seeks to show how energy efficiency can be achieved and what role occupant perception of comfort plays in relation to the future development of the built environment.

The structure of the thesis follows the research methodology with knowledge, typology and comfort as the three main chapters, each of with are disseminated through papers and case studies. Introduction outlines the basis for the research project and inscribes in to its context while discussion and conclusion summarises the main body of work.
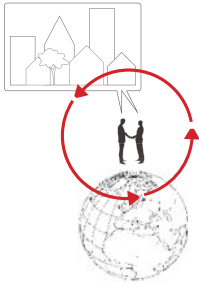
INTRODUCTION
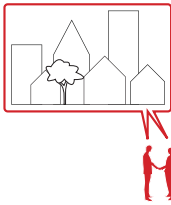
KNOWLEDGE

Range of projects   Paper I
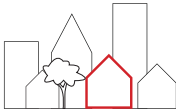
TYPOLOGY

Case studies   Paper I & II

COMFORT

Case study   Paper III

DISCUSSION & CONCLUSION

Knowledge

Knowledge shall set you free!

The way structures are designed and constructed through-out history has always been based on contemporary knowl-edge and what was technically possible. And it has always been driven forward by technological advances - sometimes to embrace the new-found possibilities, sometimes in defi-ance of them, which in itself can spur new advances. So the discipline of designing, whether for buildings, cars or kitchen appliances, relies on the presence of knowledge. To advance and develop the inclusion of new knowledge is required, ei-ther by producing truly new knowledge, acquiring it from other areas or professions, or as is often the case, a combina-tion of the two.

Technological advancements in building physics have in-fluenced architecture in a very significant way, rendering possible new ways of designing buildings and in particular building envelopes. During the industrial revolution, with its assembly lines and mass production in large indoor facilities, it became necessary to procure tolerable working conditions. Developments in several areas, from glass production result-ing in the admittance of more daylight, to the introduction of thermostats[1] and eventually full HVAC-systems, have ena-bled control and conditioning of indoor environments and the development of building designs that in many aspects are detached from the natural climate they inhabit. It was as if

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1   James Kewley's "automation gardener," patented in 1816, which helped open and close hinged roof and wall vents as temperature changes oc-curred. Though manually operated, this was a precursor of the thermostats and more sophisticated automatic devices now used to control closed environments (Lawrence, 1978).

Global aesthetic trends has to some extent resulted in a generic de-contextualised architecture.

we were trying to find a way to rein nature in via technology rather than engage in a dialogue through technology. In combination with societal changes summed up in the phrase "the global village", architecture has increasingly become a machine for living. To some extent, global awareness has resulted in a generic de-contextualised architecture defined by global aesthetic trends.

Developments in the field of building design seem to have resulted in a separation between architecture and technology, despite the fact that the core definition of architecture is the science or technology with which buildings are designed. This crippling separation between the art of architecture and the technical practice of making and operating build-

ings, which was also observed by architectural critic, Reyner Banham (Banham, 1984), is not the fault of one single profession, architects or engineers, but has arisen through common "effort". The aim should not be merely a *beautification* of science or a *machine-aesthetics*, but rather a break with the perfunctory use of science and technology by introducing a more evidence-based approach. Instead of developing generic building designs for which you then shop around for a location, architecture should be an evidence-based product with an innate contextual connection.

If we look for example at the motor industry, design is very much driven by performance enhancements which inherently have the potential to take on an aesthetic quality – at least for people that take an interest in cars. In the same way, there is a need to search for, or rediscover, a more holistic performance-based approach to the process by which buildings are designed.

The focus here is not on design theory, the historical development of design as a discipline, or on analysing and categorising the design processes described in this project to find their place in design tradition or practice. The purpose is to gain insight into the early stages of the contemporary building design process by applying an investigative approach in order to establish whether and how the implementation of technical knowledge, focusing on energy demand and indoor climate, can become a design facilitator. So the project's point of departure was an integrated approach, spurred on by considerations about energy efficiency and indoor climate. In this context, the affiliated project involved in at HLA constituted a large part of the knowledge and experience from which an approach was developed.

Building design process

The purpose of buildings is to improve the quality of life – nothing short of that should be the goal. This makes building design a highly complex problem with many interdependent parameters and many professional skills involved. Developments in technology, legal requirements, and changes in parameters such as societal and aesthetic trends, are constantly redefining both goals and options. The increased complexity enhances the need for a heightened focus on the building design process.

Energy consumption doubled in the period 1971 to 2007, and with the operation of buildings constituting 40% of overall energy consumption, the building industry is facing a new reality (International Energy Agency, 2009). The Energy Performance of Buildings Directive (EPBD) (EPBD, 2002) has become an important part of the new reality, and with the political acceptance of the new version that prescribes that all new buildings must be "nearly zero-energy buildings" by 2020 (EPBD, 2010), energy efficiency at every level within the built environment has simply become a prerequisite. The adoption of the EPBD not only represents a drastic and necessary tightening of the requirements for the energy efficiency of buildings, but is also a paradigm shift, because it moves away from restrictions for merely the individual components of the building, towards a holistic evaluation of the building's energy performance as a whole.

Many critical design decisions, which to a very great extent define the building's functional performance, are made at the conceptual stages of design. Developing concepts for the overall building design solely from an aesthetic point of view is undesirable, and a broader perspective that also takes energy demand and indoor climate performance into account should be considered a central issue when trying to strike the right balance between all performance parameters.

An integrated approach

The high degree of complexity governing the building design process calls for an integrated approach to handle all the interdependent parameters and professions. As mentioned earlier, the overall goal is integrated design implying a full integration of all the important parameters and not just considerations about energy demand and indoor climate. The need for an integrated approach to design problems is not a new reflection and the term is now widely used. In the building industry, the integrated approach, its importance and how to conduct it has been analysed from several points of view (Cross, 1984; Cross, 2001; Baker & Steemers, 2000; Santamouris, 2006 and Mumovic & Santamouris; 2009). Once again, this project was not engaged in analyses from a design theory point of view, but based itself upon these considerations and further developments in the implementation of a more integrated approach in the field of building energy efficiency such as those conducted by the International Energy Agency (IEA) in Task 23 (IEA task 23, 2002).

The starting point for any successful design process is a clear definition of the goal and aim, not only to steer the project development, but also to ensure that the right skills are represented in the design team. A clear definition will enable a matching of expectations, by which a set of performance requirements can be defined making possible a benchmarking of the design development throughout the process. This optimises the possibility for a constant performance evaluation of design alternatives and the elucidation of potential synergies, which minimises the need for subsequent time and cost-consuming design revisions later in the process.

With a clear and well-defined goal established, attention shifts towards the process by which goals are pursued and met. Design processes often differ from profession to profession, and such differences can also be found between the architectural and the engineering design process. System and rationality often govern the processes of engineers and industrial designers, whereas a mainly argumentative

Figure 1. *Illustration of the simplified traditional linear design process indicating no or very few design optimisations (top); the iterative process by which design alternatives are generated (middle); and the integrated design approach (bottom) representing a combination of the two (adopted from IEA Task 23, 2002).*

SKETCHING

CONCEPTUAL DESIGN

PROJECT DESIGN

DESIGN PROPOSAL

"CIRCLES OF ITERATION"

DESIGN PROPOSAL

Stated objective

SKETCHING

Assessment

CONCEPTUAL DESIGN

Assessment

PROJECT DESIGN

Assessment

DESIGN PROPOSAL
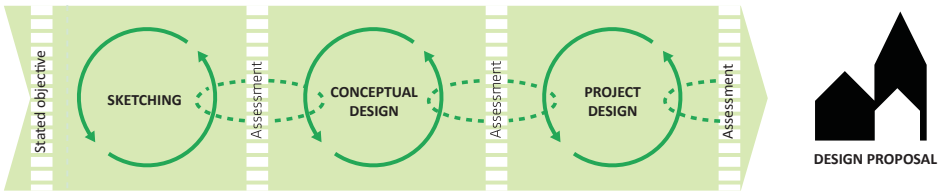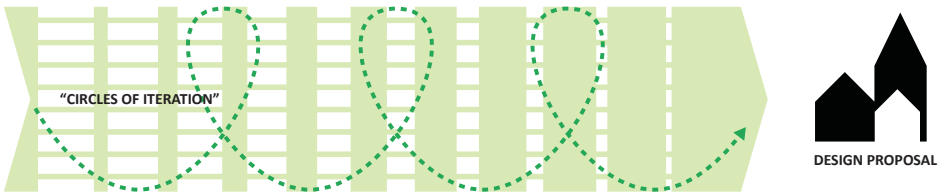
and empirical approach is found in the field of architecture and planning (Cross, 2007). So the different approaches in design methodologies of the actors involved must be taken into account to provide a basis for mutual understanding and consideration. The applied integrated approach represents a combination of the systematic, linear process of engineering and the more argumentative and iterative process of architects (Figure 1).

The process is made up of a series of iterative loops in an overall chronologically structured, forward moving motion, separated by assessment sessions where the design can be benchmarked in accordance with the objectives and requirements. The iterative nature of the integrated approach supports the reciprocal action not only between the problem and solution, but also between overall objectives and specific requirements for handling the highly complex work flow throughout the design process (Figure 2). Together with a hierarchy in the performance requirements, this provides a framework for the integration of the wide range of actors involved in the building design process and an indication of when inputs are needed. The individual actors can then move from mere performance evaluation and verification of the current design to providing inputs that support the design development by generating design alternatives and optimisations in interdisciplinary collaboration. It is not the objective of this project to advocate that only generalists can partake in the integrated approach, but on the contrary that inclusion of specialists is needed, and a framework ensuring the most efficient utilisation of their expertise has to be established.

Figure 2. *The iterative nature of the integrated approach supports the reciprocal action between not only problem and solution, but also between overall objectives and the specific requirements needed to handle the highly complex work flow during the design process (IEA Task 23, 2002).*

Overall problem

Sub problem

Individual problem

Individual solution

Sub solution

Overall solution

ANALYSIS

SYNTHESIS
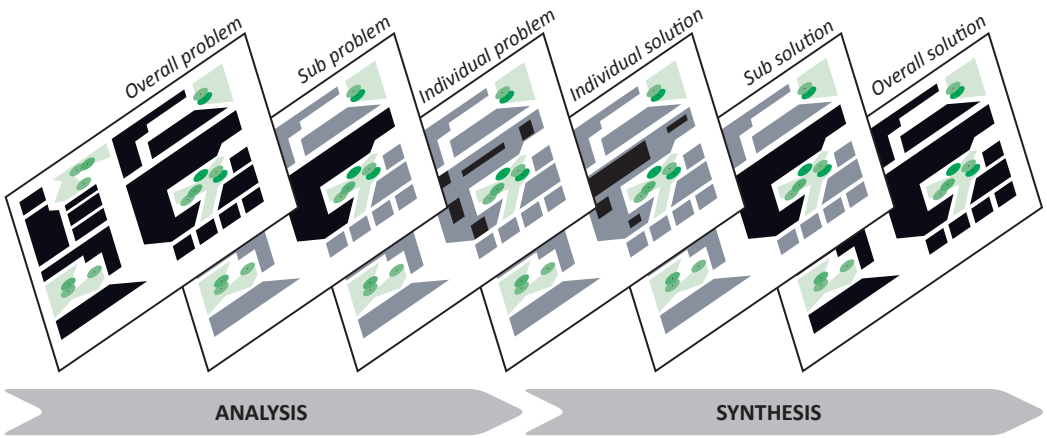
An architectural firm as test bed

The collaboration between engineers and architects is still dominated by many prejudices, and professional disputes emerge on both sides of the, at times, impenetrable professional boundary. This project, however, was aimed at trying to once again fuse together architecture, often perceived in terms of the gross structure, and technology, often seen as the rest of the "machine", because they have to exist on equal terms when buildings are being designed. True architecture is here perceived as a holistic equilibrium between all the performance parameters, aesthetics as well as all the functional requirements, as opposed to a lopsided discourse by either profession affecting the building's overall applicability.

British architect, critic and historian, Kenneth Frampton, basing himself on work by people like Schmarsow (Schmarsow, 1894), defines the concept of space and spatial feeling as an integral part of architecture (Frampton, 1995). This perception of architecture is based on the physical materialisation and tactile character of an allocation of spaces that comprises the built environment. To this extent, the ability of a space to support a given function defines its architectural quality. So architecture inherently represents a holistic evaluation of all the performance parameters, and therefore supporting the development of architecture is perceived as having great potential. True architecture should be the common goal for both engineers and architects.

As indicated, solving the highly complex problems of today's building design cannot rely on the abilities of one individual designer. As a consequence, the design methodology applied and the basic set-up of this research project relied on a high degree of interdisciplinary collaboration. The early conceptual stages of building design were the focus, so one basic prerequisite was the opportunity to actually engage in such processes. To a great extent, such opportunities exist in architectural firms in the framework of architectural competitions. The early stages of design are essential because to a great extent this is where the building's potential in terms

The complex building design process requires different actors with different skills and "languages" to work together to achieve energy-efficient buildings.

"

Coming together is a beginning, staying together is progress, and working together is success

Henry Ford

of performance is determined. So understanding the crucial initial stages of design holds the key to a collaborative process where engineers, if willing to change their often stiff "A to B"-approach, can transcend from mere problem-solvers to creative design partners.

Developing Integrated Energy Design

This quote from one of the fathers of modern architecture, Le Corbusier, draws attention to the purpose of the building, i.e. the "thing", which should be designed to optimally support its everyday use with the function it has. A building cannot merely be perceived as an icon or a "sign". IED is seen as the inclusion of an extra layer in the architectural development of the building - a layer that includes a focus on two highly interdependent parameters: energy efficiency and indoor climate. The *Trias Energetica* concept, also referred to as the *Kyoto Pyramid*, based on Lysen's work (Lysen, 1996), defines a three-step approach to energy efficiency to reduce the consumption of fossil fuels (Figure 3).
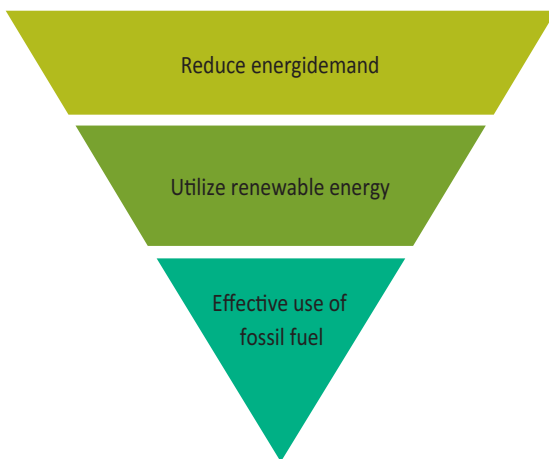
Figure 3. *The Trias Energetica concept contains three steps: 1) Reduce the energy demand; 2) Use renewable energy; and 3) Use the cleanest possible fossil fuels.*

"

One may also add that building, unlike fine art, is as much an everyday experience as it is a representation and that the built is a thing rather than a sign...

Le Corbusier
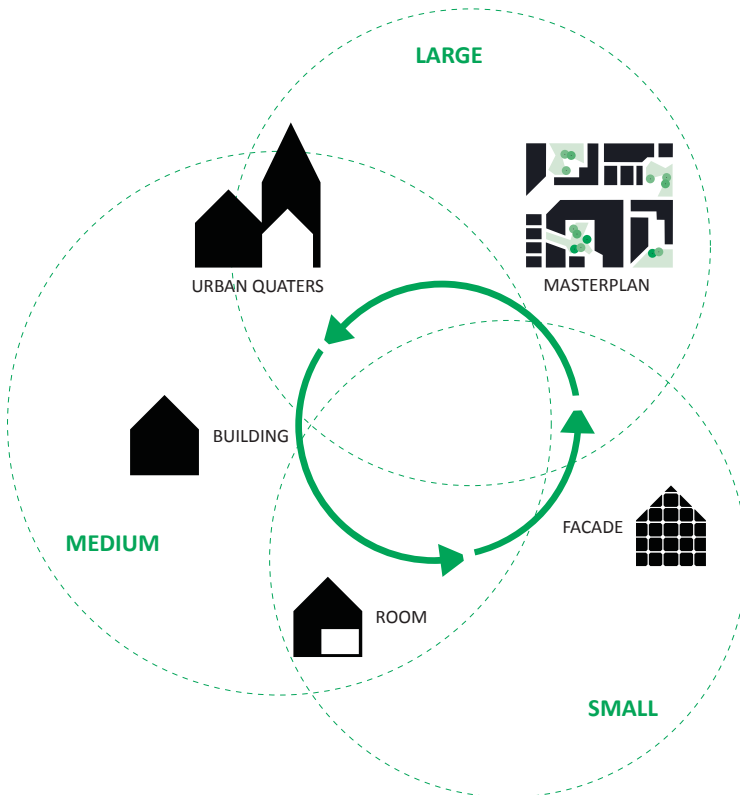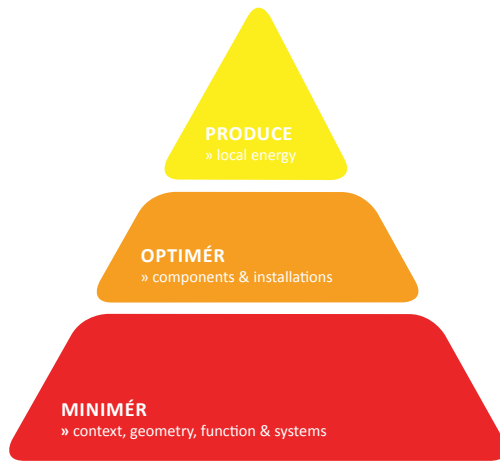
PRODUCE
» local energy

OPTIMÉR
» components & installations

MINIMÉR
» context, geometry, function & systems

LARGE

URBAN QUATERS

MASTERPLAN

BUILDING

FACADE

MEDIUM

ROOM

SMALL

With this as a point of departure, the development of the IED approach in this project worked from the premises of a more in-depth utilisation of the architectural elements, such as mass, surface and plan (Le Corbusier, 1931) – which are the geometrical DNA of the building. The objective was to sup-port the geometrical optimisation inherent in architectural design from the perspective of energy efficiency and indoor climate. The overall structure followed a similar three-step process: *minimise, optimise and produce*, but took its origin in the possibilities seen to be inherently present in architec-ture (Figure 4).

Minimising is a geometrical optimisation of passive proper-ties such as overall building form and orientation, function-al organisation, room height and depth, façade layout with transparencies and window geometry, design of the window aperture, potential for natural ventilation, etc.

Optimising focuses on optimising building components by selecting higher performance in relation to insulation, tight-ness, daylight penetration, natural ventilation, etc., and in terms of the HVAC-system and artificial lighting.

Producing investigates the potential for incorporating the production of renewable energy in the framework of the ar-chitectural concept. Since the first two steps have reduced the energy demand, the rationale is that self-sufficiency and subsequently *nearly zero energy* buildings will be easier to achieve.

All these considerations are based on the specific project and its context. The iterative nature of architectural design de-velopment moves seamlessly between problem and solution, but also leaps across scales from façade to urban level and back, to continuously evaluate whether design proposals are applicable (Figure 5).

By defining a *hierarchy*, the design can develop through it-erative loops (Figure 6). The starting point for each iterative loop is a thorough registration of the project's prerequisites in the form of the building programme, the climatic condi-

tions, and the contextual setting of the actual project. This determines the project's performance requirements and the resources which are available, in a way similar to the initial step in the overall integrated approach. Next daylight is considered, bec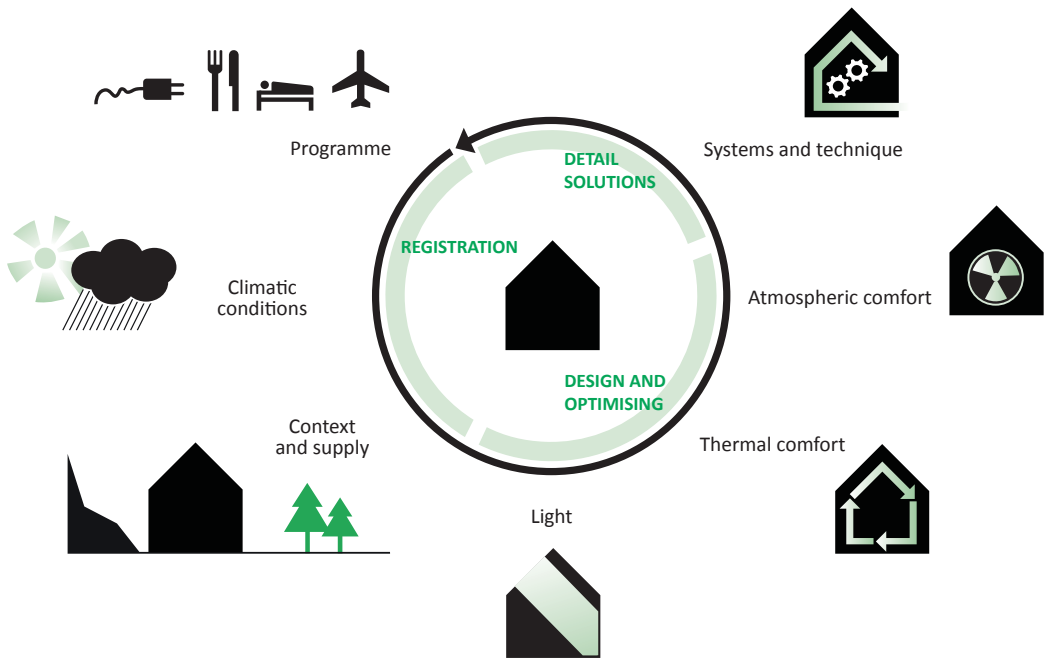ause it represents the initial interaction between the outdoor climate and the indoor environment. The desire for daylight and the way in which it is propagated has a profound effect on the building performance and consequently its energy demand. Moreover, during the many affiliated projects involved in, daylight and how it is utilised provided common ground for discussion between engineers and architects on developing building designs (further described below in *Daylight as a common denominator*). The indoor environment, both thermal and atmospheric, is a product of how the outdoor climate is filtered through the building envelope and what is taking place inside the envelope (see also *Typology* below). The thermal environment is addressed first, since it can be affected most effectively through an architectural and geometrical processing and is a decisive factor affecting the energy demand. Atmospheric indoor climate in this context mainly means indoor air quality and could in principle be handled independently of the outside climate if provided mechanically. However, if natural ventilation is used, the connection will be established. Acoustic considerations are also often included at this point, for example by analysing the effect on the reverberation time caused by the exposure of thermal mass or potential noise from the surroundings transferred by means of natural ventilation. Acoustics has been of concern and addressed in many of the projects involved in at HLA, but is not considered in detail in this project. Lastly, the technical installations (HVAC and artificial lighting) are optimised so that performance requirements are met using the least amount of energy.

This means that all actors need to be actively engaged in the design process from the very start in order to contribute to the definition of the project's overall objectives, goals and aims and subsequently the concepts that could be used to achieve these. It should be mentioned that this thesis focuses on the members of the design team who are involved in ensuring energy efficiency and high-quality indoor climate in the project.

Figure 6. *Illustration of the hierarchy in the iterative loops of IED.*

Programme

Systems and technique

Climatic
conditions

Atmospheric comfort

Context
and supply

Thermal comfort

Light

**DETAIL
SOLUTIONS**

REGISTRATION

**DESIGN AND
OPTIMISING**

Starting with the building programme, a registration could entail identifying the requirements for maximum annual energy demand, thermal indoor environment, and air quality for each of the given functions. In relation to the climate, annual temperature profiles, solar radiation, predominant wind speeds and directions could be considered in combination with the contextual setting in terms of shading from neighbouring buildings and the means of energy supply available. Only through full disclosure of the prerequisites can designs that meet the performance requirements be generated efficiently. Here the generation of design alternatives is important to navigate through the complex search for an optimal equilibrium between all the performance parameters. Design alternatives might include not only considerations on the overall building geometry, room heights and depths, and the layout of the façade, but also more detailed considerations about the optimal glazing properties and the control of solar shading and the HVAC-system, as the building design develops.

The basic principle of IED is that, by using a continuous series of iterative loops focusing on the utilisation of the various passive properties, it becomes possible to fully utilise the potentials in the geometrical optimisation inherent in architectural design development. In this way, the need for mechanical control of the indoor climate and subsequently the energy demand can be minimised. IED provides a common platform for actors involved trying to achieve energy reductions and improvement of the indoor climate to incorporate these considerations into the architecture.

Phillips Exeter Academy Library by Louis Kahn.

"

A room is not a room without natural light. Natural light gives mood to space by the nuances of light in the time of the day and the seasons of the year as it enters and modifies the space.

Louis Kahn

Daylight as a common denominator

Daylight has a mythological quality – at times sacred. We walk towards the light and the multifaceted character of daylight is compelling and enticing. Daylight is therefore naturally a fundamental element in architecture, used to define form, materials and space, and through differences in intensity, direction and colour, a series of rooms and spaces are composed creating a building concept. At the same, daylight is a component of solar radiation which is of major importance to the indoor climate and subsequently the building's energy performance.

The façade is the decisive factor as the *de facto* separation between the outdoor and indoor climate, a separation which is the fundamental premise of the built environment – providing shelter from the outside climate. A lot of a building's identity and architectural expression is embedded in the façade design, determining how the building relates to the surrounding environment. A façade often determines whether a building is introvert or extrovert and how it may be differentiated depending on its function. The transparent character of windows and glazed components is often used to establish and balance the connection with the surroundings. Moreover, it is the design of the windows and their configuration that, in combination with the properties of the glazing and the façade's overall geometry, defines how and to what extent solar radiation is transmitted to the indoor environment. If the façade is a building's skin and the windows its *eyes*, the *pupils* have to be calibrated according the building's surroundings and its functions.

So daylight becomes a common denominator for architects and engineers, making it an appropriate starting point for interdisciplinary discussion on the development of the design and the implementation of technical knowledge about energy and the indoor environment.

"

I use light abundantly, as you may have suspected; Light for me is the fundamental basis of architecture. I compose with light.

Le Corbusier

Technical knowledge as design facilitator

As mentioned above, a major part of this research project's purpose was to gain insight into the early stages of the building design process in order to investigate whether and how a consciousness about energy efficiency and indoor climate can be implemented and the possibility of it facilitating the design development. Focus was on involvement when the first sketches are made because of the great potential to influence the design development at this crucial stage. This conviction and approach was the foundation for the implementation and development of IED, but it is also important to develop and disseminate an understanding for the possibilities it opens up in the industry as a whole - not only to facilitate the implementation of the approach at HLA and its many collaborating partners, but also to get feedback on the willingness and ability to engage in an integrated design process and break down the barriers between professions involved in the design of energy-efficient buildings.

"Talking the talk"

BIn addition to testing the approach and its applicability through projects, a series of lectures, internal workshops and actual courses were planned and carried out and the appertaining course material was produced. Participants included architects, engineers, product developers and constructing architects from HLA and a wide variety of external partners (Figure 7).

The workshop activity mostly focused on specific projects with a clear sustainability focus defined in either the competition brief or as an aim or objective in the project team (participants from HLA and a number of its partners). The general theme for the workshops revolved around the start-up phase with a clear definition of the goal and aim for the project as focal point. A matching of expectations in the project teams and subsequently a precise definition of per-

formance requirements through a series of group work assignments generated a roadmap for the design development, including a number of *benchmarking sessions* (see also Figure 1).

The actual course activity included a two-day introduction to the IED approach, offered both internally and externally at HLA. As the programme indicates (Figure 8), the course included a series of lectures about national and international standards and regulatory requirements on energy demand and indoor climate, the concept of geometrical optimisation, and how it can all be included in the architectural concept. The lectures also discussed how the value of IED can be communicated to the committee of judges in an architectural competition, the owners, developers etc. The course was an attempt to stress the need for interdisciplinary collaboration amongst those involved in the design of energy-efficient buildings and to discuss IED with a wide range of professions from the building industry.

Daylight was defined as an important parameter and a common denominator when considering energy efficiency and indoor climate. So a two-day course was organised combin-

Figure 7. *Pictures from workshops and courses in IED carried out for employees at HLA and external partners.*

ing the architectural treatment of daylight with the quantification of daylight performance of both building and façade designs. The course included actual measurements of daylight availability in the participants' working environment combined with the simulation of daylight in the same spaces.

"Walking the walk"

Engaging in interdisciplinary design development was carried out in practice through a number of affiliated projects involved in at HLA as an integrated member of the design team. The projects represented both national and international competitions, prequalifications and commissions, ranging from a traditional office building outside Copenhagen in Denmark to a cultural institution in a major new part of Riyadh in Saudi Arabia.

Usually, the role was to be a consultant and facilitator in design competitions with a clear focus on energy efficiency and indoor climate. The work revolved around the development, implementation and documentation of sustainability concepts for several building design proposals, and managing the many interdependent and often conflicting parameters with regard to energy and climate. In this context, great effort went into facilitating and maintaining the interdisciplinary collaboration between architects and engineers so that the final concept combined architecture, energy and climate. The wide variety of projects and locations brought with it the opportunity to observe and collaborate with a large number of national and international engineering and consultancy firms. Figure 9 illustrates some of the projects where the involvement was of a significant character.

Figure 8. *Programme for a two-day course in Integrated Energy Design organised for a wide range of professions involved in the design of energy-efficient buildings.*

October 1st 2009   **[09:00-16:00]**

[09:00-09:15]   **Welcome and programme for the day**

MODULE 1   **[09:15-12:00]**

[09:15-09:30]   **The challenge**
What challenges do we face and how do we wish to approach it?

[09:30-10:15]   **Integrated Energy Design**
What does the approach concretely entail and how is it organized.

PAUSE

MODULE 2   **[13:00-11:45]**

[10:30-11:00]   **Geometry, energy demand and indoor climate**
The influence of building geometry on energy demand and indoor climate.

[11:00-12:00]   **Assignment part 1; "Room geometry"**

LUNCH   **[12:00-13:00]**

[13:00-13:15]   **Goals and regulatory requirements**
Standards and regulatory requirements concerning energy demand and indoor climate (Danish and European).

[13:15-14:00]   **Assignment part 1 – continued**

[14:00-14:30]   **Presentation of generated rooms**

[14:30-15:30]   **Knowledge sharing requires thoughtfulness**
The sharing of knowledge is essential when designing energy efficient buildings, but how is it ensured that it happens optimally and how cant he result be communicated.

[15:30-16:00]   **Recap and discussion**

October 2nd 2009   **[09:00-16:00]**

[09:00-09:15]   **Welcome and programme for the day**

MODULE 3   **[09:30-12:00]**

[09:15-09:45]   **Presentation of simulation results**
Simulation results of the generated rooms' performance in relation to energy and indoor environment is presented and problems are identified and discussed.

PAUSE

[10:30-12:00]   **Assignment part 2; "Optimisation"**

LUNCH   **[12:00-13:00]**

MODULE 4   **[13:00-15:30]**

[13:00-14:00]   **Comfort in an architectural context**
The notion of comfort and a visualization of the physical phenomena dealt with in relation to indoor climate.

[14:00-15:00]   **Presentation of optimised rooms**
Simulation results of the optimised rooms' performance in relation to energy and indoor environment is handed out and each group prepare a short presentation.

[15:00-15:30]   **Discussion of the assignments**
Short discussion of the assignment and its results.

[15:30-16:00]   **Recap and discussion**
Discussion of the course as a whole –criticism and lessons learned.

Figure 9. *Timeline illustrating the chronology*
of a selected range of affiliated projects involved in at HLA.

2009

2010
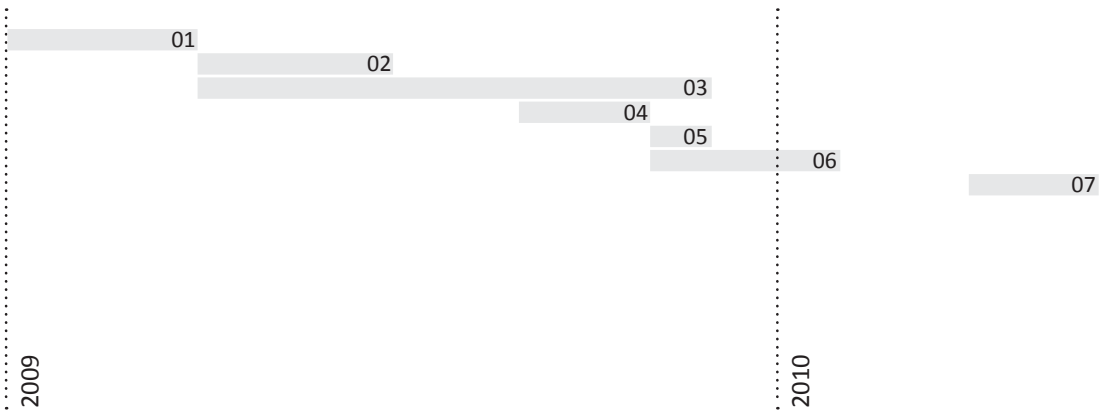
01_ ØRESTADEN SCHOOL

- EDUCATIONAL
- COPENHAGEN, DENMARK
- 14.000 M2
- PREQUALIFIED COMPETION

02_BSU (GERMAN MINISTRY OF URBAN DEVELOPMENT AND ENVIRONMENT)

- GOVERNMENTAL / PUBLIC
- HAMBURG, GERMANY
- 50,000 M2
- INTERNATIONAL COMPETITION

03_ SDU (UNIVERSITY OF SOUTH-ERN DENMARK)

- EDUCATIONAL
- KOLDING, DENMARK
- 13,000 M2
- INTERNAT. COMP. - 1ST PRIZE

04_ ENERGINET

- COMMERCIAL
- BALLERUP, DENMARK
- 4,000 M2
- COMPETITION – 1ST PRIZE

05_PRINCE NAIF CENTER
FOR HEALTH SCIENCE RESEARCH

- EDUCATIONAL
- COPENHAGEN, DENMARK
- 23,800 M2 +11,600 M2
- COMMISSION
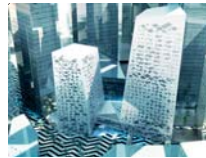
06_THREE TOWERS
IN KING ABDULLAH FINANCIAL DISTRICT

- COMMERCIAL & RESIDENTIAL
- RIYADH, SAUDI ARABIA
- 93,000 M2/41,000 M2/33,500 M2
- COMMISSION

07_ NIELS BOHR
SCIENCE PARK

- EDUCATIONAL
- COPENHAGEN, DENMARK
- 45,000 M2
- COMPETITION

08_VISITING RESEARCHER

EXTERNAL STAY AT CENTER
FOR THE BUILT ENVIRONMENT
(CBE), UNIVERSITY OF CALIFOR-
NIA IN BERKELEY .

08
09
10
11
12
13
14
15

2011
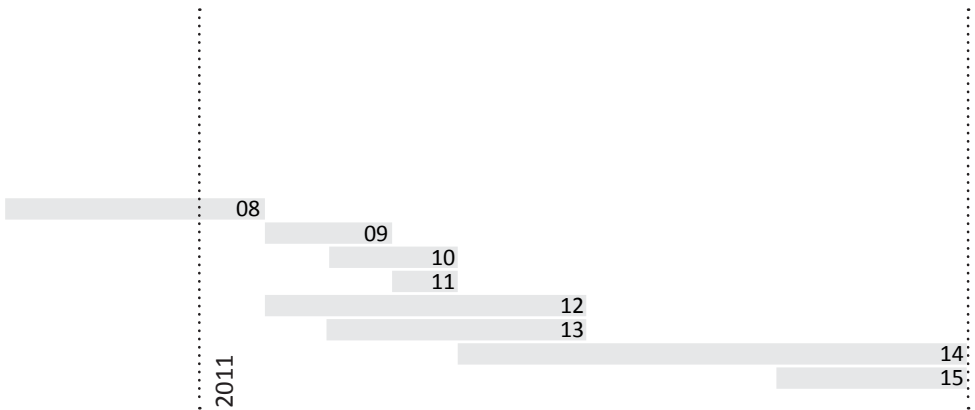
09_ COPENHAGEN PLANT SCIENCE CENTER

- EDUCATIONAL
- COPENHAGEN, DENMARK
- 7,000 M2
- COMPETITION

10_ CAMPUS BALLERUP

- EDUCATIONAL
- BALLERUP, DENMARK
- 11,000 M2
- COMPETITION

11_ODENSE UNIVERSITY HOSPITAL

- HEALTHCARE
- ODENSE, DENMARK
- 280,000 M2
- COMPETITION

12_ CHILDREN'S INTERACTIVE MUSEUM

- CULTURAL
- RIYADH, SAUDI ARABIA
- 8,500 M2
- INTERNAT. COMP. - 1ST PRIZE

13_ SIEMENS

- COMMERCIAL
- MUNICH, GERMANY
- 45,000 M2
- INTERNAT. COMP. - 1ST PRIZE

13_LABORATORY BUILDING

- EDUCATIONAL
- DENMARK
- 5,500 M2
- COMMISSION

13_LEÜTHEN'S CULTURAL GARDEN

- PUBLIC & COMMERCIAL
- TRONDHEIM, NORWAY
- 39,000 M2
- INTERNAT. COMP. - 1ST PRIZE

Different languages

The projects at HLA underlined the importance of the ability to communicate the measures taken to incorporate energy efficiency, increase indoor-climate quality, and take general sustainability into account. Here, the translation of scientific knowledge into design generating potential requires a special *language* that has to practised and refined. However, while HLA focuses on making the scientific knowledge operational in the framework of project development, academia focuses on disseminating through well-reputed scientific journals (ISI-indexed), which requires a completely different language (Figure 10).

Developing a presentation methodology through Case studies

Throughout the many projects involved in at HLA, IED was the approach used to include the concept of energy efficiency and indoor climate in the architectural development of the buildings. The design development focused on the passive properties using the three-step approach (minimise, optimise and produce), and a series of projects were selected to illustrate the potential and the development of this methodology.

Figure 10. *The communication between the individuals involved in the design process often seems to be governed by different languages, but the research covering the design process also needs to be translated for operational project development and dissemination through scientific journals (ISI-indexed).*
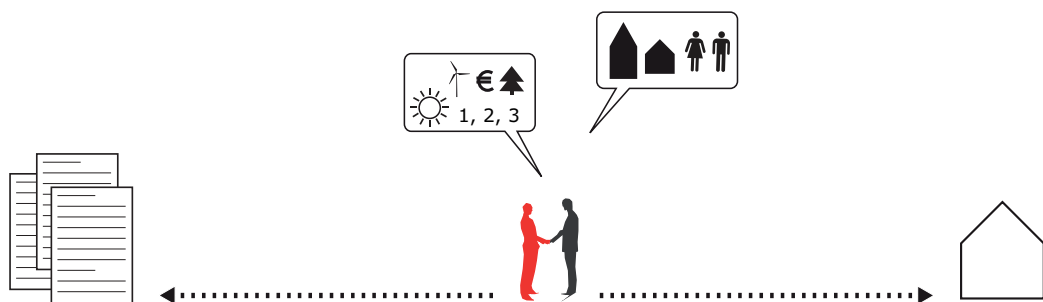
Case study: Ørestaden School

This project was selected as a spearhead project for sustainability within the municipality of Copenhagen, Denmark. It was a take on the modern school were sustainability is incorporated in the building's architectural concept and manifest itself in the functional organisation, its pedagogical potentials and performance in terms of energy and indoor climate. Ørestaden School had an annual energy demand of 63 kWh/m^2 (without producing energy) fulfilling low energy class II at the time of the competition (EBST, 2008) and obtained an indoor climate equivalent to class I according to European standards (CEN, 2007). The documentation on how this was achieved was present within the delivered material, but does not appear together and was dominated by a lot of text, giving the impression of an in cohesive concept (Figure 11).

"The committee of judges finds it difficult to pinpoint the actual spearhead element in the project"

- The panel of judges.

Figure 11. *Illustrations from different parts of the competition folder describing the design reasoning behind Ørestaden School.*

Individuality

Solidarity
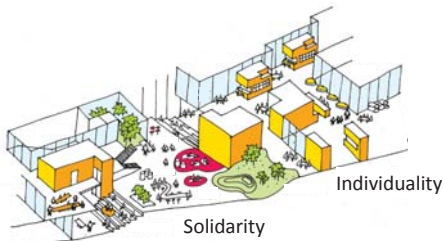
Individuality

The split levels connect the functions and provides meeting points and differentiated spaciousness.
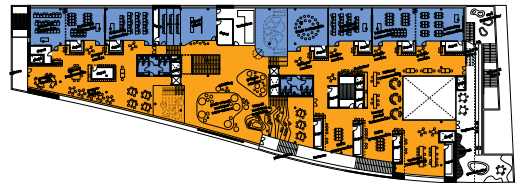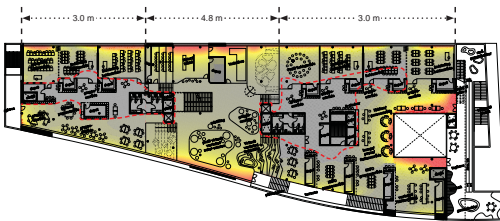
The subsequent variation in room height result in daylight availability matching the functional organisation and logically defines zonal division for ventilation, lighting etc.
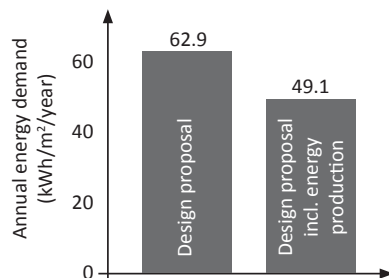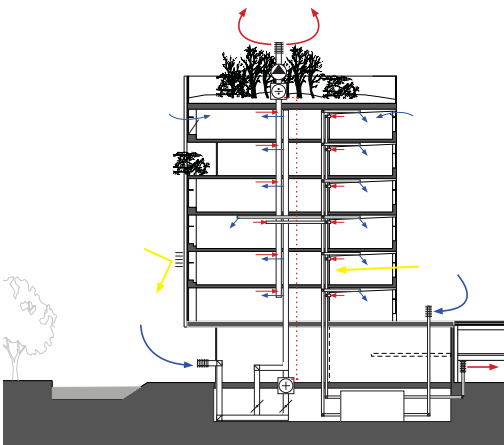
Defining the solutions implemented in the building and subsequently the energy demand.

Case study: German ministry of Urban development and Environment (BSU)

BSU was a major German office building where the competition brief required an extensive degree of flexibility combined with high standards for energy efficiency including certification according to the German standard DGNB[2] . BSU had an annual energy demand of 70 kWh/m^2 (without producing energy) and obtained an indoor climate equivalent to minimum class II according to European standards (CEN, 2007). The purpose was to assemble and structure the presentation so that it illustrated a holistic approach to energy efficiency and indoor climate where all parameters were taken into consideration. The result was a confusing, bordering chaotic, presentation lacking the transparency and clarity as to what had gone into making the building sustainable (Figure 12).

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2   Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB)-www.dgnb.de
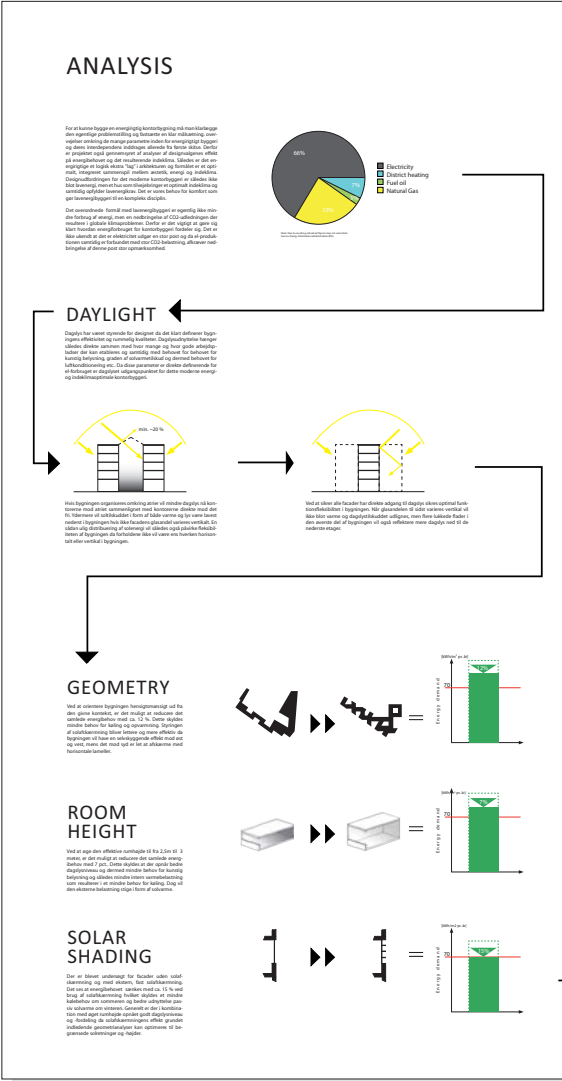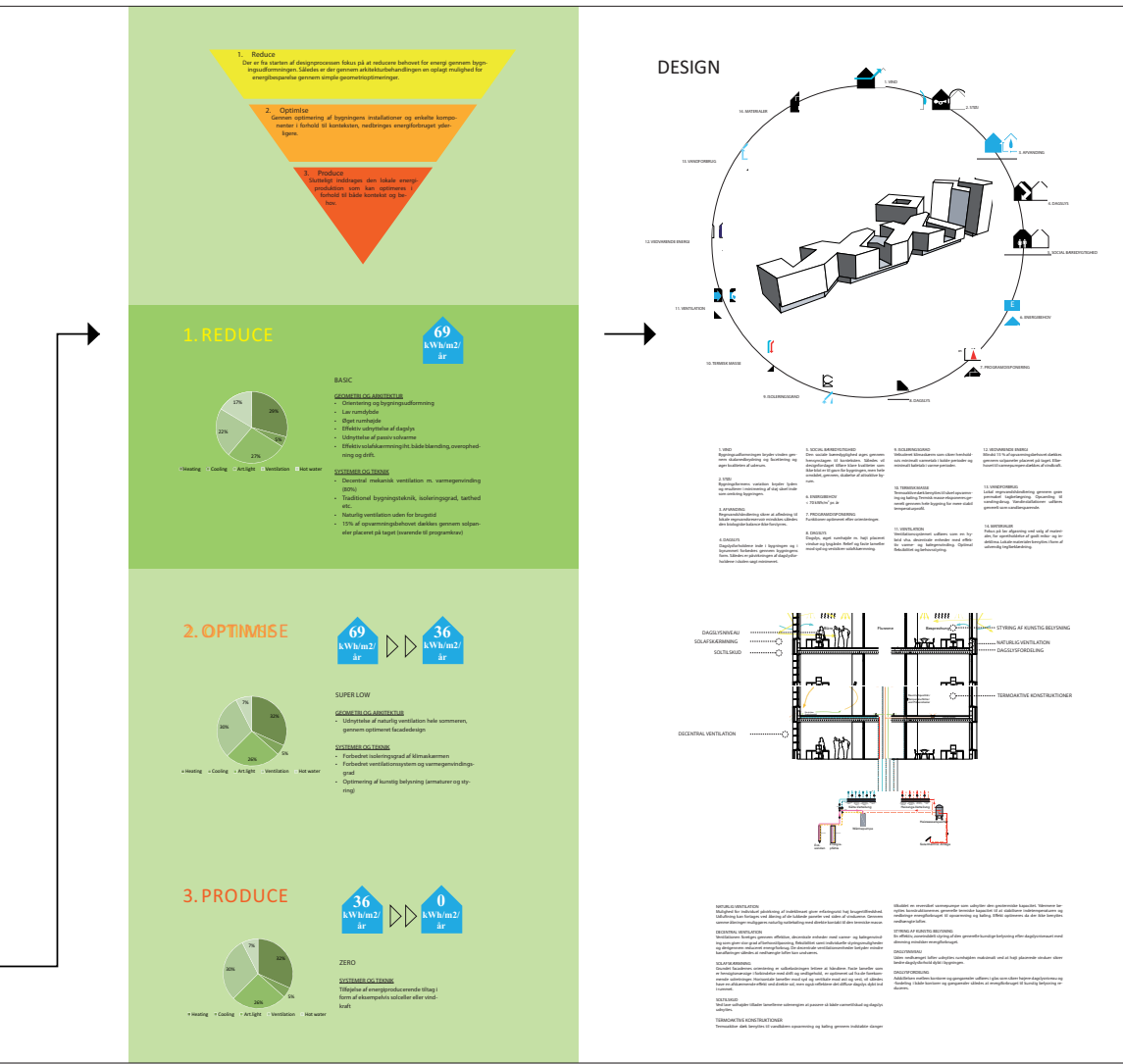
Figure 12. *The competition board illustrating the analyses in terms of energy efficiency performed for German ministry of Urban development and Environment (BSU).*

Case study: Energinet

The project was generated as a simple architectural design resulting in a flexible and easily comprehensible building. The presentation methodology was to emphasise how considerations about energy and indoor climate had assisted in generating the building form through the three step approach; minimise, optimise and produce, focussing on the utilisation of passive properties. The result is easily understandable, stepwise illustration demystifying what a concept for an energy efficient building entails (Figure 13). Energinet had an annual energy demand of 45 kWh/m^2 (without producing energy) fulfilling low energy class I at the time of the competition (EBST, 2008) and obtained an indoor climate equivalent to minimum class II according to European standards (CEN, 2007).

