

# Integrated Energy Design in Master Planning



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**PhD Thesis**

**Department of Civil Engineering  
2012**

DTU Civil Engineering Report R-254 (UK)  
March 2012

# **Integrated Energy Design in Master Planning**

Industrial PhD Programme

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BYG Rapport R-254

ISBN: 9788-778773364

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## **Preface**

The intention with this PhD thesis is to contribute to the creation of a breakthrough in the effectiveness of the Integrated Energy Design method such that it is transformed into something with relevance, meaning and positive effect for people and nature in the built environment.

This thesis is not a continuation of the tradition of theses about Integrated Energy Design (IED). The vast majority of discourse on integrated design takes a technical view of sustainable design in which performance is the primary value. The thesis presented here looks at sustainable urban design not with the eyes of an engineer (How does it work?) or of an architect (How does it look like?), but rather with the eyes of an Architectural Engineer (How is it perceived? What is wonderful about it? How is it part of a greater whole?)

*13 January 2012*

Jakob Strømmand-Andersen

## **Acknowledgements**

First and foremost, I would like to thank my supervisors Professor Svend Svendsen (DTU) and Architect, Associate and Sustainability Manager Signe Kongebro (HLA) for giving me the opportunity to become a PhD student and for their guidance throughout my study. My gratitude is also extended to my co-supervisors, Associate Professor Lotte Bjerregaard Jensen (DTU) and Adjunct Professor and Partner, Louis Becker (HLA).

I would also like to thank all my colleagues at Henning Larsen Architects and in the Section of Building Physics and Services at DTU Civil Engineering. A special thanks to my PhD colleagues, Peter Andreas Sattrup, Michael Jørgensen and Martin Vraa Nielsen for invaluable discussions.

Finally, I would like to thank the Realdania Foundation for their financial support.



## **Abstract**

This PhD thesis considers urban structure and buildings in an energy correlation and use the knowledge to design energy- and comfort-optimized cities and buildings. The parameters are: the structure of nature, the city and the landscape, both in terms of geometry and interrelationships and in terms of opportunities and limitations with regard to light, shade, sun and wind.

The aim is threefold: (1) to unfold the link between building energy use and urban density, typology and fabric; (2) to analyse how technical scientific knowledge can be integrated in early urban planning and design decisions (IED); and (3) to show the architect's responsibility and opportunities to rethink their architectural role based on new goals and knowledge.

The research results show an impact from urban form on building energy consumption which is much greater than previously thought, more precisely described, and more dynamic in character as daylight is taken into account. Furthermore the results suggest that there are limits to urban densification (200–300%) as an energy optimization strategy. The solar energy and daylight potential should be considered, and indeed protected, as a common resource in urban design.

The most important observation for qualitative design research is that the first step to improving energy performance must be taken with the architect's first sketch on paper. It is here that the framework and preconditions for the city and the building's performance will be set. Argued this way, optimization of the special properties of urban density, typology and fabric takes priority over the optimization of technical service systems. This means that in the design process the architect's responsibilities outweigh those of the engineers.

The research is reported in the main body of this thesis and in the papers for scientific journals.

## Abstrakt

Ph.d. afhandlingen betragter byens struktur og bygningen i en energimæssig sammenhæng og bruger denne viden til at designe energi- og komfortoptimerede byer og bygninger. Paramenterne er; naturens struktur, byen og landskabet, geometri og indbyrdes forhold, muligheder og begrænsninger mellem lys, skygge sol og vind.

Målet er trefoldigt: (1) at udbrede forholdet mellem byens tæthed, typologier, stoflighed og bygningens energiforbrug; (2) at analysere hvordan teknisk videnskabelig viden kan integreres i de tidlige planlægnings- og designbeslutninger (IED); (3) at illustrere arkitektens ansvar og muligheder for at gentænke den arkitektoniske rolle ud fra nye mål og viden.

Forskningsresultaterne viser, at effekten af byens struktur på bygningens energiforbrug, er meget større end før antaget, mere præcist beskrevet og mere dynamisk i sin karakter, fordi dagslys er taget med i betragtning. Dertil indikerer resultaterne, at der er en grænse for fortætning (200 % -300 %) som konsekvens af en energioptimeringsstrategi. Potentialet for solenergi og dagslys skal betragtes eller endda beskyttes som en fælles ressource i byens planlægning.

Den vigtigste kvalitative iagttagelse er, at det første step i en energioptimering sker ved arkitektens første streg på papiret. Det er her strukturen og forudsætningerne for byens og bygningens ydeevne bliver fastsat. Argumentet på den måde vil en optimering af rumlige egenskaber (byens tæthed, typologier og stoflighed) have en højere energimæssig prioritet sammenlignet med en optimering af de tekniske systemer. Dette betyder, at i en design proces, vægter arkitektens ansvar højere end ingeniørens.

Forskningen er rapporteret i afhandlingen og artikler til videnskabelige journaler.

## Scientific paper summary

During the work on this thesis, ten different papers have been published: five technical scientific papers (ISI-index), two conference papers, two popular science papers, and one design experiment.

The main hypothesis is based on three papers, (Paper I, II & III). The focus is on some key questions, which are answered in the papers:

- I. If we are going to build in a more sustainable way, we need to build more densely. But what effect does a dense city have on the building energy consumption?  
*We found that urban density in northern Europe has an impact on total energy consumption in the range of up to +30% for offices and +19% for housing compared to less dense cities. This shows that urban geometry is a key factor in energy use in buildings.*
- II. How do solar access and daylight conditions affect overall energy use in relation to the morphological design of urban building typologies?  
*We found a relative deviation in total energy performance of up to 19% and in daylight autonomy of up to 48% at similar densities, which suggests that building typology is a key factor affecting energy consumption and daylight levels.*
- III. Daylight has always played an essential role in the lay-out of cities. But is it possible to re-think the use of daylight in the urban context?  
*Our study shows that reflected light makes an important contribution to the overall daylight and indeed constitutes the majority of the daylight available to the lowest floors in high urban densities. What this emphasises is that in northern Europe, building façades should not only be considered as selective devices for creating optimal internal environments, but also in terms of their contribution to creating good and varied daylight conditions for neighbouring buildings.*



Henning Larsen

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## Appended papers

Scientific papers (ISI-index)

### Paper I

*“The urban canyon and building energy use: Urban density versus daylight and passive solar gains”*

J. Strømmand-Andersen<sup>a</sup>, P.A. Sattrup<sup>b</sup>

Published in: *Energy and Buildings*, 43, Issue 8, August (2011) 2011-2020

### Paper II

*“Building Typologies in Northern European Cities – Daylight, Solar Access and Building Energy Use”*

J. Strømmand-Andersen<sup>a</sup>, P.A. Sattrup<sup>b</sup>

Accepted for publication: *Journal of Architectural and Planning Research*, November 2011

### Paper III

*“Urban Daylighting: the impact of urban geometry, façade reflectance and window to wall ratios on daylight availability inside buildings”*

A. Iversen<sup>a</sup>, J. Strømmand-Andersen<sup>b</sup>, P.A. Sattrup<sup>c</sup>

Submitted to: *Building and Environment*, December 2011

### Paper IV

*“Urban design and pedestrian wind comfort – a case study of King Abdullah Financial District in Riyadh”*

J. Strømmand-Andersen<sup>a</sup>, J.C. Bennetsen<sup>b</sup>

Accepted and in review process: *Environment and Planning B: Planning and Design*, 2011

## Conference papers (ISI-index)

### Paper V

*“Integrated Design – paradigm for the design of low-energy office buildings”*

M. Jørgensen<sup>a</sup>, M.W. Nielsen<sup>b</sup>, J. Strømmand-Andersen<sup>c</sup>

Published in proceedings: *ASHRAE Winter Conference*, 2011, Las Vegas, Nevada

## **Conference papers**

### **Paper VI**

*“A methodological study of environmental simulation in architecture and engineering - Integrating daylight and thermal performance across the urban and building scales”*

P. A. Sattrup<sup>a</sup>, J. Strømman-Andersen<sup>b</sup>

In proceedings: *Symposium on Simulation for Architecture and Urban Design*, 2011, Boston, MA, USA

### **Paper VII**

*“Sustainable Cities – Density versus solar Access; A Study of Digital Design tools in Architectural Design”*

P. A. Sattrup<sup>a</sup>, J. Strømman-Andersen<sup>b</sup>

In proceedings: *ISES Solar World Congress*, 2009, Johannesburg, South Africa

## **Popular science papers**

### **Paper VIII**

*“Energy Design: Message to Staff on Spaceship Earth”*

J. Strømman-Andersen

Published in: *ArkitekturM*, Vol 1. No 5. 2009. Arkitektens Forlag

### **Paper IX**

*“Climatic Diversity in the City”*

J. Strømman-Andersen

Published in: *Byplan*, No. 3 september 2010/62. årgang

## **Design Experiment**

### **Paper X**

*“Thermal Observatory - Installation proposal”*

P.A. Sattrup<sup>a</sup>, J. Strømman-Andersen<sup>b</sup>

Proposal for: *Charlottenborg*, Spring Exhibition 2010 and 24/7



## Case studies

Case study A (Urban Density):

### **Thomas B. Thriges Gade**

(Invited competition)



#### **Introduction:**

The “Thomas B. Thriges Gade” project shows how densification of existing cities can reduce the need for transportation and create intense urban activity without compromising urban daylighting.

Case study B (Urban Typologies):

### **Västra Dockan**

(Invited competition)



#### **Introduction:**

The “Västra Dockan” project shows step-by-step how integrated energy design in master planning can contribute urban energy-efficient design.

Case study C (Urban Fabric):

### **Carlsberg City Distinct**

(Competition and workshop)



#### **Introduction:**

The “Carlsberg City District” project shows how technical and scientific analysis of daylight and solar gain can contribute to, inform and improve the geometric structure of a master plan.

## **Additional work (not analysed in the thesis)**

Case study D

### **Herlev Hospital**

Location: Herlev, Denmark  
Client: The Capital Region of Denmark  
Type of assignment: First prize in international competition



Case study E

### **Zuidas**

Location: Amsterdam, the Netherlands  
Client: City of Amsterdam and ING Real Estate  
Type of assignment: Commission



Case study F

**River City, Gothenburg**

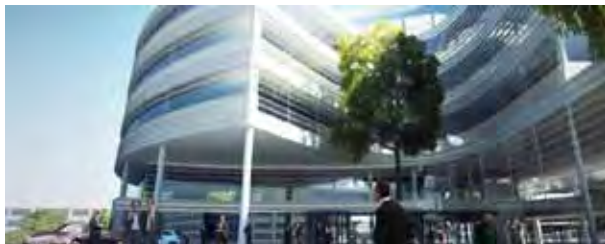
Location: Gothenburg, Sweden  
Client: City of Gothenburg  
Type of assignment: International workshop



Case study G

**Novo Nordisk Headquarters**

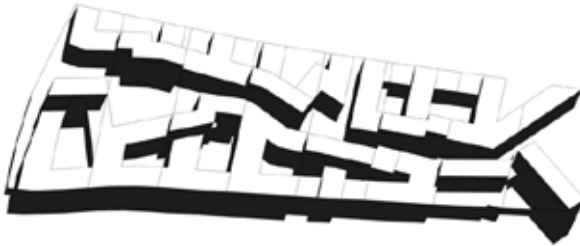
Location: Bagsværd, Denmark  
Client: Novo Nordisk  
Type of assignment: First prize in invited competition



Case study H

**Carlsby**

Location: Hillerød, Denmark  
Client: City of Hillerød, DSB and Freja Ejendomme  
Type of assignment: Invited competition



Case study I

**King Abdullah Financial District**

Location: Riyadh, Saudi Arabia  
Client: Capital Market Authority  
Type of assignment: First prize in invited competition



# Reading Guide

The thesis contains five chapters: 1) Introduction, 2) Urban Density, 3) Urban Typologies, 4) Urban Fabric, and 5) Discussion and Conclusion.

The “Introduction” outlines the basis of the thesis – the hypothesis, aim, objective, background, research methodology and design process is briefly discussed. The following chapters, “Urban Density”, “Urban Typologies” and “Urban Fabric”, list the project’s subjects consecutively.

The description of each subject is based on a scientific paper and illustrated by a case study. Finally, the results are summarized and discussed in the “Discussion and Conclusion” chapter.

## CHAPTER I Introduction



## CHAPTER II Urban Density



## CHAPTER III Urban Typologies



## CHAPTER IV Urban Fabric



## CHAPTER V Discussion and Conclusion

Case study A



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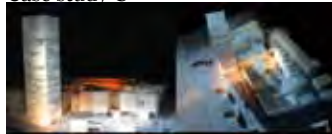
Case study B



+



Case study C



+





Office, Henning Larsen Architects



## CHAPTER 1

# **Introduction**



## **CHAPTER 1**

# **Introduction**

What is the relationship between architecture and energy? The most important thing to understand is that consumption is a question of needs and needs are affected by design. Your requirement for petrol depends on your car's design and your need for a car again depends on how the city you live in is designed. So if we can change the design, we can enable you to reduce your consumption.

The way we organize our cities, their shape and orientation, can give maximum environmental gain, and it costs very little. The city's urban structure is decisive for its energy consumption. If you move to a higher level, and for example begin to use solar shading, you can also save a lot of energy, but it also begins to cost a lot of money. And finally you can put solar panels on roofs and install the latest intelligent engineering technology, which is even more expensive. Looking at things the other way round, if you start with a badly designed building, you can put as many solar cells up as you want – it will not help. The same applies if you locate your building in the wrong place. Buildings and cities are like planes or cars: if they have the wrong shape or design, they won't function no matter what you do.

These considerations are the basis for setting up the hypothesis.

# Hypothesis

The main hypothesis of the thesis is:

**The best way to reduce building energy demand is to optimize the urban structure.**

The hypothesis is categorized into three elements governing the interstice of urban structure; Urban Density (Paper I), Urban Typologies (Paper II) and Urban Fabric (Paper III).

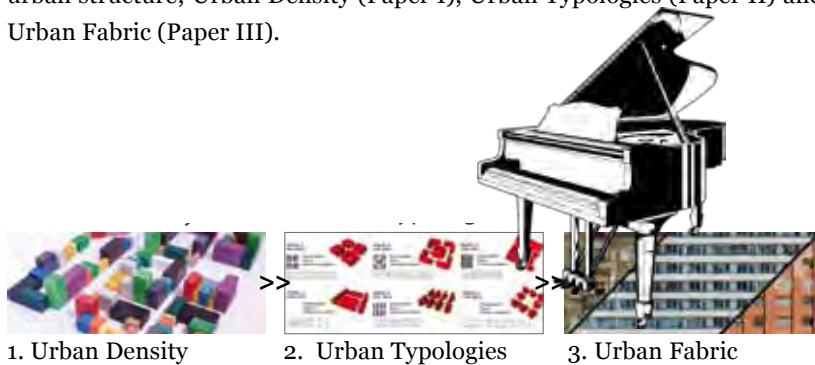


Figure 1: “The symphony of the City”

The hypothesis is examined through an interplay of 1) parametric variations studies (represented by DTU), and 2) practical empirical cases (represented by HLA). The intention is the merge scientific knowledge from the Building Physics community with pragmatic experience from Architectural Practice. The outcome should be used for improving design method in urban scale project.

## Aim and objective

The structure of a city is like a piano – made of various keys – each having its own rhythm and tone. This thesis deals only with a few of the city keys, (density, typology and fabric), but without forgetting that the structure of a city and its sustainable future depends on a symphony of elements: transport, technical infrastructure, cultural diversity, etc. Although the thesis only deals with a tiny part of the totality, it tries to reflect the city as a whole.

The aim is threefold:

- 1. Research**  
to unfold the link between building energy use and urban density, typology and fabric
- 2. Method**  
to analyse how technical scientific knowledge can be integrated in early urban planning and design decisions (IED)
- 3. Results**  
to show the architect's responsibility and opportunities to rethink the role of architecture on the basis of new knowledge and new goals

Scientifically, the project enters a new field, in which technical scientific analysis of the energy interaction between urban geometry and the individual building's performance is used as a tool in an integrated design process. What is new is to move from good intentions and strategies to being able to make actual calculations, which can constitute rules for design and be used as guidelines in architectural practice.

Methodologically, this project focuses on "Integrated Energy Design" (IED). The idea is to analyse whether IED method can be applied on an urban scale.

## The world's cities – perspective and consequences

The world's cities – from capitals and metropolises to new, innovative urban areas and old, cultural epicentres – are home to the majority of the global population. In 1900, there were 11 cities with more than 1 million residents; in 2010, there were 600 such cities. Today, more people live in cities than in rural areas. Between 2011 and 2020 the number of people living in cities will increase by 715 million. As more people migrate to urban centres, the role of cities in the global agenda increases. The rapid urbanization of the world's population over the twentieth century was described in the 2009 Revision of the UN World Urbanization Prospects report (*United Nation Report, 2009*).

But what are the consequences of this dramatic urbanization and the intensive development of agricultural land to support it? Well, this is a complicated and multifaceted question. Urbanization is not bad if done sustainably. It is generally acknowledged that high density building optimizes the use of land, reduces the need for transportation, and creates cities with intense urban activity and increased social, cultural and economic interaction (*UNEP, 2010*) & (*Newman P. W. G, Kenworthy J. R., 1989*). When cities grow, so does GDP (Gross Domestic Product)<sup>1</sup>. Every time the share of people living in cities increases by 10%, GDP increases by 30% (*DNV Research & Innovation, 2011*). Economic growth is often followed by awareness about resource consumption and energy use. But will further urbanization and densification of cities collide with future requirements for reduced energy consumption? And will a focus on energy-efficient design change the city's structure and architectural expression? Or will it just be reflected in technical additions?

### An integrated approach

The answers to the above questions are not simple. Urban design is a multifaceted discipline – at the same time cultural, technical, formal and pragmatic. The answers therefore depend on whether we emphasize one or the other nuance in the language of design. This thesis looks at urban design by examining the integrated approach. It proposes that IED (Integrated Energy Design) is based on multiple levels of developing complexity – in

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<sup>1</sup> Gross domestic product (GDP) refers to the market value of all final goods and services produced within a country in a given period. GDP per capita is often considered an indicator of a country's standard of living. Wikipedia Encyclopedia (20/10/2011): GDP, en.wikipedia.org/wiki/GDP

the intersections between technical research, cultural understanding, and architectural quality.

But the integrated approach is not always used in contemporary urban design. For some decades now, the design disciplines have been mired in adversarial distinctions, such as “design versus technology”, “creativity versus analysis”, and “art versus science” (*Giedion S., 1941*) & (*DeKay M. R., 2011*). Perhaps because of the dominance of empirically based sustainable perspectives, and culturally predisposed listening, we commonly equate urban sustainability with technology – in the form of quantifiable energy efficiency.

Certainly, there have been notable exceptions to the tendency to reduce sustainable design to the objective value sphere or to simple performance, but sustainable design is increasingly associated with performance measures, and the wider profession is increasingly ideological and pluralistic. Despite this pluralism, the design fields, and IED in particular, seem to have a weak collective framework for navigating and transcending the fragmentation that entrenches both academia and practice. In the same way, environmentalism based on scientific rationalism has until now not been very effective.

### **Energy is about quality of life**

We are filled with frightening statistics and dramatic images of the world’s future. As Mark DeKay sarcastically sums it up: *“Look, we have the facts... the sky is falling, we’re running out of everything we need, the climate is going wacky and Al Gore has pictures of the polar caps that should scare the pants off of all of us”* (*DeKay M. R., 2011*). Not to say that the predictions are not true, but it’s hard to inspire and get our collective selves in action when that is the only argument we are making. As Mark DeKay reminds us: *“Energy is about quality of life”* (*DeKay M. R., 2011*).

We have to translate scientific and statistical rationalism into qualitative visions. How is it perceived? What is wonderful about it? How is it part of a greater whole? If we look at our physical world – our cities are the most obvious example of manmade structures that affect our natural environment. Light, shade, sun and wind are all examples of physical aspects that constitute the natural environment and that are changed by the presence of,

and interaction with, buildings. As Ralph Knowles expresses it, “*Cities have taken dominance over nature*” (Knowles R. L., 1985).

The city’s dominance over nature not only affects our global climate, but also our behaviour, perception and pleasure in the city. In 1960, Kevin Lynch wrote “The Image of the City”. This classic work considered the visual quality of the city by studying the mental image held by its citizens. Lynch said, “*We are not accustomed to organizing and imaging an artificial environment on such a large scale*” (Lynch K., 1960). He was concerned that the disorientation resulting from an unclear urban image might leave us without a sense of balance and well-being.

Kevin Lynch was most concerned about the visual image, but the artificial environment is composed of many “energies”. We are continuously exchanging energy with the environment, being warmed or cooled, being able to inform ourselves and each other using our senses and motion, hearing, seeing, smelling and touching our surroundings. For instance, *comfort* in engineering terms is a technical term of climate control. It is defined by the statistical absence of discomfort in a normalized group of people. It is the cornerstone of theoretical calculations of energy consumption. In architecture, it could be considered one of the deepest levels of meaning, perhaps one of the primary aspirations of architecture throughout time.