Figure 13. *Illustration of the rationale behind the design of Energinet following the three step approach; minimise, optimise and produce.*

REFERANCE
»95 kWh/m²/year

REDUCE
»62,9 kWh/m²/year

OPTIMIZE
»48,8 kWh/m²/year

PRODUCE
»Depends on product selection

TRADITIONAL HOUSE

[kWh/m² per. year]
95,0
Energy demand
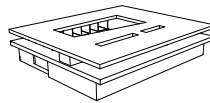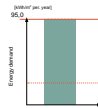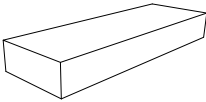
1.REDUCE

THERMAL MASS

- High desity materials exposed where possible, in the interest of passive cooling.
- Levels the fluctuations in room temperature and thereby improving the indoor climate.

[kWh/m² per. year]
62,9
Energy demand
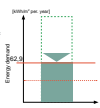
1.REDUCE

GEOMETRY AND ORIENTATION

- Compactness
- Ideal placement and orientation according to interior sunlight.
- Optimization of room depth according to natural ventilation.
- Focus on additional natural ventilation of highly populated areas e.g. atrium, canteen etc.

[kWh/m² per. year]
78,8
Energy demand
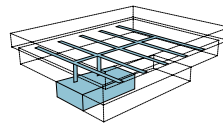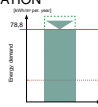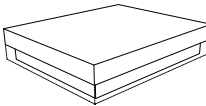
2.OPTIMIZE

VENTILATION

- Systems with high efficiency.
- Intelligent / need driven ventilation, VAV

[kWh/m² per. year]
56,4
Energy demand
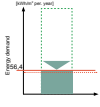
1.REDUCE

DAYLIGHT

- Ideal use of daylight reduces the use of artificial lighting.
- Demand-controlled lighting in relation to daylight.
- Skylights orientated and designed to minimize direct sunlight.

[kWh/m² per. year]
75,8
Energy demand
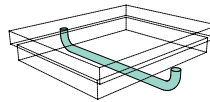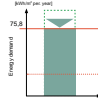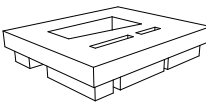
2.OPTIMIZE

PREHEATING / -COOLING OF AIR

- Use of channels in the ground for heating and cooling of fresh air.

[kWh/m² per. year]
48,8
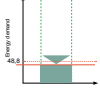
1.REDUCE

FUNCTIONDISTRIBUTION

- Ideal placement of functions and workspaces related to building orientation.

[kWh/m² per. year]
74,8
Energy demand
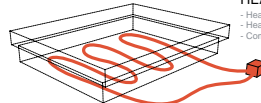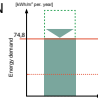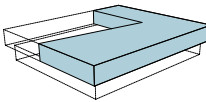
3.PRODUCE (EXTRAS)

HEATPUMP

- Heating of water for domestic use.
- Heating of the building.
- Combined with either geothermal heat or grundwater.

1.REDUCE

FACADEDESIGN

- Fixed exterior solarblinds combined with shaded glass.
- Use of corbels and roof overhang
- Interior blinds or curtains to minimize glare and reflections in e.g. monitors.
- Increased airtightness

[kWh/m² per. year]
73,8
Energy demand
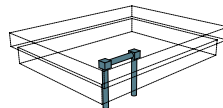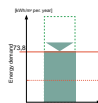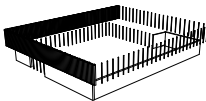
3.PRODUCE (EXTRAS)

GROUNDWATER COOLING

- Use of groundwater direct cooling.
- Use og groundwater for heatpump.

1.REDUCE

GREEN ROOF

- Reduces the need of cooling.
- Converts CO2 and other greenhouse gases into oxygen, and contributes to the buildings carbon footprint.
- Reduces the need of rainwater drainage .

[kWh/m² per. year]
64,3
Energy demand
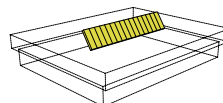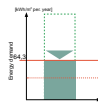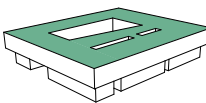
3.PRODUCE (EXTRAS)

SOLAR PANELS /SOLAR CELLS

- Heating of water for domestic use.
- Supplementary heating.
- Production of electricity.
- Optimization of the heatpunp efficiency.

Case study: Niels Bohr Science Park (NBSP)

NBSP is a university building with a highly complex program including single offices, classrooms and auditoriums, meeting rooms, different types of laboratories and a wide range of support function. The presentation methodology follows the three step approach focussing on geometrical optimisation. The result is an easily readable *comic strip* that explains how energy efficiency has constituted an extra layer within the architectural concept (Figure 14). NBSP had an annual energy demand of 48 kWh/m^2 (without producing energy) fulfilling low energy class I at the time of the competition (EBST, 2008) and obtained an indoor climate equivalent to minimum class II according to European standards (CEN, 2007).

These illustrations are examples of the translation performed of a wide range of analyses that has gone into the design development the projects at HLA. Here it should be noted that the extensive typology study behind the facade development for NBSP is further described in the paragraph *Case study: Niels Bohr Science Park*.

PRODUCE
» local energy

OPTIMISE
» components & installations

MINIMISE
» context, geometry, function & systems
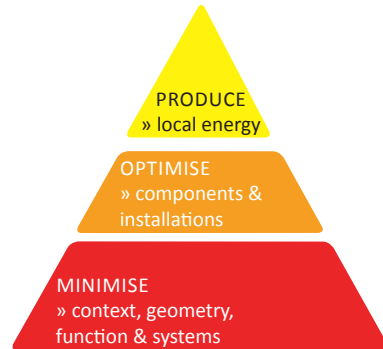
Figure 14. *Comic strip illustration of the design development for Niels Bohr Science Park (NBSP) following the three step approach; minimise, optimise and produce, describing the geometrical optimisation.*

FORM, FUNKTION & DAYLIGHT

Lighting
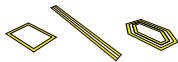
» Antallet velbelyste arealer optimeres
» Dagslysoptimeret atrium

FACADE & COOLING

Cooling
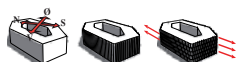
» Facaden facetteres og orienteres
» Forskydning udnytter selvskygge optimalt

Tightness	Lighting
Insulation	Ventilation
Solar shading	Energy class
Windows	Indoor climate class
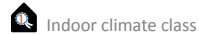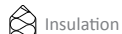
STEP 1 MINIMISE

STEP 2 OPTIMISE

ENERGY DEMAND

Trin 1: Minimér — Trin 2: Optimér

kWh/m²/år

Minimum req.
Low E class 1
Low E class 2

Reference | Stage 1 | Stage 2 | Stage 1 | Stage 2

» Procesventilation
» Køling
» Ventilation
» Belysning
» Varmt brugsvand
» Opvarmning

% DF

| 10.0 + |
| 9.0 |
| 8.0 |
| 7.0 |
| 6.0 |
| 5.0 |
| 4.0 |
| 3.0 |
| 2.0 |
| 1.0 |
| 0.0 |
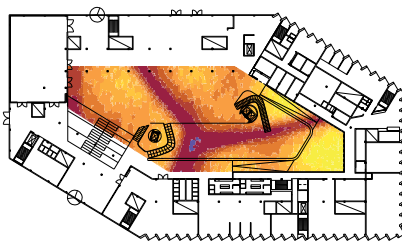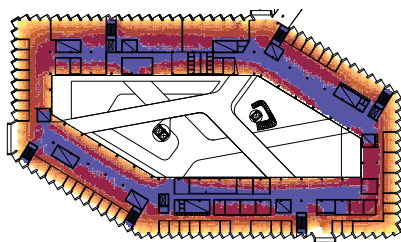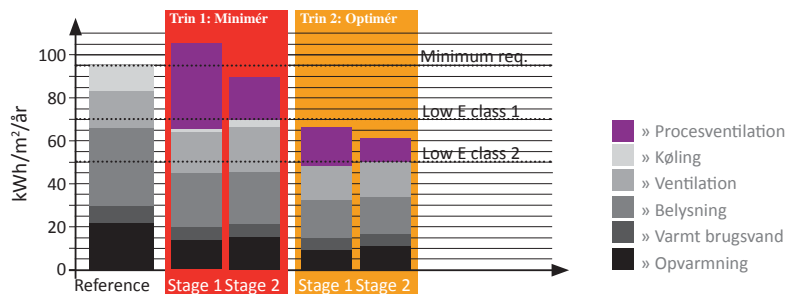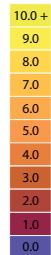
Scientific dissemination

Paper I[3] (Appendix A) is an attempt to strike a balance between the operational and the scientific approach by focussing on the support of design development as a scientific discipline. The study seeks to highlight the need for a translation of performance parameters such as daylight availability, operative temperature and air quality, into spatial reasoning. This translation of numbers and graphs result in a situation where the integration of technical input can quantify early design decisions when engaging in the interdisciplinary design process of low-energy buildings.

The case is the design of a 6-storey (15,000 m2) office building located in Copenhagen, Denmark that has to accommodate workstations for 500 employees and support facilities, such as meeting rooms, print and copy rooms, kitchenettes, etc. (Figure 15).

The competition brief stated that the building should be closely related to the surrounding area dominated by old warehouses in brick and stone from the eighteenth century and continue the line of "warehouse-like" building structures. Furthermore the building should be both solid and dynamic in its expression, make full use of the views provided by the unique location, and maintain a certain degree of openness towards the surroundings, its users, and its visitors. The nature of rough brickwork and the gentle ripples of the water in the harbor, combined with the performance potential in relation to energy and indoor climate of angling the windows (the angle dependency of the total solar energy transmittance), inspired the design of the façade (Figure 16).

The northwards angling of the windows not only optimized the views towards the city of Copenhagen and the harbour area, but also significantly reduced the energy demand for

Figure 15. *Illustration of the building's context.*

Figure 16. *The qualitative and quantitative inspiration for the design development of the facade; a) the nature of rough brickwork existing within the area and b) the angle dependency of the total solar energy transmittance for different glazing's.*

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3   *"Integrated Design - A paradigm for the design of low-energy office buildings",* Published in ASHRAE Transactions 117 (1) (2011), 230-239.

future tower and pedestrian bridge by Steven Holl

existing headquarter

new headquarter

%DF

5.00+	4.50	4.00	3.50	3.00	2.50	2.00	1.50	1.00	0.50	0.00

----- Daylight factor < 2%
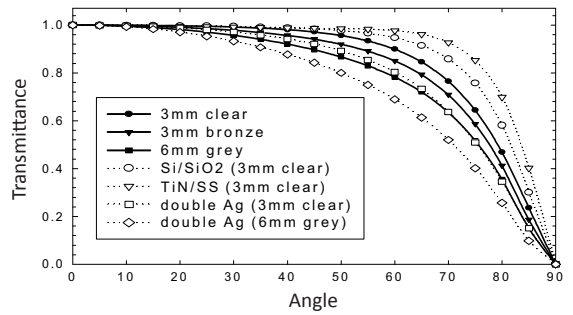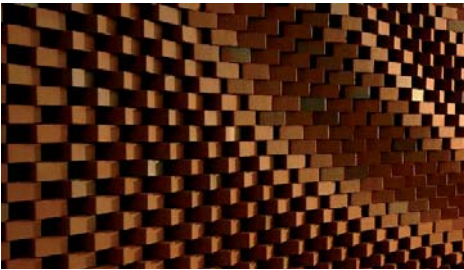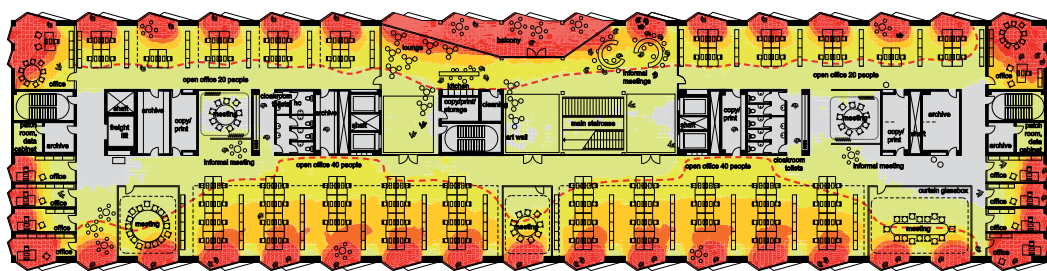
Figure 17. *Plan illustrating the correspondence between daylight availability and workstations obtained via a asymmetrical position of the cores and the double room height.*

cooling. Furthermore, daylight analyses facilitated the introduction of double room height and asymmetrical placement of the structural core, to obtain a more optimal correlation between functional requirements and daylight availability (Figure 17). This resulted in the spatial requirements being fulfilled despite reduced gross floor area, because the remaining area could be utilised more effectively.

The project had an annual energy demand of 66 kWh/m^2 (without producing energy) fulfilling low energy class II at the time of the competition (EBST, 2008) and obtained an indoor climate equivalent to minimum class II according to European standards (CEN, 2007).

Figure 18. *Final renderings of the design proposal illustrating the facetted brick façade and the spaciousness obtained by the double room height.*

A major part of the architectural expression was defined by the façade design which through common effort within the design team was able to utilize the inherent both aesthetic and energy efficient qualities. The case study shows how technical input can facilitate the design development if the results are visually translated and coupled with spatial considerations. In this manner the full performance potential at the critical sketch phase can be deduced and the architectural concept enriched (see Figure 18 on following page).

Lessons learned

Both interdisciplinary collaboration between engineers and architects and bridging the gap between industry and academia require a general focus on communication. So it is of great importance to understand the design process and have the ability and willingness to influence it. Contrary to the traditional notion that the building's performance is determined by the architect's first sketch on paper, it is important to understand that, to a large extent, it is determined by the building's context, the building programme, and the performance requirements.

The implementation of technical knowledge is relevant at all stages of design and is a prerequisite for engaging in a more integrated approach to the design development of future energy-efficient buildings. In this research project, the implementation became two-fold. It required not only a thorough knowledge and understanding of how design development is actually conducted, but also of the technical and functional performance of the building and its components. In this context, it was important to be able to translate the architectural concepts and visions into performance requirements that could help generate the development of design alternatives. It was equally important to translate, for instance, the output from energy or indoor comfort simulations into tactile and tangible design input that could support spatial reasoning and help quantify the architectural design being developed.

This research project focused on the role of the building envelope, and more specifically the façade, in the highly complex discipline of designing energy-efficient buildings. The façade is in principle the mediator between the outdoor climate and the indoor function, making it and its typology a crucial factor in the search for a way to fuse architecture and technology back together. This project sought an understanding of the existing façade typology, its great potential, and its role in architecture, instead of focusing on implementing or inventing *magic* components to rectify bad design decisions or as penance.

|03|
typology

Typology

Buildings act like organisms and the typology of the individual components, or cells if you will, determine to what extent it enters into a reciprocal co-existence with its surroundings and its occupants. A building's functional composition determines its metabolism and defines what is necessary for this co-existence. So navigating through a design process becomes a study of typologies in the search to fulfil the requirements for the particular building. Design alternatives are mapped, tested and benchmarked to enable an informed choice that achieves the desirable equilibrium between performance parameters. The parameter variations span from the start of the design process to the commissioning of the final building and require the performing of overall volume studies and the building's incorporation within its context, and analysis of its functional organisation, appropriate room geometries and façade designs – none of which can be analysed separately (see Figure 19).
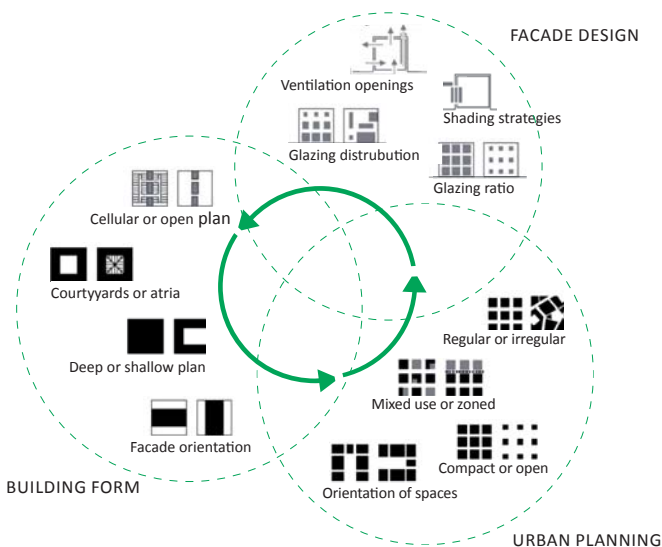
Figure 19. *The interdependent relationship between façade, room, building and the urban environment. The façade design influences everything and vice versa.*

Figure 20. *Illustration of the increased requirements for energy efficiency and the introduction of a framework for building energy performance (EPBD, 2002) that moves the focus from the component level to a more holistic conceptual level.*
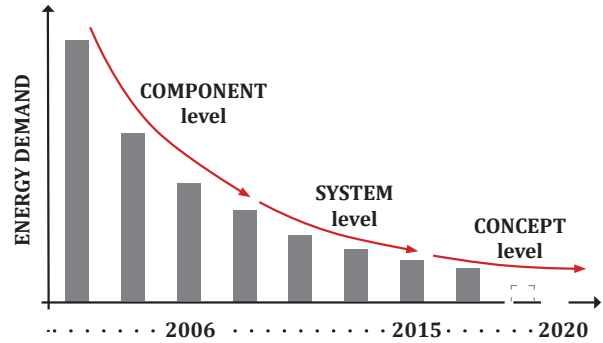
In this context, the Energy Performance of Buildings Directive (EPBD) (EPBD, 2002) and its relatively recent recast (EPBD, 2010) prescribe strict requirements for energy efficiency in the built environment. Furthermore, the EPBD represents a paradigm shift in regulations because it defines a framework for the total energy performance, unlike the earlier requirements at the individual component or system level. This not only promotes a more holistic evaluation of the building's energy performance, but also provides designers, both architects and engineers, with an opportunity to reclaim a certain design freedom in the choice of methods to meet the ever stricter energy demands.

By no longer confining requirements to component level, but broadening the view to the building as a whole, the optimisation focus is now driven towards the much needed, conceptual level (Figure 20). At every level and on every scale the typology of design alternatives helps categorise the options there are not only to meet the individual performance parameters but also to understand how they interrelate. Here, the building envelope and, in particular, the façade is the mediator between the contextual setting and the indoor climate and spatial requirements.

Façade performance

Reducing the evaluation of a façades' performance to be-ing defined only by energy and indoor climate would be to leave out part of the picture. The façade is a major part of the building's architectural expression and has the ability to communicate the building and its functions to the sur-roundings. A high level of architectural quality can, like in-door comfort, inspire and influence people's productivity and perception of working in, using or merely visiting the building, all of which can ultimately prolong the building's life span. In contrast, buildings that are not able to attract tenants and therefore need alterations or even demolition can hardly be considered sustainable. Simultaneously the façade and how it is designed, represents a significant part of the initial construction and maintenance cost. This project does not seek to determine an optimal façade design or even façade component – that is not only highly irrelevant, but simply deemed impossible due to the many contradicting parameters governing façade design (see also Figure 21). There are innumerable solutions to a well-designed façade, but it should in all instances be developed for that particular project and contextually founded. Not two projects are the same and the equilibrium in between the wide pallet of per-formance indicators varies from project to project. There-fore the goal is rather a quantification of the performance through integrated simulations taking both energy efficiency and indoor climate in to account in order to support a quali-fied development of the façade design.

The significance and relevance of an integrated approach to simulations of building performance was introduced by Morel & Faist (1993) and Clarke et al. (1998) and was further investigated by Citherlet et al. (2001). The need and require-ment for integrated simulation tools to provide a more holis-tic performance evaluation at overall building level, façade level, and in the selection of individual building components, was analysed and discussed by Citherlet & Hand (2002), Selkowitz (2001) and Wilde et al. (2002). Moreover, recent analyses advocate providing simulation support to the cru-

Figure 21. *Illustration of the complexity of façade design with the many, often contradictory, parameters of considerable interdependence.*
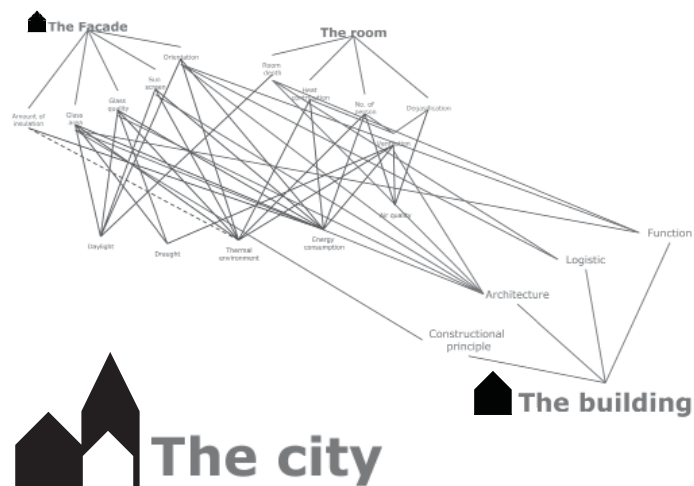
cial early design stages (Petersen and Svendsen, 2010), and this research project further highlights the importance of informed choice between design alternatives (see also papers in Appendix A). Several studies describe and analyse the potential performance optimisation benefits from integrated simulations, ranging from a reduction in total energy demand and peak cooling/heating demands to improvements in occupant comfort in terms of daylight conditions and thermal indoor environment (Lee et al., 1998; Laforgue et al., 1997; Franzetti et el., 2004; Tzempelikos et al., 2007). However, integrated simulations of building performance are rarely carried out early in the design process despite the need for design evaluation at this crucial stage. The highly iterative nature of the initial design phases in particular, where many professional disciplines are in play, are not dominated by interoperability, but require a high level of focus on the process rather than merely on the data (Augenbroe et al., 2004)

The desired equilibrium between energy demand and occupant comfort can only be achieved at room level. Only on this

scale is it possible to evaluate both behaviour and requirements with regard to the thermal and visual indoor environment as defined by the occupant. So the façade, as the actual separator between the indoor and outdoor environment, becomes a key issue in striking the balance between energy performance, occupant comfort and spatial considerations. Choosing the optimal façade is a complex discipline with many, often contradictory, parameters of considerable interdependence (Ochoa & Capeluto, 2009). The balance that results in the desired level of comfort and supports the spatial configuration with the lowest possible energy demand is often highly sensitive to a number of environmental factors (Figure 22).

The problem of shielding against the outdoor climate in terms of rain, wind, and insulating the opaque parts of the façade has largely been solved. Obviously, there is still room for improvement and product development continues at the component level. Such considerations could include the assembly and the actual construction, where achieving an acceptable performance, for example, in relation to air tightness is important[4]. However, this project focuses on the initial stages of design, where the façade is conceptually conceived. While all the above parameters are important and should be considered when designing and constructing the façade, the control of solar radiation and the attainment of sufficient amounts of daylight are the kinds of questions that need sorting out in the early stages of design.

What is the optimal equilibrium for energy efficiency, indoor climate, spatial perception, architectural quality, etc. and how will they support the overall concept? Here, the fenestration, in terms of overall transparency, the design of windows, and solar shading, is the key element.

Figure 22. *Typical room with environmental components.*

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4   According to the Danish trade organisation Klimaskærm (www. klimaskaerm.dk), which performs pressure tests on buildings, 25-30% of new buildings constructed in Denmark do not comply with the requirements (http:// ing.dk/artikel/119234).

Insolation

Daylight

Wind

Noise

View

Moisture

Air temperature
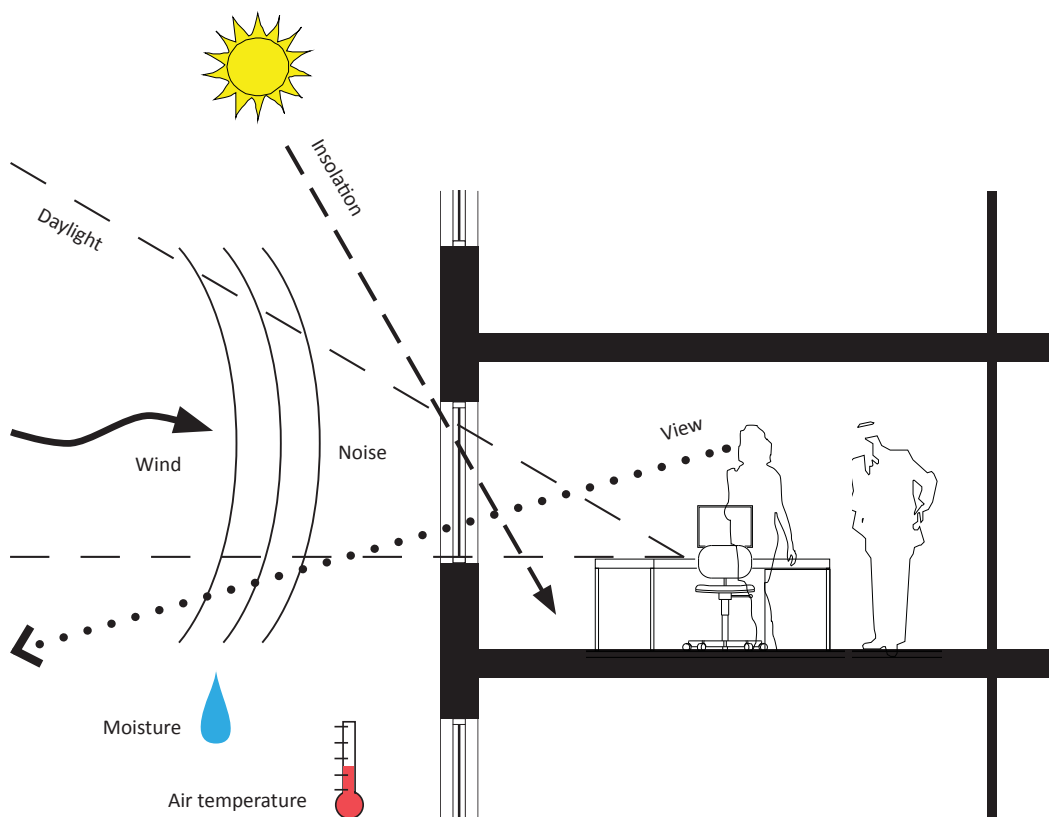
Fenestration

The fenestration system is a good representative for the often contradictory wishes governing façade design. From the architectural point of view, fenestration is a key element as it among many other things provides the visual connection to the surrounding context (see also the paragraph *Daylight as a common denominator*). This is also substantiated by research into what people regard as important parameters for facade and window design in relation to their work environment (SBI, 1999) (see also Figure 23).

From the viewpoint of energy demand and indoor climate the glazed facade component is, at the same time, the strongest and the weakest element. Its benefits include view to the outside, daylight penetration, passive heat gain and potential reduction in the demand for heating and artificial lighting; its disadvantages include increased heat loss, thermal discomfort (radiant temperature asymmetry and potentially draught), visual discomfort and increased cooling demand (Figure 24). Therefore research has through technology advancement and the development of especially glazing and solar shading, sought to accentuate the advantages and

THE WINDOW´S GREATES POSITIVE SIGNIFICANCE
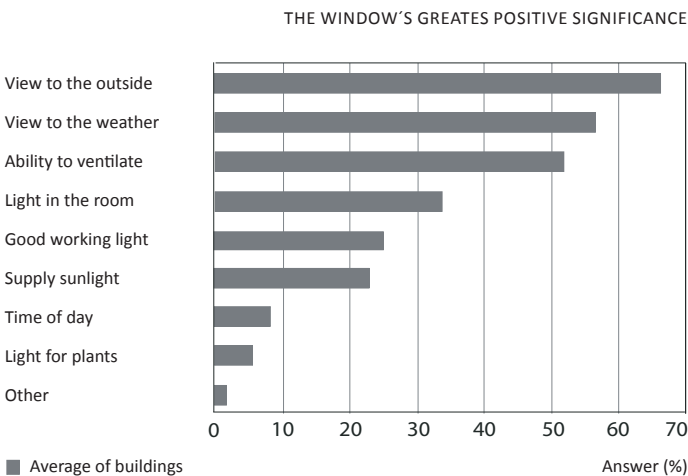
Figure 23. *Results of a field study on what occupants in offices regard as the most as important quality for window design in relation to their work environment (SBI, 1999).*
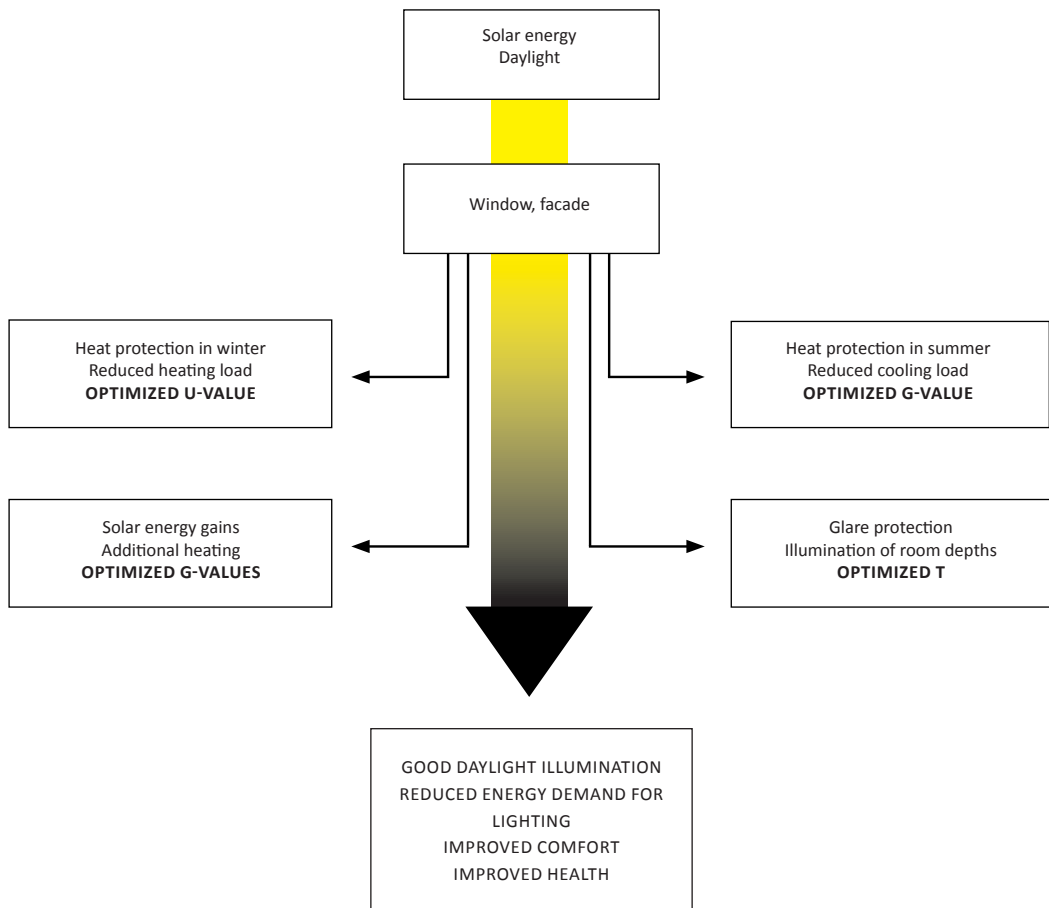
Figure 24. *The requirements and physical standards at play when optimising the fenestration system (adopted from Köster, 2000).*

RBE		Responsive Action					
		Intervention		**Physical behaviour**			
Building system	Element	Surface	Internal	Heat flux	Thermal storage	Transparency	Permeability
Envelope	Wall						
	Roof						
	Ceiling						
	Fenestration						
Super structure	Colum/beam						
	Load bearing wall						
	Load bearing floor						
Sub structure	Piles						
	Foundation beams						
Underground structure	Earth to air heat exchangers						
Renders and finishes	Partition wall						
	Floor						
	Ceiling						

eliminate the disadvantages through dynamic and if controlled appropriately, responsive facade components (IEA-ECBCS, 2010) (see Figure 25).

Dynamic and responsive façade elements

Technological advances in façade elements, especially glazing and solar shading, in combination with the enhanced focus on daylight optimisation, have resulted in many highly glazed buildings in recent decades. The increase in glazed area, however, results in highly fluctuating heating and cooling demands because it represents a lower insulation value, which increases transmission heat loss, while the transmitted solar radiation can result in problems with overheating. This has led to the introduction of dynamic fenestration, which enables the achievement of a more beneficial utilisation of the resources available, such as insolation and daylight, with respect to both energy demand requirements and occupant comfort (Lee et al., 1998).

Even minor alterations in either internal or external loads can have considerable impact on the energy demand for heating, cooling, ventilation and artificial lighting. Each of the façade components has a filtering effect on the external impacts, and the indoor environment can only be evaluated by considering the building envelope as a whole (Clarke et al., 1998). So the façade can be constructed with a number of static and dynamic components that, in combination, are capable of achieving a better control of the outdoor climate than more traditional façades (Lee et al., 2002). For example: regulating the amount of solar heat gain and daylight can be achieved by installing dynamic solar shading, and natural ventilation can be achieved through windows or openings (Figure 26). In this context, previous research into dynamic fenestration technologies to determine their significance in relation to energy consumption and occupant comfort has also yielded results such as a decrease in cooling and lighting demand (Athienitis and Tzempelikos, 2002; Tzempelikos and Athienitis, 2007), reduced overall energy demand (Lol-

Figure 25. *Illustration of categories (their typical physical behaviour) and responsive actions of responsive building elements (IEA-ECBCS, 2010).*

lini et al., 2010), and improved daylight utilisation (Koo et al., 2010). At the same time, improving the interior daylight conditions can both reduce energy consumption for artificial lighting and increase the heat gain, which affects the energy demand for heating, ventilation and cooling (Johnson et al., 1984; Tzempelikos et al., 2007).

All this provides insight into how a certain degree of adaptability in the façade in accordance with changes in seasons and occupational patterns can have a beneficial effect, but also that this potential only can be achieved through an integrated process (Lee et al., 1998).

However, in this context, it is important to mention that the use of dynamic façade components not only has potential impact on indoor climate and energy demand, but also significantly alters the architectural expression and has considerable impact on both construction and maintenance costs (Cetiner & Özkan, 2005).

This research project engaged in the early design process of a wide variety of architectural competitions, and the evaluation of dynamic façade components has been carried out within this framework. The main focus of the research was on daylight and the control of solar radiation in general.

Natural ventilation

Building envelope

Control of ventilation
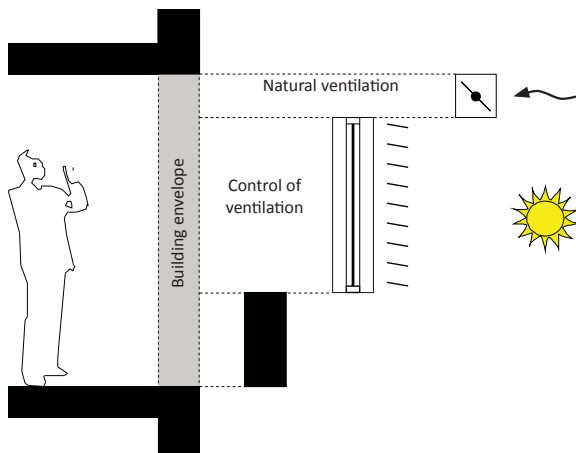
Figure 26. *Illustration of the components of the building envelope and the parameters of the external environment they can dynamically filter. Natural ventilation can be enabled through an opening above the window and controlled by a louver, while insolation can be controlled by solar shading.*

Solar shading

Solar shading, especially when externally placed, often represents the first frontier in controlling solar radiation and therefore has great potential from an energy demand and indoor climate point of view. Moreover, the design of external solar shading can play a major role in the overall expression of the façade and the differences between fixed and dynamic solar shading are considerable (Figure 27). Fixed external solar shading can consist of the self-shading effect of the overall building form, the design of the window aperture, the addition of external vertical or horizontal fins, or as a combination. This puts the achievement of solar shading through passive means within the perceived realm of architects and the architectural discipline. The affiliated projects involved in at the architectural firm demonstrated that the utilisation of these passive properties developed through a geometrical optimisation of the façade design is relatively easy to implement within the architectural concept. Dynamic solar shading is often promoted as having superior performance in relation to energy and indoor climate compared to the fixed variant, because of its ability to adapt to the considerable seasonal and daily changes. A recommendation of dynamic solar shading, however, seemed much more difficult to integrate in the design development and often represented a deal-breaker. The dynamic element was perceived almost as a foreign element for which the aesthetic quality seemed difficult to derive. Here it must be admitted that the design and aesthetic development of dynamic solar shading, often consisting in aluminium venetian blinds or some kind of screen, do leave something to be desired.

Figure 27. *Illustrations of fixed (left) and dynamic (right) solar shadings.*
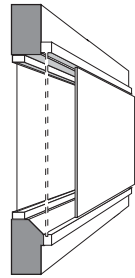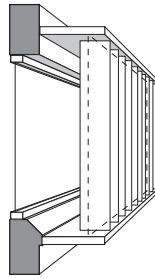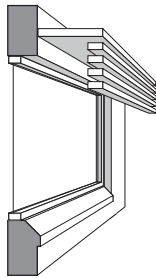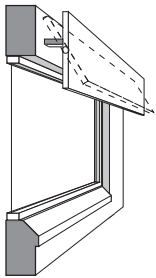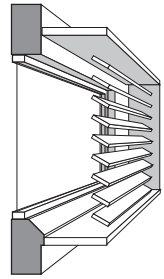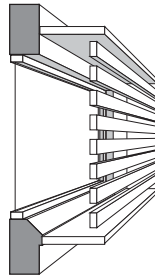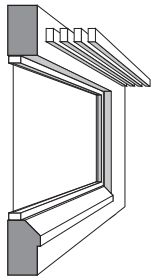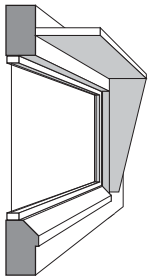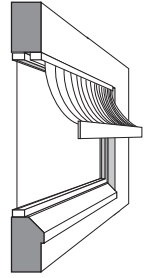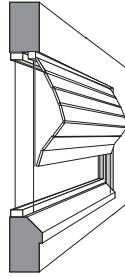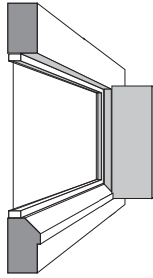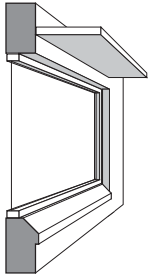
Quantifying the effect of
dynamic solar shading on the energy demand

Based on the empirical knowledge obtained at the architectural firm an initial quantification of the dynamic solar shading's performance in comparison with alternatives would be able to qualify the facade's design development. Therefore, a comparative study of three types of external solar shading for offices was performed (paper II in appendix A)[5]. The focus was on investigating the performance of dynamic solar shading compared to fixed solar shading or no solar shading (Figure 28), but also various window heights and orientations were taken into consideration. All simulations were carried out on room level (office space for two people) to perform an integrated evaluation of energy efficiency and indoor climate (Figure 29).

Evaluating façades with dynamic properties requires equally dynamic simulations. The simulations have to include weather data for the given location and generate results for both the thermal, visual and atmospheric indoor environment - especially when considering translucent components (Selkowitz, 1998). Only then can the components be controlled in accordance with both outdoor and indoor climate, and the potential reduction in energy demand as a consequence of the increased adjustability and the utilisation of the higher luminous efficiency of daylight be determined (Strachan, 2008). So there is considerable interdependence between the composition of the façades, daylight availability, need for heating, cooling and artificial lighting, the layout of workplaces, and the wishes of each individual occupant. Thus, the interaction with the building sub-systems has to be included to perform a quantified comparison between the design alternatives (Lee et al., 1998; Franzetti et al., 2004). Therefore integrated simulations taking annual energy demand (heat-

Figure 28. *Illustrations of the three different solar shading types: a) without solar shading, b) fixed solar shading, and c) dynamic and fully retractable solar shading.*

Figure 29. *Geometry of the two-person office simulation model here shown without solar shading and a window height of 1.5m. The window height was defined from a window parapet with a fixed height of 0.8m.*

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5   "*Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight*", Published in Solar Energy 85 (5) (2011), 757-768.

Window height (m)	1.0	1.5	2.0	1.0	1.5	2.0
Orientation	North			South		
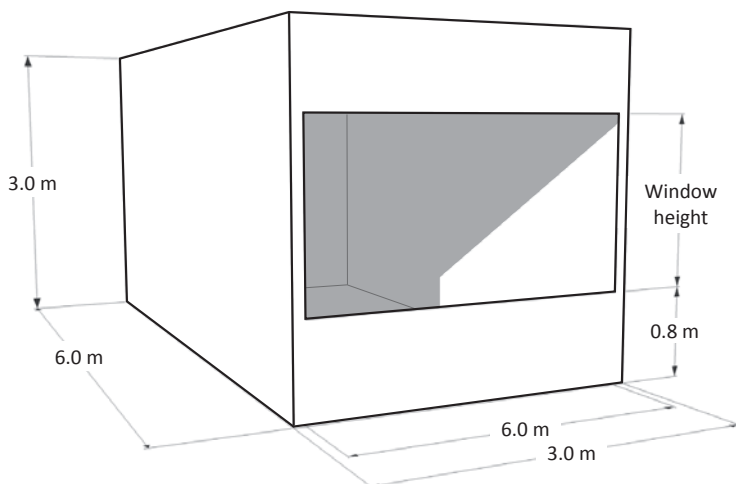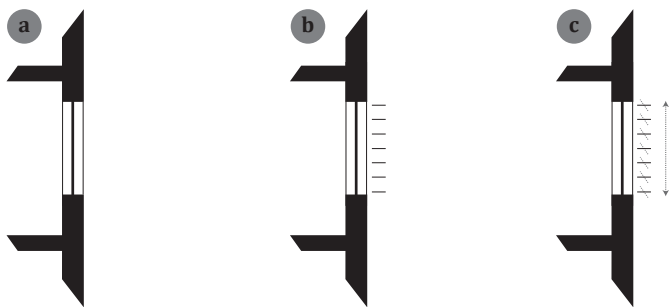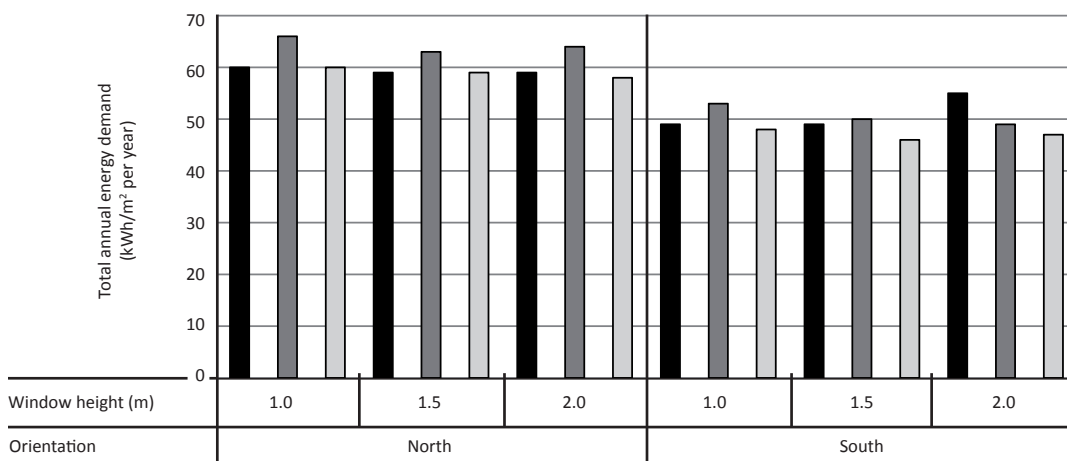
ing, cooling and artificial lighting), the indoor air quality, the amount of daylight available, and visual comfort into consideration are important to provide data that facilitates early design decisions with regard to the façade (Wilde & Voorden, 2004; Petersen & Svendsen, 2010).

To ease comparison the simulation was set up so that the indoor climate with respect to thermal environment and air quality would always fulfil Class II requirements according to European standard EN 15251:2007 (CEN, 2007). Subsequently, the energy used for heating, cooling and artificial lighting gives a clear indication of the façade's ability to control both internal and external impacts to maintain a good indoor climate. Energy performance was evaluated according to Danish building regulations for offices as annual energy demand per square metre (kWh/m² per year) for heating, cooling, ventilation, artificial lighting and domestic hot water using corresponding primary energy factors (EBST, 2006).

The study showed that dynamic solar shading in most cases constituted the best design alternative, but also that the dif-

1.0	1.5	2.0	1.0	1.5	2.0
	East			West	

■ No solar shading

■ Fixed solar shading

□ Dynamic solar shading
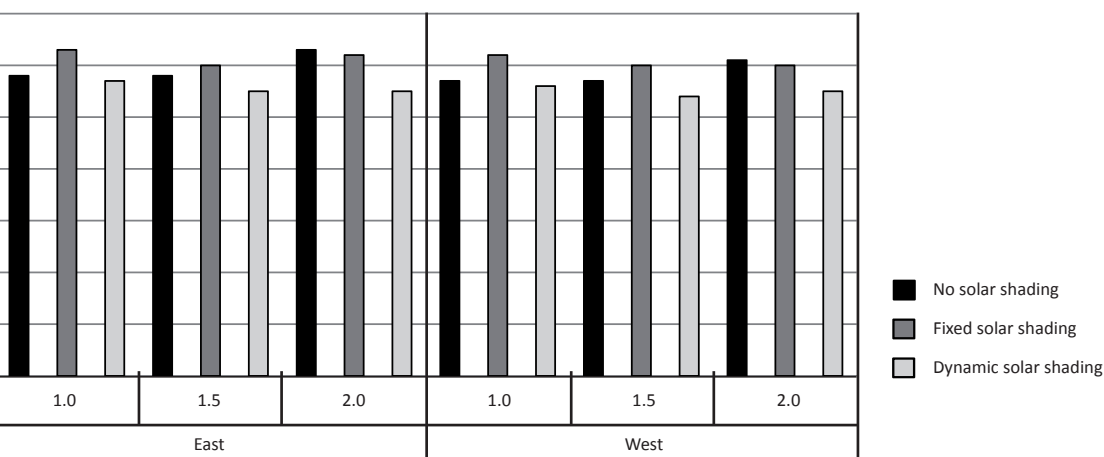
Figure 30. *Annual energy demand for simulated models depending on orientation, window height and solar shading types.*

ference in total energy demand between the best and the second best was minor nearing insignificant. Approximately 20% of the models resulted in an annual energy demand below 50 kWh/m^2 per year, while all simulation performed well below 70 kWh/m^2 per year which at the time of analysis indicated low-energy class I and II, respectively (Figure 30). Generally north-facing facades displayed the worst performance, east and west slightly better and south best.

Because air flow rates were determined in accordance with indoor air quality (number of occupants and floor area) as defined in the European standard (CEN, 2007), energy demands for ventilation and for domestic hot water were constant for all models corresponding to 13 kWh/m^2 per year and 5 kWh/m^2 per year, respectively. Subsequently the differences in total annual energy demand were caused by differences in the energy demand for heating, cooling and artificial lighting.

Considering the distribution energy needed for heating, cooling and artificial lighting dependent on orientation

Annual energy demand (kWh/m² per year)

50
45
40
35
30
25
20
15
10
5
0

Wind. height (m)	1.0	1.5	2.0	1.0	1.5	2.0	1.0	1.5	2.0	1.0	1.5	2.0	1.0	1.5	2.0	1.0	1.5	2.0
Solar shading	None			Fixed			Dynamic			None			Fixed			Dynamic		

■ Heating
□ Cooling
□ Artificial lighting
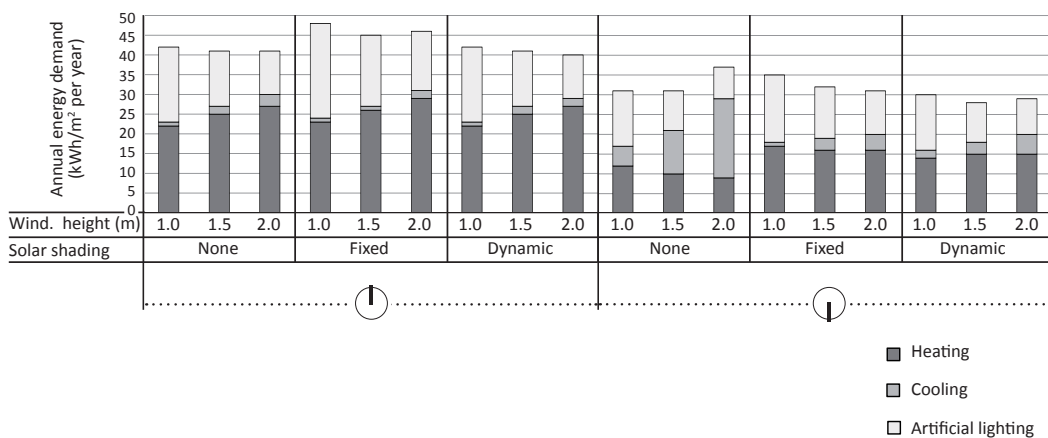
shows greater differences and conflicting tendencies (Figure 31 and Figure 32). Facades facing north, east and west have an increased heating demand when the window height (i.e. the façade transparency/window area) is increased due to the greater heat transmission through the glazed component than through the opaque parts. South-facing façades have a varying tendency depending on the solar shading types. For all models, the energy demand for artificial lighting decreases as the façade transparency and the insolation increases. The energy demand for cooling generally increases as the window height increases, but the increase is proportionally greater in the cases without solar shading for the orientations south, east and west.