## **Urban master planning**

Urban planning describes the process by which the use of land in cities and communities is regulated in the public interest. Master planning brings the issues down to a more local level. Integrated and sustainable master planning in this context is understood as a detailed planning level.

The master plan contains the basic design layout for detailed planning, building lines and planning conditions. The specific details of a development, such as building configuration, façade design, fenestration, materials, and energy supply systems, are all crucial elements in the detailed master planning process.

The master plan should have a robust structure that can withstand numerous changes and modifications in the design of buildings and urban spaces.

This flexibility ensures that the master plan will last many years into the future. Many of the contextual conditions that will be used as design parameters later on in the sketching phase are outlined in the master plan.

The spatial structure of the master plan can be characterized by the urban morphology<sup>2</sup>. M.R.G. Conzen (*Conzen M.R.G., 1960*) developed a technique called “town-plan analysis”, where he defined rules for urban morphology. Conzen characterized the key aspects for analysis by three complexes of plan element – also known as the British urban morphology; “The Conzenian tradition” (*Whitehand J.W.R., 2001*):

- *Streets* and their arrangement into a street-system
- *Plots* (or lots) and their aggregation into street-blocks, etc.
- *Buildings*, in the form of the block-plans, etc.

For Conzen, understanding the layering of these aspects and elements through history is the key to comprehending urban morphology.

In this thesis, these elements are used to explain and define the scale of urban morphology. *Streets* are translated into urban canyons and used to analyse *Urban Density*. *Plots* and their aggregation into street-blocks are applied to *Urban Typologies*. Finally *Buildings* are analysed in terms of *Urban Fabric*.

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<sup>2</sup> Urban morphology is the study of the form of human settlements and the process of their formation and transformation. The study seeks to understand the spatial structure and character of a metropolitan area, city, town or village by examining the patterns of its component parts and the process of its development. Wikipedia Encyclopedia (05/09/2011): Urban Morphology, [en.wikipedia.org/wiki/Urban\\_morphology](http://en.wikipedia.org/wiki/Urban_morphology)

## State of the art in the research topic

Knowledge of how to design buildings to be energy-efficient has increased considerably in recent decades, largely through improvements in building technology and energy calculation methods. However, given how much we know about building design, we know surprisingly little about the effects of urban structure on low-energy buildings.

Much of the literature dealing with climate and design focuses on the effect of climate on the built environment and particular on creating comfortable indoor conditions. Most authors offer the observation that throughout history the purpose of constructing buildings has been to provide shelter from the often hostile outdoor conditions, caused by a combination of temperature, wind, rain and sun. As Olgyay writes; *“House design has reflected, throughout history, the different solutions advanced by each period to the continuing problem of securing a small controlled environment within large-scale natural setting – too often beset by adverse forces of cold, heat, wind, water and sun”* (Olgyay V., Olgyay A., 1963).

The relationship between climate and the outside or urban environment has been a topic of some study and discussion for least one hundred years, but only in recent years has systematic research been undertaken in the area. Energy models and simulation techniques have been developed to study and describe the energy performance of buildings in relation to the surrounding climate. However, these models are generally intended for use by building designers and tend to consider buildings as self-defined entities, either neglecting or grossly simplifying the importance of phenomena that occur on the urban scale.

Although urban site conditions are critical for low-energy building design, very few studies have attempted to relate urban form to natural energy or solar access and daylight conditions. Attempts to model these conditions have long been limited by the range of variables which can be accurately simulated. When overall energy balance is considered, it is often done for the general “urban terrain” or for the urban canyon as a system, rather than for a body located at a particular point within it. Nevertheless, there have been some analyses e.g. (Littlefair P., 2001) of the link between the urban



geometry and the individual building's energy performance. The most detailed and complete analyses of urban obstruction affecting energy use are presented by Baker and Steemers (*Baker N., Steemers K., 1999*). Using the LT method<sup>3</sup>, they derive a correction factor to modify the specific energy consumption for non-domestic buildings. (*Ratti et al., 2005*) document an effect of almost 10% in the relationship between urban structure and the annual per-metre energy consumption of non-domestic buildings. They demonstrate the effect using a calculation that compares the DEM (Digital Elevation Model) with the LT (Lighting and Thermal) method developed by Baker and Steemers (*Baker N., Steemers K., 1996*). The LT method is a simple but non-dynamic method. (*Ratti et al., 2003*) demonstrate in their study of building form and environmental performance that some urban configurations perform better than others. For instance, they show that a courtyard configuration performs better in calculated environmental variables (surface-to-floor ratio, shadow density, daylight distribution and sky-view factor) than pavilion types in the specific context of hot arid climates. But their study does not compare the environmental variables with indoor environment and building energy consumption.

Another study (*Compagnon R., 2004*) developed a method to determine the percentage of building façade in a given urban area that receives technically and commercially useful amounts of solar radiation over a selected period of time. The thresholds for a “useful” amount of radiation differed in the four solar techniques: passive thermal heating, photovoltaic systems, daylighting systems, and solar thermal collectors. The examination of five different layouts for a dense urban redevelopment project in Switzerland led to the conclusion that the best-performing configuration was able to exceed the threshold for daylighting across 83% of the total façade area and for passive solar heating over 52% of the area.

More complex models have also been developed. One of these is the Energy and Environmental Prediction model (EEP). The EEP computer model provides information for implementing urban energy management and

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3 The LT Method (Light and Thermal) is an energy design tool. It uses the concept of *passive* and *non-passive zones*. Passive zones can be lit by daylight and naturally ventilated and may make use of solar gains for heating in winter, but may also suffer overheating by solar gains in summer. They are defined by orientation. Non-passive zones have to be artificially lit, mechanically ventilated, and in many cases cooled.

environmental planning, enabling decision makers to plan for improved energy efficiency. The EEP model uses GIS<sup>4</sup> data and was mainly developed to improve the existing built environment (*Jones P. et al., 2007*). More simple models have also been developed. One of these models is the SUNtool<sup>5</sup>. SUNtool was conceived as a decision support system for designers to optimize the environmental sustainability of master planning proposals based on integrated resource flow modelling (*Robinson D. et al., 2007*).

Few, if any, studies have analysed the results of a combined and fully integrated dynamic energy simulation. This thesis shows how the precision of energy simulation for various types of building in context improves dramatically, when developed in a multilayered, climate-based and dynamic simulation. Yet current frameworks primarily rely on the building design process. Such frameworks are often referred to as “Integrated Energy Design” (IED), for example in IEA Task 23 (*IEA task 23, 2002*), Integrated Building Design Systems (IBDS) (*Santamouris M., 2006*), or Integrated Design Process (IDP) (*Knudstrup M., 2004*). However, the individual building’s design and specific location in the context is always a result of the urban structure. By considering buildings isolated from their context in the city, the interaction between environment and building energy performance is ignored. This thesis considers the urban geometry and buildings energy consumption in an integrated energy correlation, and uses our knowledge in this field to design low energy cities and buildings.

Although the documentation and tools required are present, the energy synergy between city structure, building and climate is seldom taken into account. We often plan and design our cities as independent units – units that disregard local climate conditions. Our cities are often built to appear the same from edge to edge and from top to bottom. Large and small buildings are often built alike from block to block and even from one geographical

4 A (GIS) Geographic Information System is a system designed to capture, store, manipulate, analyse, manage, and present all types of geographically referenced data. In the simplest terms, GIS is the merging of cartography, statistical analysis, and database technology. Wikipedia Encyclopedia (05/09/2011): <http://en.wikipedia.org/wiki/GIS>

5 Project SUNtool (Sustainable Urban Neighbourhood modelling tool) represents an integrated architectural design and environmental simulation tool. SUNtool was developed by six European partners under the EC’s Fifth Framework Programme “Energy, Environment and Sustainable Development” (<http://www.suntool.net/>, September 2011)

region to another, regardless of energy costs.

But why are local climatic conditions not used in an integrated approach? One simple answer might be: There has been sufficient energy, not to be concerned about the effect of climate. As Mark DeKay puts it in his criticism of the modern world: “*Energy has broken the bonds of place and time*” (DeKay M. R., 2011).

### **The relation between urban design and a building’s energy consumption**

If we try to zoom back in time – before the bonds were broken – we find another reality.

Let me start with a personal perspective and anecdote... As a child, I spent many wonderful summers at the island of Fanø – specifically, in the small fishing village of Sønderho. Sønderho is not like other villages. It has a certain logic, which meant that we (my playmates and I) could always navigate. No matter where we were, we knew in which direction to go – whether we were going to the beach or home for dinner – we were never lost.

It was first later that I recognized that this logic is rooted in a strong cohesion between climate, urban structure and the layout of the houses. Sønderho is located directly on the edge of the North Sea. Influenced by the open terrain and the prevailing westerly wind, the inhabitants have learned to arrange their buildings through generations of evolution on the terms of nature, expressed a logical rhythmic variation in their shape and structure. The streets and houses are mainly oriented east/west with all gables facing the windy and cold west wind – see Figure 2 (C).

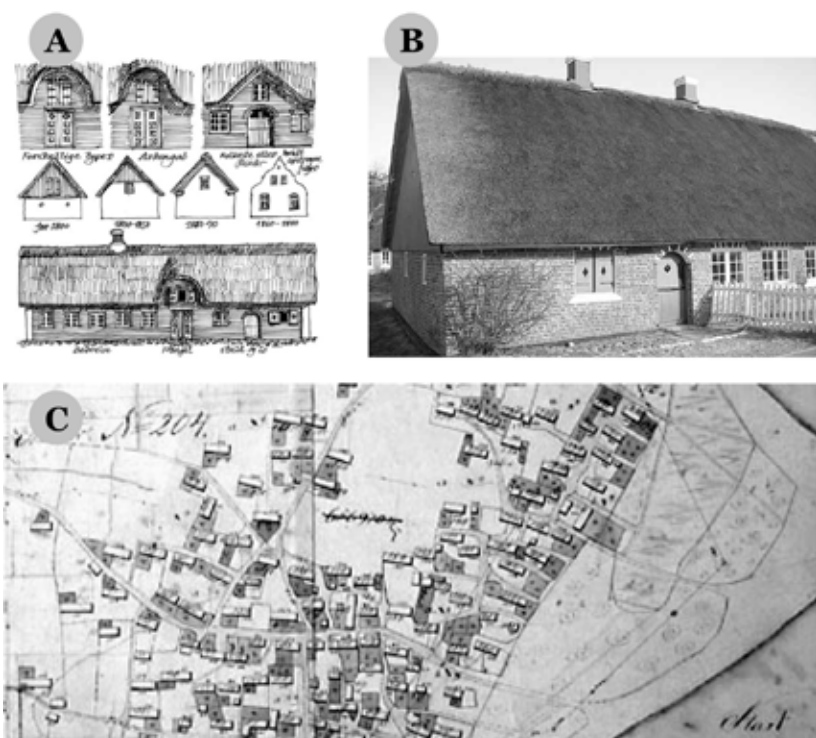


Figure 2: A & B: Thatched house in Sønderho from the 1800s. C: Map of Sønderho illustrating an urban layout with east-west oriented streets and houses.

At the time when the village was founded (early 19th century), the common building physics was very limited. The houses were draughty and poorly insulated – which meant that the external environment had a major influence on the internal comfort level. To compensate for the lack of insulation, houses were arranged so the cow house, barn or stable was located behind the west wall – see Figure 2 (B). The cows, horses and sheep formed a natural and blocking buffer for the cold west wind – the animals warmed up the air before it reached the living room, kitchen and bedroom. A simple but traditional example of how the design of buildings and urban structure interact in an integrated and natural energy system.

*“In nature, form always performs” (Mark DeKay)*

It is very doubtful that Sønderho was designed specifically to achieve comfortable conditions, at least in the sense of the word “design” as we use it.

The present-day notion of comfort, as a set of expectations, physical conditions and personal imperatives, is a relatively recent 20th century invention, as is the concept that buildings and spaces should perform in response to environmental factors. Rather, older buildings and town planning traditions resulted from a complementary process of evolution. The evolution was driven by the physical environment, resources and climate, mediated by social needs, institutional arrangements, taboos, and good deal of trial and error, rather than conscious decision-making.

### **Urban planning in modern architecture**

Buildings in our modern industrial cities are subject to the same recurring forces that act to structure nature and that caused purposive adaptations at Sønderho. Despite this fact, we continue to build and perceive our cities as nonresponsive to recurring natural forces. There are few indications of the rhythm of nature in the modern city. For instance, how is it that modern cities and buildings usually look the same on all sides in spite of differential location and natural energy impacts?

This is not a simple question. The immigration from countryside to city began with the industrial revolution in the 18th century. In the course of the next century, cities became increasingly dense and polluted. Gradually problems occurred in the small and outdated apartments. Diseases spread in the backyards and the city became more and more infected. “The answer” came at the beginning of 1920s with “The Functional City” built on the CIAM manifesto, Charter of Athens<sup>6</sup>. Based on an analysis of thirty-three cities, the Charter proposed that the social and health-related problems faced by cities could be resolved by strict functional segregation, and the distribution of the population into tall apartment blocks at widely spaced intervals (Frampton K., 1992) – see Figure 3.

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6 The “Athens Charter” was a manifesto mostly written by the Swiss architect and urban planner, Le Corbusier, summarizing the Fourth Congress of the International Congress of Modern Architects (CIAM), which took place in 1932 mostly aboard a passenger boat which steamed from Marseilles, France, to Athens, Greece, and back again. Wikipedia Encyclopedia (05/09/2011): Athens Charter, [en.wikipedia.org/wiki/Athens\\_Charter](http://en.wikipedia.org/wiki/Athens_Charter)



Figure 3: Le Corbusier, Plan Voisin proposal for rebuilding Paris, 1925

The CIAM's methodical analysis of the city's functional distribution can be criticized in many ways, but one outstanding feature was its failure to quantify the differential location and natural energy impacts. The theory was that the "Functional City" could be adapted universally and globally.

After the Second World War, the "Functional City" began to become reality as rapid growth became the order of the day. The result was a period of exuberant urban expansion (*Frampton K., 1992*). The post-war period, lasting until the late 1960s, was characterised by "comprehensive planning" – a technocratic, positivistic approach largely shaped by civil engineering. This approach centred on the idea of a big scheme – often referred to as the master plan – which, when defined and implemented, could solve all the key problems. Large-scale social housing projects and urban motorways were all developed under this paradigm.

In parallel with the urban expansion, the development of building physics began to gather speed. New building systems and materials made it possible to shape building envelopes more freely. And soon there was also greater focus on comfort and occupant efficiency. From 1918, W. H. Carrier<sup>7</sup> made it possible to air-condition and regulate buildings making them independent of the natural climate. Instead, buildings became dependent on off-site energy sources and thereby independent of location, form and urban structure. As the architectural historian Reynar Banham put it: "*While European modern*

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7 Willis Haviland Carrier (November 26, 1876 – October 7, 1950) was an American engineer and inventor, and he is known as the father of modern air conditioning. Wikipedia Encyclopedia (07/07/2011): Willis Carrier, [en.wikipedia.org/wiki/Willis\\_Carrier](https://en.wikipedia.org/wiki/Willis_Carrier)

*architects had been trying to devise a style that would ‘civilise technology’, US engineers had devised a technology that would make the modern style of architecture habitable by civilised human beings” (Banham R., 1969)*



Figure 4: A: First thermostat invented and patented by Albert Butz, 1885. B: Seagram Building, Ludwig Mies van der Rohe, in collaboration with Philip Johnson, New York, 1958. C: Interior Seagram Building.

Consequently, the new developments were often planned as “climate rejecting” – sealed, air-conditioned, deep plan, with tinted glass to cut out solar gain and daylight. One good example is the Seagram Building in New York – see Figure 4. Designed as a deep extruded box placed in the New York grid with no natural variation according to direction the Seagram Building is the ideal picture of the modern system. Based on a cheap supply of fossil fuels, such systems were developed and used so much that today something in excess of 39% of our total annual energy consumption goes to provide light, fresh air, heating and cooling to our buildings (*US Green Building Council, 2010*).

Such systems may then further worsen the local microclimate: air conditioning results in extra thermal emissions to the surroundings; reflective glass reflects solar heat and glare back out; and large, bulky buildings create hostile local wind effects and overshadow neighbouring buildings which also need daylight. The result is a vicious circle of worsening exterior environment and spiralling energy costs.

William Whyte’s (*Whyte W. H., 1980*) study of New York found that significant elements in the success of places related to the effects of sun, wind, trees and water. However, he found that in general such effects are almost

wholly unplanned. Sun and wind studies made for new buildings tend to be defensive in nature, aimed at gaining planning permission rather than analysing what benefits there might be, to whom and when.

Many planners, architects and engineers have learned the lesson. But we still plan and build buildings with no relation to the city and climate surrounding them. In 2002, Henning Larsen Architects built the Ferring International Center (FIC) in Ørestaden — one structural and architectural interpretation of the Seagram Building from 1958 – see Figure 5. There is no differentiation of the façades according to the orientation; it is one uniform extruded structure with lamella solar shading wrapped around.



Figure 5: Ferring International Center, designed by Henning Larsen Architects, 2002

Ferring International Center is an example of a building that is not regionally specific in its energy and climate strategy. In theory, the FIC could be adapted to any place and climate zone in the world. The only thing that would need adjusting is the internal energy systems and installations. The technical room would be either slightly larger or slightly smaller – see Figure 6.

If we choose to let our future cities be inspired by the “Functional City” – we may end up with a world of uniform “SimCities”.





Figure 6: Ferring International Center is not regional – it can be placed globally. B: Illustration from SimCity.

### Reconsidering the traditional professional position

There is another way to go, however, and one which aims at modulating the external and internal climate – to get the spirit of the place (*genius loci*<sup>8</sup>) back in planning. This strategy involves planning the structure and geometry of cities to allow adequate access to solar heat gain, daylight and natural ventilation. It has the potential to enhance the quality of cities worldwide. However, it requires architects and engineers to be ready to reconsider their traditional professional position.

One strategic aim of an integrated approach is to avoid conflicts between architecture and technology. This requires close collaboration between architects and engineers at the beginning of the design process. This is contrary to the usual approach in which an architect designs a building first and then an engineer is expected to make it work through the application of services (and the use of energy to “correct” poor design decisions) – see “Frameworks for collaboration” below. If energy considerations are not integrated into the design solution, it becomes difficult to improve the energy-saving potential through the use of technology alone. In theory, we have plenty of abundant natural resources. For example, the incoming energy from the Sun exceeds the energy use of the world’s population by a factor 100:1. As Ian Ritchie put it, “*We are not short of energy; we are short of atmosphere ...*” (Ritchie, 1998).

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8 In classical Roman religion a *genius loci* was the protective spirit of a place. *Encyclopaedia of modern architecture*, (1965)

## Research methodology

A main goal in choosing the research methodology has been to create not only theoretical results, but also practical results that can be applied directly in current architectural design practice – results, that can offer clearer understanding of principles, better procedures of design and new information to base future designs on.

Therefore, the research methodology has focused on quantitative simulation which frames, informs and discusses a number of qualitative case studies. Initially, the main focus was to understand the physics and technology behind urban environmental simulation and energy optimization. However, it became evident that the quantitative information offered by simulation did not make much sense in architectural practice unless discussed qualitatively, when it came to interpreting both the causes of results and their implications for urban planning and architecture.

Though architects rarely claim to follow specific design methodologies, a new attention to design methods and processes is emerging. This attention is based on the realization that even the first sketches have potentially a strong impact on the energy and environmental performance of the design. In particular, engineers have begun to promote “integrated design processes”, in which the architect-engineer collaboration has moved forward to the initial design phases, instead of the traditional process of engineers following up on designs already elaborated by architects. This might result in some rivalry for position and influence on design between the professions, but the view taken in this thesis is that collaboration is necessary and beneficial.

## Research Paradigms

The earliest efforts to define the design process focused on approaching design with the classic scientific methodology in an attempt to justify design as an academic, scientific discipline. These so-called first generation design methods were formulated in the 1960s by early pioneers like (*Archer B.L., 1965*) and (*Asimov M., 1964*). The methods were constructed with a focus on optimization and used the term “method” in its classic scientific meaning where a “method” is considered to be a systematic, rational and logical way of approaching problems – in this case, design problems. A leading

mantra in the quest of such methods is the notion “Form Follows Function” formulated by (*Sullivan L. H., 1896*)<sup>9</sup>, which means that a form must facilitate a given set of functional needs. Design methods rooted in this mantra therefore try to find the causal relationship between form and function, typically through one of the two fundamental paradigms “problem-solving” or “puzzle-making”. Problem-solving is the search for a form which facilitates a desired function and puzzle-making is the adaptation of a form until it reaches some desired functional qualities.