When all models are considered, the difference in total annual energy demand between the worst and the best-performing façade for a given orientation does not exceed 16%. This makes façades with fixed or no solar shading relevant alternatives for not surprisingly all façades facing north, but also for façades with window heights of 1.0m or 1.5m facing south, east and west. Thus, the results indicate that the passive properties such as window sizes could beneficially be optimised as an alternative. Dynamic solar shading with its ability to reduce energy consumption and improve occupant comfort may therefore not always be the optimal choice

Figure 31. *Distribution of annual energy demand for heating, cooling and artificial lighting for simulation models with façades facing north and south.*
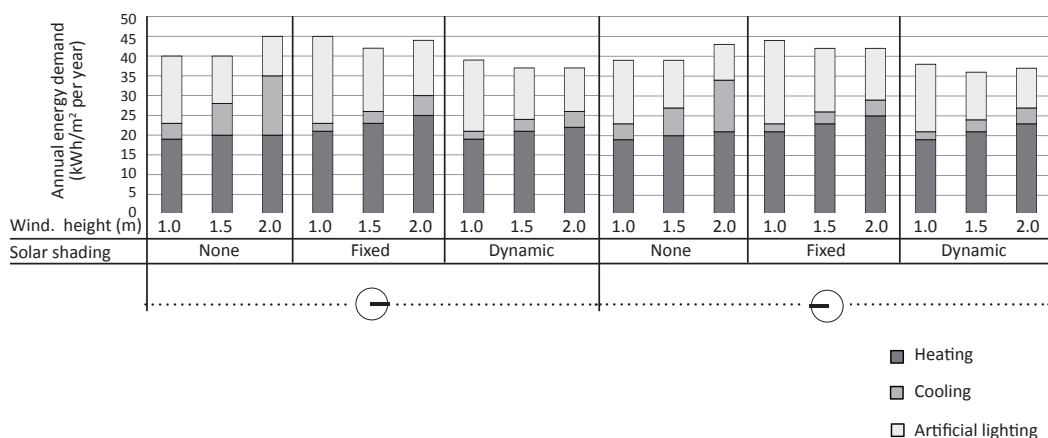
Figure 32. *Distribution of annual energy demand for heating, cooling and artificial lighting for simulation models with façades facing east and west.*

when economics (acquisition and maintenance) or subjective factors such as aesthetics are included.

It should however be noted that the increased daylight availability provided by a dynamic solar shading more adaptable to the climate, has the potential to provide a more flexible utilisation of the space and an increase in the amount of work stations. Further on this note, open plan offices with work stations far from the façade could benefit from a high façade transparency combined with a dynamic solar shading to obtain sufficient amounts of daylight without having problems with overheating, whereas fixed solar shading could be considered for a one or two-person office where work stations can be established close to the façade. This underlines the importance of performance quantification, especially on the early stages, so that the facade design can be better tailored to the actual building, its layout and its functions.

So how can these rather ambiguous results be used in the design of a facade? Focussing on an initial geometrical optimisation in terms of facade design, window size and aperture, orientation etc., to obtain a better agreement between form, function and the external climate before optimising the external dynamic solar shading accordingly, could be suitable.

Design development of a facade

-supporting an international top-level research environment

A case study with the aim to support the design development of *Niels Bohr Science Park* (NBSP) was carried out during the initial stages of design (paper III in appendix A)[6]. Focus was on a geometrical optimisation and the utilisation of the passive properties through the development of the architectural concept.

NBSP is a major new university building for the University of Copenhagen in Denmark and consists of two buildings joined by skywalks, located in the centre of the city, with approximately 46,500m2 in total floor area (Figure 33). The building is structure and organised with the intent to create a dynamic ans sustainable framework that unites people across interests and subjects, thoughts and cultures in an infinite forward-driven motion. Where inside and outside merge together to inscribe the building, its functions and the occupants within the surrounding society.

The building complex are to house five faculties; physics, chemistry, didactics, mathematics and computer science with a spatial programme that includes single offices, classrooms and auditoriums, meeting rooms, different types of laboratories and a wide range of support functions. The architectural concept does not only enable the *cross-polination* in between faculties and fields of research, but also provides a high degree of flexibility in terms of the spatial layout and system configurations, both very strongly emphasise in the competition brief in several instances (Figure 34).

Figure 33. *Site plan for the project illustrating the surroundings with the two building connected with skywalks. The largest building is the one considered while the minor building are to be constructed in the second phase.*

6 *"Simulation based design development of the facade for a new university building",* submitted to Solar Energy 2012.

STAGE 1

TEACHING

PHYSICS

CHEMISTRY

SCIENTIFIC
DIDACTIC

STAGE 2

TEACHING

MATHE-
MATICS

COMPUTER
SCIENCE

COMMON
AREA

ORGANISATION JOINS FUNCTIONS
TOGETHER

NO DEAD ENDS - FLEXIBILITY
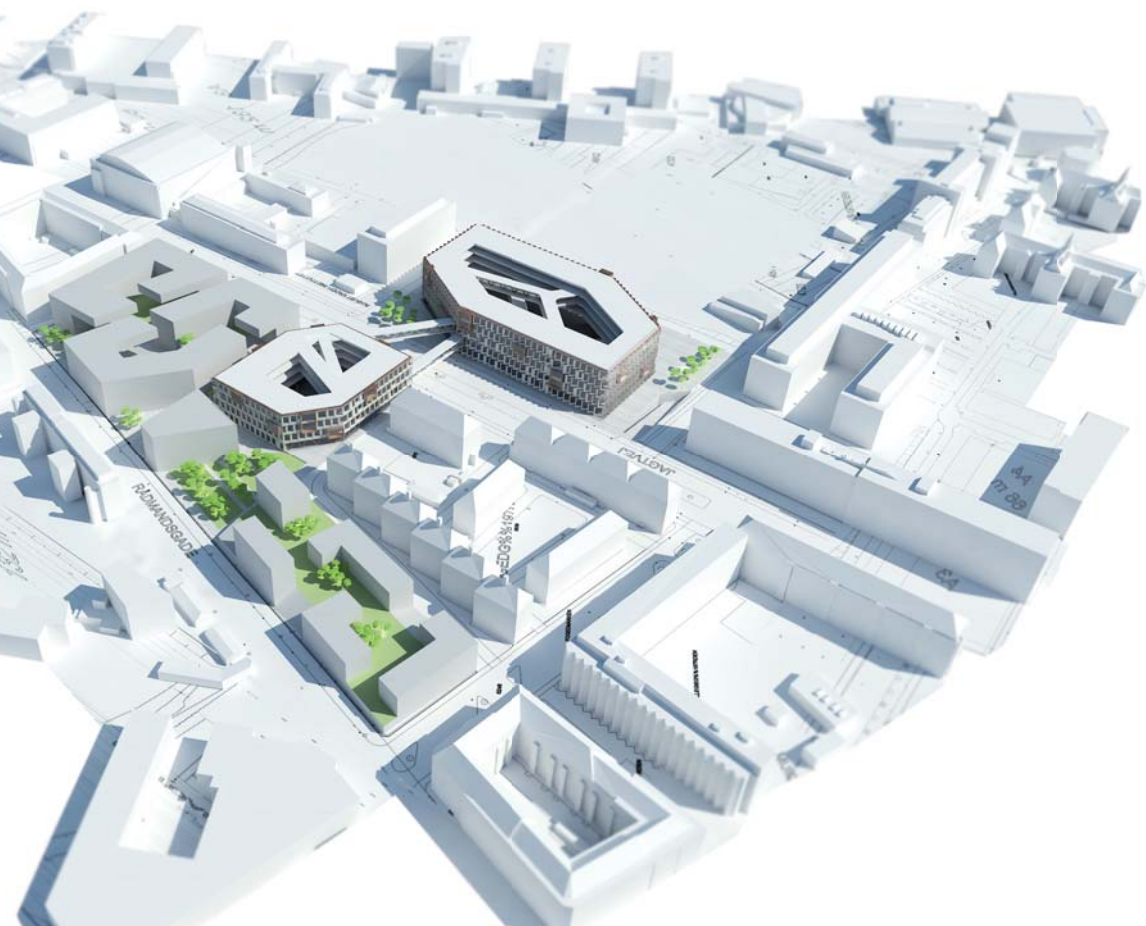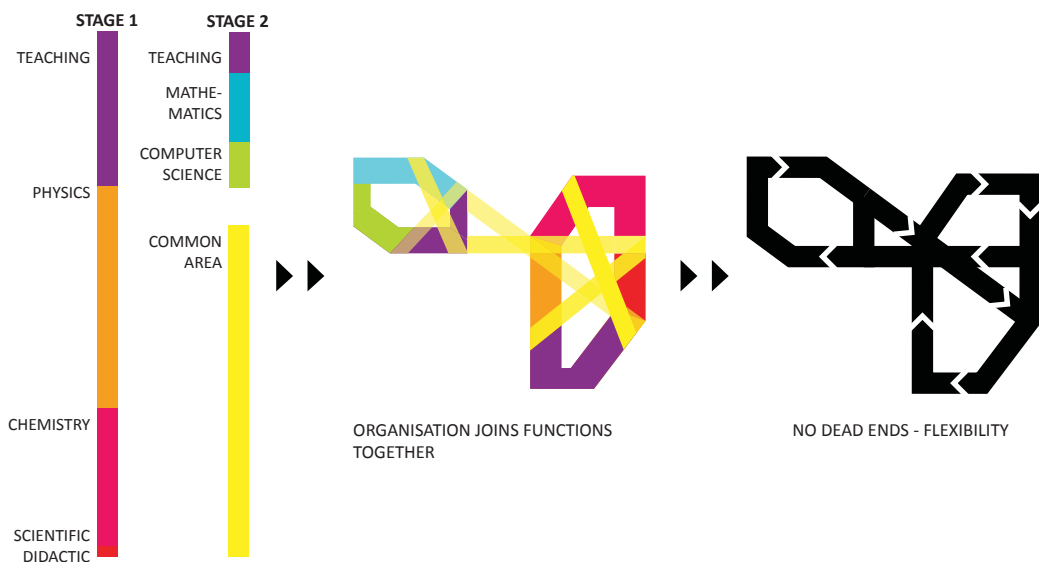
The project consists of two buildings constituting two stages of construction, where the largest building, with a total floor area of approximately 33,000m2 allocated on 6 storeys (incl. basement), and which are to be constructed first, is the main focus of the study. The building is organised around a relatively large central atrium extending from ground level throughout the full height of the building. This creates an unifying space that provide daylight centrally and from where the building and its flow is easily *readable* (Figure 35).

Simulations quantifying the facade's performance

The study presents integrated simulations carried out during an architectural competition process focussing on supporting the design development of the facade and encompasses work carried out from the very start of the project to the delivery of the final design proposal. The main objective was to develop a façade design that efficiently could control the solar radiation, uphold a satisfactory level of indoor climate, contribute to the reduction in energy demand and at the same time support and consolidate the architectural vision.

A wide range of the functions have highly specific performance demands outweighing all other considerations. Special facilities such as laboratories will often have shorter occupation periods for the single occupant, high air changes rates because of special ventilation requirements and limited needs or wishes for daylight. Two predominant functions and room typologies that are not governed by lopsidedness in terms of their performance requirements and therefore represent a design development where many interdependent parameters concerning energy and indoor climate are in play, were selected for analyses:

- Offices accommodating 2 persons (approx. 5,500m2) - 3 x 4 x 3.2 m high

Figure 34. *Illustration of the concept for the functional organisation.*

Figure 35. *Illustration of the interior atrium that provides the central part of the building with daylight and to a large degree defines the flow within the building.*

- Classrooms accommodating 30 persons (approx. 2,000m2) - 12 x 6 x 3.2 m high

The simulation models consisted of a single office and a classroom for each of the six facades (Figure 36). The approach was to procure design recommendations and evaluate the design proposition's effect on both offices and classrooms. The study presents a range of parameter analyses in relation to a three step design development of the facade:

Step 1. Facetting of the facade

Step 2. Optimising facade transparency and glazing type

Step 3. Implementation of dynamic solar shading

The evaluation of design alternatives was carried out for a set of performance indicators:

- Optimized utilisation of daylight (daylight autonomy)

- Annual demand for heating, cooling and lighting

- Peak heating and cooling load

To comply with the high degree of flexibility, single offices have to be able to be joined together to form open-plan offices, classrooms or laboratories and vice versa. To comply with this, the facade was considered to be a repetitive system of 3 meter wide and storey high modules. Thus, the facade for a single office (3 m wide) and a classroom (12 m wide) consists of one and four modules, respectively.

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Figure 36. *Illustration of how the facades are oriented and numbered. For each of the facades a simulation of both a single office and a classroom was performed.*
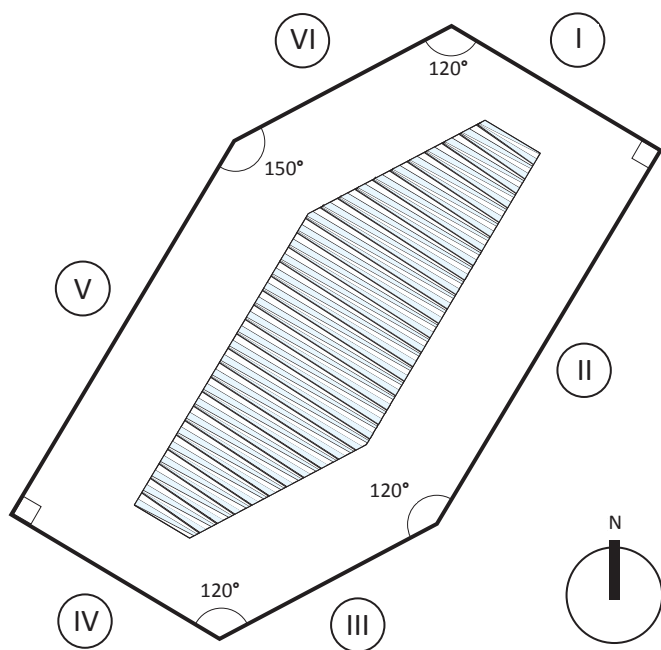
Step 1: Facetting the facade

A major part of the building's expression is defined by the facetted façade that is designed to emphasise the architectural concept which sought to optimise the visual and human interaction between inside and outside by utilising the lines of sight within the area. Figure 37 illustrates the geometrical processing of the overall building volume and the facade. Step 1 revolves around the facetting of the facade according to the four major orientations (North, South, East and West), secondly a displacement of the individual storey in relation to the one vertically adjacent. The facetting was investigated by comparing the plane facade to two different angling of the window while keeping the window size constant (Figure 38).

The purpose of these simulations was to determine the potential beneficial effect of the self-shading effect and change in window orientation caused by the facetting. Simulations was performed to quantify a suitable equilibrium in between the performance criteria; optimized utilisation of daylight, yearly demand for heating, cooling and lighting plus peak heating and cooling load.

Considering the influence of an increase in the degree of facetting on the total annual energy demand for heating, cooling and lighting, results showed a reduction for offices by 10-30% and classrooms by 15-30%, compared with the plane facades, except facade number V which displays a slight increase. Single offices displayed higher values compared with classrooms mainly caused by heating demand, but cooling demand was generally the dominating parameter for all models (Figure 39). The decrease in total annual energy demand is dominated by differences in cooling demand, which decreases as the degree of facetting increases.

The facetting also resulted in a significant reduction considering the peak load for cooling where offices displayed approximately a 20-40% reduction and classrooms 10-40% (Figure 40). However, the heating peak load increases as the degree of facetting was increased. Again results for facade V displayed opposite tendencies.

Figure 37. *Illustration of the steps in the geometrical processing, firstly of the building volume; a) utilising the lines of sight and optimising the relation and connection to the surroundings, and secondly of the facade; b) overall facetting according to the four major orientations (North, East, South and West) and c) horizontal displacement of the individual storey in relation to the vertically adjacent.*

Figure 38. *Illustration of the geometries used to analyse the influence of facade facetting on the performance in relation to energy and daylight; a) plane facade, b) 15° angling and c) 30° angling. Window sizes were kept constant for all simulation models.*

Figure 39. *Distribution of annual demand for heating, cooling and lighting for single offices and classrooms dependent on facade and the degree of facetting.*

Facetting (°)	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30
Facade	I			II			III			IV			V			VI			I			II			III			IV			V			VI		
Function	Office																		Classroom																	

■ Heating ■ Cooling ■ Artificial lighting

Facetting (°)	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30
Facade	I			II			III			IV			V			VI			I			II			III			IV			V			VI		
Function	Office																		Classroom																	

■ Heating   ■ Cooling   ■ Artificial lighting

0   10   20   30   40   50   60   70   80   90   100 %
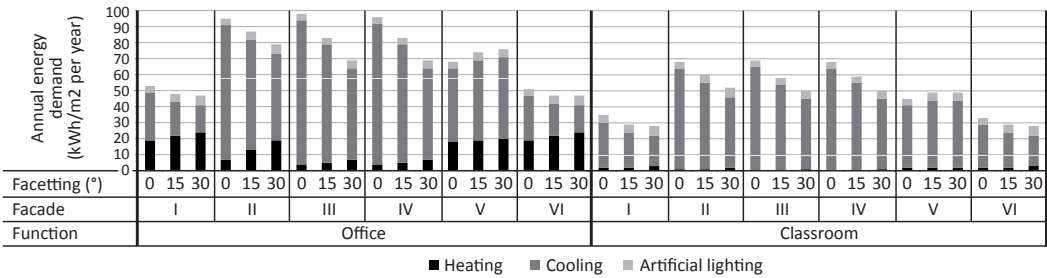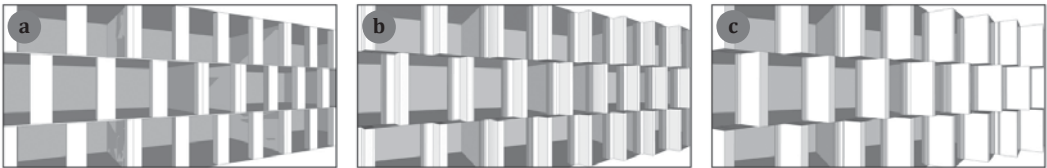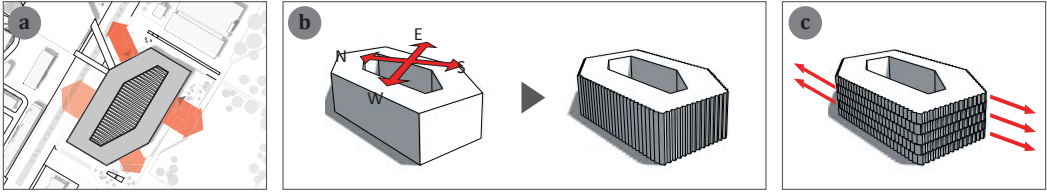
Figure 40. *Peak heating and cooling loads for single offices (left) and classrooms (right) dependent on facade and the degree of facetting*

In relation to daylight availability, simulations of the annual daylight autonomy were performed for offices adjacent to all six facades (Figure 41). Daylight autonomy results showed that increased facetting generally decreases the daylight availability, but only in the magnitude of 5-10%. Also considering the demand for lighting (controlled according to hourly daylight levels in the middle of the room) which only display minor differences in between the plane and facetted facade, the facetting was evaluated not to result in unacceptable reduction in daylight levels.

Results show that all facades except V performs significantly better in relation to the performance indicators at the highest degree of facetting (30° angling). Despite the fact that the facetting resulted in a decrease in energy performance for facade V, the maximum degree of facetting was selected to also maintain a unified aesthetic appearance. On this basis the transparency and glazing type was further optimized individually for each of the six facades.

Step 2: Optimising transparency and thermal properties

The next step was the selection of an appropriate facade transparency and glazing type. Three facade transparencies and two glazing types were analysed and their performance evaluated. Considering perimeter spaces, focus was initially on procuring good thermal comfort close to the facade. Therefore analyses of the facade transparency's and glazing type's effect on the indoor thermal environment was performed to ensure that workstations could be placed directly adjacent to the facade without the occupant experiencing thermal discomfort and thus to fulfil the requirements for flexibility. This was done by analysing the *mean radiant temperature* (MRT) and *radiant temperature asymmetry* (RTA). None of the analysed cases reveal RTA-values above 10 °C which is the required threshold according to European standards (CEN, 2001).

Figure 41. *Daylight autonomy for single offices dependent on facade and the degree of facetting.*

Results for the parameter variation of facade transparencies and glazing type generally show similar tendencies as those displayed in the investigation of the degree of faceting where facades equally oriented perform similarly (see also Figure 36). For all models a reduction in window size reduces the total annual energy demand for heating, cooling and lighting and the same was the case when selecting glazing number 2 instead of glazing number 1. Here, the beneficial effects of selecting a more high performance glazing, in this case choosing type 2 instead of type 1, was most significant at the largest window sizes. Also, selecting glazing type 1 instead of type 2 translated into capital cost savings because of the lower price on windows with lower performance glazing.

The selection of appropriate facade transparencies and glazing types was made for each individual facade balancing the improvement in relation to the performance indicators and the facade's importance for visual interaction between the building, the occupants and the surroundings (Figure 37).

Facades I and VI in principle performs equal and display similar dependency on glazing type and window size (Figure 42), but while facade I was not important in the quest for visual interaction as it faced a fully opaque neighbouring gable, facade VI was very significant in this aspect because it faces the common entrance area towards the north. Therefore a window height of 2.2 m and glazing type 1 partly because the decreased window size will result in lesser benefit from a window with better thermal properties and partly to optimize daylight utilisation for the facade that resulted in the lowest values for daylight autonomy (see Figure 41). Facade VI was designed with a window height of 2.9 m and glazing type 2.

Facades II and V also displayed similar performances (Figure 43). For facade II it was deemed important to continue the window to floor level to maintain the line of sight between indoors and the common green area at ground level towards the east and therefore a window height of 2.9 m was selected. Because facade V partly faced other building facades relatively close by (horizontal lines of sight) and partly oriented

Figure 42. *Distribution of annual demand for heating, cooling and lighting for rooms adjacent to facade I and VI dependent on window size and glazing type.*

Figure 43. *Distribution of annual demand for heating, cooling and lighting for rooms adjacent to facade II and V dependent on window size and glazing type.*

Annual energy demand (kWh/m² per year)

Office / Classroom	O	C	O	C	O	C	O	C	O	C	O	C
Glazing type no.	1		2		1		2		1		2	
Window height (m)	2.2				2.6				2.9			

■ Heating ■ Cooling ■ Artificial lighting

Annual energy demand (kWh/m² per year)

Office / Classroom	O	C	O	C	O	C	O	C	O	C	O	C
Glazing type no.	1		2		1		2		1		2	
Window height (m)	2.2				2.6				2.9			

■ Heating ■ Cooling ■ Artificial lighting
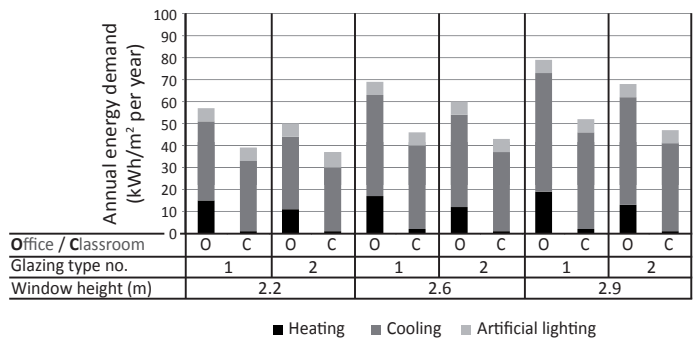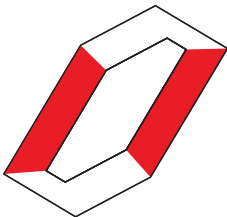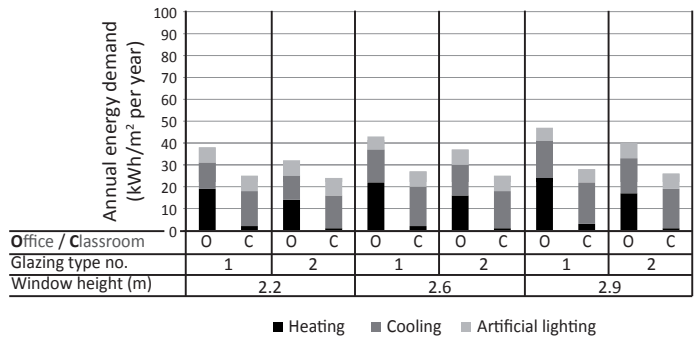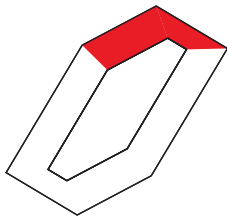
towards an arterial road (long lines of sight), window height was reduced to 2.6 m. Glazing type 2 was selected for both facades to reduce peak loads.

Facade III, mainly facing other buildings, and facade IV, having no great importance in the quest for visual connection (orientated towards an adjacent, fully opaque gable), also performed equally (Figure 44). Therefore façade III was designed with a window height of 2.6 m and glazing type 2 while a window height of 2.2 m and glazing type 1 was selected for facade IV.

The parameter variations of glazing type and window sizes generally showed similar effect on and tendency for peak loads as in the case of annual energy demands (see paper III in appendix A).

Since the differences in window sizes occurred by introducing a spandrel in height by either 0.4m or 0.8m, the reduction in the daylight availability, simulated at work plane (0.85 m above floor level), was evaluated not to be significant.

Step 3: Implementation of dynamic solar shading

Facades with windows facing east (II), south (III and IV) and west (V), displayed the highest total annual energy demand for heating, cooling and lighting. Considering the allocation of the annual demands it was cooling that despite a lower heating demand for facades II through V, resulted in the increased total value. Also considering the peak cooling loads, facades II through V generally displayed the highest values. Therefore two types of external solar shading were analysed for theses facades; an adjustable and fully retractable venetian blind and a transparent fabric solar roller screen.

Results showed that a reduction in total annual demand for heating, cooling and artificial lightning and also peak loads could be achieved for both offices and classrooms when the solar shading was employed (Figure 45 and Figure 46).

Figure 44. *Distribution of annual demand for heating, cooling and lighting for rooms adjacent to facade III and IV dependent on window size and glazing type.*

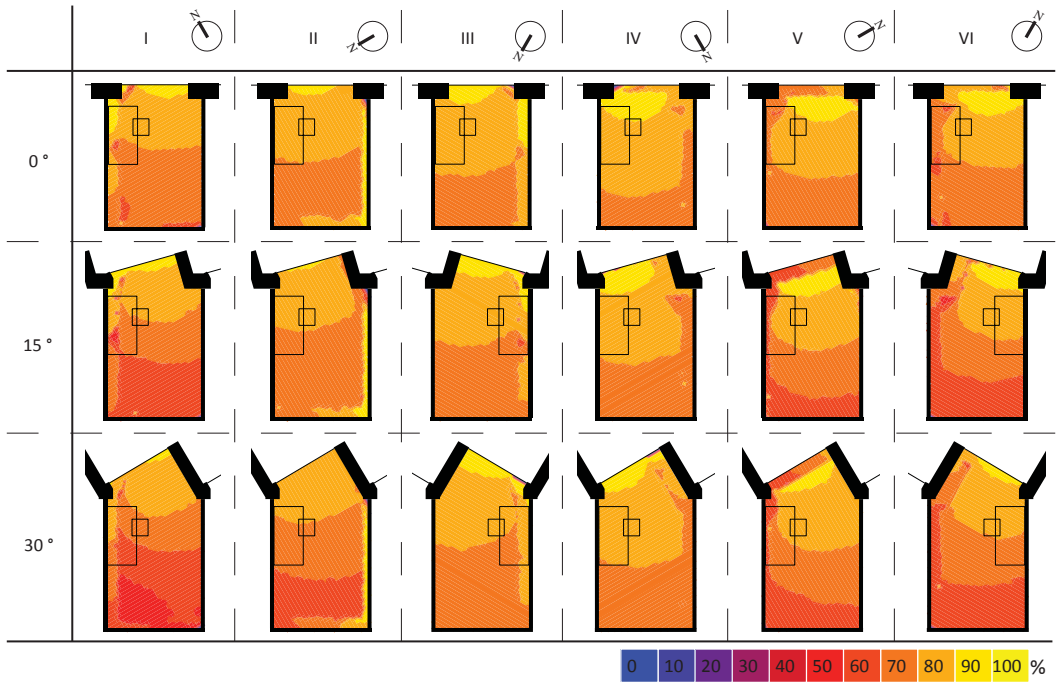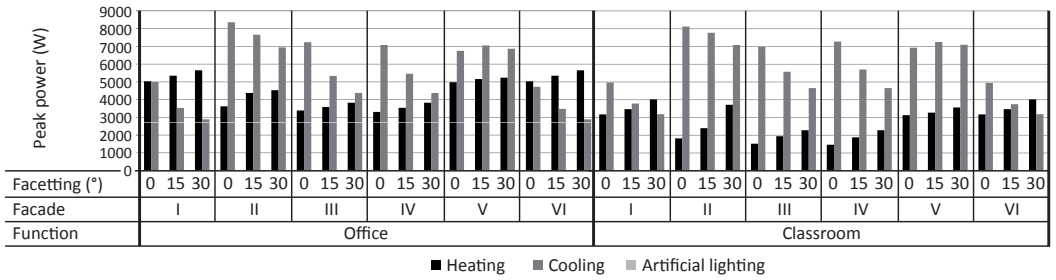**Figure 45.** *Distribution of annual demand for heating, cooling and lighting for offices and classrooms dependent on facade and the type of solar shading; None, venetian blinds (Ven.) or transparent fabric solar roller screens (Scr.).*

Figure 46. *Peak heating and cooling loads for offices and classrooms dependent on facade and the type of solar shading; None, venetian blinds (Ven.) or transparent fabric solar roller screens (Scr.).*

Annual energy demand (kWh/m² per year)

Office / Classroom	O	C	O	C	O	C	O	C	O	C	O	C
Glazing type no.	1		2		1		2		1		2	
Window height (m)	2.2				2.6				2.9			

■ Heating ■ Cooling ■ Artificial lighting

Annual energy demand (kWh/m2 per year)

Office / Classroom	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C
Shading type	None		Ven.		Scr.		None		Ven.		Scr.		None		Ven.		Scr.		None		Ven.		Scr.	
Facade	II						III						IV						V					

■ Heating ■ Cooling ■ Artificial lighting

Peak power (W)

Office / Classroom	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C
Shading type	None		Ven.		Scr.		None		Ven.		Scr.		None		Ven.		Scr.		None		Ven.		Scr.	
Facade	II						III						IV						V					
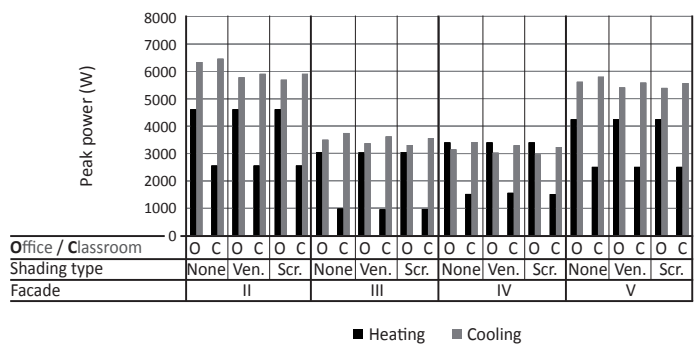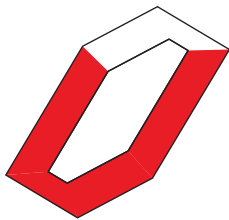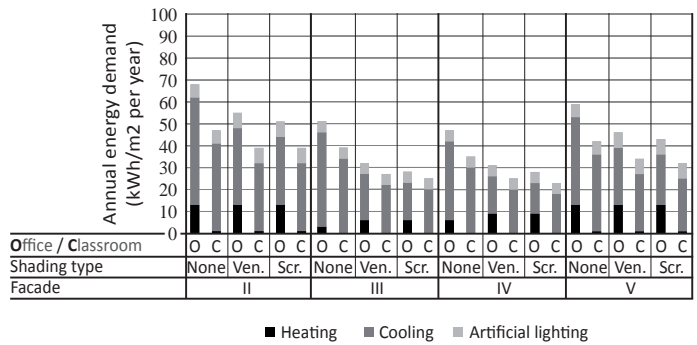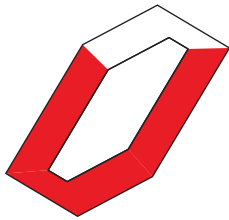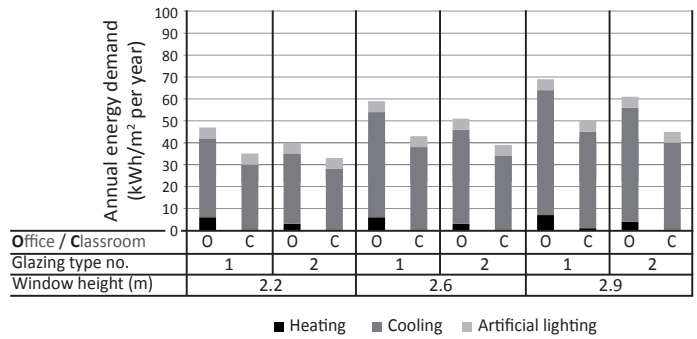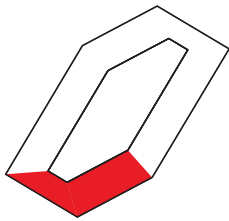
■ Heating ■ Cooling

The reduction was caused by a 30-60 % general reduction in annual cooling demand outweighing increases in the annual demand for lighting (facades II and V) and heating (facades III and V). Comparing the two types of solar shading, results show that the screen in relation to energy demand performed marginally better than the venetian blind caused by a higher reduction in the annual cooling demand and peak cooling loads. The transparent fabric screen was also deemed most appropriate to ensure the before mentioned visual connection between the building, its occupants and the surroundings, imperative to the concept behind the building. Furthermore, the screens provided a reduction in initial building cost compared to the venetian blind and were because of their ability to maintain a view to the outside even when fully activated, deemed less likely to result in manual overrides thus enabling a more optimal control.

The façade facetting underlined the architectural concept by orienting the windows towards one of the four major orientations, north, east, south and west, thereby optimising the visual interactioin with the surroundings. This provides an opportunity to optimize each facade individually, firstly through the transparency and glazing type, later the solar shading to the one predominant exposure of solar radiation occurring during occupancy. North facing facades (I and VI) could potentially receive direct solar radiation early in the morning and late in the afternoon during the summer period, but this will be shielded by the adjacent facade modules. East and west facing facades (II and V) are almost only exposed to direct solar radiation from low altitudes early in the morning or late in the afternoon, respectively. The rest of the occupied hours where solar radiation will come from a southern direction, the increased incidence angle will result in a reduced total solar energy coefficient (g-value) that shields out a large part of the direct solar radiation. South facing facades (III and IV) will mainly be exposed to direct solar radiation from high altitudes, which was reduced by the overhang created by the facetting and shielded towards east and west by the adjacent facade modules.

Figure 47. *Illustration of the concept behind varying the way the solar shading screen was activated according to the self shading the building provides dependent on orientation – a) east (facade II), b) south (facades III and IV) and c) west (facade V).*
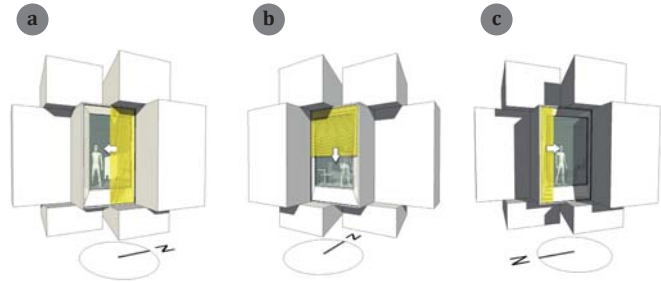
Facade transparencies and glazing types was optimized for each of the six facades according to their individual orientation and importance in relation to maintaining the visual link between the building, it occupants and the surroundings inherent in the architectural concept. Thus, facade transparencies were reduced where it was possible and the selection of glazing type based on optimal effect.

Finally, shading could be limited to the facades with the highest exposure to direct solar radiation and optimized to the predominant occurring exposure. Besides the difference in direct solar radiation caused by the orientation, the manner in which the screens were activated was optimised according to the self shading effect. Thereby the view to the outdoor environment could be optimised because the shading does not always have to be fully activated (Figure 47).

The study of NBSP shows how technical input regarding facade geometry, window orientation and size made it possible to navigate through the design development. Technically input supported the geometrical optimization that is an inherent part of the early conceptual stages of architectural design and brought both a drastic reduction in energy demand and a high level of indoor comfort while enhancing and consolidating the architectural concept (see illustration of final design on following page).

"Change of plans..."

In 2008 HLA won the competition for a new building, Kolding Campus, for the University of Southern Denmark (SDU). SDU is in the centre of Kolding, Denmark, close to the harbour, station and scenic attraction of the river. Involvement in the project as a part of the design team took place after the delivery of the conceptual design proposal.

Design proposal

The original design proposal is a geometrical optimisation of the overall form according to light, landscape and climate so it creates a north-facing recreational area towards the river with plenty of afternoon sun and shields off against the heavy traffic towards east. The distinct triangular shape represented in the overall form and as the central atrium, supports the flow, functional organisation and visual interaction with the context (Figure 48).

In relation to energy efficiency the form and orientation of as well the building and the atrium, was optimised according to the control of solar radiation often an issue in educational and institutional buildings. The objective was to create spaces obtaining sufficient amount of daylight while preventing overheating in order to reduce the energy demand for lighting and cooling. The three facades are oriented northeast, northwest and directly south. The concept was that the two facades facing northeast and northwest, would receive almost no direct solar radiation, whereas the one oriented directly south relatively easy could be shaded from the sun with a high incident angle (Figure 49). The facades was made up two layers; one functioning as the thermal separation between the inside and outside environment and one functioning as solar shading, separated by a 0.6 m maintenance bridge. The thermal separation consists of a 0.8 m parapet, a window band extending to the suspended ceiling and a top register allowing for natural ventilation entering the zone of

Figure 48. *The overall form of SDU is geometrically optimised according to light, landscape and climate, creating a north-facing recreational area towards the river with plenty of afternoon sun and shields off against the heavy traffic towards east. The distinct triangular shape and its central atrium supports the flow, functional organisation and visual interaction with the context.*

Figure 49. *The form and orientation of the building and the atrium was optimised according to the control of solar radiation in order to obtain sufficient amounts of daylight while preventing overheating.*

Baffle wall

North-east

South

North-west
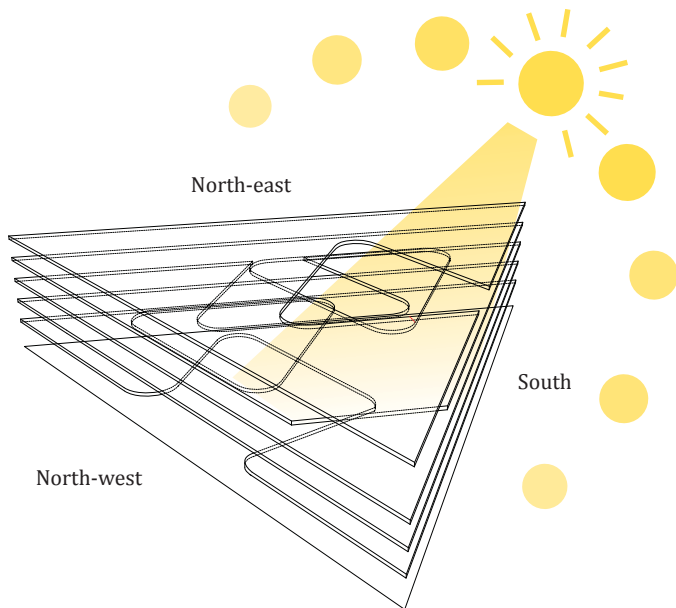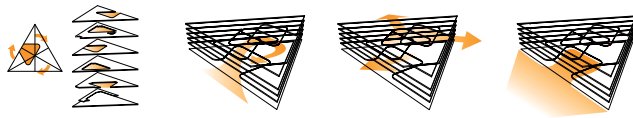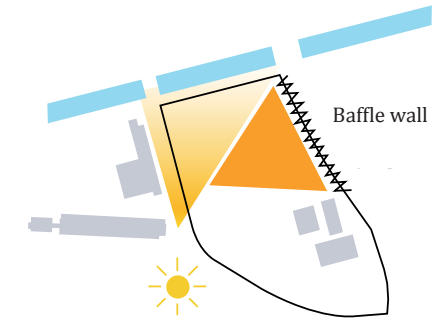
occupancy through perforated ceiling plates. The outer solar shading layer was essentially a screen in a triangular pattern wrapped around the entire building varying in depth; approximately 400 mm towards south and 200 mm at the other two facades (Figure 50).

The building's expression was to a large extend defined by the strong triangular shape represented in the overall form of the building as well as in the facade structure (see Figure 51). Subsequently, the triangular expression was after the competition, written into the district plan, making it a prerequisite for the following design development.
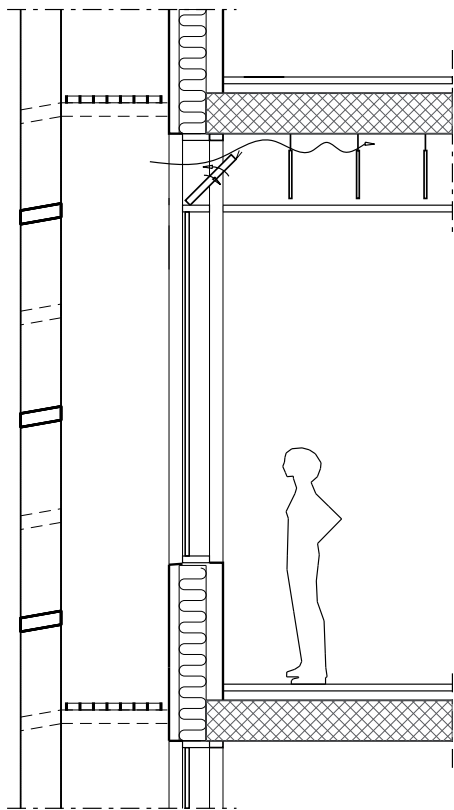
Figure 50. *Illustration of the facade for SDU made up of two layers; an outer solar shading screen in a triangular pattern and an inner traditional facade thermally separating the inside from the outside environment, separated by a maintenance bridge. The screen differentiates between the southern and the two other facades (northeast and northwest) by being 400mm and 200mm in depth, respectively.*

Figure 51. *Rendering of the competition design proposal for SDU viewed from the north-facing recreational area.*

Alterations

Relatively late in the design process (after the conceptual design phase) concerns was raised as to whether the facade design would be able to provide sufficient amounts of daylight. Daylight simulations in some cases showed problems with providing acceptable daylight levels for functions such as classrooms. Here the problems were most severe because of the high room depths and the reduction of daylight penetration caused by the fixed solar shading screen resulting in unacceptable daylight levels in the areas furthest from the facade. Thermal simulations also displayed overheating problems for some perimeter offices due to insufficient solar shading.

Because the triangular pattern had to be maintained (written into the district plan), a long and intense process where many different design alternatives for the facade were generated was performed. The design development was supported by annual hourly-based thermal and daylight simulations combined with detailed simulations of the glare issues in relation to the surfaces of the external solar shading. Among other test cases the solar shading was dramatically reduced in depth to mere mullions representing the triangular pattern on the facade.

The solution, based on general performance (including economical considerations) was to redesign the outer solar shading layer of the facade to be made of 1.5 m wide and storey-high, vertical, triangular louvers in perforated metal (Figure 52). One of the daylight simulations shows values well above the minimum requirement of 2 % (EBST, 2010) at all work stations within a classroom (Figure 53). They can be automatically and manually operated to dynamically control the solar radiation by pivoting creating a unique and varying expression of the facade illustrating how the climate affects the building and the function behind (see next page for rendering of final design proposition).

Besides the geometrical optimisation of the building and the facade, a series of energy efficient measures has also been

Figure 52. *Illustration of the storey-high triangular louvers for SDU to de made in perforated metal.*
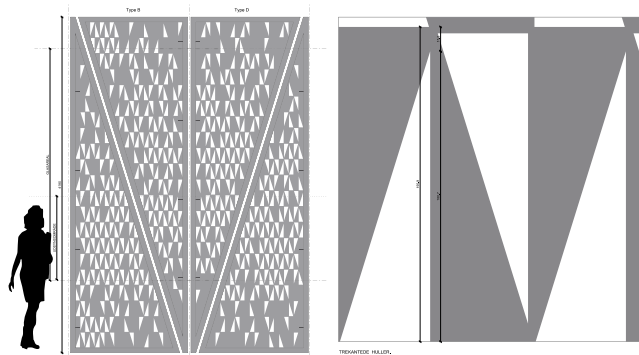
Figure 53. *Simulation of the daylight factor for one of the class rooms with high room depth with the final facade design displaying values above 2 % indicated as minimum requirement in the Danish building regulations (EBST, 2010).*
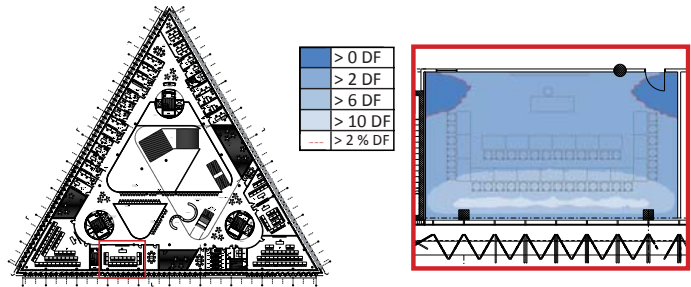
incorporated. Some of the elements incorporated in the final design are new concrete slaps with larger surface area to fully utilise thermal mass in connection to the low pressure ventilation through perforated ceilings (test case), groundwater cooling, solar cells, solar panels and the use of vacuum insulated panels in the facade.

The building will become the first large educational building in Denmark in low-energy class 2015 according to Danish building regulations (EBST, 2010). This means an energy demand below 41 kWh/m2 a year – or approx. 40 % below minimum requirement. The construction phase is assumed to start in 2012 and, in 2013, the building is expected to be completed and ready for inauguration (see illustration of final design on following page).

Lessons learned

The study shows how important it is to understand the façade typology if the aim is to achieve true architecture as a measure of a more holistic performance optimisation, combining function, aesthetics, energy efficiency, comfort, etc.. Because the façade is a central element in a building's architectural expression, there is great potential in translating the specific performance metrics, in terms of energy efficiency and indoor climate, into design facilitating input.

Solar shading was often a bone of contention in many of the affiliated projects. So, while dynamic solar shading has potential in terms of annual energy demand, parameter studies show that when compared with design alternatives, there is equally great potential in considering the passive, geometric properties of façade design. A geometrical optimisation of the façade design is also easier to integrate in the architectural concept in the critical early stages of design, because it is among the considerations taking place at this time. This includes the utilisation of the self-shading effect of the surroundings, the overall building form and façade, and the orientation and design of the window apertures. So, by entering what is usually regarded as the architectural realm, engineers can facilitate interdisciplinary collaboration.

While it can be difficult to deduce generic design recommendations, and perhaps also irrelevant since the design development of every project should be based on the specific requirements and context, the case studies can be seen as representing a potentially appropriate approach to building design. The hierarchy in supporting and quantifying the geometrical optimisation essential in the development of the architectural concept from the very beginning has the potential to achieve a more robust design proposition whose sheer form provides an energy demand well below the legal requirements.

In the case of the Niels Bohr Science Park, a geometrical optimisation of the building, its overall form, and the façade

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First we shape our buildings, then they shape us

Winston Churchill

achieved by translating the vision into performance requirements, resulted in a building design that utilises the passive properties. The geometrical processing of the façade design, was also driven by considerations about energy and indoor climate, and generated a facetting that supported a cardinal point of the architectural strategy: an enhanced connection to the surroundings. At the same time it was part of a highly complex competition brief that took into consideration parameters such as pedagogy, a very high degree of flexibility, the infrastructural situation, and the adaptation of the building into a highly urban context from both a present and a future perspective.

While the project at the University of Southern Denmark (SDU) may have ended rather well, it is an example of initially not fully understanding the façade's typology and its role for the building's performance. The lack of qualified support in the initial stages of design, in this case mainly caused by engineers failing to provide and communicate quantifiable performance evaluations, meant that critical issues which might have enabled a benchmarking of design alternatives were not identified. Instead great effort went into a façade design that did not meet the performance requirements, which subsequently resulted in extra time being spent on design alterations. That being said, SDU also indicates great effort and willingness on the part of the architects to process new information and essentially try to discover the design potential in dynamic solar shading. The result was a façade that maintained the strong triangular reference while meeting high performance requirement.

The study showed how understanding the façade typology can generate more holistic design recommendations that are not governed by lopsidedness with focus only on optimal performance in terms of energy demand. It places façade design in a design context in which an almost infinite number of design parameters have to be considered - a complex situation, but one in which both the scientific analyses and the affiliated projects emphasise that understanding of performance must depend on the building's function and, most essentially, the occupant's perception of comfort.

|04|
comfort

Comfort

The way we design our building directly influences the way in which we live our lives and can direct and manipulate the way in which we engage with our surroundings. This means that the balance between occupant and architecture is in a constant state of flux, that buildings and people continuously evolve together, and that new buildings are built and existing buildings renovated and reshaped to facilitate a new set of functions and subsequently to support our social development.

Providing shelter is the most basic requirement for the built environment, so a building enters into an "agreement" with its occupants, not only indirectly through energy demands and subsequent operational costs, but very directly and immediately in the sense of comfort. In this way the metabolisms of the building and of its occupants are closely related and need to be attuned. So it is critical to understand that occupants interact with the building from a comfort point of view.

The notion of comfort is not easily fully defined and can include not only physical but also psychological aspects and influences, and again it is shaped by an infinite number of parameters. This research accepted the complexity, but sought to place the concept of indoor climate in the bigger picture.

According to the World Health Organisation (WHO), indoor climate can be classified into five categories: thermal, atmospheric, acoustic, visual and mechanical. Since the quality of the thermal, atmospheric and visual indoor climate basically define a building's energy demand (heating, cooling, ventilation and lighting), understanding these parameters and how they are perceived, holds the key to tackling the energy issue. So, in terms of comfort, the façade again plays a very central role because it essentially provides the shelter, but also gives

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If you strip away all the ego and all the design theo-ry and all the hype, all we do is provide shelter and if you can't do that you can't call yourself an architect.

Cameron Sinclair

an opportunity for interaction with the external environment. This happens very directly by means of opening windows, activating solar shading or glare protection, enabling natural ventilation/venting, but also indirectly by the way the façade processes the outdoor climate and affects the control of the HVAC system (see also the paragraph *Typology*).

Many buildings have been tested for energy efficiency during design development, but measurements after construction often show a very different picture. This is often attributed to the buildings not being operated properly or differences between simulated and actual user patterns, but the question remains: Do we as designers fail to understand what drives occupant behaviour?

When we assess the performance of a building or a façade design, indoor climate and energy demand are closely related. So, the input parameters for the energy simulations are defined by the level of indoor climate required (CEN, 2007). The approach is to define the quality of the indoor environment by evaluating the ability of the individual parameters to stay within universally, predefined intervals, i.e. their ability to achieve a climate that is as uniform as possible. In this context, comfort is very much defined as the *lack of discomfort* in the sense that for example the temperature is within the *comfort range*, if an acceptably small number of people are dissatisfied. This is an evaluation that promotes uniformity and to some extent disregards the context in terms of the outdoor environment and how it influences the perception of comfort, cultural differences, adapting and acclimatising to reoccurrences, etc.

A lot of human beings take pleasure in a *photon shower*, i.e. staying in the sizzling heat of the direct sun even when it clearly exceeds the defined comfort range. Similarly, studies show that although perimeter work stations are governed by highly fluctuating conditions in terms of temperature, draught, daylight and glare, occupants prefer these places (SBI, 1999). The same study shows that occupants also prefer direct daylight entering the working environment, despite the discomfort that can follow. The thermal indoor en-

vironment will essentially be determined by the presence of occupants, equipment, and solar radiation in terms of direct, diffuse and also daylight. Consequently, the thermal indoor environment will determine the usability of the space in relation to a given function and its ability to procure an appropriate working or living environment for the occupants.

Understanding the human perception of comfort and what influences it is essential when designing buildings. Why do we take pleasure in a photon shower by staying in the sizzling heat of the direct sun despite that it clearly exceeds the defined comfort range?

Thermal indoor climate

The quantification of thermal comfort represented by the *Predicted Mean Vote* (PMV) model (Fanger, O.P., 1970) is widely accepted as an indicator for indoor environmental quality, and most building simulation programs provide output from which it can be evaluated. However, this model, which is used in the development of many building designs, bases its evaluation of thermal comfort on steady-state and uniform conditions and fails to fully include the asymmetrical and highly transient character of the thermal environments designed and occupied (Cheng et al., 2011). Examples of such conditions are difference in surface temperatures between interior walls and windows in a room and highly fluctuating insolation, especially for work stations in a building's perimeter zone (Tzempelikos et al., 2010).

Hoes et al. (2009) conducted a simulation study on the effects of occupant behaviour on the simulated energy performance of buildings and concluded that the simple approach used nowadays for design assessments applying numerical tools is inadequate for buildings that have close interactions with the occupants. But should not buildings and occupants always interact and be able to adapt to one another?

The adaptive approach

First proposed in the 1970s in reaction to the scarcity of available oil (Brager & de Dear, 1998), the adaptive comfort approach is based on a more flexible principle:

If change occurs such as to produce discomfort, people react in ways which tend to restore their comfort (Nicol & Humphreys, 2002).

The adaptive approach thus links the occupant and the comfort temperature range to the actual situation and includes the transient character of the environment. Furthermore, it

is inherent in the adaptive comfort approach that occupants acclimatise to their environment over time and/or actively react and interact with the building and its services, affecting their sense of comfort. Significant overall energy savings have been ascribed to this adaptability due to the more relaxed temperature criteria (de Dear & Brager, 2001; Toftum et al., 2009), but recent work shows more conflicting tendencies and differences between the American and the European implementations of the adaptive comfort approach (Sourbron & Helsen, 2011). Moreover, Andersen (2009) applied the adaptive model to evaluate not only the energy performance of buildings, but also the mental performance of the occupants. Results showed that determining acceptable thermal conditions using the adaptive model had potential for significant energy savings and had only minor consequences for the mental performance of the occupants.

The adaptive approach represents an alternative to the traditional quest for thermal uniformity and environmental asymmetry has been shown to give more pleasure than the neutrality conventionally aimed at (Kuno, 1995; Arens et al., 2006b). Perhaps some thermal diversity should be considered a positive quality?

Evaluating thermal sensibility and comfort using the adaptive approach

The adaptive approach's inherent dependency on the context and the highly transient character of the outdoor climate was studied by analysing work stations in the perimeter zones dominated by highly fluctuating climate conditions (paper IV in appendix A)[7].

The study presents a quantification of the indoor thermal performance of various façade designs exposed to a transient outdoor environment including direct and diffuse solar radiation. It builds upon previous analyses comparing dynamic solar shading with the design alternatives: a façade with fixed solar shading and a façade with no solar shading (paper II in appendix A). Similarly, a range of window sizes were simulated for each of the solar shading types and all facade designs were evaluated for their effect on the indoor thermal environment. Since the occupant's response to a thermal environment cannot simply be considered on overall body level, but must include the sensations of individual parts of the body (Arens et al., 2006a) a highly detailed comfort model taking the non-uniform distribution of solar radiation within a room into account was used. Different façades will filter the external environment differently, and solar radiation in particular will result in highly non-uniform exposure of different parts of the body. This, coupled with the adaptive approach that links the comfort range to the actual environment and façade design, made it possible to obtain a precise representation of the façade's impact on the occupant's thermal sensibility and comfort.

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7   "*Quantifying the effect of solar shading types and window sizes in office buildings by evaluating thermal sensibility and comfort using the adaptive approach*", Submitted to Solar Energy 2012.

Description of the analyses

The analyses were based on the comprehensive UC Berkeley thermal comfort model (the UCB model) developed at the Center for the Built Environment, University of California, Berkeley (Huizenga et al., 2001). The UCB comfort model is based on the Stolwijk model (Stolwijk, 1966) and the work of Tanabe (Tanabe et al., 1995). The UCB model predicts the local thermal sensation and local thermal comfort of various parts of the body (Zhang et al., 2010a-b), as well as the whole-body thermal sensation and overall comfort, as a result of the local impacts (Zhang et al., 2010c). The model is based on an extensive set of climate-chamber tests that established a relationship between the overall human thermal response (sensation and comfort) and the local skin temperature of the individual parts of the body. The thermal sensation and thermal comfort of both the individual parts of the body and the whole body were indicated on a scale ranging from -4 being "very cold" to 4 being "very hot" for the thermal sensation and from "very comfortable" to "very uncomfortable" for the thermal comfort (Figure 54).

Each simulation represented a 3x3x6m (width x height x depth) perimeter office facing south with two occupants. The thermal sensation and comfort are only considered for the
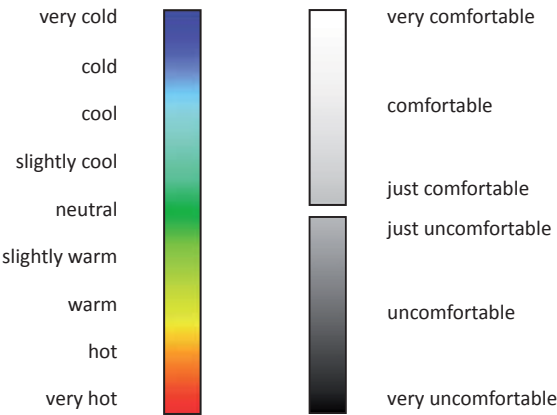
Figure 54. *Scales used to indicate the quality of the indoor thermal environment for both the whole body and individual parts of the body in terms of thermal sensation (left) and thermal comfort (right).*
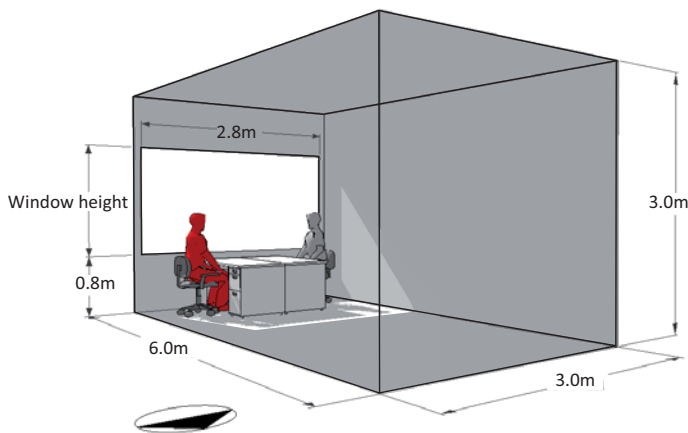
Figure 55. *Geometry of the two-person office with the placement of both occupants (the one considered facing west) and the window centred in relation to the room width and an offset of 0.1m on each side. The window height was defined from a window parapet with a fixed height of 0.8m.*

Labels in figure: Window height, 0.8m, 2.8m, 6.0m, 3.0m, 3.0m

occupant seated facing west (Figure 55). The non-uniform exposure of individual parts of the occupant's body as a consequence of the façade design was simulated by employing a virtual thermal mannequin consisting of 16 different body segments[8]. All façade designs were simulated for clear and cloudy sky conditions for both summer and winter under Danish climate conditions (Figure 56). The transient character of both the indoor and outdoor climate, clothing and metabolic conditions, was modelled, and the UCB model predicts the occupant's response.

As in the earlier study (paper II in appendix A), set points for heating and air flow rates for mechanical ventilation corresponded with the requirements for Class II in the European standard (CEN, 2007). Problems with overheating outside the heating season could be mitigated with the occupant interacting with the façade by opening windows, an inherent part of the adaptive principle.

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8   Head, Chest, Back, Pelvis, Left upper arm, Right upper arm, Left lower arm, Right lower arm, Left hand, Right hand, Left thigh, Right thigh, Left leg, Right leg, Left foot and Right foot.

Figure 56. *Climatic data from the design reference year (DRY) for representative a) summer days and b) winter days (Copenhagen, Denmark) used in the simulation. The direct solar radiation equals zero throughout the day under cloudy conditions.*
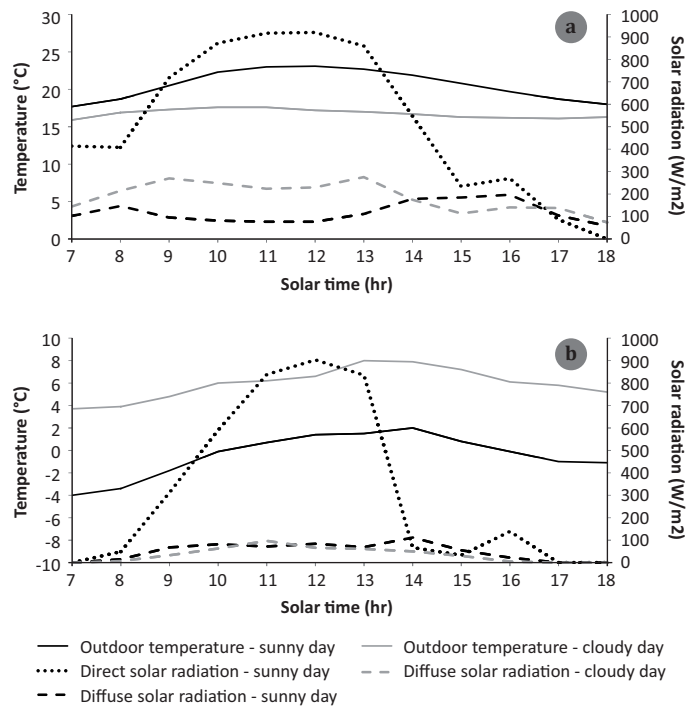
Results

To demonstrate the importance of the façade design and how it affects the indoor thermal environment, comparative results for a range of parameter variations was presented and analysed on the basis of the following parameters: the solar radiation transmitted over the course of a working day, the operative temperature, the interior surface temperature of the window pane, and finally the indoor thermal sensation and comfort of the occupant. Here, focus is on presenting the results illustrating the whole-body thermal sensation and the overall thermal comfort of the occupant simulated using the UCB comfort model. Additional results can be viewed in paper IV (appendix A).

In general the results for the thermal sensation and the ther-

mal comfort of the occupant were dependent on the outdoor climate (Figure 56 and Figure 57) and the façade designs ability to control how much solar radiation was transmitted. Thus, summer displayed higher temperatures compared to winter and sunny conditions higher solar radiation values and temperature fluctuations than cloudy conditions.

Considering the differences in between solar shading under sunny conditions, façades with no solar shading clearly allow the highest amount of solar radiation to be transmitted, whereas façades with fixed and dynamic solar shading showed similarly reductions in peak values. For façades with dynamic solar shading the activation was dependent on window size and also showed differences in between sunny and cloudy conditions. The differences in transmitted solar radiation and the outdoor air temperature resulted in significant differences between sunny and cloudy conditions in terms of more fluctuating temperatures. This was especially caused by the significant direct component present under sunny conditions which simultaneously could be controlled by means of solar shading.

Summer

Summer conditions entail a high total solar radiation values combined high outdoor air temperatures. On the other hand, the high altitude of the sun, especially for the south-facing office considered, results in the occupant's projected area being smaller, thus less exposure to solar radiation.

The increased solar radiation transmitted under sunny summer conditions when outdoor temperatures are relatively high caused a warmer sensation and a decrease in overall comfort. Thus, the majority of the simulated models under sunny summer conditions showed that the whole-body thermal sensation and the overall comfort (Figure 57) develop from near-neutral conditions when the working day starts and reach peak values between 2 and 4 (positive values for thermal sensation and negative for comfort) around 14 hours. All models result in higher thermal sensation at the

Figure 57. *Whole-body thermal sensation (a) and comfort (b) under sunny summer conditions.*
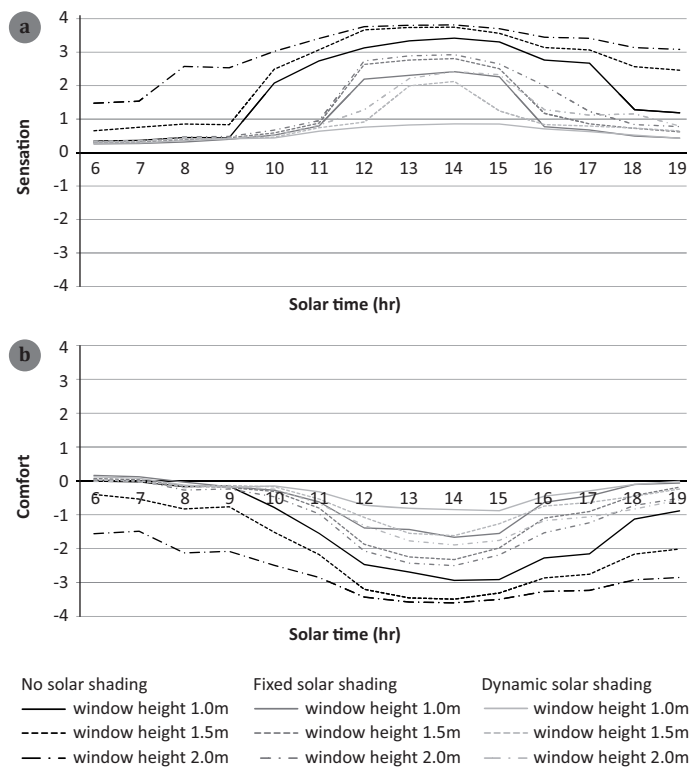
No solar shading
— window height 1.0m
----- window height 1.5m
— · – window height 2.0m

Fixed solar shading
— window height 1.0m
----- window height 1.5m
— · – window height 2.0m

Dynamic solar shading
— window height 1.0m
----- window height 1.5m
— · – window height 2.0m

end of the working day, but the extent of the increase depends on the window size and solar shading type as in the case of peak values.

The increase in thermal sensation and the decrease in comfort were most significant for the façades with no solar shading, less for the façades with fixed solar shading, and least for the façades with dynamic solar shading. Furthermore, an increase in window height and consequently a higher exposure to insolation resulted in an increase in thermal sensation and subsequently thermal comfort.

Cloudy summer conditions resulted in a significantly more stable tendency for whole-body thermal sensation and

overall comfort (Figure 58), cf. the results for transmitted solar radiation and operative temperatures. Almost all models show a similar performance with an overall thermal sensation around 0.5, while overall comfort levels are around neutral. However, the case with no solar shading and a window height of 2.0m results in noticeably higher thermal sensation and consequently a lower comfort level.

Winter

Winter represents a more complex situation than summer because of contrasting thermal interactions, caused by greater differences between outdoor and indoor temperatures,

No solar shading	Fixed solar shading	Dynamic solar shading
—— window height 1.0m	—— window height 1.0m	—— window height 1.0m
- - - - window height 1.5m	- - - - window height 1.5m	- - - - window height 1.5m
— · — window height 2.0m	— · — window height 2.0m	— · — window height 2.0m
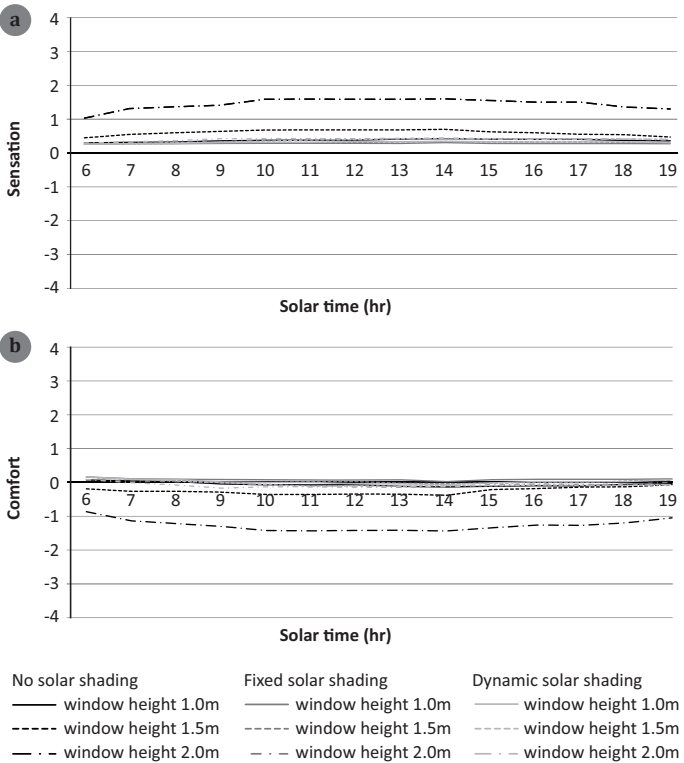
Figure 58. *Whole-body thermal sensation (a) and comfort (b) under cloudy summer conditions.*

which potentially are combined with a high level of solar radiation in the case of clear-sky sunny conditions.

The whole-body thermal sensation under sunny winter conditions starts at negative levels of around -2 at the start of the working day, decreasing further to approximately -3, and then increases to peak levels of between 2 and 3 around noon (Figure 59a). The overall comfort level under sunny winter conditions (Figure 59b) follows the pattern and levels of the whole-body thermal sensation during the first part of the day, initially decreasing slightly and then increasing, but as the thermal sensation reaches neutral levels the comfort level stagnates or decreases. The level of decrease depends on the solar shading type, decreasing most significantly for
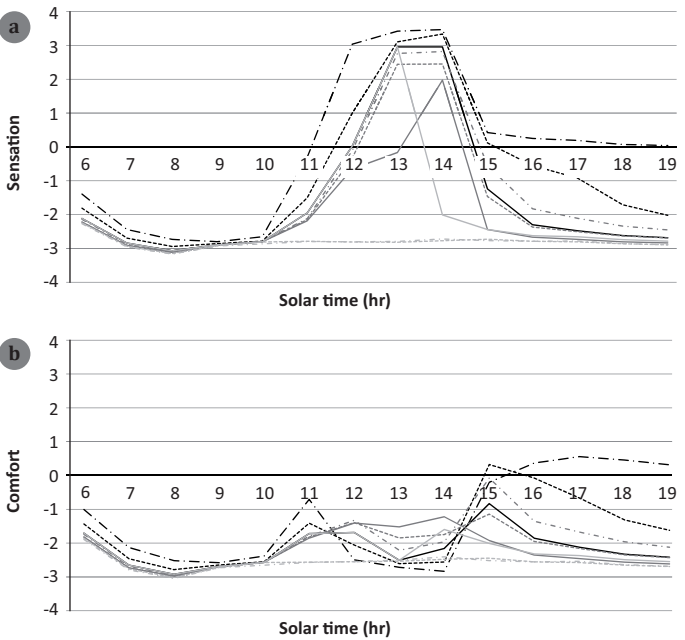
Figure 59. *Whole-body thermal sensation (a) and comfort (b) under sunny winter conditions.*

No solar shading	Fixed solar shading	Dynamic solar shading
window height 1.0m	window height 1.0m	window height 1.0m
window height 1.5m	window height 1.5m	window height 1.5m
window height 2.0m	window height 2.0m	window height 2.0m

façades with no solar shading, less for façades with fixed solar shading, and least for façades with dynamic solar shading. Furthermore an increase in window height also results in a decrease in overall comfort level. All models result in higher whole-body thermal sensation and overall comfort levels at the end of the working day than when the working day starts, most significantly for façades with no solar shading, less for façades with fixed solar shading, and only an minor increase for façades with dynamic solar shading.

Cloudy winter conditions, like cloudy summer conditions, result in a significantly more stable development in whole-body thermal sensation and overall comfort (Figure 60). All models basically show identical performances with overall thermal sensation levels dropping from approximately -2 to

No solar shading
——— window height 1.0m
- - - - window height 1.5m
— · — window height 2.0m

Fixed solar shading
——— window height 1.0m
- - - - window height 1.5m
— · — window height 2.0m

Dynamic solar shading
——— window height 1.0m
- - - - window height 1.5m
— · — window height 2.0m
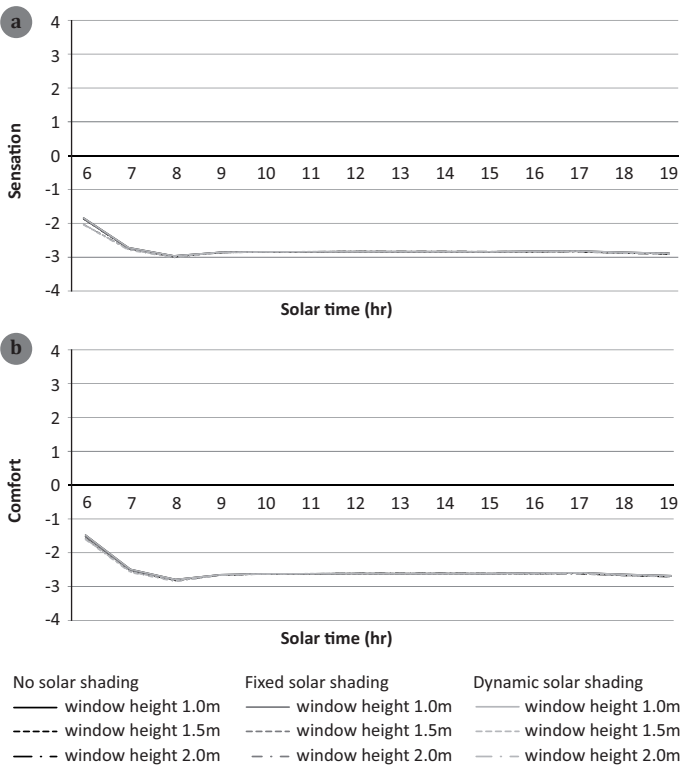
Figure 60. *Whole-body thermal sensation (a) and comfort (b) under cloudy winter conditions.*

a stable level just above -3. Moreover, the overall comfort levels are equal for all models and display similar tendencies to those of the overall thermal sensation, but with slightly less negative values.

The study illustrates the importance of the façade design in relation to the thermal indoor environment and how each layer of the fenestration system and the façade as a whole "filters" the outdoor environment.

In general, the façades with dynamic solar shading displayed the best performance throughout the study, but only by a small margin when compared to façades with fixed solar shading and façades with no solar shading. Despite a very significant difference in transmitted solar radiation between facades with different solar shading types, window height seemed to be of equal importance to thermal comfort. The superior performance of the dynamic solar shading was most clear under sunny conditions when high levels of solar radiation are transmitted, but in the winter this tendency is less significant. The seasonal difference between summer and winter and the difference between sunny and cloudy conditions revealed the importance of solar radiation and especially the direct component. During summer where high outdoor temperature occurred the transmitted solar radiation resulted in an unbeneficial overheating effect, whereas it during winter could constitute a beneficial heat gain. Under cloudy sky conditions, thermal sensation and comfort displayed only minor dependence on window height and solar shading type.

Thus, the results do not give a clear indication of an optimal solar shading type or window height out of those simulated. Increasing the thermal comfort of the occupant can be obtained by either window size, solar shading type or a combination. Façade design cannot be considered isolated, but is a central aspect in obtaining an equilibrium between functional requirements, energy efficiency and indoor climate and is very much driven by the outdoor climate and the relation with the occupants.

Comfort considerations as design input

In 2011 HLA was commissioned to design a new laboratory building in Denmark (design is ongoing and details concerning e.g. client and exact design, cannot be revealed). The building design is to represent a sustainable spearhead project for a dynamic and flexible take on the future research facility where;

"employees and students meet across areas of expertise in an experimental, cross-disciplinary and innovative environment that challenges conventional thinking where new ideas spur and scientific realisations develop."

(adopted form the building programme)

In terms of energy and indoor climate the project was pragmatically approached in an attempt to utilise the organisation of functions and their performance requirements to match the façade design with both internal and external impacts and the potential for occupants interacting with the facade.

The building enters into an existing context and has to connect to adjacent existing buildings (Figure 61). The gross floor area is approximately 5,500 m2 and the building is to house a series of different types of laboratories, traditional offices for 2-4 persons, temporary "touch-down" work spaces, a canteen, classrooms and a wide range of support functions. The building's focal point and most vital function is the research facilities which range from relatively open access and flexible laboratories for educational purposes to highly controlled GMO-laboratories with airlocks (GMO – Gene Modified Organisms).

The building is generally organised in three volumes connected by two atriums where each volume has a small, closed courtyard providing light centrally. This creates a logical division into smaller areas which are then organised according to function in plan and in section (Figure 62). The

Figure 61. *Site plan illustrating the buildings context and required connections to adjacent existing buildings.*

traditional offices with relatively low internal load are oriented towards the south on ground and first level where the highest solar heat gain will occur with reduced window sizes. In these smaller spaces where room depths do not exceed 4 meters, the 2-4 occupants can easily influence their own comfort by directly interacting with the façade by opening the windows or activating the externally mounted solar shading. Standard laboratories are placed towards the north where window areas can be increased to provide sufficient daylight for the deeper rooms without causing overheating problems. The GMO-facilities are mainly placed at the bottom floor below ground level since they already have high internal gains from equipment and require no daylight. The individual GMO-laboratories that are placed centrally at the middle level as closed boxes, provide surfaces that can direct daylight down through the courtyards. Centrally and adjacent to the courtyards are the laboratories used for educational purposes placed. With double room height they have access to the skylights and with internal glass walls to most adjacent rooms they function as a unifying space for each of

	Flexible laboratory
	Flexible offices
	Inflexible laboratory
	Common areas/group rooms
	Technique

the three *clusters* (see also Figure 63). Both standard and GMO-laboratories are fully mechanically controlled, but a special booking and control system also governing the fume cupboards enable the airflow to be efficiently adjusted acocording to the needs. The education laboratories are mostly mechanically controlled, but can in some cases utilise natural ventilation through skylights. The two atriums make use of passive solar heat gain and are naturally ventilated. The canteen and classrooms which momentarily have high internal loads are placed at the bottom floor utilising the grounds thermal mass, shieled from too much direct solar radiation, but still has daylight access.

The project has an annual energy demand equal to 41 kWh/m^2 (including 75m2 solar cells) fulfilling low energy class 2015 (EBST, 2010). Ordinary office spaces obtained an indoor climate equivalent to minimum class II according to European standards (CEN, 2007). Furthermore, a complex set of requirements for the indoor climate including very special ventilation rates defined by contamination risks etc. has been fulfilled.

Figure 63. *Visualisation of the centrally placed laboratories for educational use with double room height and access to the courtyard and skylights.*

Lessons learned

The research shows how essential and influential comfort is when considering the design of the façade and the building as a whole. Comfort is hard to quantify, but very tangible for the occupants, affecting their perception of the built environment and essentially determining the need for mechanical control of the indoor climate and subsequently the building's energy demand.

There are opposite views as to whether thermal uniformity is the *Holy Grail* or the adaptive approach represents a potential method for evaluating the quality of thermal diversity by linking the occupant and the comfort temperature range to the actual situation and context. The adaptive principle takes account of the highly transient character of both the interior and the exterior environment as well as the human ability to acclimatise or adapt if you will, including the potential for actively interacting with the building and its services. In this way, the occupants and their ability to affect their sense of comfort is not only included in the comfort evaluation, but can also be included as an inherent part of the façade design. In this context, adaptive comfort studies have shown that some parts of the body have greater effect on the overall sense of comfort than others, suggesting that façades and climate control could be designed accordingly. So, by using a more localised, instead of uniform, approach to controlling the indoor climate, there is a potential for energy savings and increased occupant satisfaction.

However, when the results of this research are compared with the PMV method, the cases analysed are in relatively good agreement with the traditional comfort range (PMV) and do not necessarily indicate more relaxed temperature criteria. So, in itself, the adaptive comfort approach does not necessarily signify an energy reduction potential.

What are the implications for façade design? Once again, it is necessary to stress that this is a complex problem influenced by a wide range of parameters and that each situation

defines its own set of rules and requires contextually driven solutions. So, the results do not give a clear indication of an optimal solar shading type or window height out of those simulated. Increasing the thermal comfort of the occupant can be achieved by either window size, solar shading type or a combination. Each building design should be a *fine-tuning* of how the given functions are organised and the hierarchy of the performance requirements. This determines the façade design appropriate for the given function, how it processes the impacts from the outdoor climate, and what the potentials are for interactions between building and façade.

The *right* façade is not a generic character and the case study of the laboratory building in Denmark illustrates how the potentials inherent in architectural processing can also be used in relation to occupant comfort. A pragmatic approach will utilise the organisation of functions and their differences in performance requirements, especially in terms of indoor climate, to achieve a better equilibrium between internal and external impacts. From this point of view, the façade design and the potential for occupants interacting with the façade can be utilised to achieve both energy savings and occupant satisfaction.

discussion and conclusion

Discussion and conclusion

Reality is not how you wish things would be, nor the way you perceive them to be, but how they actually are! That realisation has saturated this research project. Reality has been persistent and at times obtrusive, but has simultaneously been a continuous guide and motivational force throughout this research project.

The traditional approach to research in the area of building physics stands in stark contrast to how technical knowledge is implemented especially in the early stages of the building design process. This project practiced applied research implemented in an ever evolving design process that does not wait for a scientific output or goal to be defined before commencing. The design development of buildings is in reality immensely complex and can in process terms probably never be categorised as being truly optimal. However, this project did not try to *beat the process into submission* by advocating an optimal solution, but sought through quantification of the performance to qualify the design development. The project's hypothesis was:

Implementation of technical knowledge early in the building design process can quantify the effect of façades on the energy efficiency and indoor climate of a building and thereby facilitate a qualified design development.

While the research project did verify that technical support of the design process can reduce energy demand while maintaining a high-quality indoor climate, the realisation that there is no one single optimum makes a mere verification or refutation of the hypothesis, while perhaps possible, less interesting. The actual engagement in the building design process as the fundamental principle for the project made the road travelled more interesting than the destination. So, realising that no projects are alike and that there

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Reality is merely an illusion, although a very persistent one

Albert Einstein

are no generically correct façade designs, but that optimised façade designs can be generated and through that lessons can be learned, which can contribute to the next project being developed on a more qualified basis. So the description of the research project does not resort to merely traditional scientific dissemination with introduction, method, results, etc. Instead a methodology allowing research and practice to interleave and influence each other was applied. The thesis was structured in accordance with the importance and method of integrating *knowledge* in the early stages of design, understanding the façade's *typology*, and comprehending the complexity of *comfort*. The final discussion and conclusion continues this methodology.

Knowledge

A major part of this project was the actual engagement in the design process at the various stages, across a wide range of affiliated projects. So, the project had the achievement of more energy efficient buildings with high-quality indoor climate as the objective, but aimed at putting it into a realistic setting by entering as an active member of each given project's design team.

Using integrated energy design (IED) as a roadmap when engaging in the interdisciplinary collaboration between engineers and architects proved beneficial. Early process involvement helped the projects evolve from a common set of values, aims and objectives, and made it possible to have continuous performance evaluation. In this way, time and subsequently cost-consuming design revisions later in the process were minimised and an elucidation of potential synergies made possible.

This project focused, through the use and development of IED, on the utilisation of the passive properties by performing geometrical optimisation. This provided common ground because the early architectural process very much revolves around the geometrical processing. So, over the course of

this project it was shown that the integration of technical knowledge can both support qualified design choices, and also essentially facilitate the design development of both the overall building and the façade.

The further development of IED emphasises the great importance of the context of the projects. As mentioned, no two projects are alike and both the challenges and opportunities are determined by the project's context in terms of the surrounding climate, building programme with its performance requirements, interaction with occupants and adjacent buildings, supply strategies, etc., and not by the infamous first sketch on a napkin. This creates a unique fundamental basis for each project and determines the prerequisites for the subsequent design development – prerequisites that also require, and can benefit from, the input of engineers.

Furthermore, through the many affiliated projects, daylight was identified and incorporated in the methodology as the basis for a common discussion between engineers and architects, and essential in the design development. Daylight represents a fundamental parameter in architecture, defining and creating spaces, and at the same time represents a cardinal point in terms of the building's energy demand, including the potential of a beneficial interaction with the surrounding climate and context. Here, the Scandinavian architectural tradition, with its strong contextual foundation combined with great attention on the utilisation of daylight, has proven to be a great basis for designing buildings with an inherent consciousness of energy demand and indoor climate.

It should be noted that throughout this project, great attention has gone into promoting a more holistic performance evaluation. Lopsidedness in evaluating the performance should be avoided whether it *tilts* towards energy and indoor climate, or focuses purely on aesthetics. During the affiliated projects involved in at the architectural firm, it was confirmed that IED can provide a framework for integrating a consciousness about energy and indoor climate, but also that this is only a part of an immensely complex problem and that *simply* integrated design should be the goal.

To achieve an integrated design process, it is important to establish common ground so that all involved parties can take ownership of the project and engage themselves in the process. Here it is concluded that a common language is of great importance because it is the ability to translate both an architectural concept into performance requirements and, at least just as important, to translate technical knowledge into input that can support and facilitate design development. In this context, this research project also focused on the actual graphical representation which proved an important tool to convey results, guidelines and recommendations. Again, it is from a process point of view important for engineers to acknowledge, that one perfect solution does not exist and that a constant generation of design alternatives is needed as the design process develops. Only then can the design be quantified and develop in a qualified manner.

True architecture should represent a holistic performance evaluation and should therefore be seen as the common goal for all professional disciplines involved in the building design process, but this requires architecture and technology to be fused back together. To do this, engineers have to enter what is usually considered the natural realm of architects, not to take over or define the course of action, but to support. This places great responsibilities on the shoulders of both engineers and architects. Judging by the projects followed over the course of this project the engineers seem to face the greatest challenges, but if these challenges are embraced, great opportunities exist.

Typology

Optimisation of the building façade in relation to energy demand and indoor climate was the focal point for all the investigations and analyses carried out during this research project. In all the affiliated project involved in the essential role of the façade in defining the architectural concept and expression for a building was confirmed, but the façade also plays a major role in terms of basically all other performance

parameters. The façade is the building's skin and the mediator between the outside and inside environment Analyses confirm that to a large extent it defines what amount of energy is needed to achieve an indoor climate that meets the performance requirements.

So, the holistic performance evaluation should also be applied to the design development of façades. The project set out to support the design development of façades within the framework of an architectural concept rather than focusing on promoting one optimal solution or component. The research illustrates how an engagement in the architectural design process through geometrical optimisations can achieve façade designs that enhance and even define the architectural concept. So, by incorporating energy-reducing measures through geometrical processing, it becomes an inherent part of the architecture, not just an extra layer used to correct poorly designed buildings. By utilising the passive properties, a certain degree of *robustness* is achieved, where the building itself defines its performance potential – not the control of the HVAC or the lighting-system. It becomes a starting point from where the need for energy-demanding technical solutions is reduced, though they could be added either later in the design process or in connection with future refurbishments.

In this context, the design of the window aperture and solar shading with the objective of achieving better control of solar radiation proved especially important for both architects and engineers. Moreover, in this area, analyses show potential for significant energy reductions through the utilisation of the passive properties. Similarly, analyses showed a significantly inferior performance of dynamic solar shading than other studies, when compared with relevant design alternatives. Here, the research results emphasise the importance of integrated simulations of the performance of design alternatives so as to be able to benchmark and evaluate them. Simulation tools provide an opportunity to quantify the performance to some extent, but it is important to evaluate the design option holistically to prevent optimisation of the simulation model instead of the actual building design.

Results show great potential in this approach to façade design and all affiliated projects resulted in buildings with energy demands at least 25% below the minimum requirements, while still maintaining high-quality indoor climate and architectural quality.

Comfort

Comfort was also a significant parameter throughout this research, but how it is considered and handled in the building process changed. At the beginning of the project, comfort was represented by indoor climate and perceived as a necessary evil in the search for energy reductions. But over the course of this project, my view has changed to a broader and more holistic notion of comfort as not only something to be achieved in buildings, but as the fundamental principle for the built environment. Not exactly ground-breaking findings, but a fundamentally different approach to designing buildings than only taking standard people in standard situations into account when making simulations of the building's energy performance.

The highly transient character of the outdoor environment and the importance of the building's contextual setting necessitate an approach where comfort is not considered as a standard term that will then generate standard solutions. The perception of comfort cannot be disconnected from the context, and is a vast and highly diverse quantity influenced by parameters such as the time of day, seasons, the building's function, orientation, cultural differences and, for example, the psychology inherent in the possibility of deciding for oneself and being able to influence one's own environment, just to name a few. This does nothing to minimise the complexity of the building design process, but understanding that comfort is complex and evaluating it in a more holistic manner, can result in more freedom of design, which can translate into occupant satisfaction, increases in productivity, and subsequently reduction in energy demand.

Much of the research in the field of energy-efficient buildings tends to engage in a technical discourse aimed at generating generically applicable optimised solutions. While such research is definitely necessary to drive the development of energy-saving components forward, it has to be balanced with research focused on the actual implementation of energy-saving measures.

If architecture and technology can be fused back together, enabling energy efficiency and indoor comfort to become an inherent part of the idiom, true architecture has the potential of becoming a testimony of sustainability. This will transform energy efficiency into something operational that is relevant and meaningful for all and with an ability to improve the quality of life.

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When everything is said and done, more is said than done

Groucho Marx

bibliography

Bibliography

Andersen, R.K. (2009) Occupant Behaviour with regard to Control of the Indoor Environment, Ph.D. Thesis, Technical University of Denmark, Lyngby.

Arens, E., Zhang, H. & Huizenga, C. (2006a) Partial- and whole-body thermal sensation and comfort— Part I: Uniform environmental conditions. Journal of thermal biology 31 (1-2), 53-59.

Arens, E., Zhang, H. & Huizenga, C. (2006b) Partial- and whole-body thermal sensation and comfort—Part II: Non-uniform environmental conditions. Journal of thermal biology 31(1-2), 60-66.

Athienitis, A.K. & Tzempelikos, A. (2002) A methodology for simulation of daylight room illuminance distribution and light dimming for a room with a controlled shading device, Solar Energy, vol. 72, no. 4, pp. 271-281.

Augenbroe, G., Wilde, P.d., Moon, H.J. & Malkawi, A. (2004) An interoperability workbench for design analysis integration, Energy and Buildings, vol. 36, no. 8, pp. 737-748.

Baker, N. & Steemers, K. (2000) Energy and Environment in Architecture: A Technical Design Guide, E & Fn Spon, London.

Banham, R. (1984) The Architecture of the Well-tempered Environment, Architectural Press, London.

Brager, G.S. & de Dear, R.J. (1998) Thermal adaptation in the built environment: a literature review, Energy and Buildings 27 (1), 83-96.

Brundtland, G. H. & World Commission on Environment and Development (1987) Our common future. Oxford University

Press, Oxford.

CEN (2007) EN15251:2007 - Indoor environmental input parameters for design and assessment of energy performance of buildings - addressing indoor air quality, thermal environment, lighting and acoustics.

CEN (2001) EN ISO 7726:2001 – Ergonomics of the thermal environment - Instruments for measuring physical quantities.

Cetiner, I & Özkan, E. (2005) An approach for the evaluation of energy and cost efficiency of glass façades, Energy and Buildings, vol. 37, no. 6, pp. 673-684, 2005.

Cheng, Y., Niu, J. & Gao, N. (2012) Thermal comfort models: A review and numerical investigation, Building and Environment 47(0), 13-22.

Citherlet, S., Clarke, J.A. & Hand, J. (2001) Integration in building physics simulation, Energy and Buildings, vol. 33, no. 5, pp. 451-461.

Citherlet, S. & Hand, J. (2002) Assessing energy, lighting, room acoustics, occupant comfort and environmental impacts performance of building with a single simulation program, Building and Environment, vol. 37, no. 8-9, pp. 845-856.

Clarke, J.A., Janak, M. & Ruyssevelt, P. (1998) Assessing the overall performance of advanced glazing systems, Solar Energy, vol. 63, no. 4, pp. 231-241.

Cross, N. (1984) Developments in Design Methodology, John Wiley & Sons.

Cross, N. (2007) Forty years of design research, Design Studies 28 (1) editorial.

Cross, N. (2001) Designerly Ways of Knowing: Design Discipline Versus Design Science, Design issues 17 (3), 49–55.

de Dear, R. & Brager, G.S. (2001) The adaptive model of thermal comfort and energy conservation in the built environment, International journal of biometeorology 45(2), 100-108.

EBST (2008) Bygningsreglement for erhvervs- og etagebyggeri, National Agency for Enterprise and Construction, Copenhagen, Denmark.

EBST (2010) Bygningsreglement for erhvervs- og etagebyggeri, National Agency for Enterprise and Construction, Copenhagen, Denmark.

EPBD (2002) Energy Performance Building Directive - Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings.

EPBD (2010) Directive 2010/31/EU of the European Parliament and of the Council of 19 December 2010 on the Energy Performance of Buildings (recast).

Fanger P.O. (1970) Thermal comfort, Danish Technical Press, Copenhagen.

Frampton, K. (1995) Studies in Tectonic Culture: The poetics of Construction in Nineteenth and Twentieth Century Architecture, MIT Press, Cambridge.

Franzetti, C., Fraisse, G. & Achard, G. (2004) Influence of the coupling between daylight and artificial lighting on thermal loads in office buildings, Energy and Buildings, vol. 36, no. 2, pp. 117-126.

Hoes P., Hensen, L.J.M., Loomans, M.G.L.C. & Vries, B.d. (2009) User behavior in whole building simulation, Energy and Buildings 41 295–302.

Huizenga, C., Hui, Z. & Arens, E. (2001) A model of human physiology and comfort for assessing complex thermal environments. Building and Environment 36(6), 691-699.

IEA task 23 (2002) Integrated Design Process: A guideline for sustainable and solar-optimised building design, International Energy Agency (IEA) Task 23 Optimization of Solar Energy Use in Large Buildings subtask B: Design process guideline.

IEA (2009) Key World Energy Statistics 2009, International Energy Agency, Paris.

IEA-ECBCS (2010) Expert Guide – Part 1 Responsive Building Concepts, International Energy Agency Energy Conservation in Buildings and Community Systems (IEA-ECBCS) Annex 44 Integrating Environmentally Responsive Elements in Buildings.

Johnson, R., Sullivan, R., Selkowitz, S., Conner, C. & Arasteh, D. (1984) Glazing energy performance and design optimization with daylighting, Energy & Buildings 6, 305–317.

Koo, S.Y., Yeo, M.S. & Kim, K.W. (2010) Automated blind control to maximize the benefits of daylight in buildings, Building and Environment, vol. 45, no. 6, pp. 1508-1520.

Kuno, S. (1995) Comfort and pleasantness, PAN Pacific Symposium on Building and Urban Environmental Conditions in Asia, Nagoya, Japan.

Köster, H. (2000) Dynamic Daylight Architecture: Basics, Systems, Projects, Birkhäuser, Berlin.

Laforgue, P., Souyri, B., Fontoynont, M. & Achard, G. (1997) Simulation of visual and thermal comfort related to daylighting and solar radiation in office buildings, In: Proceedings of IBPSA 1997, Czech Republic.

Lawrence, G.H.M. (1978) America's Garden Legacy: a taste for pleasure, Pennsylvania Horticultural Society, McLean Library, Pennsylvania.

Le Corbusier (1931) Vers une Architecture, Paris, 1923. English translation by Frederick Etchells as Towards a New

Architecture, John Rodker, London.

Lee, E.S., DiBartolomeo, D.L. & Selkowitz, S.E. (1998) Thermal and daylighting performance of an automated venetian blind and lighting system in a full-scale private office, Energy and Buildings, vol. 29, no. 1, pp. 47-63.

Lee, E., Selkowitz, S.E., Bazjanac, V., Inkarojrit, V. & Kohler, C. (2002) High-performance commercial building façades, Lawrence Berkeley National Laboratory, LBNL Paper LBNL-50502.

Retrieved from: http://www.escholarship.org/uc/item/7d30b3rd

Leech, J. A., Nelson, W.C., Burnett, R.T., Aaron, S. & Raizenne, M.E. (2002) It's about time: A comparison of Canadian and American time-activity patterns, Journal of Exposure Science and Environmental Epidemiology, 12(6):427–432.

Lollini, R., Danza, L. & Meroni, I. (2010) Energy efficiency of a dynamic glazing system, Solar Energy, vol. 84, no. 4, pp. 526-537.

Lysen, E.H. (1996) The trias energetic: Solar energy Strategies for developing countries, Eurosun Conference, Freiburg, Germany.

Morel, N. & Faist, A. (1993) Design tools for building thermal analysis: The significance of integration, Building and Environment, vol. 28, no. 4, pp. 465-473.

Mumovic, D. & M. Santamouris, M. (2009) A Handbook of Sustainable Building Design and Engineering: An Integrated Approach to Energy, Health and Operational Performance, Earthscan, London.

Nicol, J.F. & Humphreys, M.A. (2002) Adaptive thermal comfort and sustainable thermal standards for buildings, Energy and Buildings 34(6), 563-572.

Ochoa, C.E. & Capeluto, I.G. (2009) Advice tool for early design stages of intelligent façades based on energy and visual comfort approach, Energy and Buildings, vol. 41, no. 5, pp. 480-488.

Petersen, S. & Svendsen, S. (2010) Method and simulation program informed decisions in the early stages of building design, Energy and Buildings, vol. 42, no. 7, pp. 1113-1119.

Santamouris, M. (Editor) (2006) Environmental Design of Urban Buildings: An Integrated Approach, Earthscan, London.

SBi (1999) Vinduer og dagslys – en feltundersøgelse i kontorbygninger (English: Windows and Daylight – a field study in office buildings), SBI report 318, Danish Building Research Institute, Copenhagen.

Schmarsow, A. (1894) Das Wesen der architektonischen Schöpfung. K. W. Hiersemann, Leipzig.

Selkowitz, S.E. (1998) The elusive challenge of daylighted buildings. Daylighting'98 Conference, Ottawa, Canada.

Selkowitz, S. E. (2001) Integrating advanced facades into high performance buildings, Lawrence Berkeley National Laboratory, LBNL Paper LBNL-47948.

Retrieved from: http://escholarship.org/uc/item/30g0h715

Sourbron, M. & Helsen, L. (2011) Evaluation of adaptive thermal comfort models in moderate climates and their impact on energy use in office buildings. Energy and Buildings 43(2-3), 423-432.

Stolwijk, J.A.J. & Hardy, J.D. (1966) Temperature regulation in man - A theoretical study. Pflügers Archiv für die Gesamte Physiologie des Menschen und der Tiere 291(2), 129 - 162.

Strachan, P.A. (2008) Simulation support for performance assessment of building components, Building and Environment, vol. 43, no. 2, pp. 228-236.