The so-called second generation of design methods emerged in the late 1960s/early 1970s. Researchers wanted to abandon the problem-solving approach of the first generation of design methods. They criticized the approach as a too narrow and functionally contingent definition of rationality, not fit for design problems. Instead, supporters of the second generation argued that design problems, especially architectural design problems, are “wicked” problems. In other words, they are full of intuitive leaps, fundamentally irreconcilable with the techniques of science and engineering, which dealt with “tame” problems (*Rittel H.W. and Webber M.M., 1984*) and (*Norman R.B., 1987*). Because design problems are perceived as wicked problems, they are fundamentally undefinable. This means that it is impossible to determine when a design problem has been solved: it can always be improved. There are no ultimate, optimal solutions (*Rowe P.G., 1987*). The second generation researchers argued that the design process is argumentative and based on empirical knowledge, rather than rational knowledge as in the first generation design methods. The process begins with incubation, an introspective phase, followed by iterative refinement of both form and function until some harmonious coexistence emerges, a so-called satisfactory solution (*Akin O., 1978*).

Today, designers who rely on first generation approaches (systematic and rational) are mainly found in engineering, whereas designers who rely on second generation approaches (argumentative and empirical) are mainly

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9 It was the American architect Louis Sullivan who coined the phrase, in 1896, in his article “*The Tall Office Building Artistically Considered*”. Here Sullivan actually said; ‘form ever follows function’, but the simpler (and less emphatic) phrase is the one usually remembered. For Sullivan this was distilled wisdom, an aesthetic credo, the single “rule that shall permit of no exception. Wikipedia Encyclopedia (02/08/2011): Form Follow Function, [en.wikipedia.org/wiki/Form\\_follows\\_function](http://en.wikipedia.org/wiki/Form_follows_function)

found in architecture and planning (Cross N., 2007). The latter approach is especially prevalent in the context of the beaux arts<sup>10</sup> tradition for design in architecture.

## Research method

This thesis is a combined method study, combining *systematic and rational analysis* with *environmental argumentative and empirical studies*. This is an unusual combination.



Figure 7: Architect studying a city scale model. Photo; Henning Larsen Architects

This thesis was developed in the interface between a rational approach – integrated in the natural scientific research at the University, and a more empirical approach – influenced by the architectural firm. It has often been difficult to reconcile the two methodologies or systems of inquiries.

First and foremost, it has been difficult to define a methodology for the basis of the scientific research. The University community is very focused on publishing technical scientific articles in reputable journals (ISI-indexed), while the architectural firm is interested in results that can provide usable and deployable knowledge to projects. An example of how difficult it has been to build a bridge between the two traditions arose in connection with the first publication; *Paper I*<sup>11</sup>. In collaboration with PhD colleague, architect

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10 Beaux-Arts training emphasizes the production of quick conceptual sketches, highly-finished perspective presentation drawings, close attention to the programme, and knowledgeable detailing. Site considerations tend toward social and urbane contexts. (Drexler A., 1977)

11 “The urban canyon and building energy use: Urban density versus daylight and passive solar gains” J. Strømman-Andersena, P.A. Sattrupb Published in: Energy and Buildings, 43, Issue 8, August (2011) 2011-2020

Peter Andreas Sattrup, a parametric study of urban density was developed. To support and illustrate the numerical value, great emphasis was placed on visual and spatial representations. The technical values were transformed into architectural diagrams and figures. Unfortunately, one reviewer did not appreciate the purpose.

Reviewer #2's comments:

Sat 1/8/2011

Answer:

Mon 1/10/2011

*There are too many insignificant figures - how to be arranged for publishing? Not acceptable for publication in its present form and recommend major revision.*

*The comments do not refer to the actual research. The number of illustrations has been reduced. However, we find that visualizations, spatial figures and drawings play an important role in architectural research equal to that of graphs in engineering, as it is spatial relations that are investigated.*

*Conference Paper VI*<sup>12</sup> presents a methodological framework. The framework sets out examples of how and why numerical value should be translated into visual and spatial representations. The idea is to allow for the integration and creation of knowledge across professional borders. The value of the framework was demonstrated by mapping a series of simulation studies, emphasizing the multidimensionality of environmental performance optimization. Clarifying the conceptual interconnectivity between architecture and engineering – agency and physics – not only enhances communicative power and the dissemination of knowledge, but becomes instrumental in pointing out the need for improving metrics, software and not least the performance of the built environment itself.

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<sup>12</sup> “A methodological study of environmental simulation in architecture and engineering – Integrating daylight and thermal performance across the urban and building scales”, P. A. Sattrupa, J. Strømman-Andersenb In proceedings: Symposium on Simulation for Architecture and Urban Design, 2011, Boston, MA, USA

In conference paper V<sup>3</sup>, a specific example demonstrates how diverse cultures in architecture and engineering can be integrated to facilitate design development.

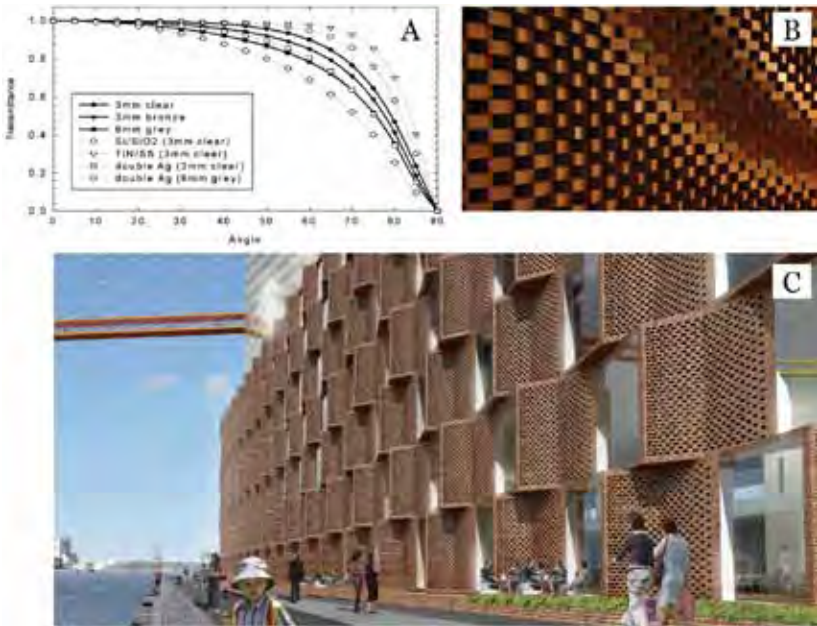


Figure 8: Design proposal for FIH Bank. A: Incident angle dependent radiation heat transfer through glazing. B: The façade was inspired by both the nature of rough brickwork and the numerical values of the angling of the windows. C: Final render of FIH Bank

The architectural intention for FIH Bank (case study in *conference paper V*) was to design a façade that would relate to the existing brick structures as required in the brief and at the same time reflect the dynamics of the water present all around the site. 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

13 “Integrated Design – paradigm for the design of low-energy office buildings” M. Jørgensen, M.W. Nielsen, J. Strømman-andersenc In proceedings: ASHRAE Winter Conference, 2011, Las Vegas, Nevada

only optimize views toward the city and the entire Copenhagen bay area, but also significantly reduce insolation and thereby the cooling demand – see Figure 8.

The case study of FIH Bank showed that a visual representation of energy and thermal simulations, coupled with spatial considerations, can form a very strong part of the design argument and enrich the reasoning behind design decisions. Although this study focused on the façade, the methodology can easily be transferred to urban structure.

## **Research process**

The research process was divided into four phases, with each phase representing a step in the developing process of creating a methodological framework for the thesis as a whole.

### *Phase 1*

#### **Gathering Information**



The first phase of the research process focused on clarifying the state of the art in theory and practice (literature studies). In this stage, information was gathered freely from the various sources to create a knowledge base of the state of the art in practice, theory and simulation technique, for use in testing the hypothesis.

### *Phase 2*

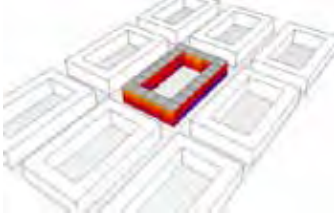
#### **Understanding the Design Process (IED)**



The second phase focused on understanding the basics of the design process in architectural practice (design studies). Independent of the method, two projects were initially followed: case studies E and H. The design process was chronologically recorded. Milestones – where technical inputs generated a new design decision – were noted. The idea was to create an overview and understanding of the architect's workflow and decision-making.

#### *Phase 3*

### **Parametric Studies**



In the third phase, three different aspects of urban structure were parametrically analysed (density, typology and fabric) to create scientific documentation that could feed the case studies with quantified information. Methodically, the documentation was created through scientific publications.

#### *Phase 4*

### **Implication of qualitative information**



The fourth and final phase was to translate, test and organize this knowledge into the architectural design process. The idea was to test whether the theoretical hypothesis has practical relevance. Here case studies A, B and C play an important role.



## Integrated energy design

This chapter argues that, for successful urban planning, it is essential to consider all aspects that affect energy use – from climate conditions to detailed system specifications. Here the emphasis is on integrated design. This implies an understanding of the relative impacts of each parameter – both those determined by design and those that can be described as technical (see phase 2 in the *Research Process*).

### Frameworks for collaboration

In the building design process, design ability is of course important. However, a mix of abilities is often required to solve today's design problems. For example, the aesthetic aspect of a design project might gain from an argumentative approach whereas the structural aspect might gain from a more systematic and rational approach. Common to both is that these design aspects, like many others, often require expert knowledge and years of training. It is therefore difficult to believe that one individual designer could possess all the abilities to solve today's design problems. As a consequence, current frameworks for the building design process rely on a high degree of interdisciplinary collaboration. Such frameworks are often referred to as "Integrated Energy Design" (IED), for example in IEA Task 23 (*IEA task 23, 2002*), Integrated Building Design Systems (IBDS) (*Santamouris M., 2006*), or Integrated Design Process (IDP) (*Knudstrup M., 2004*).

What all these frameworks have in common is that the design team is a group of individuals with different, specialized design abilities – "*In IED the design team is the designer*" (*IEA task 23, 2002*). The idea is that a multidisciplinary collaborating design team is more likely to succeed in carrying out the complex task of building design.

IED applies knowledge in parallel, unlike the traditional design process in which a "baton" is continuously passed from one specialist to another. Costs increase when one group makes decisions without receiving inputs from the others and opportunities for common advantages are lost. The conventional design process can be described as knowledge being applied in series – see Figure 9 .

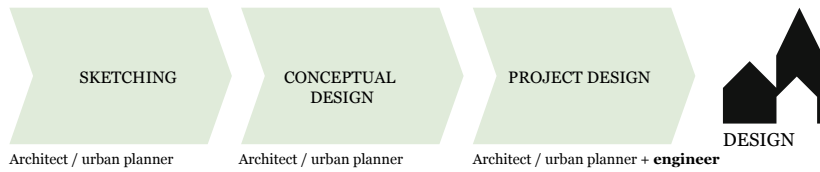


Figure 9: Traditional design process

Architects and urban planners need rapid feedback on how the performance of one design choice compares to another, if they are to judge which decision will work best with the myriad of design considerations that are in play in addition to environmental performance. It is usually only at the very end of the design process that the design performance is validated for design approval by the authorities.

While engineers have traditionally focused on validating designs quite late in the design process, architects navigate in a field of endless design possibilities, in which many design variables are compared to fit the purpose. One way of testing design ideas is to simulate energy consumption. Conducting fast functional assessments and making changes can increase the overall intelligence of the design.

In simplified terms, the actual design is made up of three roughly-defined phases which call for individual iterations at corresponding levels: Pre-design, Concept Design, and Design Development. These should be accompanied by a continuous assessment of the project goals and objectives which serve as a “roadmap” throughout the entire design process – see Figure 10.

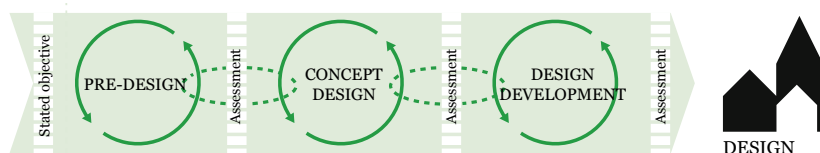


Figure 10: Integrated Design Process

IED involves the entire project team. No individual or profession possesses all the knowledge or techniques needed to see and understand all the details. The best design solution comes from an exhaustive understanding and acceptance created through contributions from several disciplines.

## IED Method

The overall characteristic of an Integrated Design Process is the fact that it consists of a series of design loops per stage of the design process, separated by transitions with decisions about milestones. In each of the design loops the design team members relevant for that stage participate in the process.

In the following chapter three different IED Methods are briefly presented: (A) IEA Task 23, (B) IBDS and (C) IDP. This PhD project is not concerned with one specific method, but operates within the framework of IED.

### (A) Integrated Design Process (IDP) by IEA Task 23

The Integrated Design Process IEA Task 23 method can be characterized as a design process method with associated tools.

The approach is based on the well-proven observation that changes and improvements in the design process are relatively easy to make at the beginning of the process, but become increasingly difficult and disruptive as the process unfolds. Changes or improvements to a building design when foundations are being poured, or even when contract documents are in the process of being prepared, are likely to be very costly, extremely disruptive to the process, and are also likely to result in only modest gains in performance – see Figure 11.

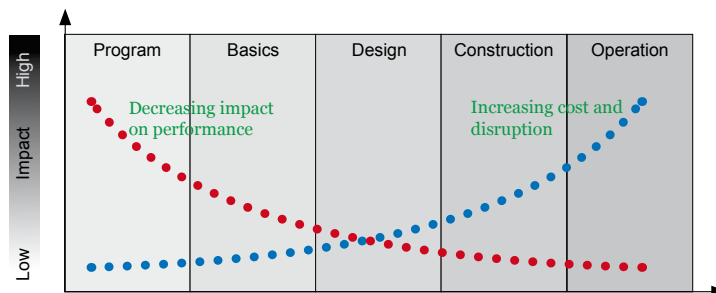


Figure 11: Influence on project performance during design progress: Only an intervention early in the process can utilise the full potential for energy and cost efficiency optimisation. The building cost and energy performance are almost defined as the final stage of design development is approached. Conceptual design alternatives are no longer possible at this point, and any attempted “design repair” will have the opposite effect to that intended: increases in expenditure and disruption.

Integrated Design process (IDP) by IEA Task 23 emphasizes the following four steps:

1. Establish performance targets for a broad range of parameters, and develop preliminary strategies for achieving these targets. This sounds obvious, but in the context of an integrated design team approach it can bring engineering skills and perspectives up front in the concept design stage. This helps the owner and architect to avoid becoming committed to a sub-optimal design solution.
2. Minimize heating and cooling loads and maximize daylighting potential through orientation, building configuration, an efficient building envelope, and careful consideration of the amount, type, and location of fenestration.
3. Meet these loads through the maximum use of solar and other renewable technologies and the use of efficient HVAC systems, while maintaining performance targets for indoor air quality, thermal comfort, illumination levels and quality, and noise control.
4. Iterate the process to produce at least two, and preferably three, concept design alternatives, using energy simulations as a test of progress, and then select the most promising of these for further development.

### **(B) Integrated Building Design System (IBDS) by Steemers, Cambridge University**

The aim of IBDS methodology is to demonstrate how the various factors interact and – more importantly – how they can be integrated successfully and holistically to achieve low-energy urban building design.

Figure 12 lists the various parameters, whether design-related or energy-related, according to the frequency of interrelationships between each category. This methodology can be applied to any key set of parameters chosen by the design team.

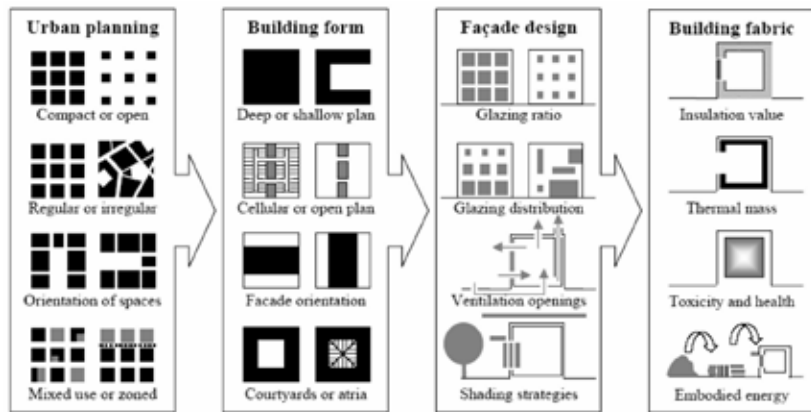


Figure 12: Schematic layout of building-related issues; the primary sub-categories of each main design consideration are depicted

The IBDS uses a matrix to show the parameters that interact and the level of interaction to help the designer evaluate various design strategies. If one combines the design variables with both the passive and active energy strategies, then it becomes possible to rank the strength of interrelationships – see Figure 13.

|        |                       | Urban           |                      |                       |                    | Form                 |                       |                    |                 | Façade        |                      |                      |                    | Fabric           |              |                     |                 |
|--------|-----------------------|-----------------|----------------------|-----------------------|--------------------|----------------------|-----------------------|--------------------|-----------------|---------------|----------------------|----------------------|--------------------|------------------|--------------|---------------------|-----------------|
|        |                       | Compact or open | Regular or irregular | Orientation of spaces | Mixed use or zoned | Deep plan or shallow | Cellular or open plan | Façade orientation | Courts or atria | Glazing ratio | Glazing distribution | Ventilation openings | Shading strategies | Insulation value | Thermal mass | Toxicity and health | Embodied energy |
| Urban  | Compact or open       |                 |                      |                       |                    |                      |                       |                    |                 |               |                      |                      |                    |                  |              |                     |                 |
|        | Regular or irregular  |                 |                      |                       |                    |                      |                       |                    |                 |               |                      |                      |                    |                  |              |                     |                 |
|        | Orientation of spaces |                 |                      |                       |                    |                      |                       |                    |                 |               |                      |                      |                    |                  |              |                     |                 |
|        | Mixed use or zoned    |                 |                      |                       |                    |                      |                       |                    |                 |               |                      |                      |                    |                  |              |                     |                 |
| Form   | Deep plan or shallow  |                 |                      |                       |                    |                      |                       |                    |                 |               |                      |                      |                    |                  |              |                     |                 |
|        | Cellular or open plan |                 |                      |                       |                    |                      |                       |                    |                 |               |                      |                      |                    |                  |              |                     |                 |
|        | Façade orientation    |                 |                      |                       |                    |                      |                       |                    |                 |               |                      |                      |                    |                  |              |                     |                 |
|        | Courts or atria       |                 |                      |                       |                    |                      |                       |                    |                 |               |                      |                      |                    |                  |              |                     |                 |
| Façade | Glazing ratio         |                 |                      |                       |                    |                      |                       |                    |                 |               |                      |                      |                    |                  |              |                     |                 |
|        | Glazing distribution  |                 |                      |                       |                    |                      |                       |                    |                 |               |                      |                      |                    |                  |              |                     |                 |
|        | Ventilation openings  |                 |                      |                       |                    |                      |                       |                    |                 |               |                      |                      |                    |                  |              |                     |                 |
|        | Shading strategies    |                 |                      |                       |                    |                      |                       |                    |                 |               |                      |                      |                    |                  |              |                     |                 |
| Fabric | Insulation value      |                 |                      |                       |                    |                      |                       |                    |                 |               |                      |                      |                    |                  |              |                     |                 |
|        | Thermal mass          |                 |                      |                       |                    |                      |                       |                    |                 |               |                      |                      |                    |                  |              |                     |                 |
|        | Toxicity and health   |                 |                      |                       |                    |                      |                       |                    |                 |               |                      |                      |                    |                  |              |                     |                 |
|        | Embodied energy       |                 |                      |                       |                    |                      |                       |                    |                 |               |                      |                      |                    |                  |              |                     |                 |

Figure 13: Matrix of planning and building design issues showing environmental interrelationships between parameters

### **(C) Integrated Design process (IDP) by Knudstrup, Aalborg University**

This tool is a “process-focused method” and a “design evaluation method”. In the sketching phase, the designer must repeatedly make an estimate of how his or her choices about the form of the building, the plans, the room programme, the orientation of the building, the construction, and the climate screen will all affect the energy consumption.

Integrated Design process (IDP) emphasizes the following five step sequence:

#### **1. Problem formulation**

The first step of the building project is the description of the problem or the project idea for a sustainable urban plan or building.

#### **2. Analysis**

The Analysis Phase encompasses an analysis of all the information that has to be procured before the designer of the building is ready to begin the sketching process, e.g. information about the site, the architecture of the neighbourhood, topography, vegetation, sun, light and shadow, predominant wind direction, access to and size of the area and neighbouring buildings.

#### **3. Sketching**

The Sketching Phase is the phase where the professional knowledge of architects and engineers is combined to provide mutual inspiration in the Integrated Design Process, so that the requirements and wishes for the building are met.

#### **4. Synthesis**

The Synthesis Phase is the phase where the new building finds its final form, and where the requirements of the aims and programme are met. Here the designer reaches a point in the design process where all the parameters considered in the sketching phase flow together or interact.