Tanabe S, Tsuzuki T, Kimura K. & Horikawa S. (1995) Numerical Simulation Model of Thermal Regulation of Man with 16 Body Parts of Evaluating Thermal Environment (Part 1 Heat Transfer at Skin Surface and Comparison with SET* and Stolwijk Model), Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan.

Toftum, J., Andersen, R.V. & Jensen, K.L. (2009) Occupant performance and building energy consumption with different philosophies of determining acceptable thermal conditions, Building and Environment 44(10), 2009-2016.

Tzempelikos, A. & Athienitis, A.K., 2007. The impact of shading design and control on building cooling and lighting demand, Solar Energy, vol. 81, no. 3, pp. 369-382.

Tzempelikos, A., Athienitis, A.K. & Karava, P., 2007. Simulation of façade and envelope design options for a new institutional building, Solar Energy, vol. 81, no. 9, pp. 1088-1103.

Tzempelikos, A., Bessoudo, M., Athienitis, A.K. & Zmeureanu, R. (2010) Indoor thermal environmental conditions near glazed facades with shading devices – Part II: Thermal comfort simulation and impact of glazing and shading properties, Building and Environment 45(11), 2517-2525.

Wilde, P.d., Augenbroe, G. & Voorden, M.v.d. (2002) Design analysis integration: supporting the selection of energy saving building components, Building and Environment, vol. 37, no. 8-9, pp. 807-816.

Wilde, P.d. & Voorden, M.v.d. (2004) Providing computational support for the selection of energy saving building components, Energy and Buildings, vol. 36, no. 8, pp. 749-758.

Zhang, H., Arens, E., Huizenga, C. & Han, T. (2010a) Thermal sensation and comfort models for non-uniform and transient environments: Part I: Local sensation of individual body parts. Building and Environment 45(2), 380-388.

Zhang, H., Arens, E., Huizenga, C. & Han, T. (2010b) Thermal sensation and comfort models for non-uniform and transient environments, part II: Local comfort of individual body parts. Building and Environment 45(2), 389-398.

Zhang, H., Arens, E., Huizenga, C. & Han, T. (2010c) Thermal sensation and comfort models for non-uniform and transient environments, part III: Whole-body sensation and comfort. Building and Environment 45(2), 399-410.

appendices

Appended papers

Paper I

Integrated Design - A paradigm for the design of low-energy office buildings

Integrated Design - A paradigm for the design of low-energy office buildings

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ABSTRACT

This paper presents a case study of the implementation of integrated design in an actual architectural competition. The design process was carried out at a highly esteemed architectural office and attended by both engineers and architects working towards mutual goals of architectural excellence, low-energy consumption, and high-quality indoor environment. We use this case study to investigate how technical knowledge about building performance can be integrated into the conceptual design stage. We have selected certain points during the design process that represented design challenges and describe the decision process. Specific attention is given to how the engineering input was presented and how it was able to facilitate the design development. Site and context, building shape, organization of functions and HVAC-systems were all included to obtain a complete picture of the building's performance. This article illustrates how a continuous implementation of technical knowledge early in the design process for an actual architectural competition resulted in a building design with an energy demand approximately 30% lower than Danish building regulations, yet which still maintains a high quality of indoor environment and meets the demands of architectural excellence.

INTRODUCTION

It has been economically and technically possible to design and erect low-energy buildings – both homes and offices – for decades. But it is not often done, and many new buildings are overly expensive and have high energy consumption. One important obstacle is the architectural process of designing buildings, in which scientific technical knowledge informs the architectural project too late (Clarke, J., 2001) & (Wilde, P. de., M. van der Voorde. 2003). Several new multidisciplinary design methods have been launched to address this problem. Integrated Design is one of these methods and is an established research area (Intelligent Energy, 2006). The traditional working processes differ greatly depending on the people involved, ranging from a very iterative and image-driven process for architects to a more linear process driven by numbers and texts in the case of engineers. The differences impact on not only willingness to generate design alternatives and what they look like, but also the way in which these and other results in general are presented. Thus considerable attention needs to be paid to the way input is communicated within the design team in order to establish common ground and provide more effective collaboration between engineers and architects during the integrated design process.

The present study describes a process where the integration of technical input gave substance to early design decisions, not only by continuously providing design alternatives, but just as important by facilitating a benchmarking process for deciding between these alternatives. The aim is both to clarify how numerous interdependent parameters define and influence performance and subsequently to show why these critical design decisions need to be made on an informed basis. The case study was a conceptual design proposal for an architectural competition for an office building in Copenhagen, Denmark, carried out at Henning Larsen Architects A/S in collaboration with the authors.

THE CASE

This case revolves around the design of a 6-storey (15,000 m^2) office building located in the harbour area of Copenhagen, Denmark (55.4°N, 12.4°E). To comply with the spatial requirements and the height restrictions in the competition brief, the building geometry was predefined as approximately 25x100x24 metres (width x length x height), corresponding to exactly the extent of the given building zone. The orientation of the site meant that the two main façades faced east and west respectively. The building was to accommodate workstations for 500 employees and support facilities, such as meeting rooms, print and copy rooms, kitchenettes, etc. The competition brief stated that the building should be closely related to the area dominated by old warehouses in brick and stone from the eighteenth century and continue the line of "warehouse-like" building structures. Furthermore the building should be both solid and dynamic in its expression, make full use of the views from the unique location, and maintain a certain degree of openness towards the surroundings, its users, and its visitors. The project was offered as an international architectural competition in 2008 under EU directive 2004/18/EX with five interdisciplinary competition teams and carried out over a period of two months.

Performance requirements

The performance requirements described in the competition brief were:

1. A thermal indoor environment and air quality corresponding as a minimum to Class II as described in the European Standard (DS/EN 15251:2007)
2. A daylight factor of 2% for all workstations
3. A maximum energy demand of 95 kWh/m^2/year, but a wish for 70 kWh/m^2/year, figures which correspond respectively to the minimum requirement and low-energy Class II in the Danish building code in force at the time of the competition (Danish Building Regulations, 2006).

Energy demand is indicated in primary energy. In principle, primary energy use is the total energy weighted using primary energy factors. The total energy demand is divided into five primary needs: 1. Heating, 2. Cooling, 3. Artificial lighting, 4. Fans (Mechanical ventilation), and 5. Domestic Hot water (DHW). Danish building regulations require the building's energy demand to be documented by means of simulation before a building permit can be approved.

Table 1.   List of primary energy factors stated in the Danish Building Code and how they were used in the simulation

Energy source	Factor	Simulation
Gas, Oil and District Heating	1	Heating and DHW
Electricity	2.5	Cooling, Fans for Mech. Vent., Art. Light, and pumps.

Throughout the project considerable attention was paid to evaluating not only the energy performance and indoor environment parameters, such as daylight availability, operative temperature and air quality, but also to translating this information into spatial reasoning. This created common understanding and contributed to the evolving design in an informed and interdisciplinary manner. To assist the iterative process with several design options being generated every day, simulations were performed for a representative section of the building with façades facing east and west in the early stages of design. System settings reflected typical occupation hours and activity levels for office buildings and were defined so that the requirements for the indoor environment described in the competition brief were fulfilled. Integrated thermal and daylight simulation was carried out using the software program iDBuild (Petersen, S., Svendsen S., 2010), which performs hourly-based simulations of the total energy demand. The program is made up of two parts that combine to perform an integrated simulation. The first part is the thermal simulation, handled by BuildingCalc (Nielsen et al., 2005), and the second part is the daylight simulation, handled by LightCalc (Hviid et al., 2008). A combination of Ecotect (Crawley D.B., et al., 2008) and Radiance (G.W. Larson, R. Shakespeare, 1998) was used to simulate and illustrate the daylight distribution.

Table 2. Input values defining the simulation model with respect to geometry, system set-up, and efficiency. (Reference model with 50% transparency)

Geometry		
Room – width x height x depth		20x10x2.8m
Window width and height		10.2x2.8m
Width of window frame construction		0.1m

Constructions		
Heat transfer coefficient of opaque façade construction (U-value)		0.18 W/m^{2}K
Heat transfer coefficient of glazing (U-value)		1.19 W/m^{2}K
Light transmittance of glazing (LT)		0.782
Total solar energy transmittance of glazing		0.625
Heat transfer coefficient of frame construction (U-value)		1.5 W/m^{2}K
Linear heat transmittance of window frame (Psi-value)		0.1 W/mK

Systems and internal loads	Occupancy (8 am to 5 pm)	Non-occupancy
Set point temperatures – heating/cooling		
Heating season	20/24 °C	18/24 °C
Outside heating season	23/26 °C	18/26 °C
Infiltration	0.17 h^{-1}	0.17 h^{-1}
Mechanical ventilation [a]	1.4 l/s m^2	0.0 l/sm^2
Heat exchanger efficiency of mechanical ventilation [b]	0.8	-
Specific fan power, SFP	2.5 KJ/m^3	-
Venting rate (maximum) [c]	-	-
Mechanical cooling, efficiency (COP)	2.5	-
Internal loads from persons and equipment	10 W/m^2	0 W/m^2
General lighting		
Illuminance set point	200 lux	-
Max. power	6 W/m^2	0 W/m^2
Min. power (stand-by)	0.5 W/m^2	0 W/m^2
Task lighting		
Illuminance set point	500 lux	-
Max. power	1 W/m^2	0 W/m^2
Min. power	0 W/m^2	0 W/m^2

a) Equivalent to indoor air quality Class II in the European standard EN 15251:2007 (CEN, 2007).
b) Bypass of heat exchanger possible.
c) Defined as ventilation through open windows. Only active outside the heating season and corresponds to the maximum values for single-sided natural ventilation in Danish energy calculations (EBST, 2006).

IDENTIFIYING IMPORTANT DESIGN DECISIONS

A large number of analyses were carried out throughout the design process to continuously monitor the expected building performance as a consequence of the design development. In order to achieve an adequate and complete picture of the process, sketches, drawings, models, minutes from meetings, energy and daylight analyses, mails, etc. were collected and arranged in chronological order (Yin, R. K., 2009). The focus was on identifying when and how technical input on energy performance and indoor environment had an impact on the design development and how it affected the design. Based on the information gathered, important design decisions, where technical input in terms of energy and daylight simulations affected the design, were identified and selected for further analysis. The design decisions were examined in three steps, describing:

1. **Analysis** - How the design decision impacts the building's performance clarified through simulations of the energy demands and the indoor environment.
2. **Presentation** - How the results from the analyses were translated and graphically processed in order to illustrate their significance and impact in terms of architectural expression and performance.
3. **Output** - How a design was generated as a product of the newly achieved knowledge.

DESIGN DECISION "TRANSPARENCY OF FAÇADE"

The optimal choice of façade should take into early consideration not only the architectural expression, but also the energy and daylight performance. The area, position and design of the windows are important factors and affect spatial perception, the layout and number of workstations supplied with daylight, the view of the outside, and the requirements for heating, cooling and artificial lighting. With the building geometry predefined, the transparency (defined as the fraction of glass in relation to the opaque façade) became an important parameter, and simulations were initiated before the sketching process began.

Analysis

Thermal and daylight simulations were carried out for a section of the building with transparencies ranging from 35% to 80%. We simulated the effect of the façade transparency on the building's energy demand and daylight availability. Default values were assigned to all variables except those that related to the transparency of the façade.

Table 3. Energy performance was simulated in accordance with the European Directive EPBD as defined in (DS/EN 15251:2007). All energy demands are stated in kWh/m^2 per year and daylight factors were simulated for the third row of tables from the façade.

	Window-to-wall ratio			
	35%	**50%**	**65%**	**80%**
Heating	9	11	12	13
Cooling	8	14	20	27
Artificial lighting	21	19	18	17
Fans	21	21	21	21
Hot Water	5	5	5	5
Total	64	70	76	83
Daylight factor [%]	1.6	2.2	2.6	3.0

Presentation

When presenting the results, it was important that they would help facilitate the design development. By showing the effect of the façade transparencies on the total energy demand and its components, coupled with visualisations of the daylight availability and pictures of reference projects with corresponding façade transparencies, we enabled the engineers and architects to discuss and identify a space of solutions that would satisfy both the performance requirements and the architectural concept.
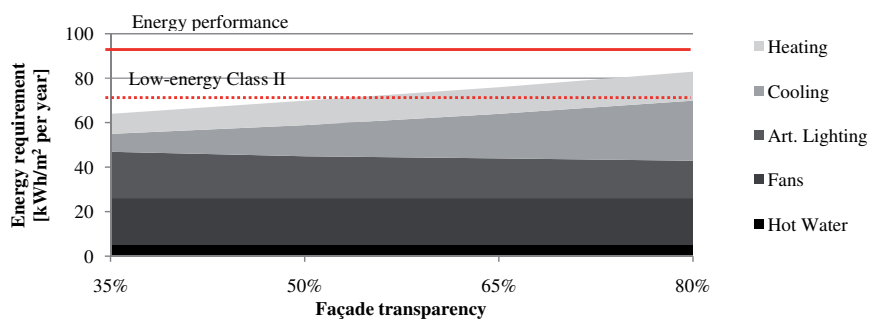
Figure 1 *Graph showing the building's energy performance dependence on the façade transparency. The red lines indicate the performance requirements stated in the competition brief.*

The daylight availability and its distribution were simulated and coupled with drawings of office plans including arrangement of desks. This made it possible both to illustrate and constantly ensure that the spatial demands could be fulfilled and the required number of well-lit workstations could be established.

Figure 2 *Illustration of the daylight availability and distribution simulated for various façade transparencies coupled with floor plans. The red area indicates a daylight factor below 2%.*

Figure 3 *Pictures of reference projects with corresponding façade transparencies (Illustrations: Baumschlager-Eberle Architects).*

Output

The energy and daylight simulations showed how an increased façade transparency resulted in an increased energy

demand but at the same time provided higher illuminance levels as shown in Table 1, which meant that a greater number of well-lit workstations could be established as a result of façade transparency. A balance between energy demand, indoor environment, and architectural intentions began to take form. A façade transparency of 50% was agreed upon, because it provided a sufficient amount of well-lit floor area to meet the spatial requirements, while at the same time it ensured that the building's total energy demand would meet the contractor's wishes.

DESIGN DECISION "ANGLING THE FAÇADE"

Further architectural processing of the façade was carried out to refine the architectural expression and to optimize performance with respect to energy and the indoor environment. The architectural intention was to design a façade that would relate to the existing brick structures as required in the brief, but at the same time reflect the dynamics of the water present all around the site. So the façade should be both solid and dynamic. The main parameters were: an architectural dynamic to the façade, better utilization of the views provided by the extraordinary location, and a significant reduction in the cooling demand. Collectively in the design team, the idea arose of faceting the façade, angling the opaque and transparent parts differently. In particular, angling the windows towards the north would not only optimize views toward the city and the entire Copenhagen bay area, but also significantly reduce insolation and thereby the cooling demand.

Analysis

Thermal and daylight simulations were carried out for a section of the building with a façade transparency of 50% and window orientations ranging from 0° (east) to 45° (northeast). Default values were assigned to all variables except those that related to the orientation of the window.

Table 4. Energy performance was simulated in accordance with the European Directive EPBD as defined in (DS/EN 15251:2007). All energy demands are stated in kWh/m^2 per year and daylight factors were simulated for the third row of tables from the façade.

Energy performance	Window orientation			
	0° (East)	15°	30°	45° (Northeast)
Heating	11	12	13	14
Cooling	14	12	9	7
Artificial lighting	19	19	19	19
Fans	21	21	21	21
Hot Water	5	5	5	5
Total	70	69	67	66
Daylight factor [%]	2.2	2.2	2.2	2.2

Presentation

Graphic illustrations were presented showing the positive effect and tendency in the cooling energy demand as the windows were increasingly angled towards the north. Simulations of daylight levels were coupled with office plans to ensure correlation between the spatial demands and the number of well-lit workstations. Furthermore, renderings of the daylight distribution in an east-facing office were generated for the various window orientations. Together, this formed the basis for an interdisciplinary discussion focused on spatial perception, possible floor plans and the effect on the cooling demand.

Figure 4   *Graph showing the dependence of the cooling demand on the window orientation. 0° corresponds to due East and 45° to Northeast.*

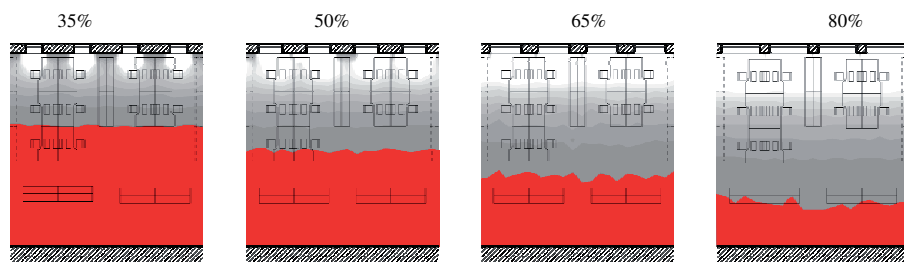| 0° (East) | 15° | 30° | 45° (Northeast) |
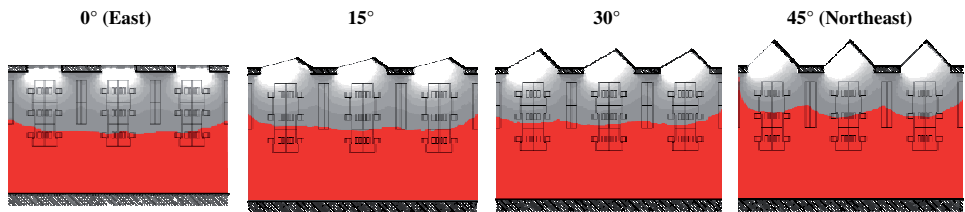
Figure 5   *Illustration of the daylight availability and distribution simulated for various window orientations coupled with floor plans. The red area indicates a daylight factor below 2%.*

Figure 6   *Renderings of the daylight distribution in an east-facing office for various façade angles*

Output

Multiple positive effects obtained by angling the façade were presented with respect to both energy performance and architectural appearance. The cooling demand was reduced, due to the combination of less sun exposure and the angle dependence of the solar heat gain coefficient, resulting in less heat from direct sun. At the same time, staggering the angling of the windows towards the north changed the character and expression of the building, providing a dynamic aspect, while the weight of the masonry provided the solid aspect. The greatest reduction in the cooling demand was found by increasing the angling of the façade from 15º to 30º, and since no major deterioration in daylight levels was registered, a 30º angling of the façade was chosen.

DESIGN DECISION "OPTIMIZING THE PLACEMENT OF THE STRUCTURAL CORE"

With a fixed building width of 25 metres, another important design challenge was optimal utilization of the relatively large room depth. A distance of approximately 10 meters from the façade to the centrally placed core resulted in a lot of floor area being unusable for workstations due to insufficient daylight. The introduction of areas with double room height was seen as an opportunity not only to increase daylight levels in the centre of the building, increasing the flexibility of the floor area, but also to generate a more inspiring spatial feel.

Analysis

Thermal and daylight simulations were carried out for a characteristic section of the building with double room height towards the east and the asymmetrically placed core towards the west. Default values were assigned to all variables.

Table 5. Energy performance was simulated in accordance with the European Directive EPBD as defined in EN15215:2007. All energy demands are stated in kWh/m^2 per year.

Energy performance	Different room height	
	Single Height	Double Room Height
Heating	13	17.5
Cooling	9	4.5
Artificial lighting	19	26.3
Fans	21	11
Hot Water	5	5.4
Total	67	64.7

Presentation

Daylight simulations were coupled with updated office plans to ensure correlation between the number of workstations required in the competition brief and the daylight availability. By illustrating the potential effect of the double height room and comparing it to the point of departure, it was easy for the design team to select and adapt the design to results.
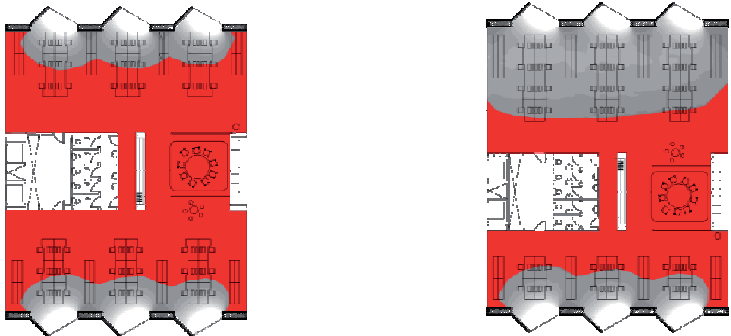
Figure 7   *Illustration of the daylight availability and distribution simulated for a typical section of the building. The double-height space is oriented towards the east. The simulation is coupled with architectural drawings of the actual floor plan. The red area indicates a daylight factor below 2%.*

Output

Results showed an improvement in daylight availability and consequently the option of a better distribution of workstations. The floor area where daylight levels were insufficient correlate with the area needed for secondary functions, such as infrastructure, meeting rooms, toilets, etc. The design presented showed that, although the floor area had been reduced, the spatial requirements could still be fulfilled by using the remaining area in a more effective manner.
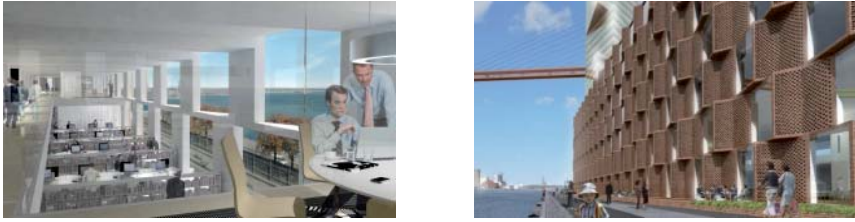
Figure 8 *Renderings of the double room height and the characteristic façade (Illustrations: Henning Larsen Architects A/S).*

DISCUSSION

The first step in improving the energy performance of a building is taken with the architect's first sketch on paper. It is here that the framework and preconditions for the performance of the building will be set. Quantitative and qualitative technical input from the beginning of the design process increases the awareness and recognition of the correlation between the building's design (transparency, orientation, functional organization, etc.) and its energy demand. This reduces the risk of having to introduce technical solutions later in the process to compensate for fundamentally bad design choices at the beginning. Uninformed decisions early in the process can limit the potential for energy savings. The integrated design process requires an interdisciplinary collaboration between engineers and architects. A traditional engineer is trained to work rationally and linearly, while an architect works iteratively with multiple potential solutions at the same time. Problems with communication and collaboration often occur in the early design process, because the engineer is not accustomed to dealing with a variety of solutions, while the architect perceives the engineer as a problem-solver and not a creative collaborator. Engineers need to be better at actively communicating and illustrate their technical input and be capable of contributing with multiple parameter solutions that can challenge and inform the architect's design.

CONCLUSION

The case study presented shows how technical input can facilitate design development if the focus is on translating results into an architecturally oriented presentation. A visual representation of energy and daylight simulations, coupled with spatial considerations, can form a very strong part of the design argument and enrich the reasoning behind design decisions. The architectural engineering background of the engineers involved was seen to have enhanced the collaboration significantly due to a training involving architectural as well as classical engineering skills. A key aspect is being able to understand architectural concepts and translate them into performance parameters and possibilities while at the same time identifying the architectural and spatial potential in the technical results.

The conceptual design proposal presented in this case study was a contribution carried out at Henning Larsen Architects A/S for an actual architectural competition. With the fusion of architectural considerations and technical knowledge, the design team produced a proposal that completed the line of existing warehouses and made full use of the views from the unique location with a more modern architectural expression. By angling the façades towards the north, it was possible to maintain a certain degree of openness towards the surroundings, improving daylight conditions while reducing the energy demand for cooling. By using passive and integrated design solutions coupled with simulations of energy and daylight, we achieved a building with architectural excellence that met the requirements for thermal indoor environment and air quality corresponding to Class II as described in the European Standard (DS/EN 15251:2007) and had a low-energy demand of 64.7 kWh/m^2/year well below the requirements stated in the competition brief.

ACKNOWLEDGMENTS

REFERENCES

Clarke, J., 2001. "Energy simulation in building design", second edition. Butterworth-Heinemann.

Crawley D.B., Hand J.W., Kummert M., Griffith B.T., 2008. "Contrasting the capabilities of building energy performance simulation programs". Building and Environment, vol. 43, 661-673.

Danish Building Regulations, 2006. "Bygningsreglement for erhvervs- og etagebyggeri", National Agency for Enterprise and Construction, Copenhagen.

DS/EN 15251:2007. "Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics", 2007.

G.W. Larson, R. Shakespeare, 1998. "Rendering with Radiance", Morgan Kaufmann.

Intelligent Energy, 2006. "Mapping of previous integrated energy approaches", Part of work package no. 2 in the EU INTEND project – task 2.1. EIE-06-021-INTEND.

Wilde, P. de., M. van der Voorde. 2003. "Computational support for the selection of energy-saving building components." Eighth International IBPSA Conference. Eindhoven, Netherlands.

Petersen, S., Svendsen S., 2010. "Method and simulation program-informed decisions in the early stages of building design". Energy and Buildings, vol. 42, no. 7, pp. 1113-1119.

Yin, R. K., 2009. "Case Study Research – Design and Methods" Fourth Edition, SAGA Publications Inc. United States of America.

Paper II

Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight

Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight

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Abstract

The façade design is and should be considered a central issue in the design of energy-efficient buildings. That is why dynamic façade components are increasingly used to adapt to both internal and external impacts, and to cope with a reduction in energy consumption and an increase in occupant comfort. To gain a complete picture of any façade's performance and subsequently carry out a reasonable benchmarking of various façade alternatives, the total energy consumption and indoor environment need to be considered simultaneously. We quantified the potential of dynamic solar shading façade components by using integrated simulations that took energy demand, the indoor air quality, the amount of daylight available, and visual comfort into consideration. Three types of façades were investigated (without solar shading, with fixed solar shading, and with dynamic solar shading), and we simulated them with various window heights and orientations. Their performance was evaluated on the basis of the building's total energy demand, its energy demand for heating, cooling and lighting, and also its daylight factors. Simulation results comparing the three façade alternatives show potential for significant energy reduction, but greater differences and conflicting tendencies were revealed when the energy needed for heating, cooling and artificial lighting were considered separately. Moreover, the use of dynamic solar shading dramatically improved the amount of daylight available compared to fixed solar shading, which emphasises the need for dynamic and integrated simulations early in the design process to facilitate informed design decisions about the façade.
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Keywords: Dynamic solar shading; Integrated simulation; Energy demand; Indoor environment; Office buildings

1. Introduction

The ever-increasing focus on the environment and climate transformation as a consequence of the emission of greenhouse gasses means that the building industry is facing a new reality (IPCC, 2008; Brundtland, 1987). Energy consumption doubled in the period 1971–2007, and the operation of buildings accounts for 40% of the overall energy consumption (International Energy Agency, 2009). The Energy Performance of Buildings Directive (EPBD, 2002) has become an important part of the new reality, and with the recent political acceptance of the new version that prescribes that all new buildings must be "nearly zero-energy buildings" by 2020 (EPBD, 2010), energy efficiency at every level within the built environment has simply become a prerequisite.

The overall reason for constructing buildings is to shield occupants from the outdoor environment and obtain a certain level of indoor comfort. Consequently, to a great extent, it is the level of occupant comfort that determines how much energy is used to operate the building. This puts the façade, as the actual separator between the indoor and outdoor climate, at the centre of the "energy reduction issue". Choosing the optimal façade, however, is a complex

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scipline with many, often contradictory, parameters of considerable interdependence (Ochoa and Capeluto, 2009).

The introduction of dynamic fenestration creates the possibility of obtaining a more beneficial utilisation of the available resources, such as insolation and daylight, with respect to both energy demand requirements and occupant comfort (Lee et al., 1998). There has been previous research into dynamic fenestration technologies to determine their significance in relation to energy consumption and occupant comfort. Results show the potential of dynamic fenestration components, ranging from a decrease in cooling and lighting demand (Athienitis and Tzempelikos, 2002; Tzempelikos and Athienitis, 2007), reduced overall energy demand (Lollini et al., 2010), and improved daylight utilisation (Koo et al., 2010). All this provides insight into how a certain degree of responsiveness in the façade can have a beneficial effect.

This article demonstrates that the selection of a façade design can only be justified by benchmarking various design alternatives early in the design process when decisions about the façade are made (Löhnert et al., 2003). When making this comparison, it is important to simulate the performance of the façades as a result of the interaction with the building sub-systems (Lee et al., 2004; Franzetti et al., 2004). The potential energy reductions and increases in occupant comfort from the ability of dynamic façades to adapt to the considerable seasonal changes can only be achieved through an integrated process (Lee et al., 1998). For example, improving the interior daylight conditions can reduce the energy consumption for artificial lighting, but also increase the heat gain, and therefore affect the energy demand for heating, ventilation and/or cooling

(Johnson et al., 1984; Tzempelikos and Athienitis, 2007; Tzempelikos et al., 2007).

The main objective of this article is to demonstrate the potential of dynamic solar shading with regard to both energy demand and the quality of the indoor environment through a series of integrated simulations. Our aim is to clarify how a number of interdependent parameters define and affect the performance of the façade. The focus is on investigating the performance of dynamic solar shading compared to fixed solar shading or no solar shading. We use integrated simulations to illustrate the importance of providing data that facilitates early design decisions with regard to the façade (Wilde and Voorden, 2004; Strachan, 2008; Petersen and Svendsen, 2010).

2. Striking a balance

Obtaining the desired equilibrium between energy demand and occupant comfort can only be achieved at room level. Only on this scale is it possible to evaluate both behaviour and requirements with regard to the thermal and the visual indoor environment defined by the occupant. The balance that results in the desired level of comfort is often highly sensitive and is represented by many environmental factors (Fig. 1).

Even minor alterations in either internal or external loads can have a relatively large impact on the energy demand for heating, cooling, ventilation or artificial lighting. Each of the façade components has a filtering effect on the external impacts, and the indoor environment can only be evaluated by considering the building envelope as a whole (Clarke et al., 1998). So the façade can be
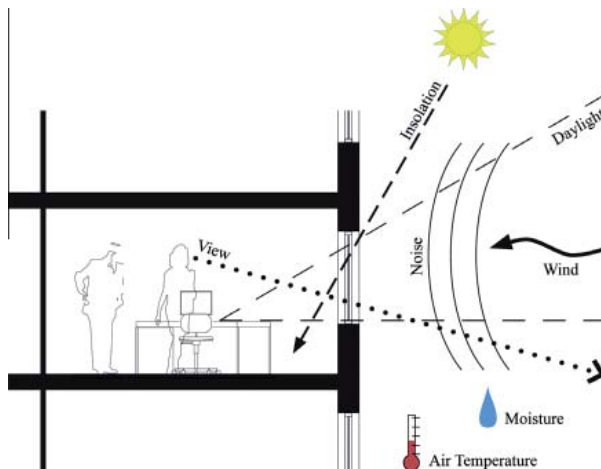

Fig. 1. Typical room with environmental components.

constructed with a number of static and dynamic components that, in combination, are capable of obtaining a better control of the outdoor climate compared with more traditional façades (Lee et al., 2002). For example: regulating the amount of solar heat gain and daylight can be obtained by installing dynamic solar shading; natural ventilation can be obtained through windows or openings (Fig. 2).

Evaluating façades with dynamic properties requires us to perform equally dynamic simulations to determine the level of indoor environment and the energy demand for heating, cooling and artificial lighting. The simulations have to include weather data for the given location and generate results for both the thermal, visual and atmospheric indoor environment – especially when considering translucent components (Selkowitz, 1998). Only then can the components be controlled in accordance with both outdoor and indoor climate, and the potential reduction in energy demand as a consequence of the increased adjustability and the utilisation of the higher luminous efficiency of daylight can be determined (Strachan, 2008). So there is considerable interdependence between the composition of the façades, daylight availability, the need for heating, cooling and artificial lighting, the layout of workplaces, and the wishes of each individual occupant.

We chose the fenestration system as a good representative for the often contradictory wishes for façades. Solar shading represents the first opportunity to control daylight and solar heat gain, which is often a key issue in obtaining workstations with sufficient amounts of daylight and avoiding overheating problems. This analysis focuses on early design decisions and therefore concentrates on the performance of dynamic solar shading in comparison with fixed solar shading and no solar shading.

3. Method

3.1. Simulation process

Analyses were carried out using iDbuild (Petersen and Svendsen, 2010), a tool developed at the Technical University of Denmark, that performs hourly-based calculations of the total energy demand taking into account the energy needed for heating, ventilation, cooling, domestic hot water and artificial lighting. In principle, the program is made up of two parts: a thermal simulation handled by BuildingCalc (Nielsen, 2005), and a daylight simulation handled by LightCalc (Hviid et al., 2008). The integrated simulation is performed by feeding hourly daylight levels into the thermal simulation program.

LightCalc essentially pre-calculates the daylight levels at given evaluation points without shading to provide initial values for the artificial lighting loads, the internal heat gain and subsequently the indoor air temperature.

3.1.1. Thermal simulation

For each hourly time step, the thermal simulation evaluates the indoor air temperature based on the solar heat gain received through the windows, and the heat exchange with internal surfaces and with the external environment. Based on the indoor air temperature, the defined heating or cooling systems are controlled to achieve given set-point temperatures. If the indoor air temperature is below the heating set point, the heating system will be activated and
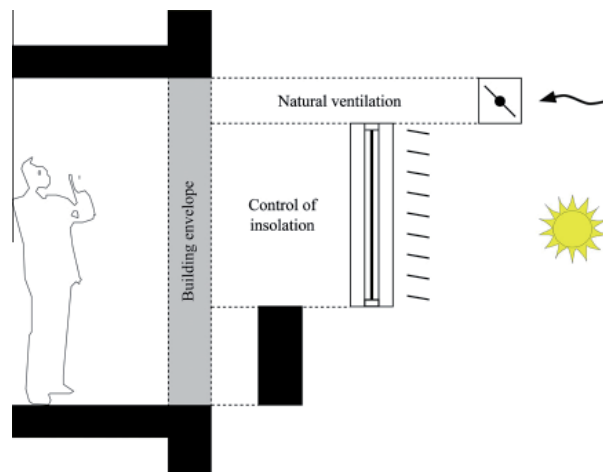

Fig. 2. Illustration of the components of the building envelope and the parameters of the external environment they can dynamically filter. Natural ventilation can be enabled through an opening above the window and controlled by a louver, while insolation can be controlled by solar shading.

the indoor air temperature is above the cooling set point, e defined systems will be activated in the following order:

Shading
Venting (natural ventilation through windows)
Increased mechanical ventilation
Mechanical cooling

hen one of these systems is activated, the thermal indoor vironment is re-simulated for the given time step to clude its effect and to determine the resulting indoor air mperature.

The shading system can be controlled in accordance ith the indoor air temperature, the risk of glare, or both. either of the two conditions is exceeded, the solar shad-g will be fully lowered and, in the case of adjustable inds, adjusted to a cut-off angle at which direct sun is just ocked. The risk of glare is evaluated in accordance with a lylight glare probability index proposed by Wienold and hristoffersen, 2006. If controlled according to both indoor r temperature and the risk of glare, the shading system ill activate if either of the two conditions occur. If shading s been activated, the angle-dependent light transmittance termined by the WIS program (WinDat, 2006) is used to lculate the daylight level at the user-defined points (see ction 3.1.2 below). The artificial lighting levels required achieve the given set points and the resulting heat gains om the lighting are determined. Finally, the solar heat in is calculated by using an angle-dependent total solar ergy transmittance for the fenestration system (including ading system) determined by the WIS program. The lar heat gain coefficient for the fenestration system is ed for both the direct and the diffuse radiation.

Venting is natural ventilation through the windows and n be activated and increased up to a given maximum air

flow. Mechanical ventilation can be varied between a maximum and a minimum air flow.

Mechanical cooling is the final measure and will be activated if the indoor air temperature exceeds the cooling temperature set point after shading has been activated and both venting and mechanical ventilation has been increased to the maximum given value. Both the heating and cooling demands are determined analytically in each time step with respect to the given set-point temperatures when all other active systems controlling the indoor temperature have been activated.

3.1.2. Daylight simulation

The LightCalc algorithm calculates hourly daylight levels, controls the shading system, and determines its effect on daylight levels, making photo-responsive lighting control possible. The simulation of daylight levels as a result of both diffuse and direct components combines several approaches in determining the external and the internal light distribution.

Externally, the diffuse light from scattering in the atmosphere and from the ground and surroundings is modelled using an upper and a lower (inverted) sky dome, as suggested by Robinson and Stone (2006). The upper sky dome uses the Perez all-weather model (Perez et al., 1993) to determine the anisotropic sky radiation, while the lower sky dome is uniform with a constant luminosity expressed by a mean ground reflectance. Both sky domes are divided into 145 patches using the discretisation scheme proposed by Tregenza (1987). The internal light distribution is based on the luminous-exitance method that, like the radiosity method, treats the subdivided internal surfaces receiving transmitted direct and diffuse light as acting like light sources. The algorithms and the methodology behind the implementation are described by Park and Athienitis (2003).
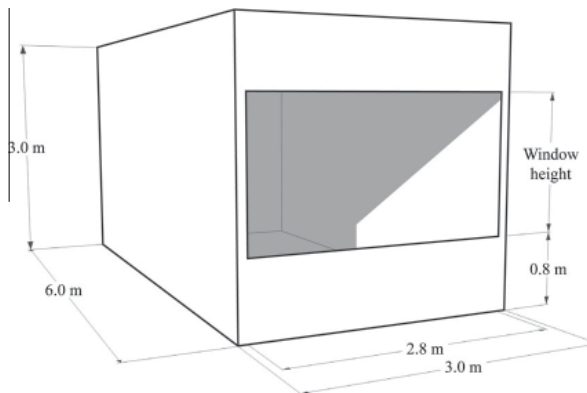

g. 3. Geometry of the two-person office with the window centred in relation to the room width and an offset of 0.1 m on each side. The window height s defined from a window parapet with a fixed height of 0.8 m.

The coupling between the internal and external environment is divided into three components: diffuse-to-diffuse, direct-to-diffuse and direct-to-direct. Each light component has a respective angle-dependent light transmittance calculated through WIS. When direct light hits the solar shading and diffuses, the diffuse-to-direct component is used. Inter-reflection between blinds and between the solar shading system and glazing is ignored.

3.2. Simulation model

The potential of the dynamic façades was investigated through a number of cases to achieve a valid and plausible estimate. Each simulation represented a $3 \times 3 \times 6$ m (width × height × depth) office space for two people, with a specific façade type and system configuration (HVAC and artificial lighting system). The window width was kept constant at 2.8 m while the window height was varied. Fig. 3 represents the model without solar shading and a window height of 1.5 m.

The room was simulated as a single unit in a larger office building located in Denmark, and only the façade was exposed to the outside climate. Ceiling, floor and internal walls were assumed to face the same thermal environment as the room investigated and their thermal capacity was included. The model was simulated in an environment without any obstructing elements.

Additional heat loss through the roof, gable and floor was added so that the energy demand of the office could still be considered representative for all rooms with the same orientation.

With respect to building services (systems) and their control, a distinction was made between 'occupancy' (8 am to 5 pm) and 'non-occupancy' (midnight to 8 am and 5 pm to midnight), and also seasonal between a 'summer' situation (weeks 1–18 and 38–53) and a 'winter' situation (weeks 19–37). The distinction between summer and winter was made in accordance with the typical heating season in Denmark (EBST, 2006) and coupled with the seasonal temperature set points defined in the European standard (CEN, 2007). The office was occupied by two people and their equipment Monday–Friday throughout the year. Table 1 contains input data on geometry, construction, system configuration, and internal loads for the simulation models.

Heating, ventilation, cooling and artificial lighting were only active during occupancy, while infiltration was constant the entire year. Natural ventilation through open windows, indicated as venting, was defined as the maximum air flow rates possible for single-sided natural ventilation during the summer season derived from the Danish standard (EBST, 2006). Set points for heating/cooling and air flow rates for mechanical ventilation corresponded with requirements for Class II in the European standard (CEN, 2007), and the power of the heating and cooling systems was assumed infinite. Both heating and cooling systems were simulated as active during occupancy the entire year, so that

Table 1
Input values defining the simulation model with respect to geometry, system set-up and efficiency.

Geometry	
Room – width × height × depth	$3 \times 3 \times 6$ m
Window width and height	2.8×1.5 m
Width of window frame construction	0.1 m

Constructions	
Heat transfer coefficient of opaque façade construction (*U*-value)	0.15 W/m² K
Heat transfer coefficient of glazing (*U*-value)	0.7 W/m² K
Light transmittance of glazing (LT)	0.53
Total solar energy transmittance of glazing	0.40
Heat transfer coefficient of frame construction (*U*-value)	1.5 W/m² K
Linear heat transmittance of window frame (Psi-value)	0.1 W/m K

Systems and internal loads	Occupancy (8 am to 5 pm)	Non-occupancy
Set-point temperatures – heating/cooling		
Summer	20/24 °C	–
Winter	23/26 °C	–
Infiltration	0.1 h⁻¹	0.1 h⁻¹
Mechanical ventilation[a]	1.48 l/s m²	0.0 l/sm²
Heat exchanger efficiency of mechanical ventilation[b]	0.8	–
Specific fan power, SFP	1.5 kJ/m³	–
Venting rate (maximum)[c]	1.8 l/sm²	0.6 l/sm²
Mechanical cooling, efficiency (COP)	2.5	
Internal loads from persons and equipment	10 W/m²	1 W/m²
General lighting		
Illuminance set point	200 lux	–
max. power	6 W/m²	0 W/m²
min. power (stand-by)	0.5 W/m²	0 W/m²
Task lighting		
Illuminance set point	500 lux	–
max. power	1.2 W/m²	0 W/m²
min. power	0 W/m²	0 W/m²

[a] Equivalent to indoor air quality Class II in the European standard EN 15251:2007 (CEN, 2007).
[b] Bypass of heat exchanger possible.
[c] Defined as ventilation through open windows. Only active outside the heating season and corresponds to maximum values for single-sided natural ventilation in Danish energy calculations (EBST, 2006).

the system set-up would result in temperatures and air quality that always corresponded to Class II requirements.

The artificial lighting, in terms of both general and task, was controlled in accordance with daylight availability. It was assumed that work stations would be placed as close to the façade as possible. To represent a relatively conservative indication of the available daylight the evaluation point for the daylight level was placed four metres from the façade, 0.85 m above the floor and centred in relation to the room width. The assumption was made for this particular simulation model with two occupants so as to explore the full effect of photo-responsive lighting control in combination with dynamic solar shading. It would need to be re-evaluated if more occupants were added, if the layout of work stations were different, or if the overall room

ometry changed. General lighting was controlled by a ntinuous, linear dimming profile that supplements the nount of daylight available with artificial lighting. The mming control of the general lighting interpolated line-ly between the maximum and minimum power in order meet the specified set point (200 lux). Task lighting as either on at maximum power, if the daylight level as below the set point (500 lux), or off, if it was above e set point. It should be noted that power for both gen-al and task lighting in Table 1 indicates a power density V/m²) applicable for the entire floor area. Thus, the value r the task lighting of 1.2 W/m² corresponds to one 11 W w-energy light bulb per occupant supplying 500 lux at the ork station, whereas the general lighting at maximum ower of 6 W/m² supplies 200 lux.

3. Parameter variations

A series of parameter variations were carried out in rder to clarify how various solar shading types affected e indoor environment and the energy consumption. The ojective was a continuous comparison of the façade alter-tives to obtain a reasonable picture of the performance the dynamic solar shading, i.e. its ability to control solar ins and thus its applicability in various situations. Three fferent solar shading types (no solar shading, with /namic solar shading, and with fixed solar shading) were vestigated through all these parameter variations (Fig. 4).

The fixed and the dynamic solar shading were modelled a horizontal, grey Venetian blind with slat thickness, idth and distance equal to 0.22 mm, 50 mm and 2.5 mm respectively and a reflectance of 0.54. The fixed lar shading was modelled as being fixed in the horizontal osition and not retractable, and thus active during both ccupancy and non-occupancy. The dynamic solar shading as modelled as pivoting and fully retractable, and during ccupancy controlled according to the indoor air tempera-

ture and risk of glare. If either of the two conditions occurred, the blinds were fully lowered and adjusted to the slat angle at which direct sun was just blocked (the cut-off angle), thus maximising the amount of daylight entering the room while optimising the indoor environment with respect to glare and overheating (Hviid et al., 2008). Outside occupancy, the dynamic solar shading was only controlled in accordance with indoor air temperature.

3.3.1. Design variables
Integrated daylight and thermal simulations of the three solar shading types were performed for two design vari-ables through a number of parameter variations as seen in Table 2.

The window height in relation to façade transparency was defined from the work plane (0.8 m above the floor) and vertical upward. The width of the window was kept constant at 2.8 m, so by increasing the window height the area of the opaque façade was reduced and both the total heat transfer coefficient (U-value) of the façade and the amount of solar radiation entering the room increased. All models were simulated with the glazing and frame properties indicated in Table 1.

3.4. Evaluation criteria

Based on the simulation results, each design variable and its effect in relation to energy performance and indoor environment were evaluated. The evaluations were per-formed on the basis of the following parameters:

- Total energy demand of the model.
- Energy demand for heating.
- Energy demand for cooling.
- Energy demand for artificial lighting.
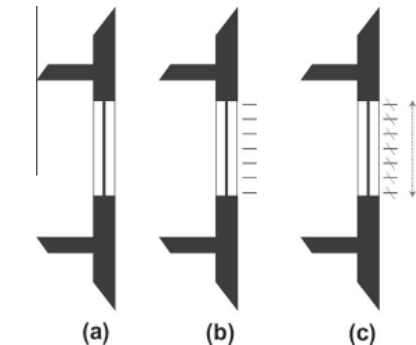
g. 4. Illustrations of the three different solar shading types: (a) ference model without solar shading, (b) Model with fixed solar ading, and (c) Model with dynamic and fully retractable solar shading.

Table 2
For all three solar shading types, integrated simulations were performed for each of the four major orientations and three different window heights.

What	Why	How	Simulated models
Orientation	Influences the incident amount of solar radiation the façade receives	Orientation of window	North, south, east and west
Façade transparency	Defines the amount of heat gain and daylight that enters the room	Window height	1.0 m, 1.5 m and 2.0 m

Table 3
List of primary energy factors as stated in the Danish building regulations (EBST, 2006) and how they are used in the simulations.

Energy source	Factor	Simulation model
Gas, oil and district heating	1	Space heating and domestic hot water
Electricity	2.5	Cooling, fans for mechanical ventilation and artificial lighting

• Daylight represented by the daylight factor and usable area for workstations.

To assess the total energy demand as required in the energy directive from the European parliament (EPBD, 2002), a domestic hot-water consumption of 100 l/m² corresponding to the Danish standard for offices was added. Energy performance was evaluated using primary energy factors as indicated in Table 3 corresponding to the Danish building regulations (EBST, 2006).

The thermal indoor environment and the air quality were both evaluated in accordance with the European standard EN 15251:2007 (CEN, 2007). The heating and cooling set points and the air flow for the mechanical ventilation corresponded to the requirements for indoor environment Class II. The energy demand for ventilation was equal for all models since the specific fan power and the airflow was constant, also corresponding to indoor environment Class II. Because the available heating and cooling power was assumed to be infinite, the requirements for indoor environment Class II with respect to thermal environment and air quality were always fulfilled for all models during occupancy. It should be noted, however, that while the heating and cooling systems were both simulated as active all year during occupancy and therefore resulted in an increased consumption, they do render possible a simple and clear comparison of the performance of the different façades. Since the requirements for the quality of the indoor environment were fulfilled, the energy used for heating, cooling and artificial lighting gives a clear indication of the façade's ability to control both internal and external impacts to maintain a good indoor environment.

The addition of natural ventilation (venting) outside the heating season was made to clarify whether or not some façade designs for certain orientations performed well enough to render cooling obsolete. E.g. problems with overheating outside the heating season would either not exist or be small enough to be handled by an increased air flow obtained through natural ventilation.

The amount of daylight available was evaluated based upon the daylight factor in the working plane (0.85 m above the floor) and simulated using the CIE standard overcast sky, which delivers 10,000 lux on an outside unobstructed horizontal surface. The daylight factor indicates the ratio between the daylight on an internal surface and the daylight on an unobstructed external surface and will therefore not differ in accordance with orientation, day or hour. Whether or not workstations could be established was defined by a daylight factor threshold of 2%, which under a CIE standard overcast sky corresponds to an illuminance level of 200 lux. The threshold connects to the general lighting level and thus corresponds to the illuminance set point for the general lighting as defined in Table 1.

4. Results

Comparative data with respect to both energy demand and daylight factors are presented below for the three solar shading types: no solar shading, fixed solar shading, and dynamic solar shading.

4.1. Energy demand

The data are arranged according to window height and orientation. All models were simulated for an entire year and the results correspond to the annual energy demand per square metre (kWh/m² per year). As seen in Fig. 5, all the simulated models resulted in an energy demand below 70 kWh/m² per year, and approximately 22% of the models (7 out of 36) show an energy demand below 50 kWh/m² per year. The best-performing façade faced south, with a window height of 1.5 m and dynamic solar shading, whereas the worst-performing façade faced north, with a window height of 1.0 m and fixed solar shading. The two façades, best and worst, were simulated to have a total energy demand of 46 kWh/m² per year and 66 kWh/m² per year, respectively.

Generally, the façade with dynamic solar shading had the best performance with respect to total energy demand. In most cases, façades with fixed solar shading had the worst performance, except for façades facing south, east and west with a window height of 2.0 m, where the façades with no solar shading had the worst performance. The vari-
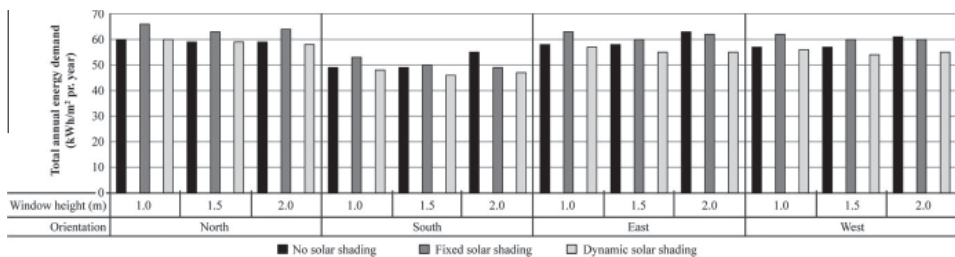

Fig. 5. Annual energy demand for simulated models depending on orientation, window height and solar shading types.

ions in energy demand between the three different solar
shading types were generally of the same magnitude in all
ses. Because air flow rates were determined in accordance
ith indoor air quality (number of occupants and floor
ea) as defined in the European standard (CEN, 2007),
ergy demands for ventilation and for domestic hot water
re constant for all models corresponding to 13 kWh/m²
r year and 5 kWh/m² per year, respectively. Subse-
ently the differences in total annual energy demand were
used by differences in the energy demand for heating,
oling and artificial lighting.

The distribution of energy demand for heating, cooling
d artificial lighting, as seen in Figs. 6–9, shows that the
orth, east and west-facing façades have an increased heat-
g demand when the window height (i.e. the façade trans-
rency/window area) is increased due to the greater heat
ansmission through the glazed component than through
e opaque parts. South-facing façades have a varying ten-
ncy depending on the solar shading types. For all mod-
s, the energy demand for artificial lighting decreases as
e façade transparency and the insolation increases. The
ergy demand for cooling generally increases as the win-
ow height increases, but the increase is proportionally
eater in the cases without solar shading for the orienta-
ons south, east and west (Figs. 6–9).

4.2. North

Models with façades facing north showed a reduction in
total annual energy demand between the worst (at 66 kWh/
m² per year) and the best-performing façade (at 58 kWh/
m² per year) amounting to approximately 12% (Fig. 6).
The north-facing façades with no solar shading or fixed
solar shading had the best performance at a window height
of 1.5 m, whereas the façades with dynamic solar shading
had the best performance at a window height of 2.0 m.
All the performance indicators showed similar tendencies
and magnitudes for all types of solar shading. When the
window height was increased, the heating and cooling
demand increased and the energy demand for artificial
lighting decreased.

4.3. South

Models with façades facing south showed a reduction in
total annual energy demand between the worst (55 kWh/
m² per year) and best-performing façade (46 kWh/m² per
year) amounting to approximately 16% (Fig. 7). The façade
with no solar shading performed equally well with window
heights of 1.0 m and 1.5 m. The façade with fixed solar
shading had the best performance at a window height of

Fig. 6. Distribution of annual energy demand for heating, cooling and artificial lighting for simulation models with façades facing north.

Fig. 7. Distribution of annual energy demand for heating, cooling and artificial lighting for simulation models with façades facing south.
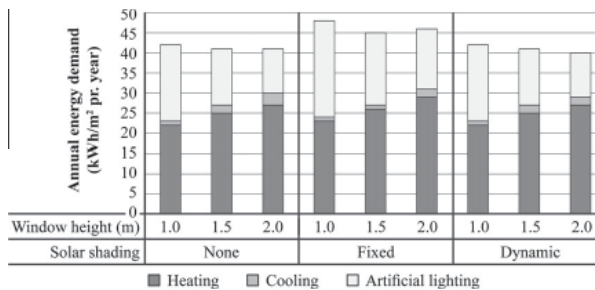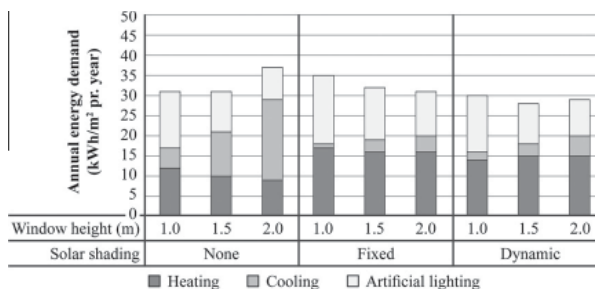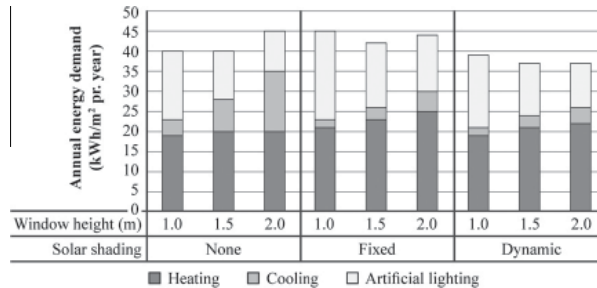
Fig. 8. Distribution of annual energy demand for heating, cooling and artificial lighting for simulation models with façades facing east.
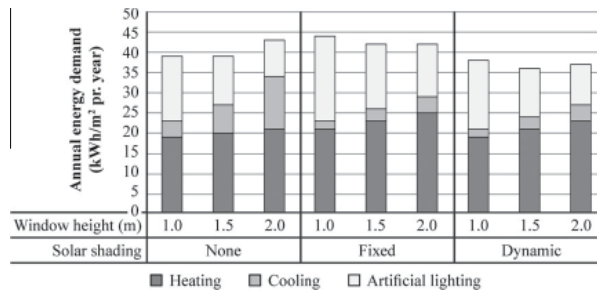
Fig. 9. Distribution of annual energy demand for heating, cooling and artificial lighting for simulation models with façades facing west.

2.0 m, whereas the façade with dynamic solar shading had the best performance at a window height of 1.5 m. The tendencies of the performance indicators were similar for façades with fixed and with no solar shading, but the magnitudes differed. When the window height was increased, the heating and lighting demand decreased while the cooling demand increased. Façades with dynamic solar shading displayed an increase in heating and cooling demand, but a decrease in energy demand for artificial lighting. The façades with no solar shading displayed considerable interdependence between all the performance indicators: increasing the window height resulted in an increased cooling demand that exceeded the combined decrease in energy demand for heating and artificial lighting. The façades with fixed or dynamic solar shading showed similar magnitudes of variation between the performance indicators.

4.4. East and west

Models with façades facing east showed a reduction in total annual energy demand between the worst (63 kWh/m^2 per year) and best-performing façade (55 kWh/m^2 per year) amounting to approximately 13% (Fig. 8). The east-facing façade with no shading performed equally well at

window heights of 1.0 m and 1.5 m. The east-facing façade with fixed solar shading had the best performance at a window height of 1.5 m, whereas the façade with dynamic solar shading performed equally well at window heights of 1.5 m and 2.0 m.

Models with façades facing west showed a reduction in total annual energy demand between the worst (62 kWh/m^2 per year) and best-performing façade (54 kWh/m^2 per year) amounting to approximately 13% (Fig. 9). The west-facing façade with no shading performed equally well at window heights of 1.0 m and 1.5 m. The west-facing façade with fixed solar shading performed equally well at window heights of 1.5 m and 2.0 m. The west-facing façade with dynamic solar shading had the best performance at a window height of 1.5 m.

For east and west-facing façades, all the performance indicators showed similar tendencies for all window heights and types of solar shading. When the window height was increased, the energy demand for heating and cooling increased and the energy demand for artificial lighting decreased. All east and west-facing façades showed a proportionally greater difference in the energy demand for artificial lighting when the window height increased from 1.0 m to 1.5 m compared to an increase in window height from 1.5 m to 2.0 m. For east and west-facing façades with no

lar shading, the energy demand for cooling was greater
an for façades with fixed or dynamic solar shading.

5. *Daylight*

  The amount of daylight for the three different types of
lar shading at window heights of 1.0 m, 1.5 m and
0 m are presented in the form of daylight factors and
picted in Fig. 10, with the threshold of a 2% daylight fac-
r indicated. Because of the uniform overcast-sky condi-
ns, the dynamic solar shading was not activated and
ylight factors for models with no solar shading and mod-
s with dynamic solar shading were equal.

  In general, the daylight factor decreases as the distance
om the façade increases and the window height decreases.
he results group the performances of the façades with
spect to daylight factors via varying dependence on the
stance from the window. The façades with no solar shad-
g or with dynamic solar shading displayed a greater
pendence on the distance from the window compared
 the façades with fixed solar shading, and they displayed
more dramatic decrease in the daylight factor as the dis-
nce from the façade increased than did façades with fixed
lar shading. The difference between the two groups was
eatest close to the façade and decreased as the distance
om the façade increased, so that daylight factors tended
converge at the back of the room, but still with consid-
able differences. However, where the window height was
e same, façades with no solar shading and façades with
namic solar shading always performed better with
spect to daylight than façades with fixed solar shading.

  With regard to the amount of daylight, only façades
ith a window height of 2 m with no solar shading or with
namic solar shading provided a daylight factor of a min-
num of 2% in the entire working zone. Under CIE over-
st-sky conditions, only these façades provided an
uminance of minimum 200 lux for the area extending 4
etres from the façade and thereby enough daylight for

the general lighting to be dimmed to the minimum effect
indicated in Table 1. Reducing the window height to
1.0 m or 1.5 m reduced the distance from the façade where
a minimum of 2% daylight factor could be maintained to
2.25 or 3.5 m, respectively. For façades with fixed solar
shading, window heights of 1.0 m, 1.5 m and 2.0 m meant
that the distance from the façade where a minimum of
2% daylight factor could be maintained was approximately
1.0 m, 2.0 m and 3.0 m, respectively.

5. Discussion

  The results for the simulated parameter variations illus-
trate that even in the relatively cold north-European cli-
mate, where heating often dominates the total energy
consumption, energy demand for cooling and artificial
lighting are also important – especially in low-energy build-
ings. General for all orientations, of course, is that
increased façade transparencies allow more insolation into
the room. A general tendency that is observed is a reverse
proportionality between cooling and artificial lighting.
However, the energy demand for heating and cooling
depends not only on increased insolation, which varies
greatly depending on the orientation, but also on the
change in the thermal performance of the façade that
occurs when glazing replaces an opaque façade. Further-
more, our simulations of the daylight factors showed a
much greater difference in performance between façades
with no solar shading or with dynamic solar shading and
façades with fixed solar shading.

  The results for the cases examined show that in most
cases dynamic solar shading constitutes the best design
alternative, but also that the difference in total energy
demand between the best and the second best are minor
and can be non-existent. Thus, when all results are consid-
ered, the difference in total energy demand between the
worst and the best-performing façade for a given orienta-
tion does not exceed 16%. With respect to energy, façades
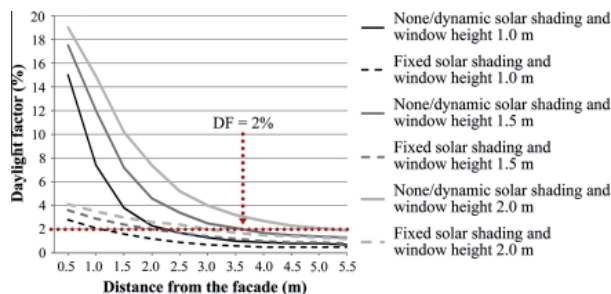
g. 10. Daylight factors in the working plane (0.85 m above the floor) along the centreline in the room in relation to the distance from the window
picted by solar shading type and window height, using the CIE overcast sky. Daylight factors for façades with no solar shading and façades with
namic solar shading are equal because the dynamic solar shading would not be activated under overcast-sky conditions. The threshold of a 2% daylight
ctor corresponding to 200 lux when the illuminance on an outside unobstructed surface is 10,000 lux has been indicated.

with fixed or no solar shading are a relevant alternative for all façades facing north and for façades with window heights of 1.0 m or 1.5 m facing south, east and west. But when it comes to daylight factors, dynamic solar shading shows a dramatic improvement in performance over fixed solar shading. The increased daylight factor results in an expansion of the well-lit area by 70–150%. The increased amount of daylight available provided by a dynamic solar shading more adaptable to the climate, therefore allows a greater and more flexible utilisation of the space, so that more work stations can be established. The façade design, the geometry of the room and its function should therefore be considered simultaneously. It should be noted that the daylight factor, although a simple indication of a worst-case scenario, is still a measure used to document the amount of daylight. Furthermore, the energy demand for the photo-responsive artificial lighting with a continuous dimming profile controlled in accordance with weather data will ultimately reflect the amount of daylight available similar to the daylight autonomy. Thereby the two measures together satisfactorily indicate the façade's performance with respect to daylight. Thus the results prove the importance of integrated simulations to quantify the potential of dynamic fenestration systems due to the great interdependence of the various parameters. Furthermore, this quantification needs to be performed in the early stages of the design process, where essential design decisions defining the framework and preconditions for the building's performance are made – not only to obtain a more complete performance assessment, but also to better tailor the façade design to the actual building, its layout and its function. Open plan offices with work stations far from the façade require high façade transparency and a dynamic solar shading to obtain sufficient amounts of daylight without having problems with overheating, whereas fixed solar shading could be considered for a one or two-person office where work stations can be established close to the façade.

Dynamic solar shading with its ability to reduce energy consumption and improve occupant comfort may therefore not always be the optimal choice when economics (acquisition and maintenance) or subjective factors such as aesthetics are included.

Each simulation was only performed on a single, but representative room in the perimeter zone of a building, and the interaction with the rest of the building was considered as increased transmission heat loss through the roof, gable and floor. The actual performance of the entire building depends not only on the control strategy chosen for each room, but on the control strategy for the entire building. However, our focus was on depicting the performances of different façade designs and the importance of considering alternatives. iDbuild provides adequate information for the comparison and evaluation of various alternatives in respect to both indoor climate and energy consumption.

It should be noted that the results represent a building placed in a totally unobstructed environment and therefore with a high degree of daylight available. In an urban envi-

ronment, where a smaller amount of daylight is available, the potential disadvantage of permanently reducing the amount of daylight by implementing fixed solar shading and thereby increasing the energy demand for artificial lighting is not fully disclosed. Moreover, this article focuses on comparing façades with no solar shading with one specific type of dynamic and fixed solar shading. Therefore the results cannot be used for an evaluation of dynamic solar shading or dynamic fenestration systems in general. However, investigation of other dynamic façade components will form part of our future work. Furthermore, the highly glazed façades which seem to be a prevailing element in modern office buildings mean that dynamic solar shading is very relevant for the control of large amounts of insolation and minimise the risk of overheating, while still providing views of the outside. This relevance will only increase when the stricter demands for "nearly zero-energy buildings" are implemented in 2020 (EPBD, 2010).

6. Conclusion

To quantify the potential of dynamic solar shading, we have presented simulation-based results from an investigation of three different solar shading types. Integrated thermal and daylight simulations were carried out to demonstrate comparable results of the performances of the façades with respect to energy consumption and indoor environment. The performances of the façades were evaluated in terms of total energy demand, the individual energy demands for heating, cooling and artificial lighting, and also the amount of daylight in terms of daylight factor. The quality of the indoor environment for all the models simulated complied with Class II defined in the European standard CEN 15251, 2007.

For a typical office located in Denmark, the significance of orientation, window area and solar shading types was investigated to emphasise the importance of involving design alternatives in the early stages of design, when critical decisions on the design of the façade are made. The work presented demonstrates how an available open source program can perform integrated simulations, reveal a high degree of interdependence between parameters, and thus make it possible to quantify a façade's performance in a given context and achieve harmony between the layout of the building and its functions.

References

Athienitis, A.K., Tzempelikos, A., 2002. A methodology for simulation of daylight room illuminance distribution and light dimming for a room with a controlled shading device. Solar Energy 72 (4), 271–281.

Brundtland, G.H., 1987. World Commission on Environment and Development. In: Our Common Future. Oxford University Press, Oxford.

CEN, 2007. EN15251:2007 – Indoor environmental input parameters for design and assessment of energy performance of buildings – addressing indoor air quality, thermal environment, lighting and acoustics.

Clarke, J.A., Janak, M., Ruyssevelt, P., 1998. Assessing the overall performance of advanced glazing systems. Solar Energy 63 (4), 231–241.

BST, 2006. Bygningsreglement for erhvervs- og etagebyggeri. In: National Agency for Enterprise and Construction. Copenhagen, Denmark.

PBD, 2002. Energy Performance Building Directive – Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings.

PBD, 2010. Directive 2010/.../EU of the European Parliament and of the Council of on the Energy Performance of Buildings (recast). <http://register.consilium.europa.eu/pdf/en/10/st05/st05386-ad01.en 10.pdf>.

anzetti, C., Fraisse, G., Achard, G., 2004. Influence of the coupling between daylight and artificial lighting on thermal loads in office buildings. Energy and Buildings 36 (2), 117–126.

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

A, 2009. Key World Energy Statistics 2009. International Energy Agency, Paris.

CC, 2008: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K., Reisinger, A. (Eds.)]. IPCC, pp. 30.

hnson, R., Sullivan, R., Selkowitz, S., Nozaki, S., Conner, C., Arasteh, D., 1984. Glazing energy performance and design optimization with daylighting. Energy and Buildings 6 (4), 305–317.

oo, S.Y., Yeo, M.S., Kim, K.W., 2010. Automated blind control to maximize the benefits of daylight in buildings. Building and Environment 45 (6), 1508–1520.

e, E.S., DiBartolomeo, D.L., Selkowitz, S.E., 1998. Thermal and daylighting performance of an automated venetian blind and lighting system in a full-scale private office. Energy and Buildings 29 (1), 47–63.

e, E., Selkowitz, S.E., Bazjanac, V., Inkarojrit, V., Kohler, C., 2002. High-performance commercial building façades. Lawrence Berkeley National Laboratory: Lawrence Berkeley National Laboratory. LBNL Paper LBNL-50502. <http://www.escholarship.org/uc/item/7d30b3rd> (accessed 14.09.10).

e, E.S., DiBartolomeo, D.L., Rubinstein, F.M., Selkowitz, S.E., 2004. Low-cost networking for dynamic window systems. Energy and Buildings 36 (6), 503–513.

ollini, R., Danza, L., Meroni, I., 2010. Energy efficiency of a dynamic glazing system. Solar Energy 84 (4), 526–537.

Löhnert, G., Dalkowski, A., Sutter, W., 2003. Integrated Design Process: A Guideline for Sustainable and Solar-Optimised Building Design. International Energy Agency (IEA) Task 23 Optimization of Solar Energy Use in Large Buildings, subtask B. Austria.

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

Ochoa, C.E., Capeluto, I.G., 2009. Advice tool for early design stages of intelligent façades based on energy and visual comfort approach. Energy and Buildings 41 (5), 480–488.

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

Perez, R., Seals, R., Michalsky, J., 1993. All-weather model for sky luminance distribution – preliminary configuration and validation. Solar Energy 50 (3), 235–245.

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

Robinson, D., Stone, A., 2006. Internal illumination prediction based on a simplified radiosity algorithm. Solar Energy 80 (3), 260–267.

Selkowitz, S.E., 1998. The Elusive Challenge of Daylighted Buildings. Daylighting'98 Conference, Ottawa, Canada.

Strachan, P.A., 2008. Simulation support for performance assessment of building components. Building and Environment 43 (2), 228–236.

Tregenza, P.R., 1987. Subdivision of the sky hemisphere for luminance measurements. Lighting Research and Technology 19 (1), 13–14.

Tzempelikos, A., Athienitis, A.K., 2007. The impact of shading design and control on building cooling and lighting demand. Solar Energy 81 (3), 369–382.

Tzempelikos, A., Athienitis, A.K., Karava, P., 2007. Simulation of façade and envelope design options for a new institutional building. Solar Energy 81 (9), 1088–1103.

Wienold, J., Christoffersen, J., 2006. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. Energy and Buildings 38 (7), 743–757.

Wilde, P.D., Voorden, M.V.D., 2004. Providing computational support for the selection of energy saving building components. Energy and Buildings 36 (8), 749–758.

WinDat, 2006. Window Information System software (WIS), WinDat Thematic Network, TNO Bouw, Netherlands. <http://www.windat.org>.

Paper III

Simulation based design development of the facade for a new university building

Submitted to Solar Energy.

Simulation-based design development of the façade for a new university building

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Abstract

This paper presents a simulation case study of façade design options for a new university building in Denmark carried out during the initial stages of design. Focus was on a geometrical optimisation and the utilisation of passive properties that is essential in the development of the architectural concept. The main objective was to develop a façade design that could efficiently control the amount of insolation, uphold a satisfactory quality of indoor environment, contribute to a reduction in energy demand, and at the same time support and consolidate the architectural vision. Detailed simulations were carried out to support the early design development of the façade in terms of overall geometrical form, window sizes, glazing types, and the selection of solar shading. Integrated thermal and daylight analyses were carried out to make design recommendations and evaluate the design proposition's effect on the daylight utilisation, the annual energy demand for heating, cooling and artificial lighting, and the peak loads for heating and cooling. Simulation results showed significant performance improvements from making use of the passive properties of the building and that substantial reductions in annual energy demand, peak loads for heating and especially cooling could be achieved.

Keywords: Integrated façade design; Energy efficiency; Case study; Geometrical optimization; Indoor environment

1. Introduction

Many critical design decisions, which to a very great extent define the building's performance with respect to both energy demand and indoor environment, are made during the conceptual stages of design. Concepts for the overall building design, and more specifically the façade, are often based solely on an aesthetic point of view, but a broader performance perspective that also takes energy demand and indoor environmental quality into account should be considered a central issue when trying to strike the right balance between all the performance parameters.

A building's performance in relation to parameters such as heating and cooling demand, ventilation rates, daylight, shading, artificial lighting, and the control of all the systems that subsequently regulate these parameters, as well as the comfort of the occupant are all closely related. In fact, the desired level of comfort to a great extent determines the energy demand, and the occupant's comfort can only be measured at room level, where requirements and behaviour can be evaluated (Clarke et al., 1998). In this context, technological advances in façade components, especially glazing and solar shading, in combination with enhanced focus on daylight optimisation, have resulted in a lot of highly glazed buildings in the last few decades. The increase in glazed area results in highly fluctuating heating and cooling demand because the transparent part of the façade increases transmission heat loss and transmitted solar radiation. So the design of the façade, especially the fenestration, is a central point in determining the building's overall performance in relation to energy efficiency and indoor environmental quality. Because of the wide variety of parameters that need to be considered and their mutual dependency, an integrated simulation approach that takes both energy efficiency and indoor environmental quality into account needs to be employed from the very beginning of the design process.

The significance and relevance of an integrated approach to simulation of building performance were pointed out by Morel & Faist (1993) and Clarke et al. (1998) and further investigated by Citherlet et al. (2001). The need for integrated simulation tools to provide a more holistic performance evaluation at overall building level, façade level, and in the selection of the individual building component, was analysed and discussed by Citherlet & Hand (2002), Selkowitz (2001) and de Wilde et al. (2002). Moreover, recent analyses suggest providing simulation support to the crucial early design stages (Petersen and Svendsen, 2010) to enable an informed choice between design alternatives (Nielsen et al., 2011). Furthermore, several studies describe and analyse the potential performance optimisation benefits from integrated simulations, ranging from a reduction in total energy demand and peak cooling/heating demands to an improvement in occupant comfort in terms of daylight conditions and thermal indoor environment (Lee et al., 1998; Laforgue et el., 1997; Franzetti et el., 2004; Tzempelikos et al., 2007).

However, integrated simulations of the building performance are rarely carried out early in the design process, despite the need for design evaluation at this crucial stage. The highly iterative nature of the initial design phases, where many professional disciplines are in play, is not dominated by interoperability, but requires a high degree of focus on the process rather than merely on the data (Augenbroe et al., 2004).

This article presents simulations carried out during an architectural competition process with the aim of supporting the design development of a major new university building for the University of Copenhagen in Denmark. The work presented here focuses on the design development of the façade and encompasses work carried out from the very start of the project through to the delivery of the final design proposal. The objective was to create a building façade capable of achieving an equilibrium between daylight, energy and indoor environment, as well as meeting the demands for a high level of architectural quality and expression. An integrated approach was followed from the very beginning of the process, constantly benchmarking design alternatives throughout the design development. Fully integrated simulations of the building's performance in terms of annual energy demand, indoor thermal environment and daylight availability were updated continuously as the design process proceeded. Focus was on utilising the potential benefits of the passive properties, such as self-shading from building and façade geometry, window size and glazing, before making use of the potential of dynamic properties, such as adjustable solar shading. The hierarchy of initially performing a geometrical optimisation essential for the development of the architectural concept was followed to achieve a more robust design proposition, whose sheer form provided energy efficiency and a high level of indoor comfort. The aim was to minimise the need for energy consuming HVAC-systems and dynamic façade components, which not only increase the total cost of the façade substantially, but also often create difficulties in terms of their control during and after commissioning.

The outcome of this work was a series of design recommendations for the building's façade that also took into account its impact and interaction with the building's sub-systems. Because the work presented in this article was carried out during an actual architectural competition, decisions for the final design proposal were also influenced by architectural constraints, overall cost considerations and building restrictions, as well as performance in terms of energy and indoor environment.

2. The building/Case

The project considered is located in the centre of Copenhagen, Denmark (55.4°N, 12.4°E) and principally consists of two buildings joined by skywalks. It is to house single offices, classrooms and auditoriums, meeting rooms, various types of laboratories, and a wide range of support functions. The total floor area is about 46,500 m^2 and the two buildings represent two stages of construction. The largest building, with a total floor area of approximately 33,000 m^2 spread over 6 storeys (incl. basement), and which is to be constructed first, is the only one considered here (Fig. 1).
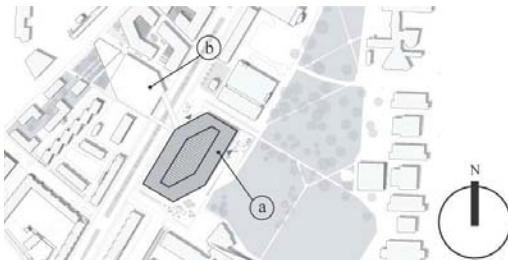
Fig. 1. Site plan for the project showing the surroundings with the two buildings connected by skywalks: a) the building considered, and b) the building to be constructed in the second phase.

The building will house a wide range of functions, many of which have highly specific performance demands outweighing all other considerations. Special facilities such as laboratories often have shorter occupation periods for the single occupant, high air-change rates because of special ventilation requirements, and limited requirement for daylight. The scope of this research was to underline the potential of simulations that support a design development in which many interdependent parameters on energy and the indoor environment are in play and show how they can be provided. So two predominant functions and room typologies, which were not governed by lopsidedness in terms of their performance requirements, were selected as the objects of analyses throughout this research:

- Offices accommodating 2 persons (approx. 5,500m^2) - 3 x 4 x 3.2 m high

- Classrooms accommodating 30 persons (approx. 2,000m^2) - 12 x 6 x 3.2 m high

The building has a relatively large central atrium extending from ground level up to the full height of the building and all rooms face either the surrounding exterior environment or the interior atrium. Here, only rooms in the perimeter zone of the building, i.e. directly adjacent to the exterior climate, are considered. Throughout the process, a number of design alternatives were analysed using integrated thermal and daylighting simulations carried out for each of the six façades (Fig. 2).

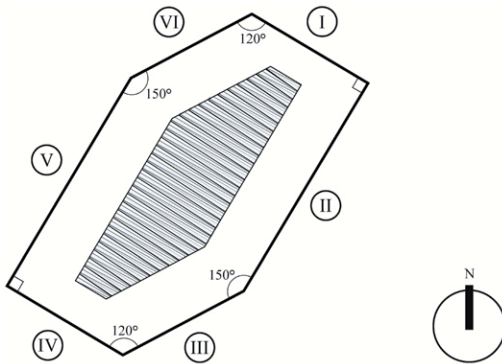**Fig. 2. Illustration of how the façades are oriented and numbered. For each of the façades, a simulation was performed for both a single office and a classroom.**

This article presents a range of parameters analysed in relation to the design development of the façade:

- Facetting of the façade

- Façade transparency

- Glazing type

- Implementation of solar shading

Focus was on controlling insolation to achieve an equilibrium between daylight utilisation and the prevention of overheating in the search for energy efficiency and a high-quality indoor environment. The evaluation of design alternatives was carried out for a set of performance indicators:

- Optimised utilisation of daylight (daylight autonomy)

- Annual demand for heating, cooling and artificial lighting

- Peak heating and cooling load

The façade performance in terms of daylight availability, the annual demand for heating, cooling and artificial lighting, as well as peak heating and cooling loads, was only evaluated for a defined occupancy period ranging from 8 am to 5 pm Monday through Friday. It should be noted that throughout the design development, a reduction in cooling demand was deemed more important than a reduction in heating demand. This was because the project was situated in an area with highly efficient district heating, whereas cooling would be tantamount to an electricity demand with a higher primary energy factor according to Danish building regulations (EBST, 2010) and an increase in building cost.

Daylight availability was evaluated for daylight autonomy based on a target illuminance of 500 lux at the work plane (0.85m above the floor). The daylight autonomy was simulated using the Radiance-based dynamic daylight simulation tool DaySim (Reinhart & Walkenhorst, 2001) and evaluated during occupancy for a full work year.

The competition brief stated an indoor environment equivalent to Class II in the European standard as the minimum requirement (CEN, 2007). So, a seasonal distinction was made for all simulation models to determine the demand for heating and cooling. Summer (weeks 1-18 and 38-53) and winter (weeks 19-37) were defined in accordance with the typical heating season in Denmark (EBST, 2010) and coupled with the Class II temperature criteria for heating and

cooling. Constant air flow rates for mechanical ventilation were determined in accordance with the air-quality requirements for Class II. Heating, cooling and ventilation were simulated as active during occupancy the entire year, so that the system set-up would result in an indoor thermal environment and an air quality that always corresponded to Class II requirements. The artificial lighting was controlled based on a work plane target illuminance of 500 lux and evaluated in the centre of the room, 0.85 m above the floor. Lighting was simulated with active dimming control in accordance with daylight availability (continuous dimming control of all lights) with a power density of 12 W/m^2. Table 1 shows the input data on temperature criteria, internal loads (people and equipment) and power density for artificial lighting used in simulation.

Table 1. Input data on temperature criteria, internal loads (people and equipment) and power density for artificial lighting used in simulations.

		Occupancy (8 am to 5 pm)	Non-occupancy
Set point temperatures – heating/cooling [a]			
	Summer	*20/24 °C*	*-*
	Winter	*23/26 °C*	*-*
Infiltration		*0.1 h^{-1}*	*0.1 h^{-1}*
Mechanical ventilation [b]			
	Office	*1.9 l/s·m^2*	*0.0 l/s·m^2*
	Classroom	*3.4 l/s·m^2*	*0.0 l/s·m^2*
Internal loads from persons and equipment			
	Office	*20 W/m^2*	*1 W/m^2*
	Classroom	*45 W/m^2*	*1 W/m^2*
Artificial lighting			
	Illuminance set point	*500 lux*	*-*
	maximum power	*12 W/m^2*	*0 W/m^2*
	min. power (stand-by)	*0.5 W/m^2*	*0 W/m^2*

a) Temperature criteria equivalent to Class II in the European standard EN 15251:2007 (CEN, 2007).
b) Equivalent to indoor air quality Class II in the European standard EN 15251:2007 (CEN, 2007).

The heat transfer coefficient (U-value) for the opaque part of the façade was kept constant at 0.2W/m^{2}K and the window frame width was kept constant at 0.1m with a U-value of 1.5W/m^{2}K.

It should be noted that both annual heating and cooling demand and peak heating and cooling load were determined numerically and do not take system set-up and efficiency into consideration. Moreover, the ventilation rates in the European standard gave different air exchange rates for offices and classrooms, which not only resulted in a higher ventilation energy demand for classrooms than offices (kWh/m^2 per year), but also potentially translates into a certain degree of overheating being removed by means of ventilation resulting in reduced cooling demand.

3. Design development of the façade

In selecting an appropriate façade design focus should be on its significant influence on the annual energy demand and the seasonal peak heating and cooling demands in winter and summer respectively, as well as its performance in relation to daylight and the thermal indoor environment. The overall configuration of the façade in transparent and opaque elements has to be considered, as well as the thermal, visual and spectral properties of each façade component, and coupled with potential control strategies for shading and artificial lighting in the light of the actual climate.

The competition brief emphasises in several places a desire for an extremely high degree of flexibility in terms of spatial and system layout. Single offices have to be able to be joined together to form open-plan offices, classrooms or laboratories, and vice versa. To comply with this, the façade was considered to have to be a repetitive system of 3-metre wide and storey-high modules. So the façade for a single office (3 m wide) is one module and that for a classroom (12 m wide) consists of four modules.

3.1 Faceting and orientating the façade

A building's expression is often largely defined by the façade design, and for this particular building it was established using a facetting mainly of the vertical surfaces and with it a change in the window orientation. The facetting of the façade was a further emphasis of the architectural concept, which sought to optimise the relationship and connection of the building with its surroundings and between people in and around the building by utilising lines of sight within the area. Fig. 3 illustrates the geometrical processing of the overall building volume and the façade, which first entailed a facetting in the four major orientations (North, South, East and West), and secondly a displacement of each storey in relation to those vertically adjacent.
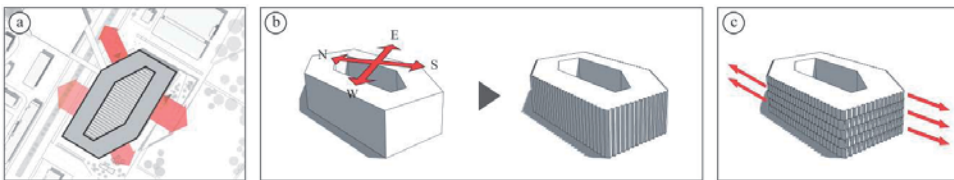

Fig. 3. Illustration of the steps in the geometrical processing, firstly of the building volume (a) utilising the lines of sight and optimising the relationship and connection of the building with the surroundings, and secondly of the façade (b) with overall facetting according to the four major orientations (north, east, south and west), and (c) horizontal displacement of each storey in relation to those vertically adjacent.

The facetting of the façade provides a self-shading effect that reduces transmitted solar radiation and can therefore reduce both the annual cooling demand and the peak cooling load. The facetting relates to the 3-metre module and was generated by sub-dividing the vertical façade plane and then changing the window orientation in relation to the initial façade plane, but this also results in an increase in both the vertical and horizontal surface areas of the façade. The facetting was investigated by comparing the plane façade with two different window angles while keeping the window size constant (Fig. 4).
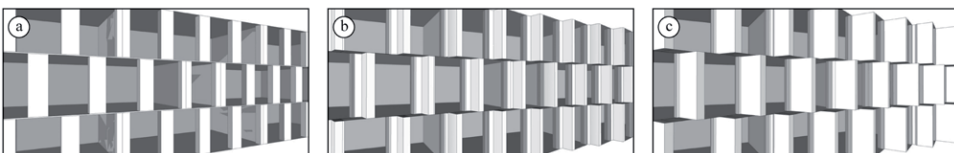
Fig. 4. Illustration of the geometries used to analyse the influence of façade facetting on the performance in relation to energy and daylight: (a) plane façade, (b) 15° angling, and (c) 30° angling. Window sizes were kept constant for all simulation models.

Simulations included the passive solar shading caused by the facetting that constantly reduces heat gain and daylight and which could result in an increase in the demand for heating and artificial lighting. The aim was to determine how the faceting influences the performance, and so facilitate the selection of an appropriate design. Design decisions are

also driven by architectural considerations, so simulations were performed to quantify a suitable equilibrium between architectural aesthetics and the performance criteria previously mentioned (optimised utilisation of daylight, annual demand for heating, cooling and artificial lighting, and peak heating and cooling load).

Simulations of the effect of the facetting on the façade performance were performed with a window size of 2 x 2.9 m (width x height) and double-layer glazing with low emissivity coatings (see Table 2). The glazing type and window size were further investigated and analysed later in the process (see section 3.2).

Fig. 5. Distribution of annual demand for heating, cooling and artificial lighting for single offices and classrooms for the different façades and facetting angles.

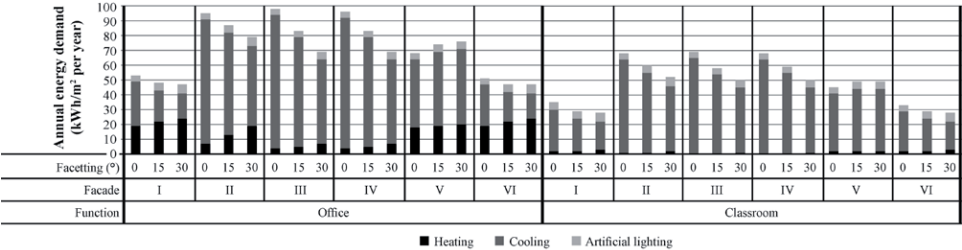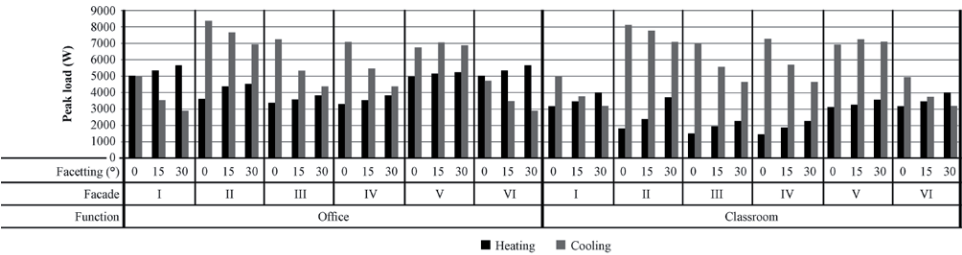**Fig. 6. Peak heating and cooling loads for single offices and classrooms for the different façades and facetting angles.**
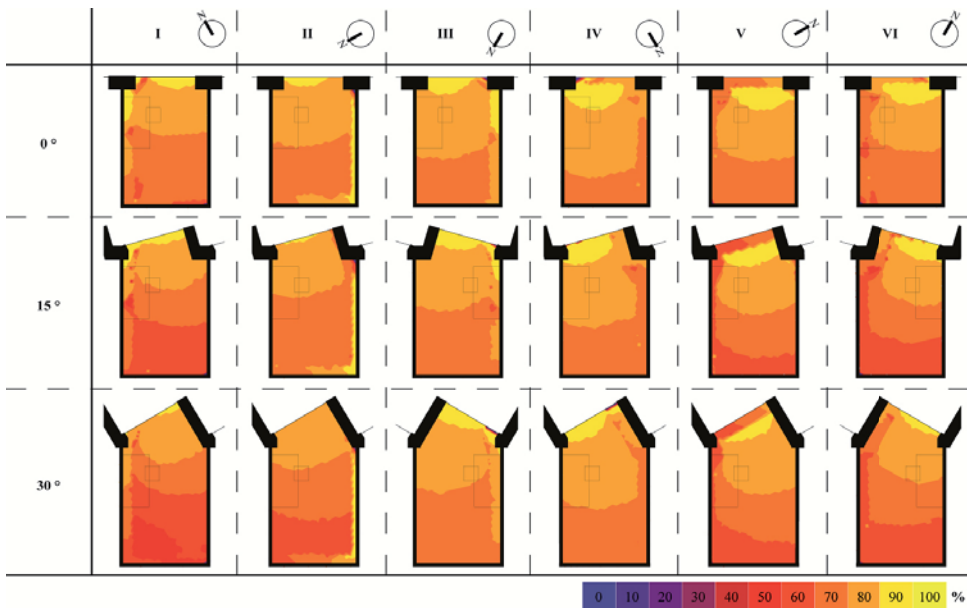
Fig. 7. Daylight autonomy for single offices for the different façades and facetting angles.

If we look at the total annual demand for heating, cooling and artificial lighting, offices displayed higher values than classrooms (Fig. 5), but cooling demand was generally the dominating parameter for all models. The difference between offices and classrooms was mainly due to differences in heating demand, but also a difference in cooling demand could be observed for the majority of models, whereas the demand for artificial lighting was fairly constant for all models. Façades II, III and IV displayed similarly high values for the total annual demand for both offices and classrooms, façade V slightly lower, and façades I and VI the lowest values. The effect of an increase in the degree of facetting was an overall decrease in the total annual demand for heating, cooling and artificial lighting for both offices and classrooms compared with the plain façades, except in the case of façade number V where there was a slight increase. The demands for heating and artificial lighting generally increased, while the demands for cooling decreased when the degree of facetting was increased. Results for façade number V were different and showed an increase in all three demands making up the overall increase.

The peak heating and cooling loads for offices and classrooms (Fig. 6) showed similar tendencies to the annual heating and cooling demands, in terms of both the difference between the six different façades and the effect of the degree of facetting. So, peak loads for heating and cooling respectively increase and decrease as the degree of facetting was increased. Again, the results for façade V showed opposite tendencies.

In relation to daylight availability, simulations of the annual daylight autonomy were performed for offices adjacent to all six façades (Fig. 7). The daylight autonomy results showed that increased facetting generally decreases the daylight availability, most significantly for façades I and VI, less for façades II and V and only slightly for façades III and IV. With the maximum degree of facetting (30° angling of the window), a minimum of 500lux at the work plane was received by offices behind façades I and VI (facing north) for at least 50-60%, by offices behind façades II and V (facing east and west, respectively) for a minimum of 60%, and by offices behind façades III and IV (windows facing south) for at least 70% of the occupied time during a year. Moreover, the demand for artificial lighting (based on hourly daylight levels in the middle of the room) only display minor differences between the plain and facetted façades, so the

facetting did not appear to result in unacceptable reduction in daylight levels. Offices were evaluated as being the worst case, because of the decrease in horizontal daylight dispersion due to the internal walls.

After evaluating the results for the effect of facetting on the performance indicators (daylight utilisation, annual demand for heating, cooling and artificial lighting, and peak heating and cooling load), it was decided to select the highest degree of facetting for all façades and further optimise the transparency and glazing type in accordance with the different orientations of the six façades.

3.2   Transparency and thermal properties

The next consideration was the selection of an appropriate façade transparency and glazing type for the façade module. In the perimeter spaces, the focus was on optimising daylight utilisation and thermal performance. So various façade transparencies (Fig. 8) and glazing types (Table 2) were investigated to optimise the equilibrium between the performance indicators.
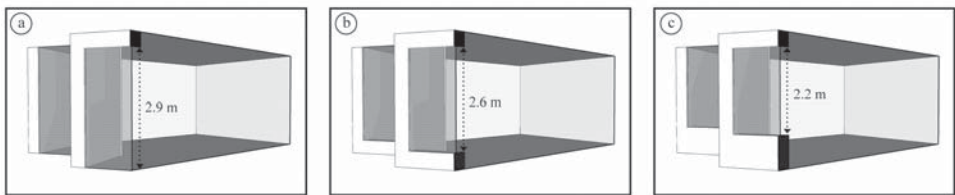
Fig. 8. Illustrations of the three different transparencies analysed for the façade modules, with a constant window width of 2 m: (a) window height of 2.9 m, (b) a window height of 2.6 m, and (c) a window height of 2.2 m.

Table 2. Heat transfer coefficient (U-value), light transmittance (LT) and total solar energy transmittance (g-value) of the two types of glazing analysed.

#	Glazing	U-value (W/m²K)	LT (%)	g-value (%)
1	Double-layer with low-emissivity coatings*	1.08	77	55
2	Triple-layer window with low-emissivity coatings	0.73	70	50

* the glazing used in the simulations of the effect of the facetting on the façade performance in paragraph 3.1.

First, the effect of the façade transparency and glazing type on the indoor thermal environment close to the façade was analysed to ensure that workstations could be placed directly adjacent to the façade without the occupant experiencing thermal discomfort so the requirements for flexibility could be met. This was done by evaluating the mean radiant temperature (MRT) and the radiant temperature asymmetry (RTA). The lowest outdoor temperature during occupancy in the design reference year (DRY) for Denmark was -18°C, which was used for analysis. The interior surface temperature of the glass pane was determined using Window 6.3 (Mitchell et al., 2011) for an indoor air temperature of 22°C (average temperature for a Class II thermal environment, see Table 1). The MRT and RTA were determined for a person seated 1m from the façade.

Table 3. Surface temperature of the glass pane, mean radiant temperature and radiant temperature asymmetry for the various glazing types and façade transparencies in offices during the coldest outdoor temperature during occupancy.

Glazing type	Surface temperature	Window height	Mean radiant temperature	Radiant temperature asymmetry*
	°C	(m)	°C	°C
1	16.0	2,9	20.9	6.0
		2.6	21.0	
		2.2	21.2	
2	18.3	2.9	21.3	3.7
		2.6	21.4	
		2.2	21.5	

* for a person seated 1m from façade.

The objective was to keep the temperatures within the range defined in the European standard (see Table 1) while keeping the RTA below 10°C (CEN, 2001; ASHRAE, 2001). Table 3 shows that none of the glazing types resulted in an RTA above the threshold under cold conditions and in principle perimeter heating would therefore not be necessary.

Further optimization of the façade transparency and glazing type was performed for each individual façade by considering the performance indicators: daylight optimisation, annual demand for heating, cooling and artificial lighting, and peak heating and cooling loads. In general, the tendencies were similar to those displayed in the investigation of the degree of facetting: offices showed higher values for the total annual demand (heating, cooling and artificial lighting) than classrooms. Both the heating and cooling demands were significant for offices whereas cooling was the main factor in the total annual demand for classrooms. Similar tendencies were observed in the peak loads for heating and cooling. Peak loads for heating were significantly higher for offices than for classrooms, whereas cooling peak loads for the individual façades are similar for both offices and classrooms. For all models a reduction in window size reduces the total annual demand for heating, cooling and artificial lighting and the same is the case when glazing number 2 is used instead of glazing number 1. Here it should be noted that the positive effect of selecting a higher-performance glazing, in this case type 2 instead of type 1, is generally greatest at high façade transparencies. So the most significant beneficial effects are found in the largest window sizes.

Façades I and VI in principle perform equally well, both in terms of annual demand for heating cooling and artificial lighting and their allocation (Fig. 9) and in terms of the heating and cooling peak loads (Fig. 10). However, while façade I was not important in the quest for visual interaction between the building, the occupants and the surroundings because it faces a fully opaque neighbouring gable, façade VI was very significant in this aspect, because it faces the common entrance area towards the north, which connects to other buildings used by the same occupants (see Fig. 1 and Fig. 3). So a window height of 2.2 m was selected for façade I, while façade VI was designed with a window height of 2.9 m (without spandrel) to optimise the visual connection. Glazing type 1 was selected for façade I partly because the decreased window size will result in less benefit from a window with better thermal properties and partly to optimise daylight utilisation for the façade that gave the lowest values for daylight autonomy (see Fig. 7). Glazing type 2 was selected for façade VI, resulting in a reduction of the annual demand for heating, cooling and artificial lighting and peak loads. Furthermore, this translated into capital cost savings because of the lower price for windows with glazing type 1 than for type 2.

Fig. 9. Distribution of annual demand for heating, cooling and artificial lighting for rooms adjacent to façades I and VI by window size and glazing type.

Fig. 10. Peak heating and cooling loads for rooms adjacent to façades I and VI by window size and glazing type.

Façades II and V also displayed very similar performances. The annual demands and peak loads for façade II were slightly higher than for façade V, as shown in Fig. 11 and Fig. 12. For façade II, it was deemed important to continue the window to floor level to maintain the line of sight between indoors and the common green area at ground level towards the east, so a window height of 2.9 m was selected. Because façade V partly faces other building façades relatively close by and is partly oriented towards an arterial road (long lines of sight), the window height was reduced to 2.6 m. Façades II and V both displayed high peak loads, especially for cooling, with the highest values of all six façades, so glazing type 2 was selected for both façades to reduce peak loads.
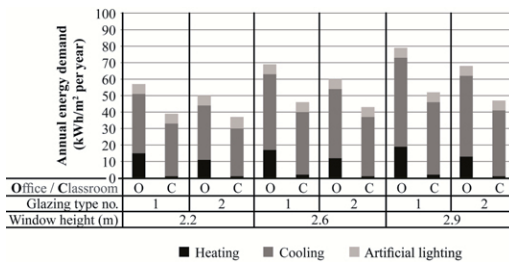
Fig. 11. Distribution of annual demand for heating, cooling and artificial lighting for rooms adjacent to façade II (with slightly higher values than façade V) by window size and glazing type.
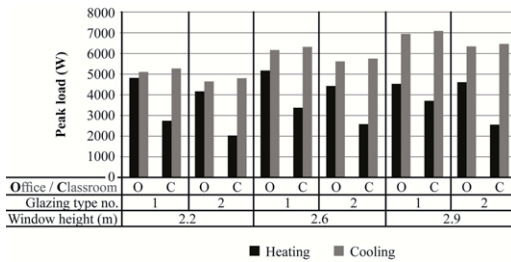
Fig. 12. Peak heating and cooling loads for rooms adjacent to façade II (with slightly higher values than façade V) by window size and glazing type.