## **5. Presentation**

The Presentation Phase is the final phase, which includes the presentation of the project. The project is presented in such a way that all qualities are shown and it is clearly pointed out how the aims, design criteria and target values of the project have been fulfilled.

From “Analysis Phase” to “Synthesis Phase”, the process consists of least two and preferably three concept design alternatives, using energy or environmental simulations as a test of progress. The most promising of these is selected for further development.

### **Applied IED guide for case studies**

The three methods are very similar to each other. They all operate with multistep iterative design loops, where the project becomes more and more clarified in scale and detail.

Based on IED methods and building experience from case studies, Henning Larsen Architects has developed a strategy for IED. The strategy is based on the knowledge of context and passive energy strategies.

The approach is that the most fundamental level of integrated design is one in which the use of passive strategies is exploited to reduce the reliance on conventional mechanical services. To illustrate the method an “Energy Triangle” has been developed – see Figure 14. The “Energy Triangle” is a simplification of the “Kyoto Pyramid” method described by (*Haase M. and Amato A., 2005*) and is related to the work of (*Lysen E. H., 1996*).

The method involves a three-step approach:

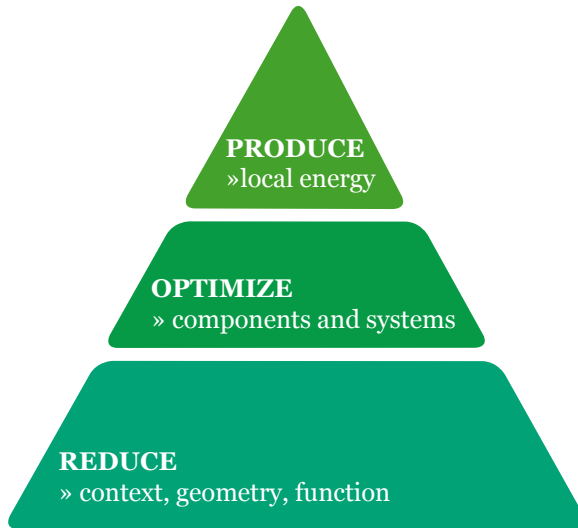


Figure 14: **Reduction:** Energy consumption is reduced by optimizing the design, functional configuration and overall technical systems of the urban plan and buildings. **Optimisation:** Energy consumption is further reduced by incorporating components, intelligent control and energy-reducing materials supporting the objective. **Production:** By means of local or building-integrated energy production and additional energy infrastructure, a surplus of energy can be achieved. Illustration: Henning Larsen Architects

## Unfold to Urban Master planning

Through the work on case studies (Phase 4 in the *Research Process*), the idea of design loops has been developed to a more precise focus on the urban scale, as pictured in Figure 15. The central issue at the urban level is to define systems in a conceptual way, based on the structure/scheme of the urban structure. In a loop, several options are considered, paying attention to the integration of the building in the city as a whole, and not just restricted to the technical aspects.

It was also important to link the different and individual scales. Koen Steemers IBDS method is based on a schematic scaling down from Urban Planning to Urban Fabric – see Figure 12. This thesis acknowledges the importance of working across scales. As described in IEA Task 23, it is essential to have a multidisciplinary team consisting of individual competences.



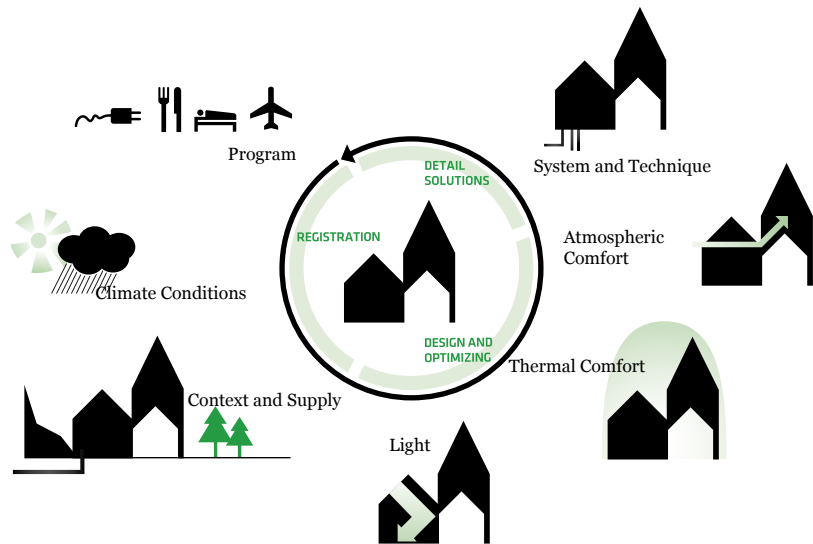


Figure 15: Schematic layout of building design-related issues depicting the primary sub-categories of each main design consideration. Method and illustration: Henning Larsen Architects

Working with Henning Larsen Architects, it has been possible to test this interdisciplinary collaboration in practice through specific case studies. Not only has there been integrated collaboration with external consultants, but there has also been integrated sparring internally between the three PhD projects<sup>14</sup>, which have had an overlap in both theory and case studies. The interaction is illustrated in Figure 16.

## Experience with IED

The key to obtaining a sustainable and architecturally good urban plan in IED is to combine architectural and engineering skills in the early phase of the project. However, this calls for a good communication between the two different disciplines. The various members of the design team need to have an understanding of the integration aspects. This requires that they have some knowledge of the whole range of professional fields.

14 In collaboration with the Technical University of Denmark, Henning Larsen Architects employed three industrial PhD students. The three research projects are connected: The city, the building and the façade. By working on all three scales, the overall city strategies are connected with the building and the design, efficiency and aesthetics of the façade.

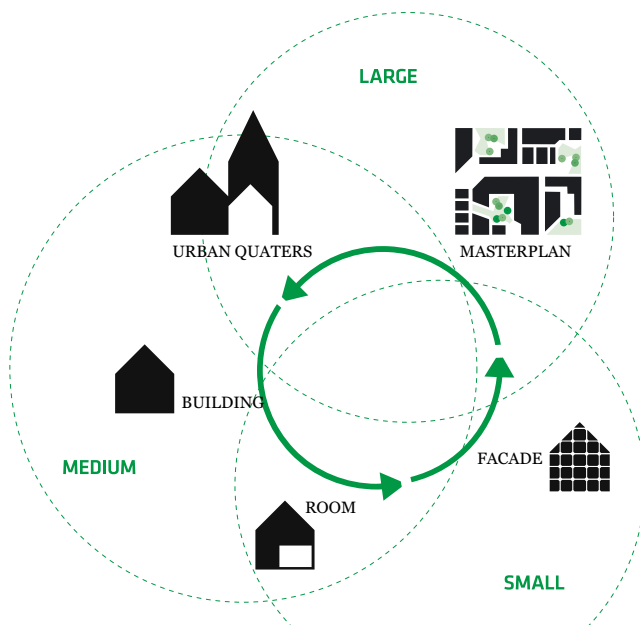


Figure 16: The fundamental need of continuous and quickly changing perspectives between solutions and problem on the one hand and between the totality and particularity on the other hand illustrates the multi-dimensionality and complexity of the design workflows embedded in the scale of IED. Illustration: Henning Larsen Architects

None of the design methods directly ensures good communication, but only they do ensure that the parameters which influence sustainability are taken into consideration. IEA Task 23 has associated tools (the Matrix, the Multi-Criteria Decision-Making method and the Energy 10 Program) that can help the communication, but the tools do not create communication on their own. Experience shows that it really requires insight and common understanding to communicate objectives and measurements. It is important that the engineer can respond with a spatial design and that the architect appropriates a certain understanding of the physical phenomena (see *Paper V*<sup>15</sup>, *VI*<sup>16</sup> and Discussion and conclusion).

15 “Integrated Design – paradigm for the design of low-energy office buildings” M. Jørgensen, M.W. Nielsen, J. Strømmand-andersenc In proceedings: *ASHRAE Winter Conference, 2011*, Las Vegas, Nevada

16 “A methodological study of environmental simulation in architecture and engineering - Integrating daylight and thermal performance across the urban and building scales” P. A. Sattrupa, J. Strømmand-Andersen In proceedings: *Symposium on Simulation for Architecture and Urban Design, 2011*, Boston, MA, USA



CHAPTER 2

# **Urban Density**

## CHAPTER 2

# Urban Density

Urban density is a term used in urban planning to refer to the number of people inhabiting a given urbanized area. Urban density is considered an important factor in understanding how cities function. Research related to urban density is found in various fields including economics, health, innovation, psychology and geography, as well as sustainability.

It is commonly asserted that high-density cities are more sustainable than low-density cities. A lot of planning theory has been developed on increasing urban densities, such as New Urbanism<sup>17</sup>, Transit-Oriented Development<sup>18</sup>, and Smart Growth<sup>19</sup>. However, the link between urban density and aspects of sustainability remains a contested area of planning theory. Many experts on sustainable urbanism, including well-known urban designer Jan Gehl, argue that low-density, dispersed cities are unsustainable because they are automobile-dependent (*Gehl J., 1986*). And at a broader level, there is evidence to indicate a strong negative correlation between the total CO<sub>2</sub> emission of a city and its overall urban density, i.e. the lower the density, the more energy consumed (*Newman P W. G., Kenworthy J. R., 1999*) – see Figure 17.

On the other hand, it can be argued that increasing densities result in more expensive real estate, and increased road congestion, air pollution, and energy consumption.

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17 New Urbanism is an urban design movement, which promotes walkable neighbourhoods that contain a range of housing and job types. It arose in the United States in the early 1980s, and has gradually continued to reform many aspects of real-estate development, urban planning, and municipal land-use strategies. See Charter of the New Urbanism <http://www.cnu.org/charter>

18 A transit-oriented development (TOD) is a mixed-use residential or commercial area designed to maximize access to public transport. Wikipedia Encyclopedia (02/08/2011): Transit-Oriented Development, [en.wikipedia.org/wiki/Transit-oriented\\_development](http://en.wikipedia.org/wiki/Transit-oriented_development)

19 Smart growth is an urban planning and transportation theory that concentrates growth in compact walkable urban centres to avoid sprawl and advocates compact land use. Wikipedia Encyclopedia (02/08/2011): Smart Growth, [en.wikipedia.org/wiki/Smart\\_growth](http://en.wikipedia.org/wiki/Smart_growth)

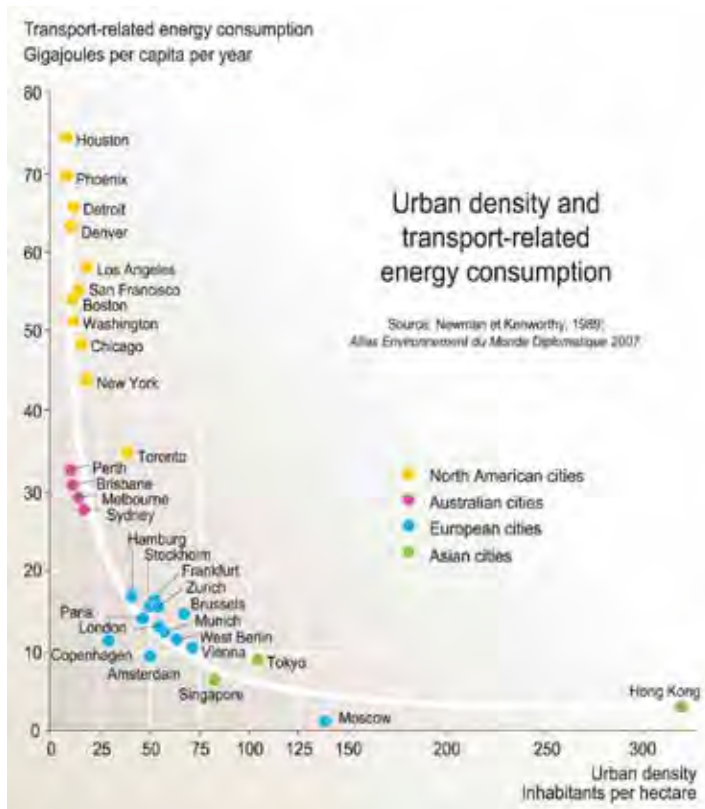


Figure 17: The Newman and Kenworthy hyperbola: Urban density and transport-related energy consumption

In current architecture and planning, urban densification is seen as one of the key instruments for improving sustainability by reducing energy use for transport, and future cities are likely to become denser than now. In the coming decades, up to 100,000 additional housing units could be required for the Copenhagen metropolitan area. At the same time, we are moving towards a low-energy paradigm for future buildings. In Denmark, low-energy buildings will be the new standard by 2015.

Incentives and regulations to improve the performance of the existing building mass are being discussed for implementation (*Erhvervs- og Byggestyrelsen*). The big question is: Will this future low-energy paradigm collide with the urban densification strategy?

## Scientific outline – Urban Density

In the already built cities of northern Europe, urban density is of particular concern, because the high latitudes and the associated low solar inclinations mean that urban geometry affects solar access much more here than in many other urban centres around the world. Overshadowing is an obvious problem. The relative scarcity of light, particularly during the long winter season, is increased by the overcast skies that dominate the region throughout the year, creating special conditions for the region's architecture and planning to deal with.

### Urban density's impact on total energy consumption

As a result of this study, it can be stated that urban density in northern European cities has an impact on total energy consumption in the range of up to +30% for offices and +19% for housing, which shows that urban density is one of the key factors in energy use in buildings<sup>20</sup>.

From the given specifications of the building layout and a free horizon, it is possible to design a low-energy office building with an energy consumption of around 50kWh/m<sup>2</sup>/year<sup>21</sup>. If the context around the building over time transforms into a dense urban area, the energy consumption will increase proportionally to approximately 70kWh/m<sup>2</sup>/year, resulting in a relative increase in energy consumption of up to 30% depending on orientation – indicating that increasing urban densification does not necessarily mean low energy use in buildings.

The urban patterns of Copenhagen were taken as reference, and six different canyons were defined by their height/width ratio (H/W) ranging from 3.0 to 0.5. The highest H/W ratio spaces are found mostly in the medieval parts of the city, such as passages and very narrow courtyards, and the lowest ratio

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20 Paper I: "The urban canyon and building energy use: Urban density versus daylight and passive solar gains" J. Strømman-Andersena, P.A. Sattruph Published in: *Energy and Buildings*, 43, Issue 8, August (2011) 2011-2020

21 In the "old" building code (2010) an energy consumption of 50kWh/m<sup>2</sup>/year was the 2015 standard for low-energy buildings. (*EBST, Bygningsreglement for erhvervs- og etagebyggeri, National Agency for Enterprise and Construction, Copenhagen, Denmark, 2010*). This standard was used as reference in Paper I.

reflects conditions found in urban squares, boulevards and more spatially generous courtyards – see Figure 18.

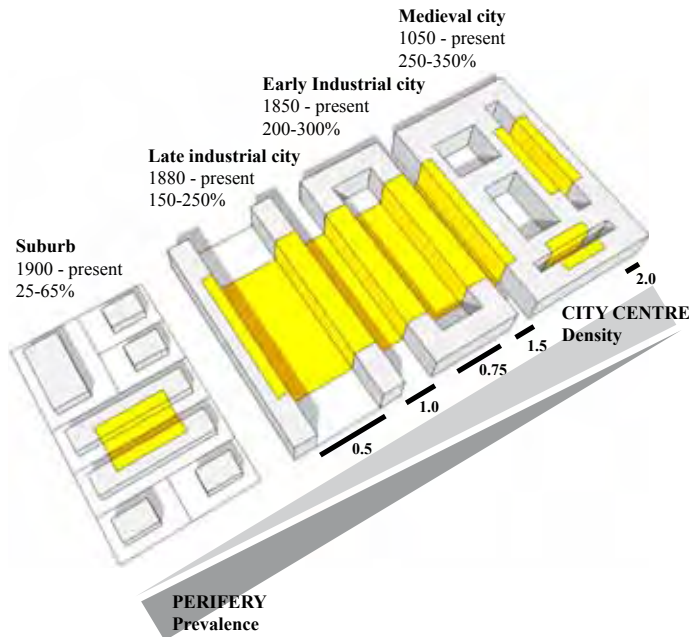


Figure 18: Typical urban patterns and proportions of urban canyons in Copenhagen, showing H/W-ratios.

The relative “fit” of the urban canyon concept to real urban patterns is scale-dependent. Because the urban canyon concept is an abstraction of the spatial complexities of real cities, its relation to density is somewhat simplified too. The graphs (Figure 19 to Figure 23) show the base case from Paper I.

## Energy consumption for offices

Figure 19 illustrates a typical office building’s energy consumption as a function of the density of the city (H/W ratio). It shows a general increase in energy consumption as a result of increased density as expressed by the H/W ratio. Because the results are balanced by a 2.5 primary energy conversion factor for electricity use compared to heating and cooling, artificial lighting becomes both the dominant factor in energy use at very high densities and the factor most susceptible to changes in density. Cooling demand decreases with increasing density due to overshadowing, while the reduction in solar gains due to the very low solar altitude during the heating season results in increased use of energy for heating. Artificial lighting has the largest



variability of the individual energy needs. Energy use for artificial lighting is doubled even at the lowest density (H/W 1.0) compared to an unobstructed context, and increases more than six times at the highest density (H/W 3.0).

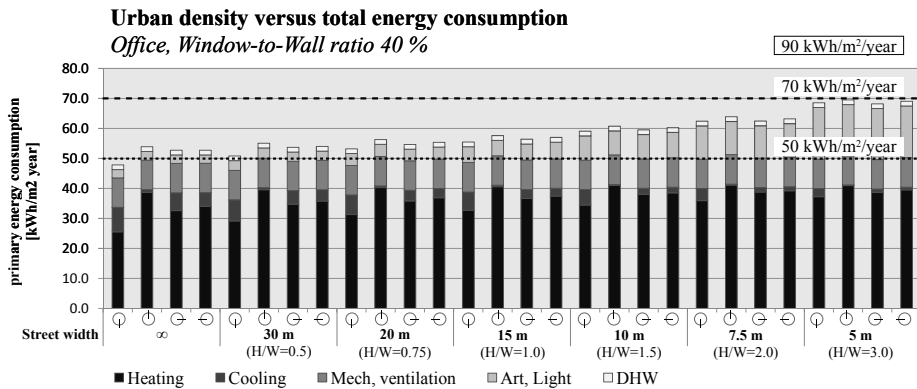


Figure 19: Total primary energy consumption (kWh/m²/year) for a 5-storey office building as a function of urban density, (Height/Width ratio).

Figure 20 shows that the relative deviation in the total energy consumption from free horizon to a height/width ratio of 3 varies from between +2.1% and +30.2% for offices depending on their geographic orientation. The greatest relative deviation was found with the south/north building orientation. The south-oriented units in particular stand out with density having a large relative influence even with large canyon widths. For example, the relative influence is +10% for a street width of 30m (H/W 0.5). This means that the relative variation is 2–3 times greater than for other orientations.

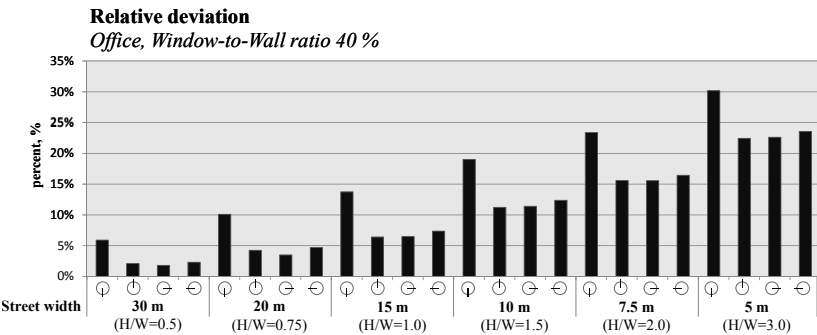


Figure 20: Relative deviation (%) of energy consumption for a 5-storey office building as a function of urban density compared to free horizon.

Daylight is the design parameter most dynamically affected by increased urban density – see Figure 21. In cloudy climates, diffuse light from the sky is the main source of daylighting. At the site planning stage, the aim is to ensure that there is a sufficient area of sky visible to give good interior lighting with windows of reasonable size. The availability of daylight at a window is determined primarily by the block form of the building and its surroundings, so wrong decisions at an early design stage are difficult to correct later. Energy used for artificial lighting may even become the single most important factor affecting primary energy use in high density cities.

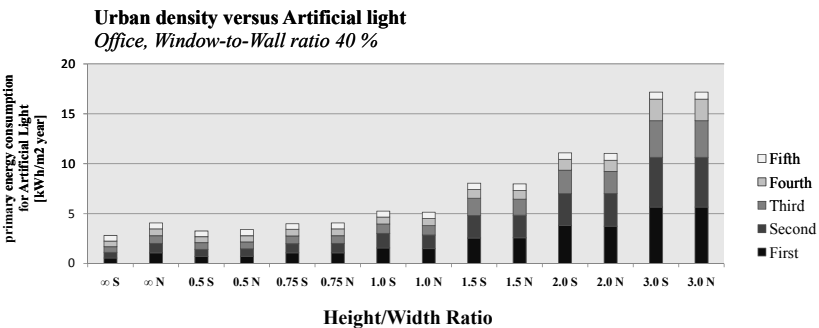


Figure 21: Primary energy consumption for artificial light (kWh/m²/year) for a 5-storey office building (north/south) as a function of urban density

### Energy consumption for housing

The relative impact of increased density on energy consumption is more moderate for housing than for offices – see Figure 22. The largest single need in housing is heating. This means that the heating contribution from solar radiation is an essential element for housing – unlike for offices, in which illumination level is the most important parameter. For example, the energy consumption varies by 11.2kWh/m²/year, from a north to a south orientation for a free horizon, due to variations in solar access. However, the denser the city becomes the smaller the variation in passive solar gains.

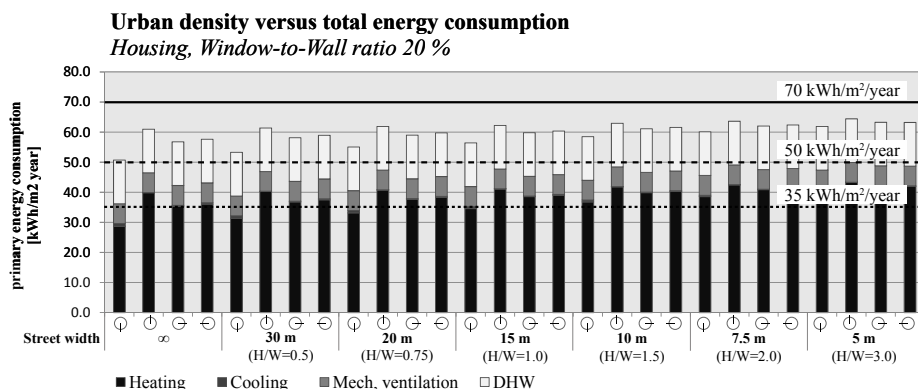


Figure 22: Total primary energy consumption (kWh/m²/year) for a 5-storey housing building as a function of urban density, (Height/Width ratio).

The relative deviation of the total energy consumption from free horizon to a height/width ratio of 3 varies from between +2% and +19% for housing – see Figure 23. The relative development of individual needs for heating and cooling is approximately the same for housing as for offices.

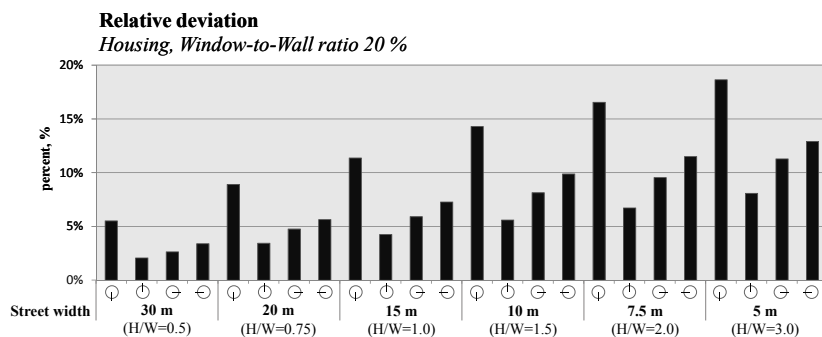


Figure 23: Relative deviation (%) of energy consumption for a 5-storey office building as a function of urban density compared to free horizon.

The energy consumption for lighting is also more uniform across the city's density. This is due to the consumer pattern, where the number of hours with a need for lighting in housing falls in the periods with a global illuminance level less than 200 lx. During winter, the most active hours of a housing unit occur in the morning and evening while it is still dark and artificial light is turned on.

Understanding the variations in energy use requires a holistic understanding of the socio-spatio-temporal relations between climate, building use, form, material and technology. Climate-based simulation modelling is an essential tool in understanding these relations better.

The question is: How can this knowledge be integrated into the architectural design process?

## Case study A: Thomas B. Thriges Gade

*From streetscape to cityscape – remodelling Thomas B. Thriges Gade*

The task was to transform the existing 4-track expressway (Thomas B. Thriges Gade) into a new dense urban area with mixed functions of housing, offices and retail.



### Project facts:

|                     |   |
|---------------------|---|
| Location:           | Odense, Denmark   |
| Client:             | City of Odense  |
| Gross floor area:   | 50,000 m <sup>2</sup>   |
| Year of design:     | 2011–2012   |
| Type of assignment: | Competition   |
| Design team:        | Polyform, Henning Larsen Architects, Dress & Sommer, WTM Engineers International (D); Argus (D); Jonathan Speirs + Major (UK) |

The decision to establish the road was a result of developments in Odense<sup>22</sup> and in increasing motor traffic after World War 2. Traffic flows between the urban area in the south and the harbour in the north were particularly problematic, and a plan for improving the traffic situation was prepared in the late 1940s. The final plan for radical intervention in the urban structure was adopted by Odense City Council in 1952 and work on the urban expressway started in 1960. Thomas B Thriges Gade (TBTG) was completed and opened on 6 May 1970. Having served as a thoroughfare for many years, the street

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<sup>22</sup> The city of Odense is the third largest city in Denmark. Odense City has a population of 167,615 (as of 1 January 2011) and is the main city of the island of Funen. Wikipedia Encyclopedia (02/08/2011): Odense, <http://en.wikipedia.org/wiki/Odense>

now needs to be modernized so that it will help create and reintroduce cohesion in the city – see Figure 24.



Figure 24: Photo, Thomas B. Thriges Gade

**The Project Area, TBTG**

The project area is roughly 50,000 m<sup>2</sup> large and about 700 metres long. It is part of an area that can be dated back to medieval times when the first urban settlements in Odense were established. The project area is delimited by the River Odense to the south and Østre Stationsvej to the north, where Thomas B Thriges Gade continues towards the harbour – see Figure 25.



Figure 25: Project Area – indicated by the blue line

## Competition assignment & Programmatic requirements

The competition brief described how the remodelled street must be integrated into the existing urban structure to provide density, new connections and, in combination with adjacent areas, a coherent district.

The most important programmatic requirements:

- New buildings in the project area must provide a total floor area of 50,000 to 70,000 square metres
- New buildings must respect their context, both in the project area and in the city centre as a whole
- It must be explained in architectural guidelines for the new buildings how the desired quality can be achieved, although any indication of a specific architectural design should be avoided
- At least 50% of the buildings must be used for housing purposes
- Between 30% and 50% of buildings must be used for commercial facilities such as offices, cafés, restaurants, etc.
- No more than 10% of the floor space may be used for retail outlets

The master plan should illustrate the general concept governing the transformation of the project area as well as the physical structures to be established. The focus should be on creating density, coherence and completeness in combination with adjacent neighbourhoods.

*“We wish to see high-density urban development within the perimeter of the existing city, particularly in the city centre, as this will enable us to utilise Odense’s shared facilities better and thus also reduce resource consumption.” (Anker Boye, the Mayor of Odense)*

With regard to sustainability, it is stated that it is basically a matter of quality of life and making Odense an attractive place to live for both present and future generations. In Odense, sustainability is not seen in terms of solutions that simply fulfil a number of specified technical requirements: *“sustainability should be seen in a holistic perspective that takes its starting point in a vision of ‘people in the city’. But in the description of the environmental*

*sustainability it is a standard that building should be healthy and meet the future requirements for low-energy buildings”, (Competition Brief).*

### **The “right” density**

The most important task in the project was to structure the “right” density. An analysis of density is complex and requires insight into a network of parameters. In the specific project, the transport and technical infrastructure was determined in advance. The road was to be replaced by a light rail system and the area was to be coupled to the public supply facilities (including district heating and cooling systems).

In addition to the infrastructural requirements defined, there was an underlying schism in the programme between social/environmental sustainability and economic sustainability. For financial reasons, Odense City Council wanted to develop as many square meters as possible – thereby creating the largest directly profit through the sale of square meters. On the other hand, the Council wanted good and healthy buildings and urban spaces – i.e. buildings and urban spaces that require light, air, and green areas. It was a great challenge to identify and meet the conflicting expectations.

The project’s main point was to develop a physical design for density, structure and buildings. In addition to the economic agenda, the design had to relate to two basic parameters;

- The quality of the buildings (comfort and energy consumption)
- The quality of urban spaces (social life, function and climate)

To find a solution, the design team used an integrated design approach – see Figure 14 and Figure 15. First, the competition programme, the local climate and context were registered (**Step 1**), then the relationship between micro-climate and building structure was optimized (**Step 2**), and finally it was considered whether active energy systems could support the design (**Step 3**).

### **Step 1: Programme, climate and context**

To understand the potentials and limitations, the design team had to understand Odense both as a city and as part of a greater environment – see



Figure 26. What is the density of the city? And what climate conditions are applicable?

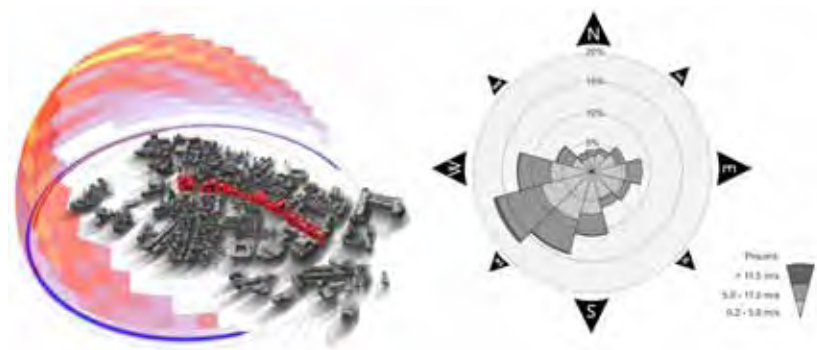


Figure 26: Solar Access, Annual Sun Path and Shadow Range and wind statistic, Thomas B. Thriges Gade, Latitude 55°23'55.00"N, Longitude 10°23'40.00"E

An analysis of the density in Odense shows that the City centre consists of 3-5-storey houses with a street width ranging from 10-15 m, which is equivalent to an H/W ratio around 1.0 – see Figure 27 and Figure 28.

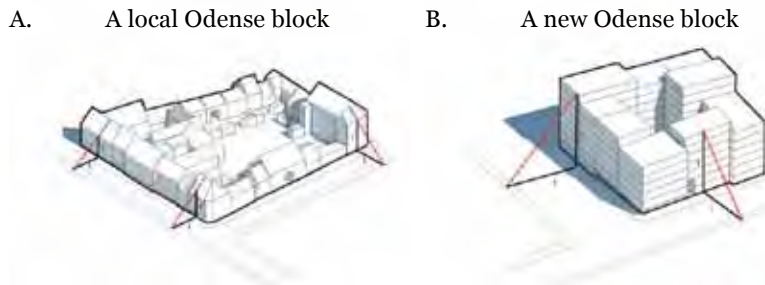


Figure 27: H/W ratio 1 to 1 is transferred from the existing structure in Odense

Initially the design team used a 1 to 1 ratio to define building envelopes along TBTG. The envelopes formed a basis, which corresponded to the scale of the surrounding buildings and at the same time was a good starting-point for a low-energy strategy. The 1 to 1 strategy yielded a total floor area of about 40,000 m<sup>2</sup>.

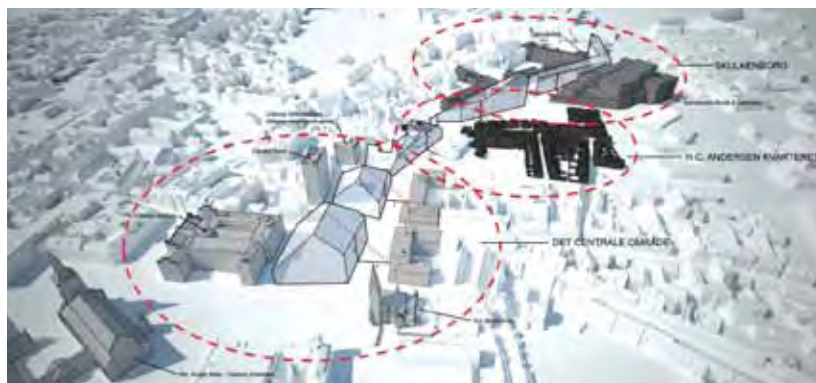


Figure 28: The first test was to strike a line at an angle of  $45^\circ$  from the bottom of the existing building towards TBTG.

Since the project operates with a higher density (50,000-70,000  $\text{m}^2$ ) than the 40,000  $\text{m}^2$  defined by the sketched building envelopes, we had to re-think the 1 to 1 requirement. The scientific analysis showed that an H/W ratio of 1.0 (density about 300%) would threaten the possibilities for creating low-energy buildings – see Figure 19 and Figure 22. Therefore it was important to increase the density on a very informed basis.

The H/W-ratio in its true form is a uniform average model, i.e. a model that does not contain spatial variation. Most streets and buildings vary in width and height. If there is only moderate variation, drawing a horizontal line at the average height provides a reasonable estimate. But if the skyline varies greatly in height – such as towers and courtyards – a more precise calculation is needed in critical cases. Techniques are described in (BR209, 1998)<sup>23</sup>. The design team decided to consider density from another and more spatial perspective. To calculate daylight availability, BR209 has a routine for finding the vertical sky component (this is the ratio of light received on a vertical surface from an overcast sky to that received by unobstructed ground).

First the existing urban structure and density was analysed based on the Vertical Cloud Component (VSC) to create a baseline for new structure and

23 This guide complements BS8206 (British Standard) Part 2 and CIBSE Applications manual on window design by providing advice on the planning of the external environment. It covers: rights to light and indicators for calculating access to daylight, sunlight and solar radiation; how to protect the daylighting and sunlighting of existing buildings when new developments are proposed; and guidance on passive solar site layout.



Figure 29: The Vertical Sky Component analysed in Vestergade, Odense city centre. VSC is a measure of the amount of daylight incident on a vertical plane. For a standard overcast sky, the maximum value is 50% (since the point is on a vertical plane, clearly only half the hemisphere can contribute).

density – see Figure 29 and Figure 34. The BR209 guidelines suggest that if a window receives a VSC greater than 27% then it should continue to receive enough daylight.

## Step 2: Building typologies

We used various strategies to create greater density. The TBTG area was divided into three parts and design strategies were defined for each part – see Figure 30, Figure 32 and Figure 32.

The various strategies were constantly confronted with their effects on the existing settlement. VSC was used as a simulation and visualization platform.



Figure 30: I. Vilh. Werners Plads (southern part of TBTC)

### **South**

In the southern part of TBTC a vertical density was created around a block. Towers were introduced in the north-eastern corner of the block.



Figure 31: H. C. Andersen's Plads (Central part of TBTC)

### **Central**

The central part of TBTC was scaled down to correspond to the medieval part of the city around H. C. Andersen district (minimum densification).



Figure 32: Fisketorvet, (northern part of TBTC)

### **North**

In the northern part of TBTC the density was increased vertically around the existing block structure. The original block structure had been split by the construction of TBTC, but it was now united by the new buildings.

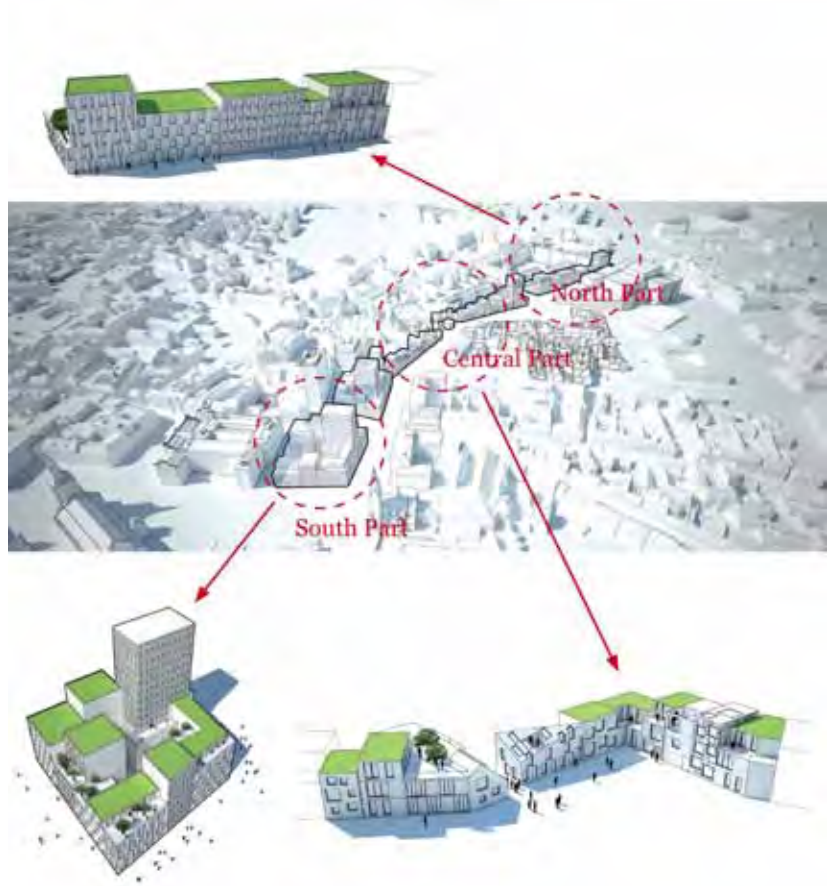


Figure 33: Variation of urban densification strategies

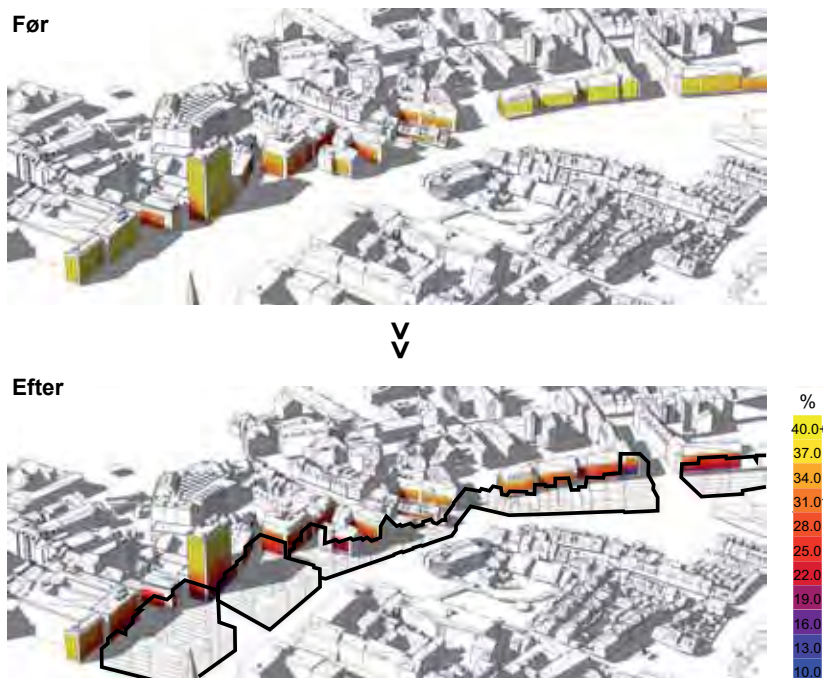


Figure 34: VSC calculated before and after new construction.

After several model iterations, the building geometry was decided. At some places the requirement of  $VSC > 27\%$  was not met – see Figure 34. But these “dark” points were localized and taken care of. For example, a greater density can be permitted near gable façades without windows, or near business functions with large cooling needs. The total gross floor area landed at  $50,000 \text{ m}^2$  – equal to the minimum requirement in the competition brief.

An important parameter for Odense City Council – in addition to the comfort and energy consumption in buildings – was the quality of the urban spaces created. Microclimate plays an important role here.

There are lots of good examples of well-functioning urban spaces. They are often characterized by having a defined and integrated interaction, between the form of the urban space, activity and climate: form in relation to architecture and arrangement; activity by functional diversity, cultural options and recreational areas; climate in terms of opportunities and limitations with regard to light, shadow, sunlight and wind.



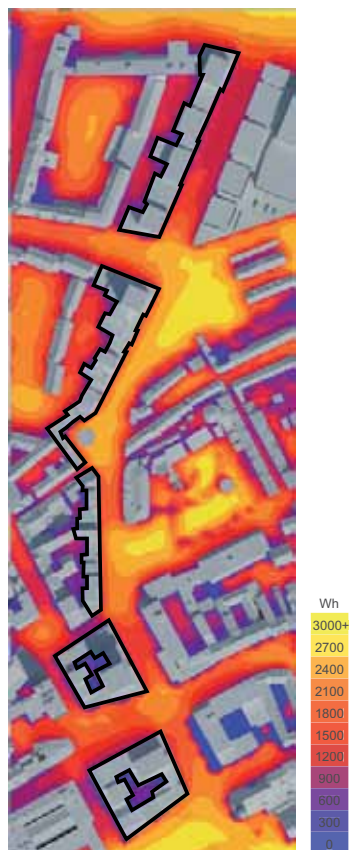


Figure 35: Simulation of direct and diffuse solar radiation on TBTG (Wh, daily averages).