Façades III and IV perform equally well in terms of annual demands (Fig. 13) and peak loads (Fig. 14). Façade III mainly faces other buildings, so a window height of 2.6 m and glazing type 2 was selected. Façade IV has no great importance in the quest for visual connection because it is orientated southwards towards an adjacent, fully opaque gable, so a window height of 2.2 m and glazing type 1 was selected.
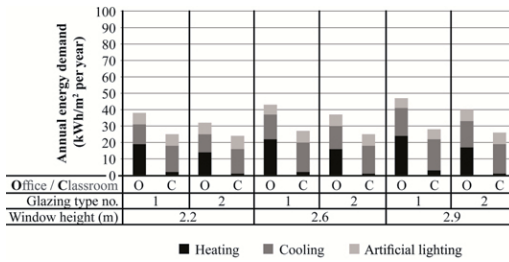

Fig. 13. Distribution of annual demand for heating, cooling and artificial lighting for offices and classrooms adjacent to façades III and IV by window size and glazing type.
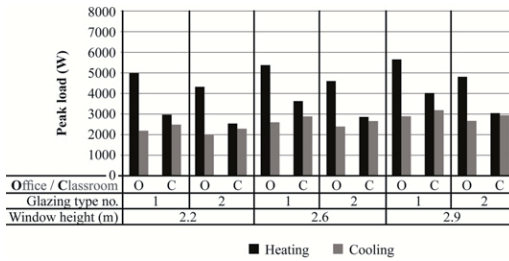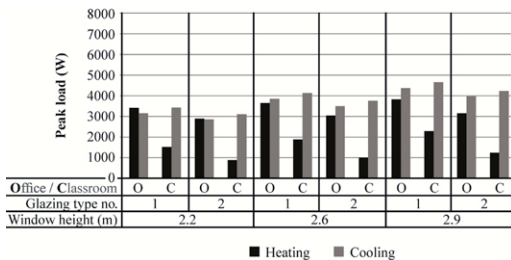

Fig. 14. Peak heating and cooling loads for offices and classrooms adjacent to façades III and IV by window size and glazing type.

Since the differences in window sizes were made by introducing a spandrel of either 0.4m or 0.8m in height, the reduction in daylight availability at work plane (0.85 m above floor level) would not be significant.

3.3 Implementation of solar shading

External adjustable solar shading can control solar radiation and thereby achieve a better equilibrium between internal and external loads. This can be done by blocking the direct solar radiation while admitting diffuse daylight, which mitigates overheating and reduces cooling demand while minimising the reduction in daylight availability. At other times, more solar radiation can be admitted to utilise all available daylight and passive heat gain to reduce the demand for lighting and heating. So the selection of solar shading is an optimisation problem between all the defined performance indicators.

The façades with windows facing east (II), south (III and IV) and west (V) displayed the highest total annual demand for heating, cooling and artificial lighting. Among the annual demands, it was cooling that, despite a lower heating demand for façades II through V, resulted in the increased total value. Façades II through V generally displayed the highest values for the peak cooling loads. So, two types of external solar shading were analysed for these façades: an adjustable and fully retractable Venetian blind, and a transparent fabric solar roller screen. Both were simulated as being controlled by the risk of both overheating and glare during occupancy, and overheating alone outside occupancy. The risk of overheating was evaluated based on the indoor operative temperature determined by the cooling set-point corresponding to a Class II thermal indoor environment according to European standards as stated in Table 1 (CEN, 2007). The risk of glare was evaluated in accordance with a daylight glare probability index proposed by Wienold and Christoffersen, 2006. If conditions were exceeded, the solar shading was activated and, in the case of the adjustable blinds, adjusted to a cut-off angle at which direct sun was just blocked.

Results generally showed that a reduction in the total annual demand for heating, cooling and artificial lighting could be observed for both offices and classrooms when the solar shading was employed (Fig. 15). For all models, this was due to a significant decrease in cooling demand. The individual annual demands for heating, cooling and artificial lighting for façades II and V show a 30-40% reduction in cooling demand and only a slight increase in the annual lighting demand. Results for façades III and IV showed a 50-60% reduction in the annual cooling demand, but an increase in the annual demand for heating. When the two types of solar shading were compared, the screen performed marginally better than the Venetian blind in relation to the total annual demand for heating, cooling and artificial lighting because it results in a greater reduction in the annual cooling demand. The peak load for heating was unaffected by the solar shading type whereas that for cooling showed similar reductions for no solar shading and either of the two solar shading types analysed, though with the screen performing marginally better (Fig. 16).
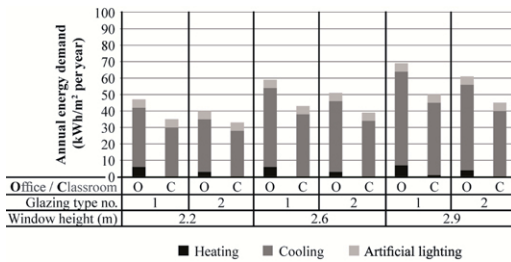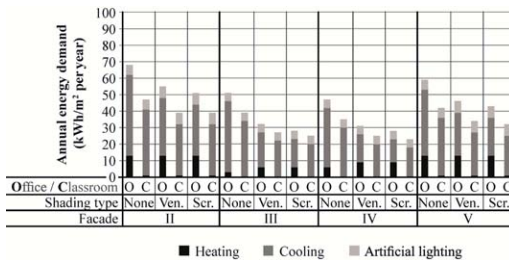

Fig. 15. Distribution of the annual demand for heating, cooling and artificial lighting for offices and classrooms by façade and type of solar shading: None, Venetian blind (Ven.) or transparent fabric solar roller screen (Scr.).
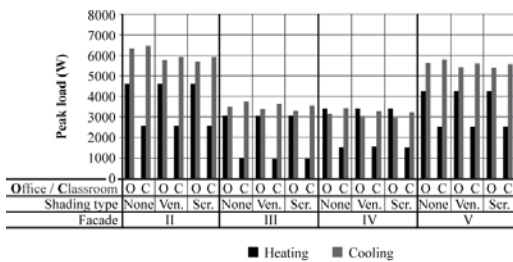
Fig. 16. Peak heating and cooling loads for offices and classrooms by façade and type of solar shading: None, Venetian blind (Ven.) or transparent fabric solar roller screen (Scr.).

Since the results showed that solar shading generally had a significantly positive effect on both the overall demand for heating, cooling and artificial lighting as well as on the peak cooling load, it was decided to implement solar shading for façades II through V. The transparent fabric screen gave the best energy performance and was deemed most appropriate to ensure the visual connection between the building, its occupants and the surroundings that was imperative for the architectural concept behind the building. Furthermore, the screens provided a reduction in the initial building cost compared to Venetian blinds and, because they did not obstruct the view to the outside even when fully activated, were deemed less likely to result in manual overrides, enabling a more optimal control.

4. Discussion

The work presented here formed part of an extensive amount of work that went into designing a new 45,000m^2 addition to Copenhagen University in Denmark. The work should therefore be considered in the light of the need to fulfil a highly complex competition brief, including parameters such as pedagogy, future developments in education and therefore a very high degree of flexibility, the infrastructural situation of the present and the future, fitting it all into a highly urban context, etc. In this context, selecting an appropriate façade design is a complex discipline with many often conflicting performance parameters, and even more if economic considerations and subjective factors such as aesthetics are included. It should also be noted that the highly iterative nature of the architectural design process makes it difficult to compare projects and thus the design solution developed for this project cannot be generalised.

This work concentrated on the design development of the façade and showed how technical input in the form of performance simulations can inform choices throughout the process. Technical support to the geometrical optimisation that is an inherent part of the early conceptual stages of architectural design can dramatically reduce energy demand and a high level indoor comfort can be achieved. So the use of passive properties such as façade geometry, window orientation and size can bring great improvements in performance and should be tried before focusing on optimisation of components like glazing type, solar shading or the HVAC-system.

The simulation study focused on an integrated simulation approach to evaluate the design using a number of performance indicators: daylight optimisation, annual demand for heating, cooling and artificial lighting, and peak cooling and heating loads. Using this approach, façade performance could constantly be quantified and design alternatives benchmarked. Results showed that, although the project was located in a north European climate, cooling demand constituted the greatest part of the annual energy demand for all models. So the main focus for the design development of the façade was to achieve an optimised control of insolation while maintaining a high degree of daylight utilisation.

The façade facetting was a key point in the architectural strategy, which sought to enhance the connection to the surroundings, and technical input made it possible to navigate through the design development, also optimising this concept in relation to energy efficiency and indoor environment. The facetting resulted in windows being oriented

towards one of the four major orientations: north, east, south or west. This provided an opportunity to optimise first the transparency and glazing type, and then the solar shading to the one predominant exposure to solar radiation occurring during occupancy to improve energy efficiency and thermal comfort. North facing façades (I and VI) could potentially receive direct solar radiation early in the morning and late in the afternoon during the summer period, but this would be shielded by the adjacent façade modules. East and west facing façades (II and V) are almost only exposed to direct solar radiation from low altitudes early in the morning or late in the afternoon, respectively. For façades II and V, the increased incidence angle results in a self-shading effect from the facetting and a reduced total solar energy coefficient (g-value) that shields out a large part of the direct solar radiation from the southern direction. However, it should be noted that since façade V initially faced mainly north and the angling results in the window being oriented towards the west, it will be more exposed to insolation. South-facing façades (III and IV) will mainly be exposed to direct solar radiation from high altitudes, which was reduced by the overhang created by the facetting and shielded towards east and west by the adjacent façade modules. Results show that all façades except V performed significantly better in terms of the annual energy demand at the highest degree of facetting (30° angling). The annual energy demand for heating, cooling and artificial lighting for offices adjacent to façades I, II, III, IV and VI was reduced by 10-30% and for classrooms by 15-30%. Façade V showed an increase of about 10% in the annual energy demand for both offices and classrooms.

The facetting also resulted in a significant reduction in the peak load for cooling, approximately a 20-40% reduction for offices and 10-40% for classrooms. Despite the fact that the facetting resulted in a decrease in energy performance for façade V, the maximum degree of facetting was selected to maintain a unified aesthetic appearance and because of the significant overall performance improvements.

Façade transparencies and glazing types was optimised for each of the six façades depending on their individual orientation and importance in maintaining the visual link between the building, its occupants, and the surroundings inherent in the architectural concept. So façade transparencies were reduced where possible, and the selection of glazing type was based on optimal effect. Façades II and VI were essential with respect to the visual connection and therefore high transparencies were selected; façades III and V played a minor role, so transparencies were reduced; while façades I and III had no importance and were therefore designed with the smallest window size. At the same time, glazing types were optimised so that higher transparencies, in principle decreasing the façades' overall thermal performance, were combined with glazing that had a better thermal performance. Window sizes were reduced by introducing a spandrel of either 0.4m or 0.8m in height, thus keeping the reduction in daylight availability at the work plane to a minimum.

Finally, shading could be limited to the façades with the highest exposure to direct solar radiation and optimised to the predominantly occurring exposure. In addition to the difference in direct solar radiation due to orientation, the manner in which the screens were activated was optimised to fit the self-shading effect caused by the facetting and its horizontal displacement from storeys vertically adjacent (Fig. 17). The self-shading effect meant that the dynamic screens did not always have to be fully activated, which optimised the view to the outdoor environment.
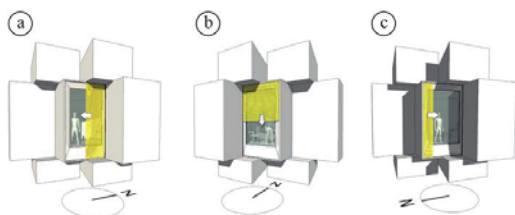

Fig. 17. Illustration of the concept behind varying the way the solar shading screen was activated to fit the self-shading the building provides due to orientation – (a) east (façade II), (b) south (façades III and IV), and (c) west (façade V).

This work illustrates that great potential lies in the utilisation and optimisation of the passive properties, which if used can result in a building design where energy efficiency and occupant comfort are an inherent part of the architecture (see Fig. 18). The work presented here shows how engineers essentially entering what is usually regarded as the architectural realm can help facilitate an interdisciplinary collaboration from the very start of the design process.

Fig. 18. Illustration of the final design proposition viewed from the green area to the east displaying façade II with high transparencies and solar shading screens activated in some of the rooms.

5. Conclusion

This paper has presented a simulation case study of façade design options for a new university building in Copenhagen, Denmark. The focus was on geometrical optimisation and the utilisation of the passive properties and was investigated over a wide range of parameter variations throughout the design development. The design was evaluated for a series of performance indicators: daylight optimisation, annual demand for heating, cooling and artificial lighting, and peak loads for heating and cooling. All models complied with Class II in relation to indoor thermal environment and air quality as defined in the European standards (CEN, 2007) and results showed the potential for significant energy reductions through geometrical optimisation.

The main objective was to develop a façade design that can efficiently control the amount of insolation, maintain a satisfactory quality of indoor environment, contribute to the reduction in energy demand, and at the same time support and consolidate the architectural vision. The final design proposition represents a building in which these considerations are an inherent part of the architectural expression that was developed through a highly integrated approach.

References

ASHRAE, 2001. ASHRAE Handbook – Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta (Chapter 30).

Augenbroe, G., Wilde, P.d., Moon, H.J. & Malkawi, A. 2004, "An interoperability workbench for design analysis integration", Energy and Buildings, vol. 36, no. 8, pp. 737-748.

CEN, 2001. EN ISO 7726:2001 – Ergonomics of the thermal environment - Instruments for measuring physical quantities.

CEN, 2007. EN15251:2007 - Indoor environmental input parameters for design and assessment of energy performance of buildings - addressing indoor air quality, thermal environment, lighting and acoustics.

Citherlet, S., Clarke, J.A. & Hand, J. 2001, "Integration in building physics simulation", Energy and Buildings, vol. 33, no. 5, pp. 451-461.

Citherlet, S. & Hand, J. 2002, "Assessing energy, lighting, room acoustics, occupant comfort and environmental impacts performance of building with a single simulation program", Building and Environment, vol. 37, no. 8-9, pp. 845-856.

Clarke, J.A., Janak, M. & Ruyssevelt, P., 1998. Assessing the overall performance of advanced glazing systems. Solar Energy, vol. 63, no. 4, pp. 231-241.

de Wilde, P., Augenbroe, G. & van der Voorden, M. 2002, "Design analysis integration: supporting the selection of energy saving building components", Building and Environment, vol. 37, no. 8-9, pp. 807-816.

EBST, 2010. Bygningsreglement for erhvervs- og etagebyggeri, National Agency for Enterprise and Construction, Copenhagen, Denmark.

Franzetti, C., Fraisse, G. & Achard, G. 2004, "Influence of the coupling between daylight and artificial lighting on thermal loads in office buildings", Energy and Buildings, vol. 36, no. 2, pp. 117-126.

Laforgue, P., Souyri, B., Fontoynont, M., Achard, G., 1997. Simulation of visual and thermal comfort related to daylighting and solar radiation in office buildings. In: Proceedings of IBPSA 1997, Czech Republic.

Lee, E.S., DiBartolomeo, D.L., Selkowitz, S.E., 1998. Thermal and daylighting performance of an automated Venetian blind and lighting system in a full-scale private office. *Energy and Buildings,* vol. 29, no. 1, pp. 47-63.

Mitchell, R., Kohler, C., Ling Zhu, L. & Arasteh, D., 2011. "THERM 6.3 / WINDOW 6.3 NFRC Simulation Manual" LBL Report 48255. Berkeley CA.

Morel, N. & Faist, A. 1993, "Design tools for building thermal analysis: The significance of integration", Building and Environment, vol. 28, no. 4, pp. 465-473.

Nielsen, M.V., Svendsen, S. & Jensen, L.B. 2011, "Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight", Solar Energy, vol. 85, no. 5, pp. 757-768.

Petersen, S. & Svendsen, S. 2010, "Method and simulation program informed decisions in the early stages of building design", Energy and Buildings, vol. 42, no. 7, pp. 1113-1119.

Selkowitz, S. E., 2001. Integrating advanced façades into high performance buildings. Lawrence Berkeley National Laboratory. LBNL Paper LBNL-47948. Retrieved from: http://escholarship.org/uc/item/30g0h715 (accessed January 6th 2012)

Reinhart, C.F. & Walkenhorst, O., 2001, "Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds", Energy and Buildings, vol. 33, no. 7, pp. 683-697.

Tzempelikos, A., Athienitis, A.K., Karava, P., 2007. Simulation of façade and envelope design options for a new institutional building. *Solar Energy,* vol. 81, no. 9, pp. 1088-1103.

Wienold, J. & Christoffersen, J., 2006. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings,* vol. 38, no. 7, pp. 743-757.

Paper IV

Quantifying the effect of solar shading types and window sizes in office buildings by evaluating thermal sensibility and comfort using the adaptive approach

Under review at Solar Energy.

Quantifying the effect of solar shading types and window sizes in office buildings by evaluating thermal sensibility and comfort using the adaptive approach

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Abstract

The façade design is a central issue for building designers. The separator between the external and internal environment is a key element in balancing the conflict between energy efficiency and occupant comfort. To cope with high seasonal and even daily variations in the external environment and consequent demands on the façade, it has become increasingly common to suggest the use of dynamic/responsive components. However, most simulation software fails to fully consider the highly transient and non-uniform character of the indoor environment to which an occupant is exposed as a result of outdoor conditions and façade design (e.g. solar shading). This article presents a very detailed analysis of the indoor thermal environment under varying climate conditions and façade designs (solar shading types and window sizes) using a model that evaluates the overall thermal sensation and comfort level experienced by the occupant. Simulation results show all models displaying predominantly negative overall comfort levels mostly due to sensations of heat in summer and cold in winter. Furthermore, the results show that direct solar radiation has a great impact on the occupant's thermal sensation and overall comfort – even resulting in overheating during winter. Thus, the performances of the various façade designs simulated in relation to the quality of the indoor thermal environment basically only differ under sunny sky conditions, whereas cloudy conditions result in very similar performances. Generally the best performing façades are the ones with dynamic solar shading and the smallest window area, but no great differences exist and there is no clearly superior façade design out of the ones simulated. These results underline the importance of performing detailed simulations very early in the design process to inform the design development of the façade.

Keywords: Thermal comfort; Computer simulations; Transient Conditions; Predictive; Adaptive; Façade Design

1. Introduction

Constructing a well-performing façade is becoming increasingly complex as requirements for sustainability get stricter. Requirements for the indoor environmental quality are becoming ever more specific and elaborate, but less quantifiable values, such as architectural expression, also have to be considered. In particular, indoor thermal comfort is and should be considered a cardinal point when designing new façades and refurbishing existing façades because it will effectively determine the usability of the space in relation to a given function and its ability to procure an appropriate working or living environment for the occupants. Moreover, the performance of the façade determines to a considerable degree the energy demand for the operation of the HVAC system and thus consequently greatly influences the building's degree of sustainability.

The quantification of thermal comfort represented by the pioneer PMV model (Fanger, O.P., 1970) is widely accepted as an indicator for indoor environmental quality and most building simulation programs provide output from which it can be evaluated. However, this model, which is used in the development of many building designs, bases its evaluation of thermal comfort on steady-state and uniform conditions and fails to include the asymmetrical and highly transient character of the thermal environments that are being designed and occupied (Cheng et al., 2011). Examples of such conditions are difference in surface temperatures between interior walls and windows in a room and the highly fluctuating insolation, especially for work stations in a building's perimeter zone (Tzempelikos et al., 2010).

First proposed in the 1970s in reaction to the scarcity of available oil (Brager & de Dear, 1998), the adaptive comfort approach is based on a more flexible principle: *if change occurs such as to produce discomfort, people react in ways which tend to restore their comfort* (Nicol & Humphreys, 2002). The adaptive approach thus links the occupant and the comfort temperature range to the actual situation and includes the transient character of the environment. Furthermore, it is inherent within the adaptive comfort approach that occupants acclimatize to their environment over time and/or actively react and interact with the building and its services, affecting their sense of comfort. This adaptability has been ascribed to result in significant overall energy savings due to the more relaxed temperature criteria (de Dear & Brager, 2001; Toftum et al., 2009), although recent work shows more conflicting tendencies and differences between the American and the European implementations of the adaptive comfort approach (Sourbron & Helsen, 2011).

Dynamic fenestration systems are increasingly emphasized as the solution to the often conflicting demands for energy efficiency and increased thermal comfort. A greater degree of adaptability in the façade has the potential to achieve a more beneficial utilization of the available resources, such as insolation, thereby reducing energy demand and improving indoor climate (Lee et al., 1998). Dynamic solar shading provides a more efficient reduction in transmitted solar radiation and thereby a reduction in not only peak cooling load, but also in annual cooling demand (Tzempelikos et al., 2007). In principle dynamic solar shading also provides increased uniformity in both daylight levels and the indoor thermal environment, making temperatures within the comfort band defined by the PMV model more easily attainable. However, environmental asymmetry has been shown to give more pleasure than the neutrality conventionally aimed at (Kuno, 1995; Arens, 2006b). Furthermore, recently published work, consisting of fully integrated simulations of energy demand, indoor thermal environment, and indoor air quality, shows only minor potential reductions in total annual energy demand in using dynamic as opposed to fixed solar shading (Nielsen et al., 2011). The models, ranging from differences in window sizes and solar shading types to differences in orientation, all complied with Class II in terms of both indoor thermal environment and indoor air quality as defined in the European standard (CEN, 2007). So if dynamic solar shading fails to achieve energy reductions, will its adaptability result in an optimised indoor thermal environment under transient conditions?

This article presents a quantification of the indoor thermal performance of various façade designs exposed to a transient outdoor environment including direct and diffuse solar radiation. The focus is on comparing dynamic solar shading with the design alternatives: a façade with fixed solar shading and a façade with no solar shading. For all three solar shading types, a range of window sizes were simulated and evaluated for their effect on the indoor thermal environment using a highly detailed comfort model. These considerations can only be evaluated at room level, where occupant behaviour and comfort are represented, and even within such a relatively defined space many different parameters influence the thermal comfort of the occupant (Raja & Nicol, 1997; Kubaha et al., 2004). Furthermore, the occupant's response to a

thermal environment cannot simply be considered on overall body level, but must include the sensations of individual parts of the body (Arens et al., 2006a). Different façades will filter the external environment differently, and solar radiation in particular will result in highly non-uniform exposure of different parts of the body. Therefore, a detailed model was used, taking into account the non-uniform distribution of solar radiation within a room. This, coupled with the adaptive approach that links the comfort range to the actual environment and façade design, made it possible to obtain a more precise representation of the façade's impact on the occupant's thermal sensibility and comfort.

2. Description of the thermal comfort model

The analyses were based on the comprehensive UC Berkeley thermal comfort model (the UCB model) developed at the Center for the Built Environment, University of California, Berkeley (Huizenga et al., 2001). The UCB comfort model is based on the Stolwijk model (Stolwijk, 1966) and the work of Tanabe (Tanabe et al., 1995). The UCB model predicts the local thermal sensation and local thermal comfort of various parts of the body (Zhang et al., 2010a-b), as well as the whole-body thermal sensation and overall comfort, as a result of the local impacts (Zhang et al., 2010c).

On the basis of an extensive set of climate-chamber tests, in where the subject's local skin temperatures individually were forced through a range of temperatures, their local skin temperatures were measured, and they were repeatedly surveyed for their local and whole-body thermal sensation and comfort levels. This established the relationship between the overall human thermal response (sensation and comfort) and the local skin temperature of the individual parts of the body. This correlation included coefficients for various scenarios, varying the rate of temperature change and whether individual parts of the body were cooler or warmer than the rest of the body.

The thermal sensation and thermal comfort of both the individual parts of the body and the whole body were indicated on a scale ranging from -4 being "very cold" to 4 being "very hot" for the thermal sensation and from "very comfortable" to "very uncomfortable" for the thermal comfort (Fig. 1).
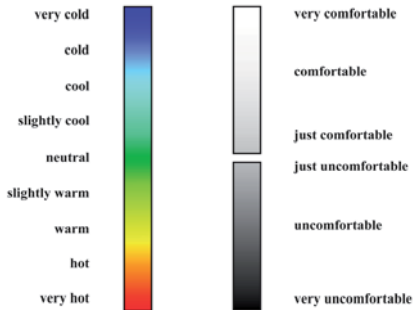
Fig. 1. Scales used to indicate the quality of the indoor thermal environment for both the whole body and individual parts of the body in terms of thermal sensation (left) and thermal comfort (right).

The method for determining the whole-body thermal sensation depends on the predominant tendency of the thermal sensation in individual parts of the body. All the individual parts of the body are assigned different coefficients for warm and cool sensations. Strong local sensations dominate the whole-body sensation, and the chest, back and pelvis are particularly influential. Two basic situations can occur: all parts of the body have similar thermal sensations, either hot or cold, or some parts have a thermal sensation opposite to the predominantly occurring sensation. If there are no opposing sensations, the overall thermal sensation is determined as an average of the sensation in individual parts of the body. If there are opposing sensations, the individual parts are evaluated in groups according to sensation (hot or cold), where the group's size and sensation extremity determines the whole-body sensation. If all sensations are near neutral, the whole-body sensation is close to the average sensation of all parts of the body.

The method for determining the overall thermal comfort depends on whether or not the occupant is exposed to a stable or transient environment. Under stable conditions, the extensive climate chamber tests showed that the evaluation process is "complaint-driven". This means that the occupants evaluate their overall thermal comfort level in accordance with the comfort level of the two least comfortable parts of the body, disregarding the comfort of all other parts of the body. Under transient conditions, or if people have some means of affecting the environment they inhabit, the overall thermal comfort is determined as the average of the two least comfortable parts of the body and the most comfortable one.

2.1 The software

A transient environment can be modelled through a series of "phases", consisting of combinations of environmental, clothing and metabolic conditions, in which the model predicts the occupant's response. The transient character of the external climate and the non-uniform exposure of individual parts of the occupant's body as a consequence of the façade design are simulated by placing a virtual thermal mannequin consisting of 16 different body segments[1] in a defined environment (Fig. 2).
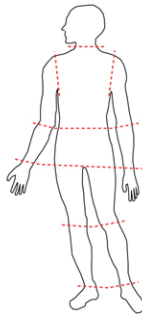
Fig. 2. Illustration of the highly detailed virtual mannequin and the partition into individual body segments.

The explicit radiation heat transfer between the mannequin and the surrounding environment is calculated using angle factors for each of the body segments, including a radiation heat flux model to simulate the exposure to e.g. sunlight. The model differentiates between direct and diffuse solar radiation, and determines both for each individual body segment.
Each body segment consists of four body layers (core, muscle, fat and skin tissue), a clothing layer (including heat and moisture capacitance) and a contact surface (including an initial temperature, thermal conductivity, specific heat capacity and thickness). For each body segment, the ratio between exposed and clothed skin in contact with a surface is taken into account.

3. Simulation model and building parameters

Quantifying the effect of the dynamic façade in relation to the indoor thermal environment was investigated through a number of cases. Each simulation represented a 3x3x6m (width x height x depth) perimeter office with a south-facing façade with two occupants (Fig. 3).

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[1] Head, Chest, Back, Pelvis, Left upper arm, Right upper arm, Left lower arm, Right lower arm, Left hand, Right hand, Left thigh, Right thigh, Left leg, Right leg, Left foot and Right foot.
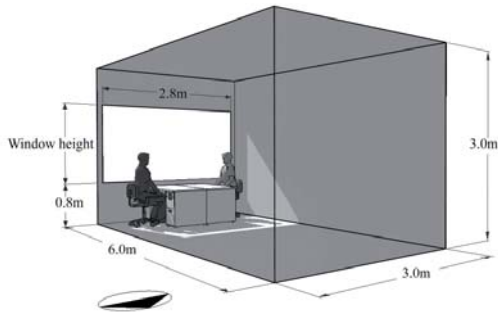
Fig. 3. Geometry of the two-person office with the placement of both occupants (the one considered facing west) and the window centred in relation to the room width and an offset of 0.1m on each side. The window height was defined from a window parapet with a fixed height of 0.8m.

3.1 Climate

Representative days for clear and cloudy sky conditions for both summer (Fig. 4) and winter (Fig. 5) were chosen from the design reference year (DRY) weather data for Copenhagen, Denmark.

The period December–February was considered winter and June–August was considered summer. The sunny day representing weather data in clear-sky conditions was selected as the day with maximum direct solar radiation while the cloudy day was selected as the day with maximum diffuse solar radiation and at the same time the minimum amount of direct solar radiation.

Fig. 4. Climatic data from the design reference year (DRY) for representative summer days (Copenhagen, Denmark) used in the simulation. The direct solar radiation equals zero throughout the day under cloudy conditions.

Fig. 5. Climatic data from the design reference year (DRY) for representative winter days (Copenhagen, Denmark) used in the simulation. The direct solar radiation equals zero throughout the day under cloudy conditions.

3.2 Simulation of indoor air temperature and surface temperature

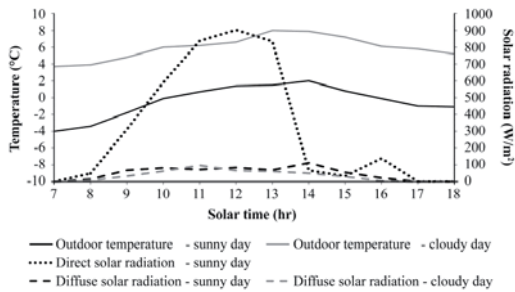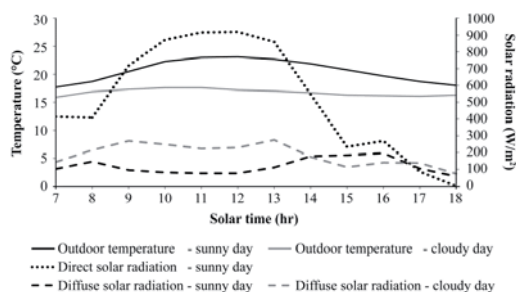Hourly indoor air temperature, as defined by the external environment, internal heat gains from people and equipment, and also the control of heating, ventilation, cooling, artificial lightning and solar shading, was determined initially and input into the UCB comfort model. The set-up of the building simulation model for determining indoor air temperature was based on recently published work (Nielsen et al., 2011). Simulations were performed using the integrated tool IDbuild (Petersen and Svendsen, 2010), which is made up of two parts: a thermal simulation handled by BuildingCalc (Nielsen et al., 2005), and a daylight simulation handled by LightCalc (Hviid et al., 2008). LightCalc essentially pre-calculates hourly daylight levels at given evaluation points with no shading to provide initial values for the artificial lighting loads and the internal heat gain. The thermal simulation evaluates the indoor air temperature based on the heat exchange between the external and internal environments, and the building systems defined are controlled to achieve set-point temperatures defined in accordance with European standards for indoor environment Class II (CEN, 2007). Where adjustable solar shading was defined, it was activated if either the indoor air temperature was above the cooling set-point or there was a risk of glare. If solar shading was insufficient to eliminate overheating, increased air exchange rates for natural ventilation (venting) were employed. Subsequently, the artificial lighting load needed to obtain the given illuminance level set-points was determined taking possible daylight reductions caused by solar shading into account. Finally the internal heat gain and consequently the indoor temperature for that time step were calculated.

The indoor air temperatures determined through IDbuild were implemented as surface temperatures in the UCB model for all internal surfaces except the window pane, where the temperature was determined using Window 6.3 (Mitchell et al., 2011) taking the outdoor and indoor temperatures and the solar radiation into account.

3.2.1 Control of heating and ventilation

Heating and ventilation systems were only active during occupancy and set points for heating and air flow rates for mechanical ventilation as indicated in Table 1 corresponded with the requirements for Class II in the European standard (CEN, 2007).

The addition of natural ventilation (venting) outside the heating season was made to clarify whether or not some of the façade designs tested for certain orientations performed well enough to obtain a satisfactory level of indoor thermal comfort through increased air flow. E.g. problems with overheating outside the heating season could be mitigated with the occupant interacting with the façade by opening windows, an inherent part of the adaptive principle. Natural ventilation through open windows, indicated as venting, was defined as the maximum air flow rates possible for single-sided natural ventilation during the summer season derived from the Danish standard (EBST, 2006).

3.2.2 Internal gains and occupancy profile

Internal gains from two occupants plus equipment and both task and general lighting were modelled with a maximum power density of $10W/m^2$ and $7.2W/m^2$ respectively, based on a daily occupancy profile (8 am to 5 pm). The lighting control and the set points are shown in Table 1.

Table 1. Data for system set-up and efficiency used in simulation of indoor air temperature.

Systems and internal loads		Occupancy (8 am to 5 pm)	Non-occupancy
Set point temperatures – heating/cooling			
	Summer	20/24°C	-
	Winter	23/26°C	-
Infiltration		0.1 h^{-1}	0.1 h^{-1}
Mechanical ventilation [a)]		1.48 l/sm^2	0.0 l/sm^2
Venting rate (maximum) [b)]		1.8 l/sm^2	0.6 l/sm^2
Internal loads from people and equipment		10 W/m^2	1 W/m^2
General lighting			
	Control	Continuous, linear dimming	Always off
	Illuminance set point	200 lux	-
	max. power	6 W/m^2	0 W/m^2
	min. power (stand-by)	0.5 W/m^2	0 W/m^2
Task lighting			
	Control	On/Off	Always off
	Illuminance set point	500 lux	-
	max. power	1.2 W/m^2	0 W/m^2
	min. power	0 W/m^2	0 W/m^2

a) Equivalent to indoor air quality Class II in the European standard EN 15251:2007 (CEN, 2007).
b) Defined as ventilation through open windows. Only active outside the heating season and corresponds to maximum values for single-sided natural ventilation in Danish energy calculations (EBST, 2006).

3.3   Fenestration system

A series of parameter variations for fenestration configurations were tested out to determine the effect of façade design on the indoor thermal environment. The two parameters varied were the window size and solar shading type. Three different solar shading types were investigated:

  I.   no solar shading
 II.   fixed solar shading
III.   dynamic solar shading

All solar shading types were simulated with window heights 1.0m, 1.5m and 2.0m. The window height was defined as from spandrel height (0.8m) and upward, while the width of the window was kept constant at 2.8m (see Fig.3).

The fixed and the dynamic solar shadings were modelled as a horizontal, grey Venetian blind with a slat thickness of, 0.22mm, a width of 50mm, a distance of 42.5mm, and a reflectance of 0.54. The dynamic solar shading was modelled as pivoting and fully retractable, and controlled during occupancy by the cooling set-point and risk of glare; if either of the two conditions occurred, the blinds were fully lowered and adjusted to the slat angle at which direct sun was just blocked (the cut-off angle), thus maximising the amount of daylight entering the room while optimising the indoor environment with respect to glare and overheating (Hviid et al., 2008). Outside the period of occupancy, the dynamic

solar shading was only activated by the cooling set-point. The fixed solar shading was modelled as constantly fixed in the horizontal position and not retractable.

The thermal and optical properties of the fenestration systems were generated using the WIS program (WinDat, 2006). Solar energy transmittances as a function of incident angle for the three fenestration systems are presented in Fig. 6 for the direct component and in Table 2 for the diffuse component. Additional optical and thermal properties for the façade in general are presented in Table 3.
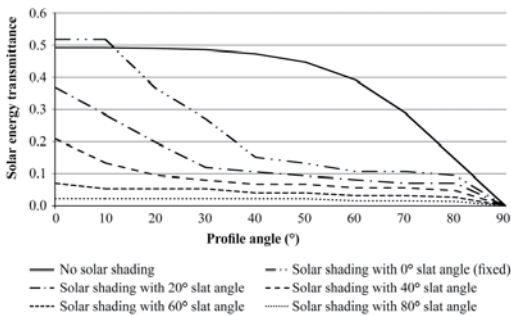

Fig. 6. Solar energy transmittance for the direct component as a function of profile angle for the fenestration systems simulated.

Table 2. Solar energy transmittance for the diffuse component for fenestration systems with and without solar shading and for the fenestration systems with solar shading for slat angles in ten-degree increments.

No solar shading	Solar shading									
	Slat angle									
	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
0.40	0.25	0.25	0.24	0.23	0.21	0.18	0.14	0.10	0.05	0.02

Table 3. Input values defining the properties of the façade used in the simulations.

Heat transfer coefficient of opaque façade construction (U-value)	$0.15\ W/m^2K$
Heat transfer coefficient of glazing (U-value)	$0.7\ W/m^2K$
Light transmittance of glazing (LT)	0.53
Total solar energy transmittance of glazing	0.40
Heat transfer coefficient of frame construction (U-value)	$1.5\ W/m^2K$
Linear heat transmittance of window frame (Psi-value)	0.1 W/mK

3.4 Occupant and indoor environment properties

Simulations include the internal gain from two occupants, but the thermal sensation and comfort are only considered for the occupant seated facing west (Fig. 3). Additional parameters related to occupant properties and indoor environment used in the simulation are shown in Table 4.

Table 4. Parameters of occupant and indoor environmental properties used in simulation of thermal comfort and sensation. Clothing levels were determined for each body part separately and the clo-values indicated were averaged from these.

Body mass [kg]	DuBois Area [m2]	Metabolic rate [met]	Clothing [clo] (average)		Air speed [m/s]	Relative humidity [%]
			Summer	Winter		
74	1.6	1.0	1.15	1.26	0.1	50

4. Results

The most important results were the simulations performed using the UCB comfort model illustrating the whole-body thermal sensation and the overall thermal comfort of the occupant. To demonstrate the importance of the façade design and how it affects the indoor thermal environment, comparative results for a range of parameter variations are presented and analysed on the basis of the following parameters: the solar radiation transmitted over the course of a working day, the indoor operative air temperature, the interior surface temperature of the window pane, and finally the indoor thermal sensation and comfort of the occupant.

In general, results from the simulated models for the summer and winter situations under both sunny and cloudy conditions (Fig. 7 – Fig. 22) show similar tendencies to those shown in the weather data presented in Fig. 4 and Fig. 5. Thus, sunny and cloudy summer conditions show an increase in solar radiation transmitted during the working day and higher indoor temperatures, which result in an increase in sensation and a decrease in comfort compared to the respective sunny and cloudy winter conditions. Moreover, sunny conditions result in higher indoor operative temperatures and higher interior window pane surface temperatures than cloudy conditions.

4.1 Summer

Summer conditions entail relatively high total solar radiation values and outdoor air temperatures. On the other hand, the high altitude of the sun, especially for the south-facing office considered, results in the occupant's projected area being smaller, thus less exposure to solar radiation.

Considering the total transmitted solar radiation under sunny summer conditions (Fig. 7), façades with no solar shading clearly allow the highest amount to be transmitted, whereas façades with fixed and dynamic solar shading showed similarly lower peak values. For façades with dynamic solar shading, an increase in window area resulted in earlier activation of the solar shading, resulting in a difference in transmitted solar radiation early in the day. Façades with dynamic solar shading and window heights of 1m and 1.5m resulted in shading being activated at 7 and 8 hours respectively, both remained activated the rest of the day. At a window height of 2.0m the shading was active throughout the day. At peak hours, the fixed solar shading reduced the total solar radiation (W/m^2) by 67% and the dynamic by 83%. Under cloudy conditions, in which only diffuse solar radiation was present (Fig. 8), the dynamic solar shading was generally activated less: a window height of 1.5m resulted in shading being active between 12 and 13 hours, a window height of 2.0m resulted in activation between 8 and 17 hours, while the solar shading was not active at all with a window height of 1.0m. Results for façades with fixed solar shading showed a constant reduction in transmitted solar radiation.

With respect to indoor operative temperature and interior window pane surface temperatures, results showed significant differences between sunny (Fig. 9) and cloudy conditions (Fig. 10). The significant direct component present in sunny conditions resulted in more fluctuating temperatures, especially with regard to the interior surface temperature of the window pane. The significantly lower values for transmitted solar radiation in cloudy sky conditions also contributed to more stable indoor air and surface temperatures. Furthermore, the results showed that adding solar shading significantly reduced the indoor temperature, especially in the case of dynamic solar shading.

The results for the thermal sensation and the thermal comfort of the occupant during the summer show similar patterns to those for indoor temperatures and total transmitted solar radiation (Fig. 7 – Fig. 10). Sunny summer conditions gave higher fluctuations in both sensation and comfort than cloudy conditions.
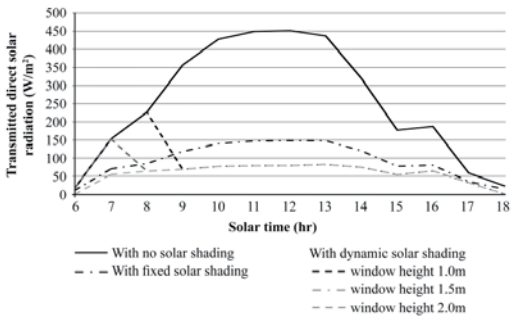
Fig. 7. The effect of the solar shading types simulated on the solar radiation transmitted under sunny summer conditions.
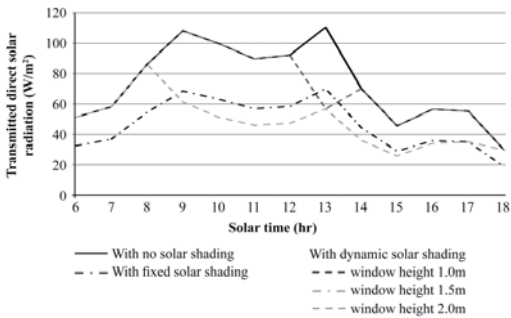
Fig. 8. The effect of the solar shading types simulated on the solar radiation transmitted under cloudy summer conditions. Values for transmitted solar radiation for façades with no solar shading and for the façade with a window height of 1.0m with dynamic solar shading were the same because the solar shading was not activated under these conditions.
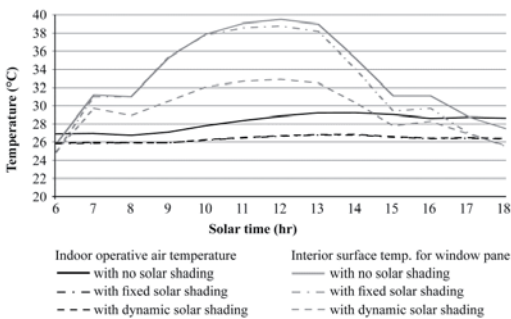
Fig. 9. Effect of the three solar shading types simulated on the indoor operative temperature and the interior surface temperature of the window pane under sunny summer conditions for façades with a window height of 1.5m.

Fig. 10. Effect of the three solar shading types simulated on the indoor operative temperature and the interior surface temperature of the window pane under cloudy summer conditions for façades with a window height of 1.5m.

Under sunny summer conditions, the results for the occupant's whole-body thermal sensation (Fig.11) and overall comfort (Fig. 12) showed a significant increase around noon for the majority of the simulated models. However, for the façade with dynamic solar shading and a window height of 1.0m the impact is less significant. In general, the increase in thermal sensation and the decrease in comfort were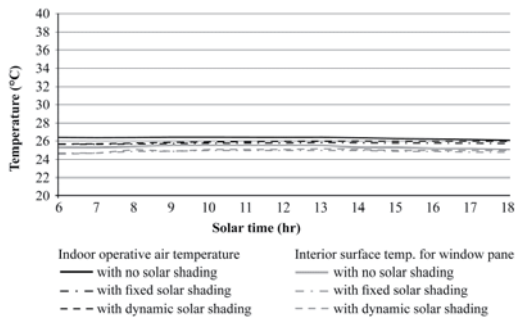 most significant for the façades with no solar shading, less for the façades with fixed solar shading, and least for the façades with dynamic solar shading. Furthermore, an increase in window height and consequently a higher exposure to insolation resulted in an increase in thermal sensation. Basically identical tendencies and magnitudes were observed with regard to overall comfort. The increased solar radiation transmitted under sunny summer conditions when outdoor temperatures are relatively high caused a warmer sensation and a decrease in overall comfort. Thus the majority of the simulated models under sunny summer conditions showed that the whole-body thermal sensation and the overall comfort develop from near-neutral conditions when the working day starts and reach peak values between 2 and 4 (positive values for thermal sensation and negative for comfort) around 14 hours. All models result in higher thermal sensation at the end of the working day, but the extent of the increase depends on the window size and solar shading type as in the case of peak values.

Cloudy summer conditions resulted in a significantly more stable tendency for whole-body thermal sensation (Fig. 13) and overall comfort (Fig. 14), cf. the results for transmitted solar radiation and indoor temperatures (Fig. 8 and Fig. 10). Almost all models show a similar performance with an overall thermal sensation around 0.5, while overall comfort levels are around neutral. However, the case with no solar shading and a window height of 2.0m results in noticeably higher thermal sensation and consequently a lower comfort level.
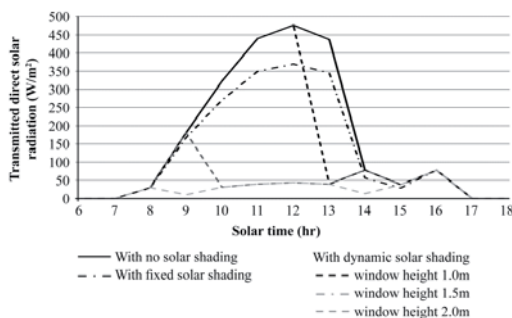
Fig. 11. Overall thermal sensation under sunny summer conditions.
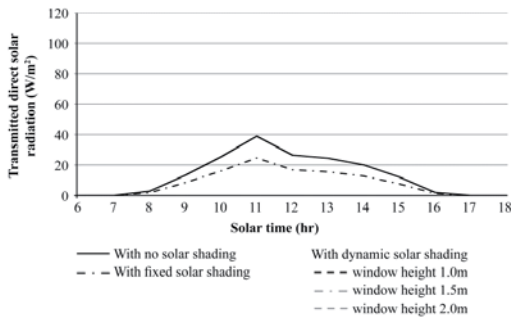
Fig. 12. Whole-body thermal comfort under sunny summer conditions.
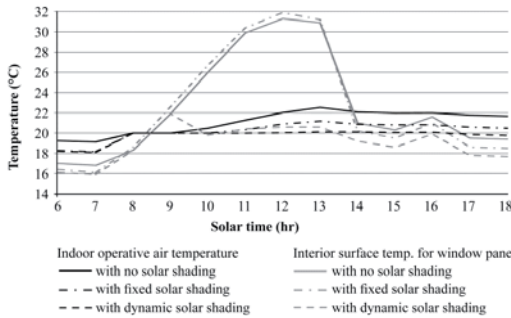
Fig. 13. Overall thermal sensation under cloudy summer conditions.
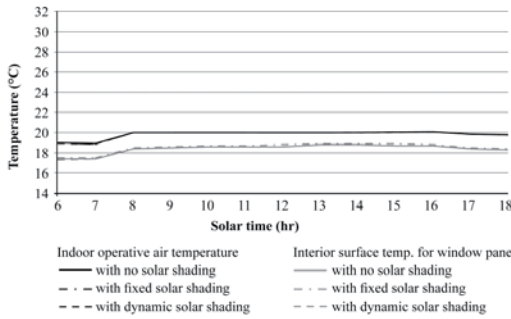
Fig. 14. Whole-body thermal comfort under cloudy summer conditions.

4.2 Winter

Winter represents a more complex situation than summer because of contrasting thermal interactions, such as greater differences between outdoor and indoor air temperatures, which can be combined with a high level of solar radiation in the case of clear-sky sunny conditions.

Total transmitted solar radiation peaks at similar values under sunny conditions in the winter (Fig. 15) as in the summer, but at substantially lower values under cloudy conditions in the winter (Fig. 16) than in the summer. For façades with dynamic solar shading under sunny winter conditions, the solar shading was active 12-13 hours with a window height of 1.0m, from 9-13 hours with a window height of 1.5m, and from 8-14 hours with a window height of 2.0m. At peak hours, the fixed solar shading reduced the total solar radiation (W/m^2) by 22% and the dynamic solar shading reduced it by 91%. Under cloudy sky conditions, the dynamic solar shading was not activated for any of the models, so the amount of solar radiation transmitted was the same as for façades with no solar shading. As for models under cloudy summer conditions, façades with fixed solar shading showed a constant reduction in transmitted solar radiation throughout the day.

Indoor operative temperatures and interior window pane surface temperatures, for the sunny and cloudy winter conditions (Fig. 17 and Fig. 18) showed similar patterns to those of the respective summer cases: fluctuating indoor and especially window pane surface temperatures under sunny sky conditions and more stable temperatures under cloudy conditions.

No solar shading	Fixed solar shading	Dynamic solar shading
—— window height 1.0m	—— window height 1.0m	—— window height 1.0m
----- window height 1.5m	----- window height 1.5m	----- window height 1.5m
— ·— window height 2.0m	— ·— window height 2.0m	— ·— window height 2.0m

Fig. 15. The effect of the solar shading types simulated on solar radiation transmitted under sunny winter conditions.