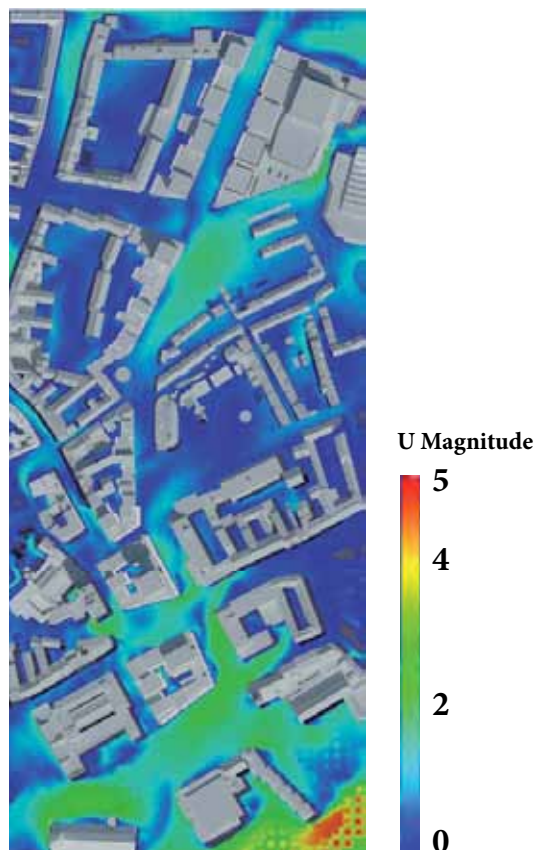


Figure 36: Wind analysis (CFD simulation) of south/west (240° north) winds on TBTG (m/s)

It is theoretically possible to predict comfort as a function of climatic parameters, e.g. temperature, air velocity and radiant heat, and personal variables, such as clothing and activity – see *Paper IV*<sup>24</sup> and *Paper IX*<sup>25</sup>. In the real world, there can be huge variation in both the microclimate and the perception of comfort. Some urban spaces can be exposed to direct sunlight for most of the day, while other areas are in the shade or roofed. To illustrate

24 “Urban design and pedestrian wind comfort – a case study of King Abdullah Financial District in Riyadh” J. Strømman-Andersena, J.C. Bennetsenb. Accepted and in review process: Environment and Planning B: Planning and Design, 2011

25 “Climatic Diversity in the City” J. Strømman-Andersen Published in: Byplan, No. 3 september 2010/62, årgang

the significance of sunlight, consider that a variation of approx. 70 W/m<sup>2</sup> horizontal solar radiation changes the air temperature by 1°C. For the Danish climate it is not unusual for the solar radiation in an urban space to vary by up to 1,000 W/m<sup>2</sup> or the equivalent of a temperature change of 14°C.

Analyses of the microclimate were used in the design of individual spaces. For example, H. C. Andersen's Plads (Figure 31) has been organized in function and orientation. The idea is that H. C. Andersen's Plads, amongst other things, should function as a meeting place and information centre for guided tours, i.e. a space addressed to activity in the morning. That is why the space is angled to the South/East, which means that the space receives a daily average of 920Wh in the morning, compared to 700Wh in the afternoon – see Figure 37 to Figure 39.

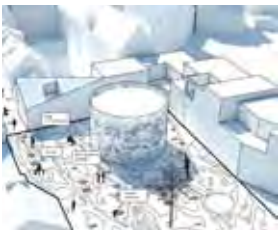


Figure 37: H. C. Andersen's Plads, 3D visualisation.

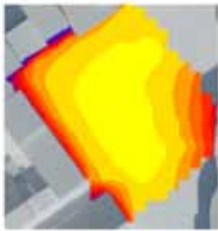


Figure 38: Avg. Daily Radiation (8am-12am)

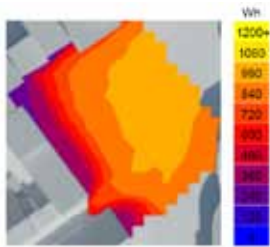


Figure 39: Avg. Daily Radiation (12am-4pm)

### Step 3: Active energy systems

Focus on active energy systems was limited. The area is provided with an efficient district heating system from waste incineration. In addition, the City Council is working to establish district cooling. Since the energy needs for heating and cooling are based on sustainable energy supply, the main focus has been on electricity consumption. To meet the growing electricity demand, one suggestion is to place solar cells on the roofs. But the idea is only to use the most exposed roof surfaces. If 25% of the roof surfaces are filled with solar cells electricity-related energy consumption can be reduced by 15%.



## **Lessons to be learned – Chapter 2**

It is difficult to directly conclude from the case study and it is not possible to give a final answer to the question of optimal density. However, from the process, we can extract a number of observations and guidelines.

Firstly, we have registered that it is important to analyse and understand the surrounding context before the design process begins. It sounds simple, but usually designers (architects, engineers and planners) are tempted to focus the process on the “new development” and forget to examine, understand and accept the interaction between the existing and the new, both structurally and with regard to resource management.

Secondly, the Thomas B. Thriges Gade case has demonstrated the importance of visual simulations and communication. Since the design process is fluid and fast, it is more important for architects that environmental simulation offers *reliable* information about effects of design choices, than that it is highly accurate. However, it is fundamentally difficult for engineers to “override” the accuracy. It is important for the engineers not to focus on just validating the design, but just as important to try to respond with alternative design proposals.

Finally, it can be concluded that it is fairly unusual for the architects to see climate as a primary consideration in the first step in the development of the overall master plan. In many cases, constraints due to the size of the site and the total built floor area requirement of the brief will dictate, or at least limit, the range of options. Where site area is not so constrained, other planning and organizational issues will normally take precedence over considerations about urban climate.

## “It can go wrong”

In 2010, Henning Larsen Architects took part in an architectural competition for a new primary school in Ørestad<sup>26</sup> (Ørestad School).

One of the challenges was that the school had a very limited construction site. A school with 17,000 m<sup>2</sup> of space for 750 pupils was to be built on a site of 2,500 m<sup>2</sup>, i.e. a settlement rate of approximately 700%. Another challenge was that the school was to be located only 8 m from the existing Ørestad Gymnasium (Ørestad High School), equal to a H/W ratio of 2.5 – see Figure 40A.



Figure 40: Ørestad Gymnasium before Ørestad School was built. B: Ørestad School under construction.

Ørestad High School is designed as a freestanding building with a focus on passive energy systems. The buildings have natural ventilation and no cooling system. The natural ventilation occurs through the house atrium, where passive solar heat from large south facing glass areas ensures the natural airflow. The construction of the new primary school changes the assumptions for the design of the comfort system and function problems could arise – see Figure 40B.

Project engineer for the Ørestad high school and former employee of Søren Jensen Consultant Engineering Company<sup>27</sup>, Jan Christensen explains: *“The building is based on passive principles ... the thermal indoor climate was*

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<sup>26</sup> Ørestad is a developing urban area in Copenhagen. It is expected that 20,000 people will live in Ørestad, 20,000 will study there, and 80,000 people will be employed in the area. Wikipedia Encyclopedia (20/10/2011): Ørestad, [en.wikipedia.org/wiki/%C3%98restad](http://en.wikipedia.org/wiki/%C3%98restad)

<sup>27</sup> Søren Jensen Consultant Engineering Company, [www.sj.dk/da/projekter/projekt.2006-05-19.2724736144](http://www.sj.dk/da/projekter/projekt.2006-05-19.2724736144) (20/10/2011)

*carefully planned after BSim<sup>28</sup> simulations ... we did not know what was going to be built on the neighbouring sites, therefore, the simulation was performed without any surrounding buildings<sup>29</sup>.*

If a new building of 7 floors is placed 8 meters from the south façade of the existing building, it will affect the passive energy supply and thus the building's total energy consumption. If this is not allowed for in the design of the building, it will have a negative impact on the energy balance and indoor climate of the building.

In the design process a great deal of effort was therefore put into understanding and analysing the impact of the new building (Ørestad School) on the existing high school. Various design solutions were tested with a view to maximizing the solar radiation on the south façade of the high school – see Figure 41. However, Henning Larsen Architects did not win the competition.

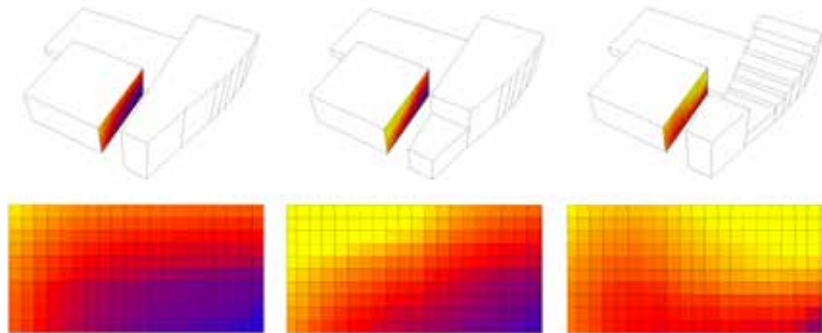


Figure 41: Solar radiation on Ørestad Gymnasium with various building configurations for Ørestad School. Simulation carried out by PhD colleague Michael Jørgensen

Subsequent monitoring has shown that the energy consumption for heating in Ørestad High School has increased by 2-5 MWh per month, a relative increase of 5-10%<sup>30</sup>. In addition, there are problems with the integrated

28 BSim (Building Simulation) an energy simulation tool which creates a fully integrated thermal and daylight simulation with detailed hourly output of the electrical energy consumption for lighting, mechanical ventilation, heating load, cooling load and indoor operative temperature.

29 Telephone interview with Jan Christensen (20/10/2011)

30 Operational data 2007-2011 supplied by Ørestad Gymnasium. The values listed should be viewed with some reservation, since the dataset only covers a few months. Monitoring will be continued.

management systems. E.g. the mechanical solar screening is controlled by lux-censors, which are adjusted according to glare conditions. Before the construction of Ørestad School the sunshades operated dynamically following the daily rhythm and weather conditions. With the new building, a more complex play of light has arisen, a play that is difficult for the sensors to handle. Direct reflections in the windows can cause the illuminance levels to jump from 500 lux to 5,000 lux in a few seconds. In addition, the solar shades are controlled by an anemometer on the roof, so the shades close when the wind speed becomes too high – to prevent the shades being damaged. The problem is that the new building has created a wind funnel where turbulence is reinforced causing the wind speed to be higher on the façade than on the roof, where the anemometer is placed. As a result the sun shade has had to be deactivated.



Figure 42: Kim Sogaard (Superintendent and plant manager) checks the CTS-system



Figure 43: Urban canyon between Ørestad High School (right) and Ørestad Primary-School (left).

The problems are not so great that they cannot be solved by a technical upgrade of Ørestad High School – but it would have been better if the problems had been completely avoided: “Prevention is better than cure”.

As a consequence, any building project, whether new-build or refurbishment, would be advised to integrate not only a detailed simulation of the energy impact of the context as it is, but also an estimate based on the maximum density allowed on neighbouring sites.



## CHAPTER 3

# **Urban Typologies**

## CHAPTER 3

# Urban Typologies

In urban areas building layout or urban typology is the most important factor affecting the daylight, sunlight and solar heat gain reaching a building.

Although urban site conditions are critical for low-energy building design, very few studies have attempted to relate urban form to energy use or solar access and daylight conditions. Those that do, study regional climatic conditions, and are therefore not universally applicable – an important point in environmental design supporting Frampton’s early call for a regional, climatically conscious architecture (*Frampton, K., 1985*). With the extreme global diversity of urban climatic conditions in mind, it is rather provocative that we know so little about the impact of urban form on the environmental and energy performance of buildings.

A recent publication (*DeKay M. R., 2010*) asks the question: “*What would the form of the city be like if we were to take seriously the provision of daylight to all buildings?*” Using “Daylight Envelopes<sup>31</sup>”, (*DeKay M. R., 2010*) shows how an urban pattern of blocks and streets can be generated so that the limits of building boundaries provide lower floors of neighbouring buildings with sufficient light.



Figure 44: Urban Housing over Commerce: Solar envelopes (left) replaced by student designs (right) viewed from east, Ralph L. Knowles, 1999

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31 When the “Daylight Access Rule” is applied to an urban pattern of blocks and streets, a development envelope can be generated that describes the limit of building boundaries that will provide lower floors of opposite or neighbouring buildings with sufficient daylight. (*DeKay M. 2010*)

Another recent study by Poul Bæk Pedersen, (*Pedersen P. B., 2009*) analyses urban typology in the context of the compact city. The research concludes that the compactness of the typology plays an important role, but it can also be concluded that an increased building density does not, by definition, lead to a decrease in the daylight conditions – see Figure 45.



Figure 45: Urban typologies, Compact city

DeKay summarize the complexity: *“There are still no basic massing rules ... to ensure that the massing decisions intended to provide daylight are actually dimensioned within parameters that allow sufficient levels within the rooms of lower floors. This is clearly an unresolved subject for future research efforts”*. This indicates the need for more detailed investigation of the effect of urban form on the environmental performance of buildings.

## Scientific outline – Urban Typologies

Analysis of urban patterns, from traditional to patterns in very recent architectural projects, shows relative deviations in total energy performance of up to 19% and in daylight autonomy of up to 48% at similar densities. This indicates that urban patterns and building typology are key factors affecting energy consumption and daylight levels<sup>32</sup>.

### Urban Morphology – Northern European Cities

Urban patterns develop over time, typically shaped by the climate and transport patterns, among many other parameters. They also reflect the technical

32 “Building Typologies in Northern European Cities – Daylight, Solar Access and Building Energy Use” J. Strømman-Andersena, P.A. Sattrupb. Accepted for publication: Journal of Architectural and Planning Research, 2011



possibilities of the periods in which they were developed. Northern European cities (Copenhagen, Stockholm, Oslo, Hamburg, etc.) are characterized by a relatively uniform urban scale, ranging from 5 to 6-storey buildings in the city centre to a widespread carpet of single-level family homes in the periphery. The city centres are characterized by the prevalence of the urban perimeter block pattern with remarkably similar sizes – see Figure 46. The patterns have been subject to gradual dissolution due to modern developments and the introduction of new building types, such as the building slab and the detached house. In the case of Copenhagen, this development was regulated by the famous “Finger plan” of 1947. A sample of typical building patterns is shown in Figure 47.

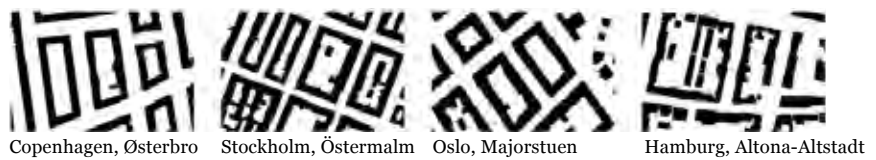


Figure 46: Local typologies from various northern European cities (Copenhagen, Stockholm, Oslo and Hamburg)

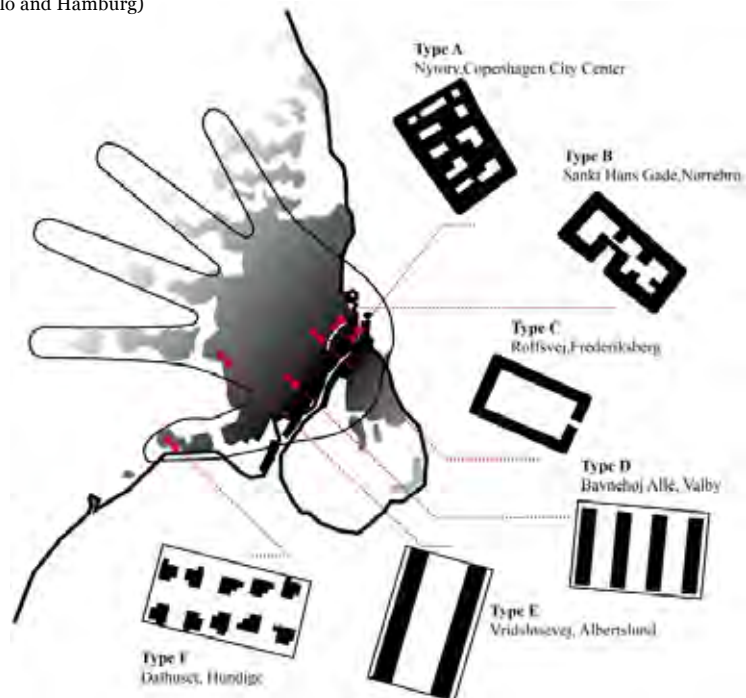


Figure 47: Samples of urban patterns and their location in Copenhagen (“Finger plan”)

The study is parametric in approach. Six generic models representing a range of urban building type patterns were compared for energy and day-light performance. The six urban patterns correspond to different typologies in northern European cities – see Figure 47 and Figure 48. While generic, the models were structured to represent the most important geometric factors that regulate the development of the urban fabric over time.

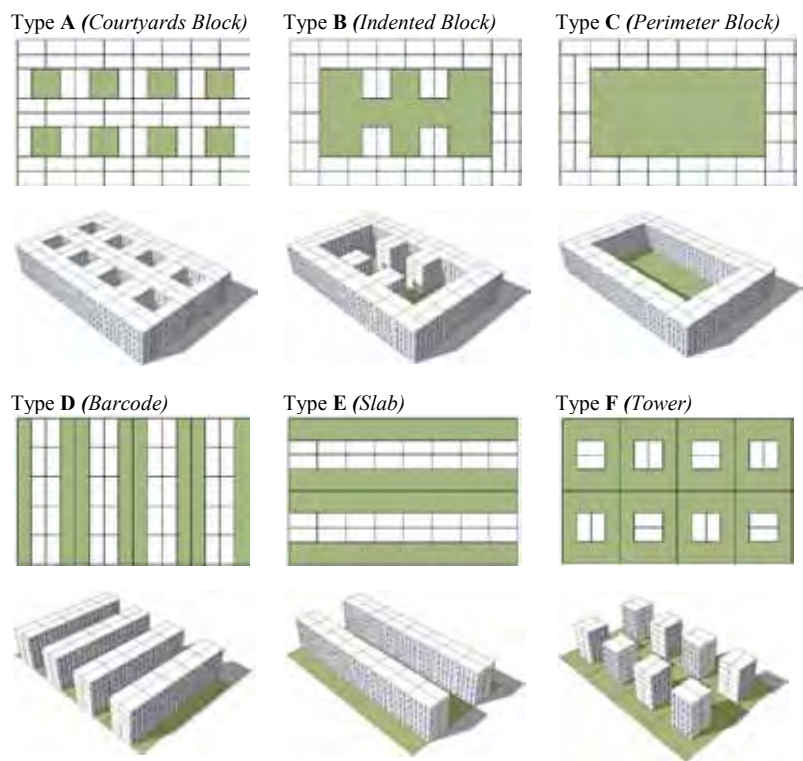


Figure 48: Six traditional urban building patterns



Figure 49: Student mapping typologies in Copenhagen

## Energy and daylight results

Correlation between density, energy use and daylight autonomy are shown in Figure 50 and Figure 51. Figure 50 shows that the energy use varies from 41.5-49.5 kWh/m<sup>2</sup>/year. Type A has the highest density and least energy use compared with the other types. For Types B, C, D and E, the energy consumption varies between +2 and +8%. Type F is the only type that has significantly higher energy consumption (19% higher than Type A). A general tendency is that energy consumption increases with decreasing urban pattern density, but the big jump in energy performance is achieved when using additive urban forms instead of detached building types. Density is defined as the total covered floor area on the building plot.

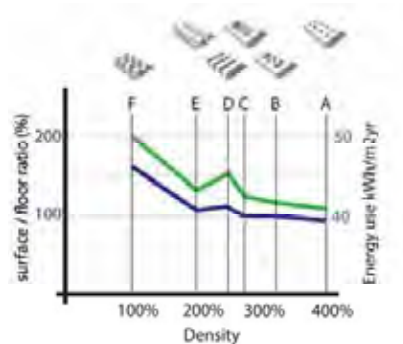


Figure 50: Correlation: Density, Energy Use and Compactness

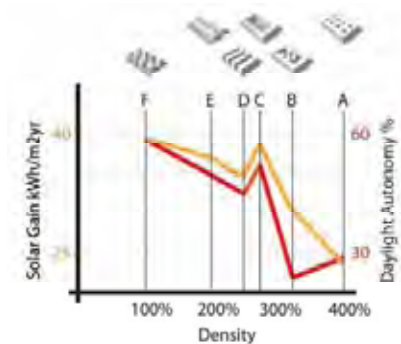


Figure 51: Correlation: Density, Daylight Autonomy and Solar gains

The dominant factor in the total energy consumption is heating. This is partly due to Copenhagen’s low mean temperature of 8.2 °C (compared with London at 10.2 °C and New York City at 12.4 °C)<sup>33</sup>, which necessitates more energy for heating to achieve thermal comfort.

Figure 52 demonstrates a clear correlation between urban density and passive solar gain. Type A has the lowest passive solar gain. More surprising is the fact that the solar gain does not fall proportionally with the density (plot ratio). Type C has a high building density (275%), but also a high level of passive solar gain. This shows that exposure to sunlight is not linearly connected with urban density, but depends to a high degree on the design of the individual typology.

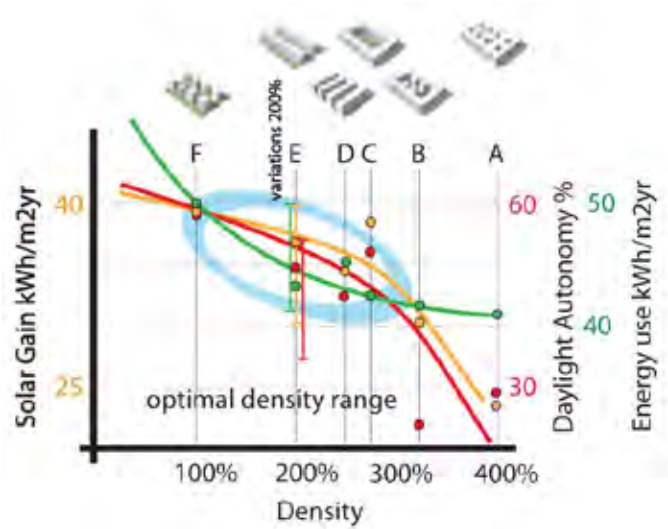


Figure 52: Optimal density range for daylight, solar access and energy use, Copenhagen. The curves illustrate the tendencies from Figure 50 and Figure 51.

Returning to the question of how urban density affects building energy use, it can be noted that high density generally leads to reduced energy use. But, as can be seen in Figure 52, the effect is mainly caused by the compactness of each typology (surface to floor area ratio) since heating losses in winter remain the main cause for energy demand in northern Europe, even with a well-insulated façade. But the effect fades out for developments denser than 250%. Parallel to the lessened energy demand, daylight and solar gains

33 Data from U.S. Department of Energy, Energy Efficiency & Renewable Energy

are severely compromised by the increase in density. But there is, very interestingly, a middle range between densities of 150% and 275% which are both energy efficient and have adequate daylight and solar access. The performance differences of types B, C, D and E suggest that there is plenty of opportunity to achieve better performance by designing with attention to orientation and solar access.

A relative variation of 19% in annual energy performance by urban pattern design alone is very considerable over the (perhaps 50-100 years) lifetime of a building. However more interesting from a qualitative architectural point of view is that daylight and passive solar gains distribution vary even more and are not linearly connected to urban density. This implies that there should be a strong case for architectural design at the interstice of urban and building design to improve these aspects of environmental performance.

## Case study B: Västra Dockan

*From windy waterfront to urban recreation – remodelling Västra Dockan*

The task was to convert the existing harbour area into a new dense urban area with mixed functions. The focus was on rethinking the urban space into green and liveable recreation.



### Project facts:

|                     |                                     |
|---------------------|-------------------------------------|
| Location:           | Malmö, Sweden                       |
| Client:             | Malmö City & Dockan Exploatering AB |
| Gross floor area:   | 80,000 m <sup>2</sup>               |
| Year of design:     | 2008–2009                           |
| Type of assignment: | Invited competition                 |

### **Start with the urban space**

The idea behind Västra Dockan emerged from the space between the buildings. The idea was to plan the urban space based on the existing surroundings – think urban space before buildings, e.g. connections, recreational areas and existing functions.

The area stretches from the waterfront towards Malmö city centre – see Figure 53. In the area, there were four existing warehouses, which were to be preserved for recreational purposes. The structural idea was to link the city to the harbour front via a green public passage – see Figure 54.

The harbour front is very “rough” and windy. The existing urban structure – with its rigid grid and forms – does not promote a good microclimate. It is not pleasant to stay in Västra Dockan area.



Figure 53: Planning area, (four existing warehouses are located within the area)



Figure 54: Green space penetrating and connecting the area with the surrounding developments

## Design strategy

Three strategic points were formulated, which were to function as guiding principles through the design process. The points were: spatial planning, urban quality and the design process.

- Optimize the area's "land use" without compromising on comfort and resource consumption both in urban space and in the individual buildings.
- Improve the quality of the streets, courtyards, gardens and open spaces by maximizing exposure to daylight/sunlight through conscious planning of the building mass.
- Be reflexive and flexible in attitudes to design solutions to find new opportunities and chances at all levels in the design and development process.

## The measurable spaces

The basic idea was to perform simulations of microclimates that could serve as ground rules for the design of new urban spaces. Working Group 1 of

COST Action C14<sup>34</sup> describes how activity can be categorized into four levels by a physiological hierarchy that describes the function of an urban space – see Table 1 (Koss *H.*, 2006). Using this categorization makes it possible for example to quantify when the wind environment will be on uncomfortable for the current activity.





|   |          |   |   |
|---|----------|---|---|
|  | <b>A</b> | + | Stay of longer duration, quiet position, sitting or lying,          |
|   |          | - | <i>terrace, street café or restaurant, pool, amphitheater, etc.</i> |
|  | <b>B</b> | + | Stays of short duration, standing / sitting in the short term,      |
|   |          | - | <i>public parks, playgrounds, shopping streets etc.</i>             |
|  | <b>C</b> | + | Actively stay, comfortable and normal walking pace, strolling,      |
|   |          | - | <i>walkway, entrance, shopping street, etc.</i>                     |
|  | <b>D</b> | + | In transit; objective walk; rapid or quick pace,                    |
|   |          | - | <i>parking lot, boulevard; sidewalk, etc.</i>                       |

Table 1: Categorization of activity in urban space

Figure 55 illustrates the various categories of the urban space. The goal is to have good recreational areas around the existing warehouses, i.e. areas with a stable and comfortable microclimate. These areas are categorized as (A) and (B) areas. In return parking facilities should be established in the southern part of the area. Here you can “compromise” on the microclimate – this area is therefore categorized as class D.

It is important to note, however, that the categories should be used with some degree of wisdom. It makes no sense, for example, to search for a category A site for every urban space in the city. The city, as opposed to buildings, provides a space for a greater abundance and diversity of activities.

The microclimate laid the cornerstone for the optimization of building typologies. But together with an optimal microclimate, it was also important to use a typology that would enable low energy consumption. That is why the closed block was chosen as the basis typology – see Figure 56 to Figure 58.

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34      COST | European Cooperation in Science and Technology, COST Action C14; Impact of wind and storm on city life and the built environment.



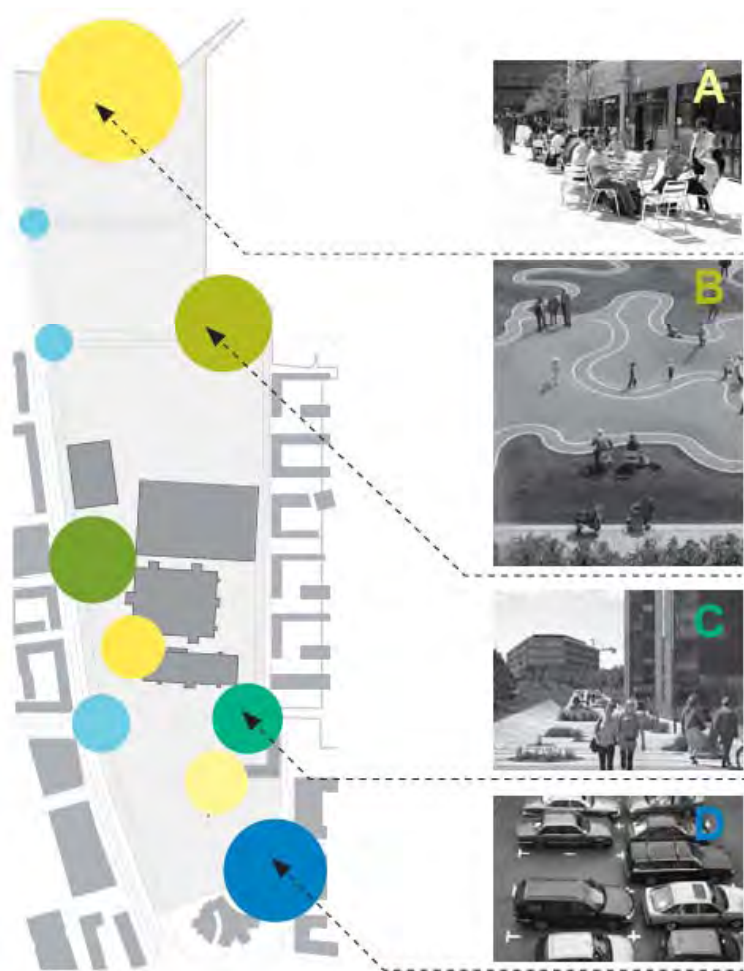


Figure 55: Categorize mapped on urban plan.

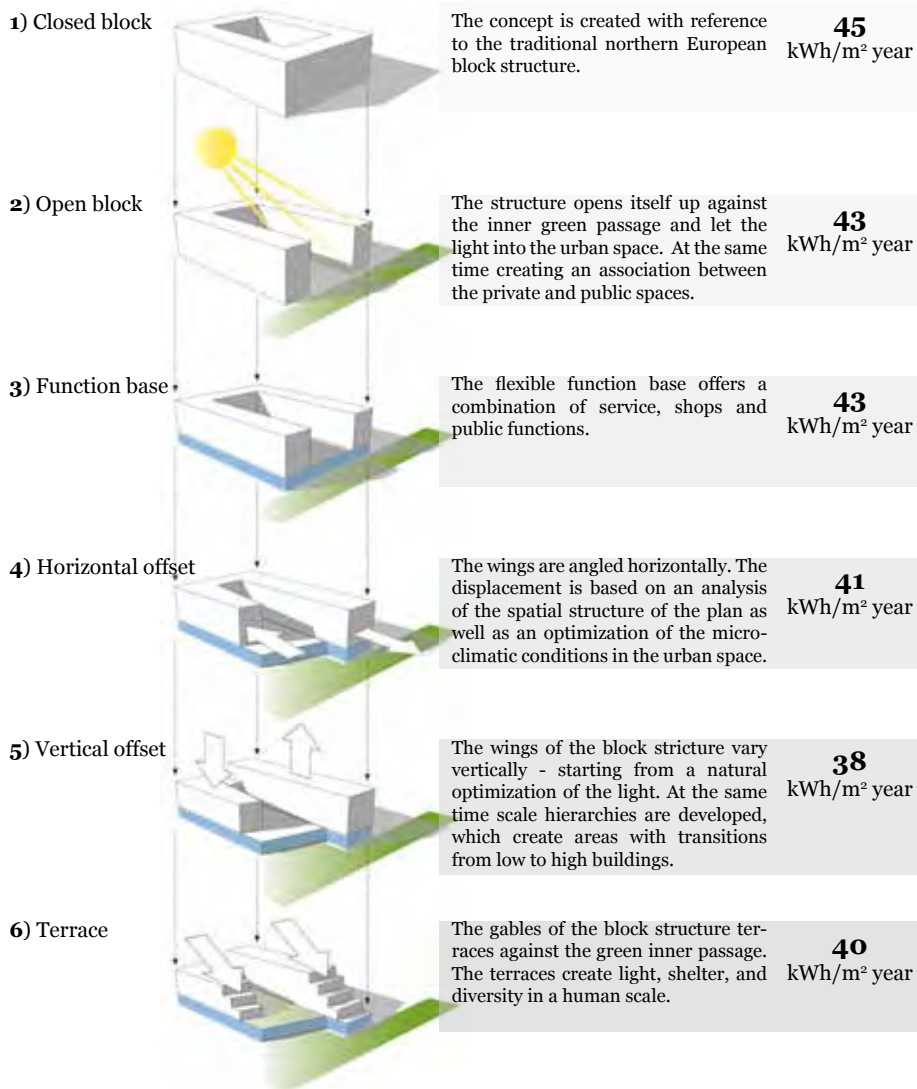


Figure 56: Step-by-step optimization of urban typologies and energy consumption

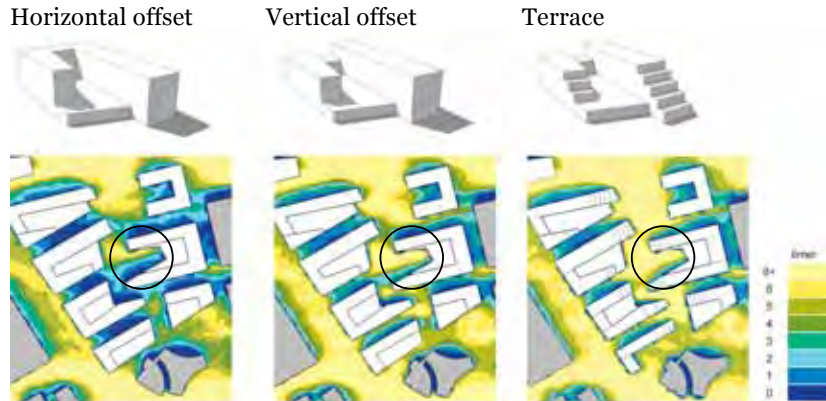


Figure 57: Step-by-step optimization of sunlight hours (summer period from 1st July to 30th September). In the marked building/courtyard is to have a kindergarten.

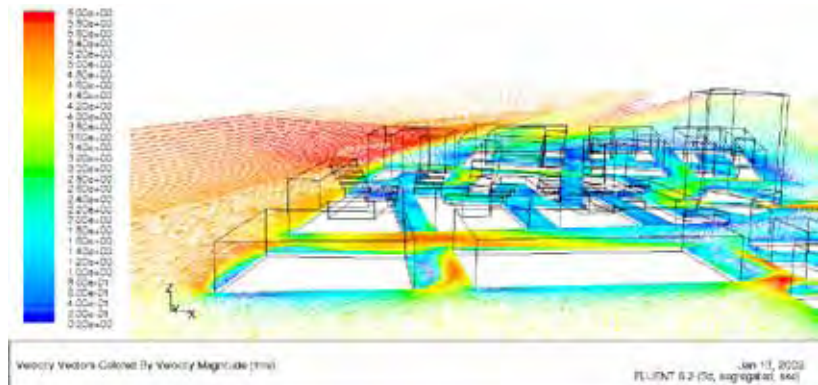


Figure 58: CFD (Computational Fluid Dynamic) study of wind flow at Vätra Dockan. The vector colours indicate wind velocity magnitude (m/s).

Västra Dockan illustrates how scientific technical assessment tools can be used in the design process. Taking the approach and categorization beyond the design process, they can also be used in a political agenda. It will, for example, be possible for local authorities to establish requirements for the outdoor environment, much like entrepreneurs who nowadays require an indoor climate classification in the construction programme. There will then be a continuously measurable indicator of how the urban space performs.



Figure 59: Model of Västra Dockan illustrating the building typologies.

### **Lessons to be learned – Chapter 3**

What are the consequences for urban developments in the future? The concise answer is that geometric design parameters become critical when planning for energy-efficient cities and communities. Energy efficiency is however not the main issue of urban design – it remains a question of how to improve the experiential and environmental qualities of cities.

These findings give strong evidence that architects and planners should design for daylight and solar access rather than focusing on energy use alone, and they should pursue innovative solutions that are dense, compact and distribute daylight and sun in the urban fabric for both public and private benefit. While energy use may be reduced further by applying advanced building technology and integrated energy production, the results shown here indicate that basic typology design is able to reduce energy loads well below the relatively strict Danish standards (BR10) using urban design and building fabric as the main means of energy reduction. Further optimization through building technology is typically expensive and may have limited functional lifetimes, while daylight and solar access are decided at the interstice of urban and building design, and have long lasting impacts on the urban and indoor environmental qualities.



CHAPTER 4

**Urban Fabric**

## CHAPTER 4

# Urban Fabric

One of the most basic and fundamental questions in urban master-planning and building regulations is how to secure common access to sun and daylight. For the owners of individual properties, it is often a question of getting the most out of what is available. This creates a potential for repetitively recurring conflict between public and private interest. Solar access and the right to light remain contested territory in any society, vital as they are to health, comfort and pleasure.

The link between urban design and the utilization of daylight in buildings is a complex balance between climatic factors and spatial, material and use patterns. Many studies have shown that the optimization of daylight in buildings would result in significant savings in electricity consumption for lighting, while creating a higher quality indoor environment.

### Access to daylight

Access to daylight in cities has long been a concern of lawmakers. The ancient Greeks and Romans mandated minimum lighting standards for their cities. The British Law of Ancient Light (which dates back to 1189) and its later embodiment into statute law, the Prescription Act of 1832, provided that if a window enjoyed uninterrupted access to daylight for a twenty-year period, right to that access became permanent (*Bryan et al., 1981*).

The most important impact on daylight is due to obstructions that shade the site from part of the sky and direct sun at certain periods of day and year. If these obstructions are quite far away (e.g. mountains or other terrain formations) the shading will be apparent over the whole site, and the impact on the daylight conditions can be analysed for one representative point on the site only. If the obstructions are close to the site (i.e. other buildings) overshadowing may affect only parts of the site, and daylight conditions have to be studied in more detail. Another important point is that obstructions not only shade direct sun, they will typically also obstruct parts of the sky vault and thus reduce diffuse illumination levels as well. Obstructing the diffuse sky will reduce the availability of daylight within the building and thus require

longer periods of artificial illumination, increasing energy consumption.

However, adjacent buildings can make positive contributions as well. Consider a north-facing window, looking out onto a light-coloured south-facing wall that is being strongly illuminated by the sun.

## Scientific outline – Urban Fabric

The result of this study shows that in dense cities the orientation of the buildings has a minor impact on daylight availability. However, the results indicate that there is a preference for northern orientations in terms of daylight availability on the lower floors. Furthermore, the northern façade benefits greatly from the use of urban fabric of high reflectivity on the opaque part of street façades. The effect is seen in increased daylight penetration depth for the lower floors<sup>35</sup>.

### The façade as a light source

The photometric term for the time rate of light flow is luminous flux. The unit of measurement of luminous flux is lumen. When luminous flux strikes an opaque surface, it is either reflected or absorbed – see Figure 60. Reflectance is the ratio of reflected flux to incident flux. Absorptance, conversely, is the ratio of absorbed flux to incident flux. In cases where the surface is not opaque (i.e. transparent or translucent), some of the incident flux is transmitted through the material. As a result highly glazed façades are dark and reduce the urban daylight potential by “privatizing” the daylight resource, leaving less for neighbouring buildings.



Figure 60: Measuring reflectance on various urban fabrics

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35 Paper III “Urban Daylighting: the impact of urban geometry, façade reflectance and window to wall ratios on daylight availability inside buildings” A. Iverserna, J. Strømman-Andersenb, P.A. Sattrup Submitted to: Building and Environment, December 2011



The reflectivity of the façade depends mainly on the colour and transparency of the materials and the glazing ratio. While glass may seem bright from below as it reflects the sky, its reflectivity is quite low.

Different configurations of urban fabric provide different visual environments in the street. Figure 61 shows that daylight autonomy<sup>36</sup> (annual illuminance > 10,000 lux) can vary from 50% to 10% depending on the surface reflectance. Bright façades can improve daylight autonomy considerably at the deepest levels of the urban canyon, improving urban quality and decreasing dependency on artificial lighting in the buildings – see Figure 62 and Figure 63.

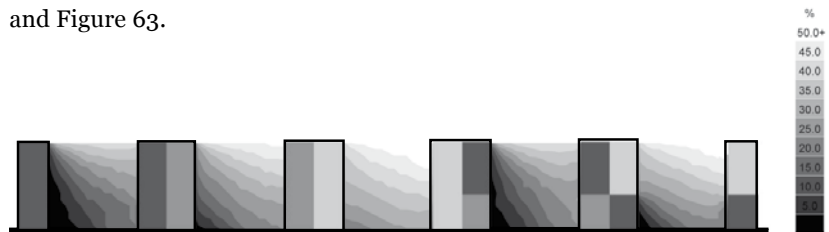


Figure 61: 5 street sections: Annual illuminance > 10,000 lux in street canyon with surface reflectance variables. Façade reflectances are 25%, 45% and 65% of the total representing a range from medium dark to very bright. Calculated in RADIANCE/DAYSIM (working hours 08–17, contour range 0–50% in steps of 5%). Weather data, Copenhagen (\*epw).



Figure 62: LaSalle Street Canyon.  
Façade reflectance approximately equal to 15–25%.



Figure 63: Wall Street Canyon.  
Façade reflectance approximately equal to 45–55%.

<sup>36</sup> Daylight Autonomy is defined as the percentage of the “occupied” times of the year when the minimum illuminance requirement at the sensor is met by daylight alone. Daylight Autonomy Metric is quantified combining both direct and diffuse radiation.