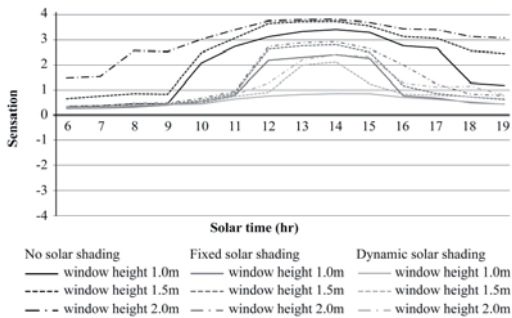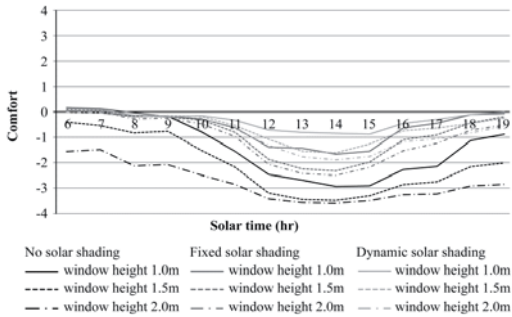| No solar shading	Fixed solar shading	Dynamic solar shading
—— window height 1.0m	—— window height 1.0m	—— window height 1.0m
----- window height 1.5m	----- window height 1.5m	----- window height 1.5m
— ·— window height 2.0m	— ·— window height 2.0m	— ·— window height 2.0m

Fig. 16. The effect of the solar shading types simulated on solar radiation transmitted under cloudy winter conditions. Values for transmitted solar radiation for façades with no solar shading and façades with dynamic solar shading were the same because automatic solar shading was not activated under cloudy winter conditions.
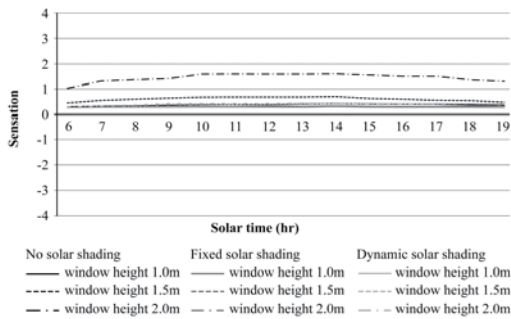
Fig. 17. Interior surface temperature of the window pane under sunny winter conditions for façades with a window height of 1.5m for the solar shading types simulated.
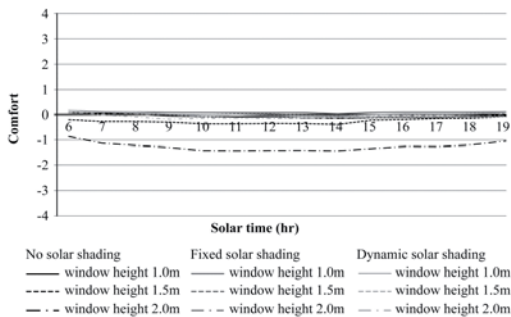

Fig. 18. Interior surface temperature of the window pane under cloudy winter conditions for façades with a window height of 1.5m for the solar shading types simulated.

The whole-body thermal sensation and overall comfort (Fig. 20) under winter conditions follow similar patterns to those of transmitted solar radiation and indoor temperatures (Fig. 15 – Fig. 18). Again, sunny conditions resulted in higher fluctuations than the cloudy conditions, but winter conditions in general display cold sensation levels in contrast to the warm sensations found under summer conditions.

Under sunny winter conditions all the simulated models showed a significant increase in whole-body thermal sensation level around noon, except for those with dynamic solar shading and a window height of 1.5m or 2.0m, which showed near-constant thermal sensation levels (Fig. 19).

The differences in thermal sensation levels between solar shading types show a similar pattern to that found under sunny summer conditions: in general, the increases in thermal sensation were most significant for the façades with no solar shading, less for the façades with fixed solar shading, and least for the façades with dynamic solar shading. The same was the case with window size, where an increase in window height resulted in an increase in thermal sensation levels. In contrast to the sunny summer conditions, the whole-body thermal sensation starts at negative levels of around -2 at the start of the working day, decreasing further to approximately -3, and then increases to peak levels of between 2 and 3 around noon. The overall comfort level under sunny winter conditions (Fig. 20) follows the pattern and levels of the whole-body thermal sensation during the first part of the day, initially decreasing slightly and then increasing, but as the thermal sensation level increases above neutral the comfort level stagnates or decreases. The level of decrease depends on the solar shading type, decreasing most significantly for façades with no solar shading, less for façades with fixed solar shading, and least for façades with dynamic solar shading. Furthermore an increase in window height also results in a decrease in overall comfort level. All models result in higher whole-body thermal sensation and overall comfort levels at the end of the working day than when the working day starts, most significantly for façades with no

solar shading, less for façades with fixed solar shading, and with only a minor increase for façades with dynamic solar shading.

Cloudy winter conditions, like cloudy summer conditions, result in a significantly more stable development in whole-body thermal sensation (Fig. 21) and overall comfort (Fig. 22), cf. the results for transmitted solar radiation and the indoor temperatures (Fig. 16 and Fig. 18). All models basically show identical performances with overall thermal sensation levels dropping from approximately -2 to a stable level just above -3. Moreover, the overall comfort levels are equal for all models and display similar tendencies to those of the overall thermal sensation, but with slightly higher values.

No solar shading	Fixed solar shading	Dynamic solar shading
——— window height 1.0m	——— window height 1.0m	——— window height 1.0m
- - - - window height 1.5m	- - - - window height 1.5m	- - - - window height 1.5m
— · – window height 2.0m	— · – window height 2.0m	— · – window height 2.0m

Fig. 19. Overall thermal sensation under sunny winter conditions.

No solar shading	Fixed solar shading	Dynamic solar shading
——— window height 1.0m	——— window height 1.0m	——— window height 1.0m
- - - - window height 1.5m	- - - - window height 1.5m	- - - - window height 1.5m
— · – window height 2.0m	— · – window height 2.0m	— · – window height 2.0m

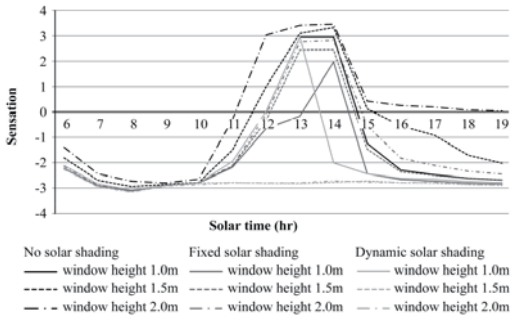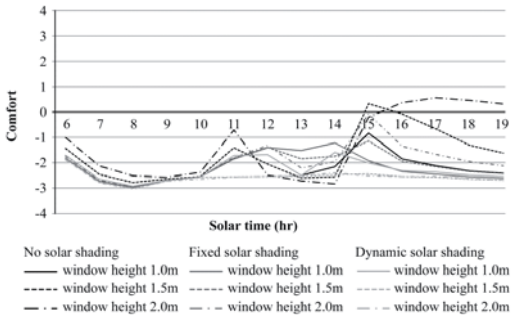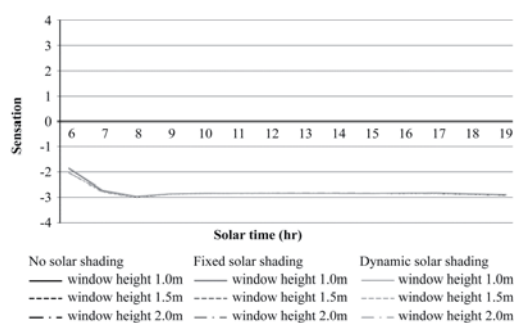**Fig. 20. Whole-body thermal comfort under sunny winter conditions.**

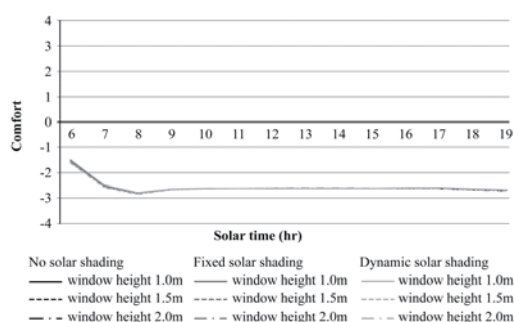**Fig. 21. Overall thermal sensation under cloudy winter conditions.**

Fig. 22. Whole-body thermal comfort under cloudy winter conditions.

5. Discussion

Results for the models simulated show that, when exposed to the highly transient character of the outdoor environment, the façade affects the indoor thermal environment as each layer of the fenestration system and the façade as a whole performs a "filtration" of the outdoor environment. The parameter variations show that window size and solar shading type can have a very direct impact on an occupant's thermal sensation and consequently her level of thermal comfort, but that this impact also greatly depends on the outdoor conditions. Here the results show the importance of considering both direct and diffuse solar radiation when evaluating the occupant's indoor thermal environment.

It should be noted that solar radiation will be of special importance in perimeter zones where the occupant has a larger projected area facing the sun thus absorbs more solar radiation. The occupant's close position to the façade also increases the radiation heat exchange with the internal surfaces of the façade and therefore also the significance of changes in window pane surface temperature. Furthermore, the effect of the solar radiation on the occupant's thermal sensation and comfort does not peak around noon together with the solar radiation, but displays a displacement. This is caused partly by the occupant's position and partly by the accumulation of heat in the room during the day. The occupant is seated in the eastern side of the room facing west, and is thus exposed to more solar radiation in the afternoon than early in the day.

Furthermore, it should be noted that the dynamic solar shading is activated not only by indoor air temperature but also the risk of glare, which could result in shielding out otherwise beneficial solar heat gain during winter. Glare could be mitigated by internal solar shading, allowing more solar radiation to enter the room, but in these simulations, glare is

evaluated in accordance with a proven method and the activation of any solar shading inevitably results in a significant reduction in heat gain.

Many of the factors assumed in these studies (the position and orientation of the occupant in the room, clothing level, metabolic rates, etc.) will greatly influence the thermal comfort of the occupant and can vary over time and from person to person. Thus the results presented in this article cannot be generalised, but should be seen as indications of how the façade design impacts only the thermal indoor environment.

In general, the façades with dynamic solar shading display the best performance, but only by a small margin when compared to façades with fixed solar shading and façades with no solar shading. Despite a very significant difference in transmitted solar radiation between the solar shading types, window height seems to be of equal importance to thermal comfort. The superior performance of the dynamic solar shading is most clear under sunny conditions when high levels of solar radiation are transmitted, but in the winter this tendency is less marked. The differing results for sunny conditions in summer and winter show how the outdoor air temperature determines what impact the transmitted solar radiation has on the occupant's thermal sensation and comfort. In sunny summer conditions, when relatively high outdoor temperatures dominate, the transmitted solar radiation always results in a decrease in overall comfort, and the best-performing façade over the course of a working day is the façade that most efficiently blocks out solar radiation. That is why the dynamic solar shading performs the best, followed by fixed solar shading, and then no solar shading, while a decrease in window height also results in an increase in overall thermal comfort. A similar tendency is not observed in sunny winter conditions, when the solar heat gain benefits overall thermal comfort during the first and final parts of the working day but causes overheating during the middle part of the day. Despite a cold outdoor environment and indoor air temperatures that does not exceed 23°C in any of the models, thermal sensation already surpasses neutral levels around 11 hours signifying a negative development in the overall comfort level. Therefore none of the façade designs has an ideal performance over the course of a sunny winter day, but the greatest differences occur in the middle of the day when dynamic solar shading performs significantly better.

Under cloudy sky conditions, thermal sensation and thermal comfort are little affected by window height and solar shading type. When only minor amounts of solar radiation are transmitted into the room, the transmission heat loss through the façade seems to define potential differences in thermal sensation and comfort. There are only minor differences in heat transfer coefficients (U-value) between glazing and the opaque façade, as can be seen by observing the difference in indoor air temperature and indoor surface temperature of the window pane. That is why all the façade designs simulated show basically the same performance in relation to thermal sensation and comfort, though with greater dispersion during the summer.

The seasonal difference between summer and winter and the difference between sunny and cloudy conditions reveal how the solar radiation greatly impacts the indoor thermal environment and consequently the occupant's thermal sensation and comfort level. Solar radiation also results in a dramatic increase of the surface temperature of the window pane. Here the radiant heat transfer between the window pane heated by insolation and the occupant affects the significant increase in thermal sensation. Once again it should be noted that this effect is accelerated by the close distance of the occupant to the façade.

Analysing the results for the indoor air temperature can show whether or not the adaptive approach to indoor thermal environment results in more relaxed temperature criteria being accepted than in the PMV method proposed by Fanger. In the summer, sunny conditions see indoor air temperatures reach approximately 26-29°C and cloudy conditions see them reach approximately 25-26°C, resulting in thermal sensation levels ranging from 1 to 3 and 0 to 1, respectively. In the winter, sunny conditions see indoor air temperatures reach 20-22°C and cloudy conditions see them reach 19-22°C, resulting in thermal sensation levels spanning from -3 to 3 and around -3, respectively. The European standard gives a comfort range based on the PMV model and defines a temperature range of 23-26°C during summer and 20-24°C during the winter as achieving a Class II indoor thermal environment (CEN, 2007). So the results are in relatively good agreement with the traditional comfort range and do not indicate more relaxed temperature criteria. Therefore the adaptive comfort approach do not necessarily signify an energy reduction potential.

When focusing on the indoor thermal environment the results presented here do not give a clear indication of an optimal solar shading type or window height out of those simulated. Increasing the thermal comfort of the occupant can be obtained by either window size, solar shading type or a combination. At the same time, it should be noted that considerations about the indoor thermal environment should be balanced with the need for energy efficiency, and the insolation could have a beneficial effect on the heat demand. Furthermore, in terms of daylight, dynamic solar shading will in most instances perform significantly better than fixed solar shading. Because dynamic solar shading can be adjusted and even fully retracted, daylight will be able to penetrate deeper into the room – especially under cloudy conditions. Thus, when other performance metrics are included in the evaluation, dynamic solar shading can prove the optimal choice.

The lack of any clear indication of an optimal performance among any of the fenestration systems analysed underlines the importance of performing very detailed simulations early in the design process to "fine-tune" concordance between function and façade design. Dynamic solar shading does not always seem to be the optimal choice when trying to obtain a pleasant indoor thermal environment for the occupant, despite its ability to control insolation efficiently – even in a north-European climate where relatively low outdoor temperatures often occur.

6. Conclusion

This article demonstrates how façade designs, in terms of solar shading type and window size, affect the indoor thermal environment. Analyses were carried out using a very detailed program predicting the thermal sensation and thermal comfort of the 16 separate body parts of a virtual occupant in a 3x3x6m perimeter office to evaluate the whole body sensation and over all comfort. These analyses were carried out using the adaptive approach relating the evaluation of thermal comfort to the actual situation.

All the models simulated display a predominantly negative thermal comfort mainly due to hot sensations during summer and cold sensations during winter. The difference between sunny and cloudy conditions shows the significance of direct solar radiation in indoor thermal comfort. Sunny conditions show that parameter variations in fenestration design influence the indoor thermal environment through control of insolation, while all models perform very similarly in cloudy conditions. This not only highlights the importance of including solar radiation in the evaluation but also the importance of performing such detailed evaluations fairly early in the design process and taking into account the highly transient character of the surrounding environment. Only then can the complex equilibrium between achieving a high level of indoor thermal environment and the increasing demand for energy efficiency be balanced, not to mention such aspects as the need for flexibility in the work space now and in the future, aesthetics and costs, which all go into selecting the optimal fenestration design.

References

Arens, E., Zhang, H. & Huizenga, C., 2006a. Partial- and whole-body thermal sensation and comfort— Part I: Uniform environmental conditions. Journal of thermal biology 31 (1-2), 53-59.

Arens, E., Zhang, H. & Huizenga, C., 2006b. Partial- and whole-body thermal sensation and comfort—Part II: Non-uniform environmental conditions. Journal of thermal biology 31(1-2), 60-66.

ASHRAE Standard 55, 2004. Thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating and Air Conditioning Engineers. Atlanta, USA.

Brager, G.S., Paliaga, G., De Dear, R., Olesen, B., Wen, J., Nicol, F. & Humphreys, M., 2004. Operable windows, personal control, and occupant comfort. ASHRAE Transactions (110), 17-35.

Brager, G.S. & de Dear, R.J., 1998. Thermal adaptation in the built environment: a literature review. Energy and Buildings 27 (1), 83-96.

CEN EN 15251. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Brussels, Belgium: European Committee for Standardization; 2007.

Cheng, Y., Niu, J. & Gao, N., 2012. Thermal comfort models: A review and numerical investigation. Building and Environment 47(0), 13-22.

de Dear, R. & Brager, G.S., 2001. The adaptive model of thermal comfort and energy conservation in the built environment . International journal of biometeorology 45(2), 100-108.

Fanger PO. Thermal comfort. Copenhagen, Denmark: Danish Technical Press; 1970.

Huizenga, C., Hui, Z. & Arens, E., 2001. A model of human physiology and comfort for assessing complex thermal environments. Building and Environment 36(6), 691-699.

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

Kubaha, K., Fiala, D., Toftum, J. & Taki, A.H., 2004. Human projected area factors for detailed direct and diffuse solar radiation analysis. International journal of biometeorology 49(2), 113-129.

Kuno, S., 1995. Comfort and pleasantness. PAN Pacific Symposium on Building and Urban Environmental Conditions in Asia, Nagoya, Japan.

Nicol, J.F. & Humphreys, M.A., 2002. Adaptive thermal comfort and sustainable thermal standards for buildings. Energy and Buildings 34(6), 563-572.

Nielsen, M.V., Svendsen, S. & Jensen, L.B., 2011. Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight. Solar Energy 85(5), 757-768.

Raja, I.A. & Nicol, F., 1997. A technique for recording and analysis of postural changes associated with thermal comfort. Applied Ergonomics 28(3), 221-225.

Sourbron, M. & Helsen, L., 2011. Evaluation of adaptive thermal comfort models in moderate climates and their impact on energy use in office buildings. Energy and Buildings 43(2-3), 423-432.

Stolwijk, J.A.J. & Hardy, J.D., 1966. Temperature regulation in man - A theoretical study. Pflügers Archiv für die Gesamte Physiologie des Menschen und der Tiere 291(2), 129 - 162.

Tanabe S, Tsuzuki T, Kimura K, Horikawa S. Numerical Simulation Model of Thermal Regulation of Man with 16 Body Parts of Evaluating Thermal Environment (Part 1 Heat Transfer at Skin Surface and Comparison with SET* and Stolwijk Model). Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, 1995.

Toftum, J., Andersen, R.V. & Jensen, K.L., 2009. Occupant performance and building energy consumption with different philosophies of determining acceptable thermal conditions. Building and Environment 44(10), 2009-2016.

Tzempelikos, A., Bessoudo, M., Athienitis, A.K. & Zmeureanu, R., 2010. Indoor thermal environmental conditions near glazed facades with shading devices – Part II: Thermal comfort simulation and impact of glazing and shading properties. Building and Environment 45(11), 2517-2525.

Tzempelikos, A. & Athienitis, A.K., 2007. The impact of shading design and control on building cooling and lighting demand. Solar Energy 81(3), 369-382.

WinDat, 2006. Window Information System software (WIS), WinDat Thematic Network, TNO Bouw, Netherlands. http://www.windat.org

Zhang, H., Arens, E., Huizenga, C. & Han, T., 2010a. Thermal sensation and comfort models for non-uniform and transient environments: Part I: Local sensation of individual body parts. Building and Environment 45(2), 380-388.

Zhang, H., Arens, E., Huizenga, C. & Han, T., 2010b. Thermal sensation and comfort models for non-uniform and transient environments, part II: Local comfort of individual body parts. Building and Environment 45(2), 389-398.

Zhang, H., Arens, E., Huizenga, C. & Han, T., 2010c. Thermal sensation and comfort models for non-uniform and transient environments, part III: Whole-body sensation and comfort. Building and Environment 45(2), 399-410.

Mitchell, R., Kohler, C., Ling Zhu, L. & Arasteh, D., 2011. THERM 6.3 / WINDOW 6.3 NFRC Simulation Manual. LBNL Report 48255. Berkeley, USA.

Paper V

Energy renovation of listed buildings

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ENERGY RENOVATION OF LISTED BUILDINGS

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1. Introduction

Energy renovation often includes adding an insulating layer to the building envelope either on the exterior or the interior. The positive effect of this is well documented, and in many cases reducing the heat loss by a better insulating and tighter building envelope is a reasonable solution. However, the design scope of energy renovation should be constantly challenged in order to attract the interest of investors, architects, designers and, last but not least, local authorities involved with the preservation of cultural heritage in our cities. When renovating any built environment, subjective factors such as aesthetics and spatial quality should be included to provide robust solutions that achieve more than just a reduction in heat loss.

Recladding of façades can have qualitative drawbacks for the architectural expression when placed on the exterior where the patina and history of e.g. a brickwork façade is lost. Insulation placed in the interior of the façade can cause moisture accumulation and the build-up of mould (Byg-Erfa # 31 09 10 29). Insulating the interior of the façade also prevents the insulation of connections between the floor structure and the façade, thus allowing thermal bridges. The most important drawback with interior insulation is that it consumes often extremely valuable square metres. It should be noted that in recent years new insulation products based on capillary and diffusion-open materials that distribute moisture to the surface and air in the building have reached the market. The moisture, however, must be removed from the air by means of increased mechanical ventilation, which also demands extra energy.

Furthermore, whether on the exterior and the interior of the façade, insulation can result in an increased risk of overheating problems, the potential scale of which is often neglected in historical buildings. It is important to take the indoor climate quality into account and not just look at the energy balance of the building. Since the basic geometry of these existing buildings will not change, it could be a good idea to start the design process with an advanced simulation that would normally be made later in the process.

The design strategies are presented using residential buildings built between 1870 and 1950. The walls are traditional loadbearing, and consist of exposed brickwork. All the cases have architectural qualities worth preserving.

In the presentation of the cases, we only consider the effect on energy demand and the number of overheating hours. Cost, payback time, LCA, extended indoor climate analysis, etc. are not considered. The cases are not directly comparable. The aim of this paper is to use the cases to present alternative design strategies and expand the scope of solutions for energy renovation of listed buildings. The case studies were initially carried out using the professional simulation software thought most adequate for the requirements by students of the department of civil engineering at the Technical University of Denmark; Nikolaj Noerregaard Rasmussen, Morten Rung (REPO) Rene Bukholt, Mads Rasmussen (Case 1) and Stine Rolle (Case 2).

2. Case 1: Beneficial use of passive solar heat gain

Public housing projects from the 1950s in Denmark have high architectural quality. But the energy consumption and out-dated spatial organization of the flats call for renovation to achieve a better mix of employed and unemployed occupants. The construction is loadbearing massive brick walls. The floor structure is made of in situ-cast reinforced concrete with a wooden cladding.

The design strategy for this case was based on quite substantial simulations of the existing building's indoor climate in a representative flat carried out at the beginning of the design process.

Fig. 1: *The representative flat marked on the existing south-west façade (left) and in plan (right)*

The energy demand was simulated using the calculation method prescribed in the Danish Building Regulations (EBST, 2010), while the simulation of the indoor thermal environment was carried out in the more detailed program BSim (BSIM, 2006). The BSim simulation model was divided into two segments: a north-east-facing and a south-east-facing, to evaluate the risk of overheating due to orientation. The number of hours above 27°C allowed was compared to Danish standards for offices because there are currently no guidelines for evaluating overheating problems in domestic settings. The guideline threshold value for when an office environment can be considered as having overheating problems is 25 hours above 27°C (REF: DS 474).

2.1. Current situation

The energy simulation of the flat's current construction shows an energy demand of 116.7 kWh/m^2/year. The heating demand of 94.2 kWh/m^2/year constitutes the majority of the total energy demand, while the electricity demand (for ventilation fans and pumps) is 7.7 kWh/m^2/year and the energy demand for domestic hot water (250 l/m^2/year) is 14.8 kWh/m^2/year. (fig. 4)

The simulation of the building's current indoor thermal environment shows potential overheating problems, particularly for south-facing rooms, with a considerable number of hours where the temperature exceeds 27°C. Hours above 27°C total 27 for the north-east-facing and 101 for the south-west-facing zone. (fig.5)

2.2 Renovation solutions

Based on the simulations of the current building's energy demand and indoor thermal environment, three renovation solutions aimed at reducing energy demand and overheating problems are proposed and analysed:

1. External insulation on the north-east-facing façade
2. External insulation on the north-east-facing façade and internal insulation on the south-west-facing façade
3. External insulation on the north-east-facing façade, no interior insulation on the south-west-facing façade, but increased potential for passive solar heating.

The variations were chosen in order to investigate the possibility of replacing interior insulation by improved access for solar heating. Due to a wish to preserve the architectural expression facing the park and the technical difficulties posed by the extruding balconies, exterior insulation of the south-west-facing façade was not considered an option. Exterior insulation was, however, considered possible for the less expressive north-east-facing façade. Furthermore, another difference between the north-east and south-west-facing façades was in the potential for passive solar heat gain.

To establish the increased potential for passive solar heating, the south-west-facing window area in the living room is increased in the simulation from 3.78m^2 to 5.67m^2 by replacing the existing opaque brick parapet with window. As mentioned earlier, the simulation of the indoor thermal environment made early in the design process, showed excessive numbers of hours with temperatures above 27°C. Thus, a more beneficial utilization of the passive solar heat gain to reduce heating demand during the winter season would simultaneously have to include remedies to reduce solar heat gain during the summer season. Therefore, a

solution combining fixed and dynamic solar shading was proposed.

The fixed solar shading was designed using an application in Ecotect (REF for Ecotect) that depicts where direct sunlight meets a model of a sunshade. This made it possible to minimize the surface area and thereby optimize daylight intake while affecting the architectural expression the least.(fig.2)

Fig. 2: Illustration of the design of the fixed solar shading showing insolation intensity and minimization of surface area (left) and the final geometry added to the existing façade (right)

The dynamic solar shading, which could be perceived as a dynamic parapet, was added to further reduce the number of hours with temperatures over 27°C. The reasoning behind shading the window from below is that an area at the top of the window can be maintained for view to the outside, and the top is already shaded by the fixed solar shading.(fig.3)

Fig. 3: Illustration of renovation solution 3 with increased window area and the dynamic parapet inactive (left) and active (right)

The parameter variation with and without interior insulation shows a general decrease in heating demand when the insulation of the façades is increased. Adding external insulation to the north-eastern façade, as proposed in Solution 1, reduces the heating demand by 35%. Adding insulation to both north-eastern and south-western façades reduces the heating demand by 46% as proposed in solution 2.

Combining increased insulation on the north-eastern façade with an increased window area and solar shading as proposed in Solution 3 reduces the heating demand by 39% compared to the existing situation.

Electricity demand and energy demand for domestic hot water is constant for all simulated models because the mechanical ventilation rate, pump operation and use of domestic hot water are assumed constant. (fig.4)
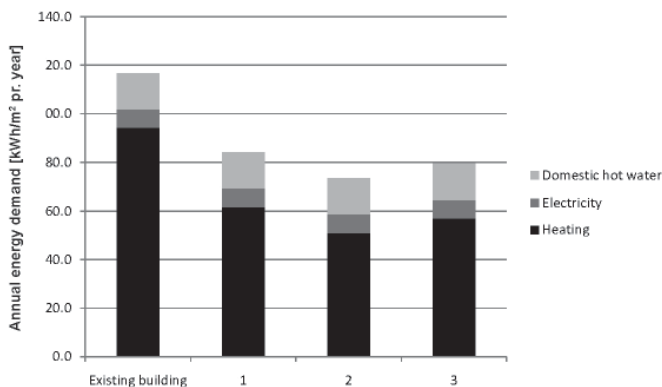
Fig. 4: Annual energy demand simulated in accordance with Danish standards for the existing building and for Solutions 1-3)

The number of hours with an indoor temperature exceeding 27°C decreases when external insulation is added to the north-east-facing façade (Solution 1) by 81% for the north-eastern and by 24% for the south-western zone. On the other hand, overheating increases by 40% for the south-western zone compared to the existing situation, when interior insulation is also added to the south-west-facing façade (Solution 2). The difference between Solutions 1 and 2 has little effect on overheating problems in the north-eastern zone.

The potential for a more beneficial utilization of the available passive solar heat gain combined with effective solar shading, as proposed in Solution 3, results in a decrease in the number of hours where the indoor temperature exceeds 27°C by 81% for the north-eastern and by 20% for the south-western zone, showing similar reductions to Solution 1. (Fig.5)
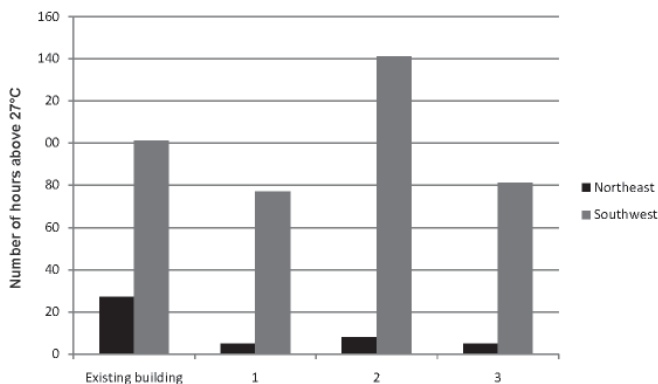

Fig. 5: The annual number of hours with indoor temperatures exceeding 27°C simulated in BSim for the existing building and for Solutions 1-3

The general tendency for increased numbers of hours with indoor temperatures exceeding 27°C when adding insulation to the opaque parts of the building envelope seems to be partially caused by the decrease in U-value, and partially by the reduced utilization of the thermal mass. The increased insulation value reduces heat transmission not only during winter, but also during summer, which results in an accumulation of heat and subsequently overheating. Furthermore, the additional internal insulation dramatically reduces the heat

exchange between the internal environment and the thermal mass represented in the massive brick façade with a high heat capacity. This makes it impossible to use the potential beneficial cooling energy stored in the brick façade as a result of the lower temperatures during the night. Solution 3, however, combines the passive heat gain that is possible to obtain from the south-west with the reduction in heat loss from the north-east, where the amount of solar radiation is low, while maintaining the thermal storage capacity in the masonry walls.

2.3 Conclusion

A careful design process informed by advanced energy and indoor climate simulations from the start can lead to proposals with a combination of larger windows and shading which will increase the daylight level and increase the passive solar heat potential in the thermal mass of the structure. A more precise placement of insulation at the most efficient locations, instead of a full cover wrapping, combined with the above-described alternatives, leaves more space for creativity in energy renovation. Thus, Solution 3 represents a relevant alternative to traditional insulation by being able to obtain the desired equilibrium between energy reduction and improved thermal indoor environment.

It could be concluded that – even in buildings which have potential problems with overheating – passive solar heating in combination with dynamic and fixed solar shading could be an alternative to interior insulation. However, a solution based on passive solar heating risks changing the architectural expression and structure of the building dramatically and in the case of some listed buildings would therefore not pose an alternative to interior insulation of the façades.

3. Case 2: Energy production as an alternative

Fig. 6: Picture of the building used in Case 2 (left) Illustration of the building context (left) and the representative section used for simulations (right).

The case is a listed building, originally designed as a hospital and erected between 1890 and 1900 but converted to small independent flats for retired people in the 1990s. The area consists of several narrow three-storey buildings oriented east-west with windowless gables facing south and north (fig. 6). The construction is massive, load bearing masonry walls. In the reference building, the walls, roof and windows are unaltered, but a new ventilation system with heat recovery was added in 1990.

As in the previous case, extensive and detailed simulations of the indoor climate, energy balance and energy demand formed the starting point for the design process. In this case, the simulations were made in IES Virtual Environment (CIBSE, 1999). The simulations were of a representative section containing two apartments – one facing east and the other facing west with a common corridor between. The simulation model was built up so that each room was represented by a thermal zone.(fig. 6)

3.1 Current Situation

The energy simulation of the current construction displayed in Fig. 7 shows an energy demand of 110.1 kWh/m^2/year. The heating demand of 72 kWh/m^2/year constitutes the majority of the total energy demand, while the electricity demand for ventilation is 10.6 kWh/m^2/year and the energy demand for domestic hot water (523 l/m^2/year) is 27.5 kWh/m^2/year.

The detailed simulation of the current building's indoor thermal environment shows no critical problems

with overheating. The number of hours where the indoor temperature exceeds 26°C varies between 33 and 0.(fig.8)

Furthermore, simulations of the representative section show that the narrow building and relatively large windows result in apartments with ample daylight.

3.2. Renovation solutions

As mentioned earlier the building is listed, which means that the exterior expression of the building cannot be altered. Therefore renovation solutions include interior insulation of the building envelope, replacement of existing windows with more energy-efficient ones, and especially the potential for producing electricity with solar cells and using solar panels for heating and domestic water. The aim was to investigate whether the reduction in heat loss achievable with interior insulation of the building façades could be compensated for by an equivalent production of energy, thus posing a design alternative. Three renovation solutions where simulated and analysed:

1. insulation of attic and replacement of windows
2. insulation of attic, replacement of windows and interior insulation of façades
3. insulation of attic, replacement of windows and production of energy

Simulations of the annual energy demand and the indoor thermal environment for renovation solutions 1 and 2 show a decrease in heating demand and an increase in the number of hours where the indoor temperature exceeds 26°C. Heating demand decreases by 34% with Solution 1 and by 70% with Solution 2 compared to the existing situation.
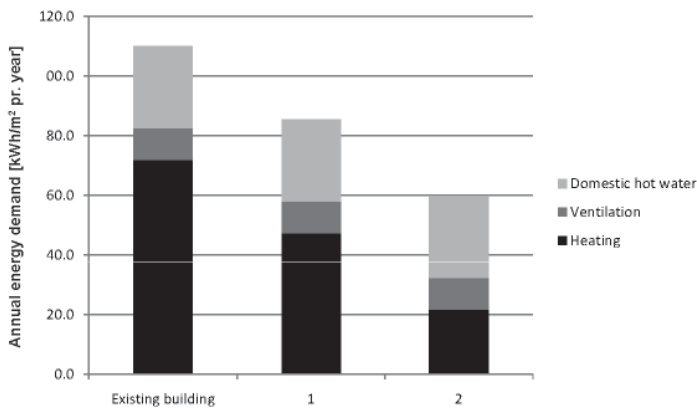

Fig. 7: Annual energy demand simulated in accordance with Danish standards for the existing building, and for Solutions 1 and 2.

The risk of overheating increases for all rooms and the total number of hours where the indoor temperature exceeds 26°C increases by 75% with Solution 1 and 113% with Solution 2 compared to the existing situation (Fig. 10).

The difference between the annual energy consumption in solutions 1 and 2 indicates the effect of insulating the façade on the interior side was 70,000kWh for the entire building. So it was investigated whether or not 70,000kWh can be produced by solar cells and/or solar panels instead, thus avoiding the overheating tendency caused by adding interior insulation to the façade.
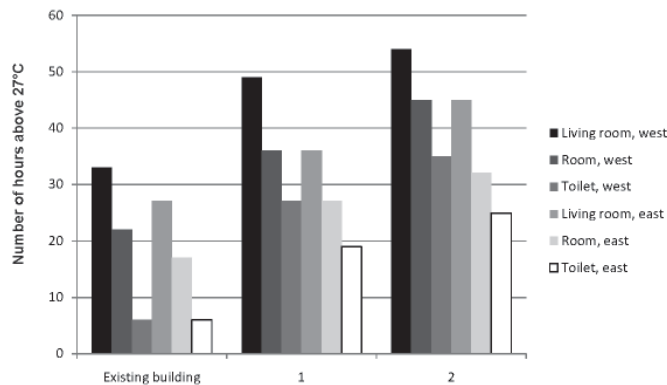
Fig. 8: Annual number of hours where the indoor temperature exceeds 26°C for the existing building, and for Solutions 1-2

3.3. Solar cells

Since the building is listed, it is of importance that the adding of solar cells and solar heating should not disfigure the architectural expression. An investigation of the solar potential for this building shows that the south, west and east-facing roof surfaces and the south-facing gable have the greatest potential.

A dialogue with the conservation authorities suggests that the roof is less sensitive to alterations. The aim is to maintain a uniform roof surface that does not rearrange the geometry and general outline of the roof. A solution where the entire roof consists of solar cells was plausible for the authorities. This solution would be costly, but is arguably plausible since the existing roof needs replacement and it would make it easier and more economical to insulate the attic in the same process. Placing 'islands' of solar cells on the existing roof would change its appearance much more than covering the entire roof.

The roof surface is penetrated by a number of chimneys and bay windows. Some of them could be removed, but in order to preserve a history some should be left. None of the chimneys currently function as chimneys, but some have been converted into ventilation outlets. However, the preserved chimneys and bay windows will cast shadow on some of the solar cells, which will result in the need for more complicated wiring of the panels and the addition of extra bypass diodes.

In this solution, standard panels of mono-crystalline solar cells with an efficiency of 15% were chosen and placed on roof surfaces facing east, south and west. Calculations show that the 36 panels would generate 43,400kWh per year, taking into account the mean efficiency throughout the solar cells' service life and system efficiency.

Tab. 1: Generated effect from solar cells dependent of orientation and sum for the entire roof surface.

Orientation of roof surface	West	South	East	Sum
Area [m^2]	227	18	236	
Solar Radiation [kWh/m^2]	947	1,152	958	
Effect [kWh]	20,400	2,000	21,000	**43,400**

The calculation in tab. 1 shows that solar cells on the roof would only generate enough energy to cover 62% of the energy reduction obtained by reducing the heating demand by means of interior façade insulation shows how electricity demand always exceeds the potential production. However, it should be noted that the price of the kilowatt hours electricity produced is higher than the kilowatt hours saved on heating.
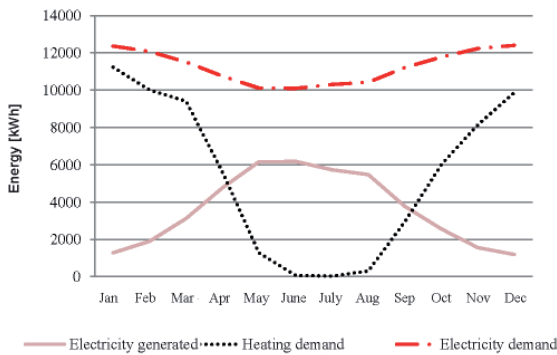
Fig. 9: Illustration of potential electricity production and the building's annual heating and electricity demand.

3.4. Solar heating panels

Instead of solar cells, solar heating panels could be placed on the roof to supply hot water to the building and thus substitute for interior insulation. The potential for supplying heating by means of the solar heating panels is also investigated in the following.

Tab. 2: Generated effect from solar heating panels dependent of orientation and sum for the entire roof surface.

Orientation of roof surface	West	South	East	Sum
Effect [kWh]	44,400	10,200	44,900	**99,400**

Tab. 2 shows that solar heating panels placed on the same roof surface can generate a maximum of 99,400kWh per year. The energy balance of the building was simulated in IESve and indicates the heating demand on a monthly basis, assuming that the demand for hot domestic water is the same the whole year round. The production varies with the time of the year depending on hours of sun. On this basis it is possible to compare production from the solar heating panels with the demand as shown in Fig. 10.
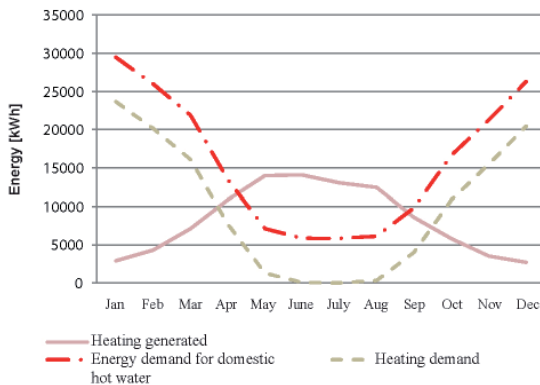
Fig. 10: Illustration of monthly distribution of potential production of heating energy via solar heating panels and the building's energy demand for heating and domestic hot water

Fig. 10 shows that there is an overproduction of heating energy from the solar panels from April to August even if the building's energy consumption of both heating and domestic hot water is taken into account. However, during the winter season the panels do not supply enough energy even to cover the demand for

domestic hot water.

4. Case III - Combining preservation of cultural heritage with energy renovations

The preservation of cultural heritage is of great significance and importance to a society, but has to be balanced with the ever-increasing focus on a new common value in society: sustainability. Achieving equilibrium between these criteria and many others is a complex process with many interdependent parameters. Methods of working with evaluation based on multiple criteria are thus of major importance and these tools should adapt to the new circumstances in society. In the following, a fusion of tools to register cultural heritage and the registration of solar potential is presented. The solar gain is of major importance for the energy efficiency and effect on the indoor environment of renovation solutions as illustrated in presented cases, and therefore for sustainability.

Existing buildings have the drawbacks that their geometry is fixed and that the geometry of the urban fabric around them has changed since their construction resulting in often less advantageous use of daylight and solar heat gain. This section outlines a mapping method developed by students at the Technical University of Denmark. The mapping method supplements the well-established SAFE method (Algreen-Ussing) in giving an overview of which buildings in an urban context have the greatest renovation potential with special attention to the utilization of solar energy. The traditional SAFE method evaluates the qualities of a given building and its contribution to the cultural heritage of the neighbourhood.

The SAFE method has two levels. The first consists of a holistic analysis of context worth preserving with subgroups: dominating features, general layout of the built area and importance in relation to the context (cultural environment, landmark, landscape qualities). The second level concerns the building itself: the architectural value, value in terms of cultural heritage, originality, condition, etc.

Each category is rated from 1-9, with 1 meaning that the building should be listed, 2-3 that the building is worthy of preservation to some extent, 4-6 is a medium level and 7-9 means that no features on the building are worthy of preservation. The individual ratings collectively make up an overall rating for each building. These ratings are communicated with colour-coded maps of all major historical urban areas.(fig.11)

Fig. 11: Map showing the SAFE ratings for the area in Copenhagen, Denmark, that contains the building used in Case III. The dark red colour means that the building is listed

4.1. REPO (REnovation POtential): a tool based on Multi Criteria Decision-Making (MCDM)

When evaluating a building's renovation potential, a large number of parameters need to be taken into account. In handling this complexity, the theories and tools behind Multi-Criteria Decision-Making (MCDM) have proven to be useful.

A research group under the International Energy Agency's Solar Heating and Cooling Task 23 investigated how MCDM could be used in the design process in the building industry (Balcomb et al). Their investigation led to the development of a software tool to facilitate the objective evaluation, prioritizing and selection of design proposals and criteria.

in determining the building's indoor environment and energy performance. It is to a large extent the outdoor conditions that determine how much energy has to be used to obtain a good indoor environment and here the mapping of the solar potential is of great importance. The above-mentioned criteria for the REPO analysis address these issues. In the following, the solar potential of a residential block of flats originally constructed in 1870 is analysed.

Fig. 13: Map showing the location of the case building in its context (to the left) and picture of the existing building showing the façades towards the street facing north and west

From the analysis, it can be concluded that the insolation is highest on the south-facing façade and roof surface. Because the building is a corner building, facing a broad crossing, neighbouring buildings do not cause much shadow (fig. 13). After noon the west-facing part of the block casts a shadow on the south façade facing the courtyard. The solar potential is thus greatest on the upper eastern part of the south-facing façade.

Before noon, the east-facing façade and its roof receive sun, while the west-facing façade only receives sun during the evening. At midday, the almost horizontal roof of the typical Copenhagen block has a large solar potential.

Such a simple mapping and analysis of the solar potential is very beneficial when designing renovation solutions for either a single block or an area as a whole. On this basis, techniques and solutions can be tailored to the specific buildings and in larger scale renovation projects result in a collective of buildings functioning together. Thus, based on the REPO analysis, renovation proposals for the building described above very early in the design process included PV-panels on the rear, south-facing roof and a Canadian sun wall on the part of the back yard façade with the largest solar potential. This proposal could be accepted by the local authority because the street façade would remain unaltered.

Interviews with preservation authorities in Denmark, point to a tendency to allow considerable design freedom for façades facing the rear yard. Another tendency is that the authorities are mainly preoccupied with the preservation of the general character of a historical neighbourhood. A mapping of both cultural heritage and solar potential together would point to which listed buildings could be 'sacrificed' in order to comply with demands for sustainable solutions.

5. Conclusion

It is important to increase the motivation of investors and public authorities with regard to energy renovation. In this respect, the design strategies applied to the process should be carefully considered. Design strategies that lead to an automatic choice of a full cladding with insulation and new windows risk creating design proposals that have poor aesthetic qualities and add no extra qualities apart from a reduction in heating demand. Furthermore, the results of this paper question whether full cladding with insulation automatically leads to the best solution if indoor environmental quality is considered alongside energy reduction.

A number of historical buildings have a large potential for energy storage due to thermal mass with high heat capacity. This embodied energy can be addressed and used to the advantage of energy reduction and a good indoor climate, but interior insulation risks neutralizing this potential. The carefully considered positioning of insulation at the most efficient locations in a building is a precondition for expanding the scope of energy renovation.

Information on the original building's indoor climate is of importance. A starting point where the original building has severe problems with overheating or inadequate daylight focuses the design process and leads to design solutions that will not only reduce energy demand but also give an experience for users of having gained extra qualities.

To expand the scope of design proposals for energy renovation, it is important to make an advanced indoor climate and energy simulation model at the beginning of the design process. The information gained from this model will suggest design potentials unique for the building in question. Since the geometry and orientation of the building in question are fixed from the beginning, the advanced simulations early in the design process represent an efficient method. These simulations increase the space of solutions and thus give space for a wider scope of proposals that can match the demand for preservation of the cultural heritage and architectural content of a building.

Society will have to value sustainability on an equal level with cultural heritage and listed buildings have to be addressed as well. The mapping of a building's solar potential in its specific urban context, and thus its embodied capacity for producing energy, is an important benchmark that could be used to point to less publicly exposed parts of the building with high solar potential, which could be redesigned without loss of cultural heritage. For instance the roofs and façades facing the back yards of the traditional European urban block structure hold such potential.

The integration of energy-producing elements in energy renovation projects should be considered as part of a holistic design solution. The careful selection of energy-producing elements is part of a technically and scientifically informed design process. In energy renovation projects, each building is unique and the energy-producing elements adequate for one building might not suit a neighbouring building. The architectural integration of such elements is challenging, so finding the places on the building that allow the most freedom for design is vital. Combining solar potential mapping with mapping of cultural heritage can reveal such areas on the building.

Taking care to analyse and utilize the potentials of the existing building and designing from that point of departure will reduce the risk of problem shifting. A holistic approach informed by simulations already at the beginning is a prerequisite for design renovation solutions that can enhance the building's qualities and reduce energy demand. A larger design platform for carrying out energy renovation is desirable in order to motivate and increase the number of energy renovation projects in the future.

References

Byg-Erfa Foundation, 2009, Document # 31 09 10 29, Denmark

Danish Building Research Institute, 2006, BSIM, Integrated Software for Thermal Analysis of Buildings and Installations, Denmark

CIBSE , Guide A, Environmental Design.

EBST. Bygningsreglement for erhvervs- og etagebyggeri, National Agency for Enterprise and Construction, Copenhagen, Denmark, 2010.

Balcomb, D.,Andresen, I., Hestnes, A.G.,2002.Multi-CriteriaDecision-Making MCDM-2, Colorado

Algreen-Ussing,G., 1995. Survey of Architectural Value in the Environment, Denmark

Further dissemination

Selection of projects supervised over the course of this research project.

- Bachelor project "Facetted facades – integrated daylight and energy design" by civil engineering students Birthe G. Uldahl & Neel Schmidt.

- Supervision of DTU's participation in the international student competition "Solardecathlon 2010".

- Bachelor project "Dynamiske vinduessystemer" by civil engineering student Lasse Brandt.

- Special course "Danmarks energistrategi i byggeriet" by civil engineering student Rene Bukholt.

- Master project "Energirenovering af enfamiliehus" by civil engineering students Dorte Skaarup Larsen & Mia Cynthia Paasche.

- Bachelor project "Energirenovering af en 50'er ejendom" by civil engineering students Mads Holten Rasmussen & René Bukholt.

- Bachelor project "Energirenovering af etagebyggeri - Undersøgelse af renoveringspotentialet for Københavnske karrébygninger fra perioden 1850-1940" by civil engineering students Morten Brink Rung & Nikolaj N. Rasmussen.

- Bachelor project "Projektforslag – solar decathlon 2012" by civil engineering students Jakob Bukh Kristensen & Malte Bülow Agerskov.

- Supervision and member of the faculty team for DTU participation in the international student competition "Solardecathlon 2012". The final proposition will be erected in full scale at the bi-annual competition event in Madrid, Spain summer 2012.

- Master project "Building envelope design based on analysis of window opening behavior and the effect on energy consumption and indoor climate" civil engineering student Jannie Sørensen.

- Bachelor project "Tværfagligt bygninsdesign i praksis: Konceptudvikling med fokus på bæredygtighed" by civil engineering students Mathias Jon Schandorff og Rasmus Onsberg.

Integrated energy design of the building envelope analyses how the implementation of technical knowledge early in the building design process can quantify the effect of a building's façades on its energy efficiency and indoor climate and thereby facilitate a more qualified design development.

The engagement in a wide range of architectural competitions seeks to test out incorporating a consciousness about energy and comfort as part of a more holistic performance evaluation. Here, great potential exist in considering the passive properties in the geometrical optimisation inherent in the development of the architectural concept. This approach resulted in building designs with an energy demand at least 25% below the minimum requirements while simultaneously maintaining high-quality indoor climate and architectural quality.

In this context understanding the interdisciplinary collaboration between engineers and architects is a cardinal point. Contrary to the traditional notion that the building's performance is determined by the architect's first sketch on a napkin, it is to a great extent already determined by the building's context and the building programme.

Energy efficient buildings affect our quality of life as it is the required level of indoor climate that defines the degree of energy efficiency obtainable. Therefore energy efficiency has to become an inherent part of our buildings, substantiating and merging with an architecture that aspires to more than aesthetics. True architecture can achieve holistic performance optimisation through an integrated and interdisciplinary approach in which responsibilities fall on both engineers and architects. Architecture is not a profession or a product; it is an attitude to the world we live in. And this project set out to embrace the challenge.