Daylight availability within the room

Figure 64 shows the daylight autonomy (DA) through the room for various façade reflectances for the northern and southern orientations for the H/W-ratio of 1.0 and for the 5<sup>th</sup> floor. As expected, increasing reflectance increases the daylight penetration depth within the room, for both northern and southern orientations.

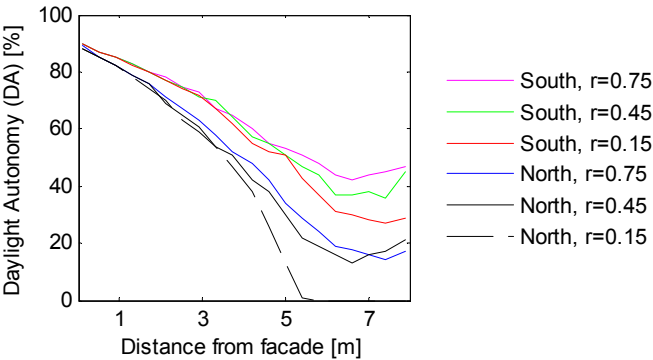


Figure 64: Daylight Autonomies through the room for north and south orientations and various reflectances of the building opposite, H/W-ratio of 1.0 and 5<sup>th</sup> floor, r=reflectance.

Figure 64 describes a room located on the 5<sup>th</sup> floor in an urban canyon of H/W-ratio = 1.0. If we look at the other floor plans in this typology, the DA on the 1<sup>st</sup> and 3<sup>rd</sup> floor increases for the northern orientation to the same level or even higher than for the southern orientation – see Figure 65.

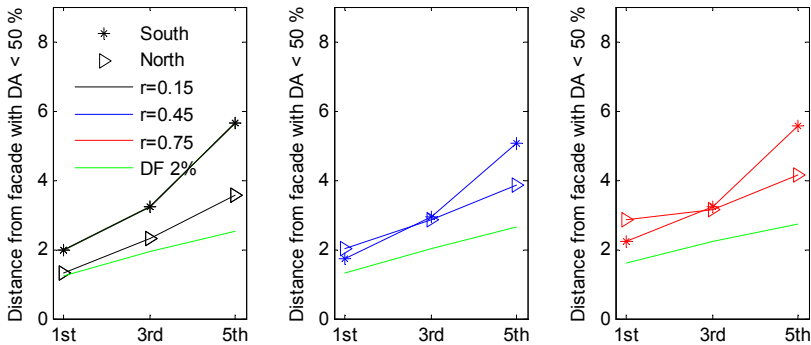


Figure 65: Distance from the façade with DA below 50% as a function of floor level (1st, 3rd and 5<sup>th</sup> floor), and three different façade reflectances, r=reflectance. The green line shows the distance from the façade with a Daylight Factor of 2%.

A very visible trend in Figure 65 is that for the windows facing north the influence of reflectance is remarkably clear for the 1st floor. Here the reflected light increases the DA of 50% from 1.3 m to 2.8 m from the façade. For the control of artificial lights, this might have an impact on the energy consumption, as shown in Paper I<sup>37</sup>.

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37 Paper I: "*The urban canyon and building energy use: Urban density versus daylight and passive solar gains*" J. Strømman-Andersena, P.A. Sattrupb Published in: *Energy and Buildings*, 43, Issue 8, August (2011) 2011-2020

## Case study C: Carlsberg City Distinct

*From simple building envelope to dynamic light source –  
rethinking the urban fabric*



### Project facts:

|                   |  |
|-------------------|--|
| Location:         | Copenhagen, Denmark  |
| Client:           | Carlsberg Properties   |
| Gross floor area: | 80,000 m <sup>2</sup>  |
| Year of design:   | 2011–2011  |
| Architect team:   | Henning Larsen Architects, Dorte Mandrup Architects,<br>Polyform Architects and Signal Architects. |

### **Competition assignment – behind the Master Plan**

The Carlsberg area of Copenhagen is undergoing a transformation from industrial headquarters and brewery to vibrant urban district. A competition for a master plan for the entire Carlsberg area was held in 2008. The competition was won by Entasis Architects. The idea behind the master plan was to condense the existing structure from a strong urban perspective. A variety of open squares and enclosed courtyards were to be established. Block typologies became the focal point for the physical formatting. In addition to the block structure, nine small towers were added – see Figure 66.

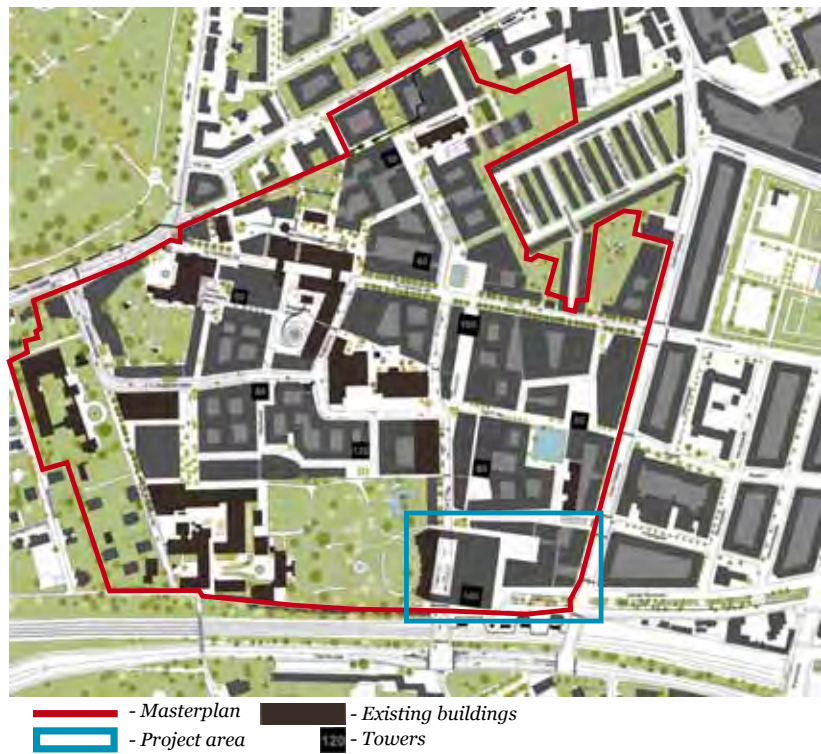


Figure 66: Carlsberg Master plan

## The first step in transforming Carlsberg

This project is the first building plot that is to be developed as part of the master plan. The project includes 54,000 m<sup>2</sup> educational buildings, 14,000 m<sup>2</sup> housing and approx. 12,000 m<sup>2</sup> shops, cafes and commercial buildings. The functional programme is to be adjusted given structure, i.e. the task was to create a programmatic distribution and function and to create a vision for building expression – a strategy for the façades.

The project was handled as a “shared” assignment. Various architectural firms were invited to make a tender as one team. Each firm was then assigned to a specific part of the project. The challenge was to develop a common strategy and concept for the project and at the same time give each firm the architectural freedom to develop their own ideas.

Henning Larsen Architects made a team with three other architects; Dorte Mandrup Architects, POLYFORM and SIGNAL Architects. Each office was allocated a functional programme – see Figure 67.

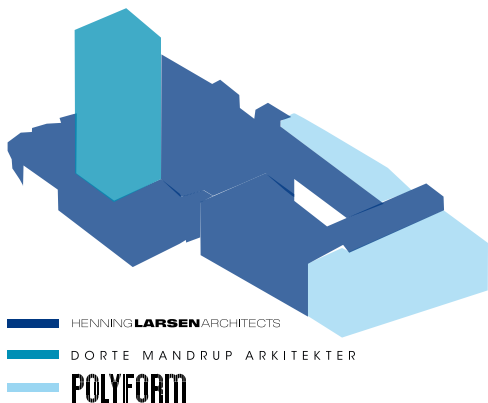


Figure 67: Building structure defined by the master plan. Each office was assigned a programme in the building plot; Henning Larsen Architects was to have responsibility for the university buildings, Dorte Mandrup Architects was given responsibility for the residential towers, POLYFORM for office buildings, and SIGNAL Architects was to describe the process and the building costs.

## Daylight as the common vision

It was important to create a common vision and strategy for the project – here daylight became the focal point. There was a strong common under-

standing in the team that daylight could be the element that could bring a common cohesion into the project.

The idea was to create a strategy for distribution of light and dark façades and their texture. The structure and the façades should serve as daylight fittings for buildings and functional programmes and at the same time create a pleasant microclimate for life on the square. The idea was to modulate each building – so that they not only followed their own rhythm of changing weather, season and day but also added to the quality of the surrounding buildings. No construction plot or functional programme should privatize daylight, but instead distribute it equitably according to need.

The first step in the process was to define common guidelines. Two sets of rules were laid down:

1. Create a vertical differentiation of exterior expression – from bright to dark façades upwards
2. Select a number of “active” façades that were important for the horizontal distribution of daylight.

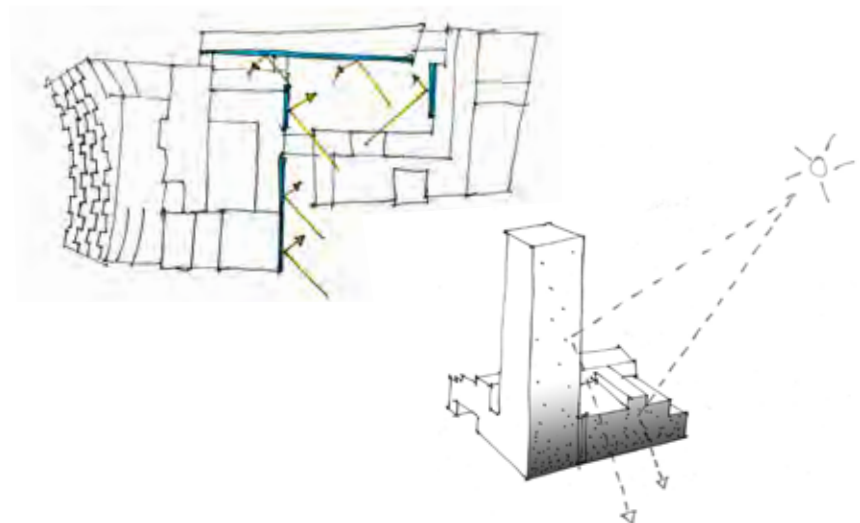


Figure 68: Façades are actively used to reflect light. The lower floors connected to the plazas of the district appear in dark colours that retain the heat from the sunlight, while the upper, light façades open up the area and reflect the sunlight into the urban space and opposite buildings

The idea was that the bright façades at the top of the buildings could reflect daylight down into the courtyard and the lower floors, where the need is greatest. In addition “active” façades should function as daylight reflectors for the university in particular. So when the students need light (mainly in the morning hours) the façades should reflect the low morning sun into the courtyard and further into the teaching rooms – see Figure 68.

**Re-modelling the Master Plan**

The master plan was “locked” from the beginning. Not only was the geometric structure fixed, but the expression of the squares was fixed as well. The project square was conceived as a dark, quiet and intimate space – a space for contemplation.

The challenge occurred when the functional programme did not meet the function and thoughts of the square. The programme implied that the university area should be formed around the square – an area that would require activity and good learning conditions. From the prerequisites, it was difficult to create good daylight conditions for the university’s functions and facili-

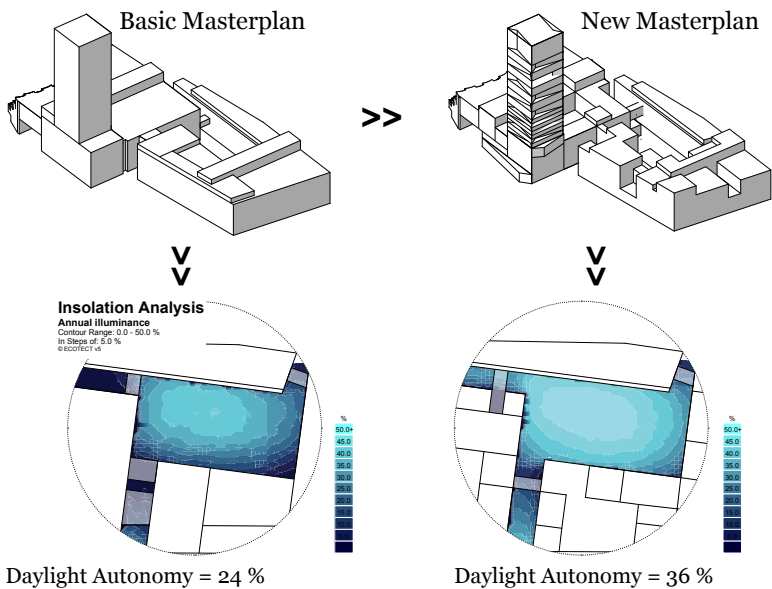


Figure 69: DA > 10.000 lux, 8 am – 6 pm, annual average



ties. The square was simply too dark and narrow. So the original structure of the area was modified based on a specific daylight strategy – see Figure 69. Work was done on offsets and withdrawals of the building structure, which ensured that windows have the highest possible sky vault and thus natural daylight access. In interaction with the “active” façades – angled and broken façades refract the light’s direct and diffuse components, and provide rich and dynamic play onto the square. For example, the façade of the tower is angled  $10^\circ$  to  $30^\circ$  so that the light is reflected differently depending on the time and day – see Figure 70. Windows are sized in connection to their orientation, as part of an energy optimization. By optimizing the geometry and the façade’s reflectances, it was possible to improve the available daylight (DA) on the square by 12% – see Figure 69.



Figure 70: Shadowing and reflection, 9 am to 13 pm, equinox

The modification of the structure also brought more daylight into the educational learning facilities. In other words, the façade – the narrow street that connects the courtyard with the surroundings – was pulled back on the upper four floors. In this way, the urban space retained its intimacy but it was suddenly possible to provide the classrooms with sufficient daylight.

Unfortunately, the reformatting of the master plan was not well received by the judging Committee. Their goal was to maintain the Master plan’s structural idea and basis – which, seen with aesthetic master plan eyes, also makes sense. However, this approach creates challenges for future comfort and energy-efficient buildings. For example, the University building is very

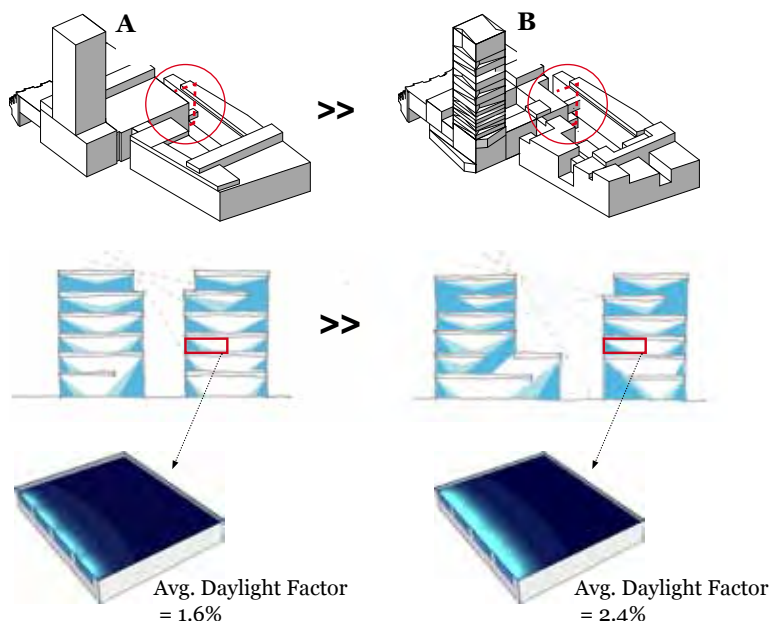


Figure 71: Daylight simulation with various design alternatives

dependent on good comfort – visual, as well as thermal and atmospheric. Here the analyses showed that the dark and dense urban structure would create challenges – see Figure 71.

## Lessons to be learned – Chapter 4

From a scientific point of view, it can be stated that building façades have great influence on the visual comfort conditions in both the urban space and in neighbouring buildings.

What is new is to move from good intentions and strategies to being able to make actual calculations, which may constitute rules for design of the urban geometry in connection to the energy efficiency and comfort of individual buildings. For architects, however, the main interest in simulation models is not necessarily the accuracy of the model, or the advance in simulation technology itself. The interest is more oriented towards the application of environmental simulation technology in the design process, and what simulation may tell us about the built environment that the model represents. The project has shown it is more relevant that the simulation model is able

to feed information into a design process that is directed towards achieving improvements in life quality for the client, users and general public. It is a breakthrough in using simulation models. But it is essential that simulation models and tools are introduced early on in the process. If not, there is a possibility that the master plan may hinder sustainable development. It is important to be aware of the master plan's responsibility down through the different scales.

The case study illustrates that formulating a common objective in terms of sustainability early on in the process ensures that all partners take the same approach to the process and work constructively to reach the same goals. It is important to provide the framework for an operational, integrated design process with measurable criteria. This ensures a smooth and open process and provides the opportunity to apply the most central criteria and themes for each development area more systematically.





## CHAPTER 5

# **Discussion and conclusion**

## CHAPTER 5

# Discussion and conclusion

One of the main lessons from this thesis is first and foremost that knowledge and reality interact socially and that multiple realities exist. Acknowledged, that conclusions are transferable rather than repeatable. Instead of formulating a clear hypothesis, the aim is rather to describe the complexities of a dilemma. Ask for example: “How can daylight be used to improve urban conditions?”, “Can building fabric provide thermal and visual qualities?”, and “Can natural rhythm define the urban programme?” These are some of the fundamental questions that arise from this PhD project.

However the project started with formulating the main hypothesis: “The best way to reduce building energy demand is to optimize the urban structure” To discuss and conclude on this question, it must be broken down into smaller pieces – pieces that can describe the complexities from: **Research, Method and Results.**

### Conclusion on research

The research results show an impact from urban form on building energy consumption, which is much greater than previously found, more precisely described, and more dynamic in character, when daylight is taken into account. This finding could be further enhanced if lifecycle and transport analysis were added to the evaluation of the influence of urban design on energy use on the urban scale. Furthermore, the results suggest that there are limits to urban densification as an energy optimization strategy, and solar energy and daylight potential should be treated, and indeed protected, as a common resource in urban design.

The most important observation for qualitative design research is that the first step in improving energy performance is taken with the architect’s first sketch on paper. It is here that the framework and preconditions for the building’s performance will be set. Argued this way, optimization of the special properties of urban density, typology and fabric take priority over the optimization of technical service systems, and this means that in a traditional design process the architect’s design responsibilities outweigh those

of the engineers.

If the architect goes into the design process without the awareness and recognition that there is a correlation between design and energy consumption, there is a considerable risk that, later in the process, it will be necessary to introduce technical solutions to compensate for fundamentally bad choices. This can lead to limited potential for energy savings. On the other hand, if these points are borne in mind, the architect has the very best opportunities for using passive solutions in relation to the outdoor climate, low energy-heating, cooling, ventilation, daylight, etc. An urban master plan can always, of course, be optimized later using the latest techniques, but an urban master plan that is designed with energy-saving in mind right from the very beginning will always be better than a plan that needs later adjustment to compensate for poor design – simply because the starting point for passive solutions is so much better.

### **Conclusion on method**

Multidisciplinary integration between different professions sounds simple and easy – but is not always so. Basically, it is difficult for architects, planners and engineers to work together.

A traditional engineer is trained to work rationally from A to B to C, while an architect works on multiple potential solutions at the same time. Problems often occur in the 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.

The case studies show that multidisciplinary integration is not something that comes from sitting around the same table. It is more a matter of being able to tell a common story. The architect is the storyteller and the engineer's role is to enrich the architect's story and add new facets to it. To be able to do this, the engineer needs architects, who are prepared to let technical knowledge into the process early, and who also are critical and inquisitive in relation to technical challenges. Moreover, the engineer needs to be better at actively communicating her or his knowledge and be able to contribute with multiple solutions that can challenge and inform the architect's design.



*“Good architecture balances aesthetics, location, function, space, comfort and materials into a whole. Energy reduction is a parameter just like the traditional parameters. We constantly strive to improve our designs and creative intuition by means of knowledge and evidence” (website, Henning Larsen Architects, after end PhD 2012).*

To be concrete, the engineer must learn how the architect reads and understands the urban environment. A good solution in one place is not necessarily a good solution somewhere else — a fact which actually fits in very well with knowledge gained in technical scientific studies. However, it would be a great help if the architect were more explicit in the reading of the urban context. The subjective feeling and understanding of the urban context is often difficult to translate, because it is implicit in the way architects work.

## **Conclusion on results**

The method has shown that there are significant advantages in using Integrated Energy Design. Integration at the level of process results in synergies at both the building level and the master plan level: (1) Early discussion of the project goals with the client, architects and engineers may identify anomalies and ambiguities, and rapid clarification of these will lead to subsequent energy identification and improvements in the urban plan. (2) Careful densification, orientation, massing, fenestration, and the design of fabric can reduce heating and cooling loads, and will often improve thermal comfort. (3) A deeper understanding of the nature and inter-relationships of all the issues described above, will lead to the possibility of a higher level of architectural expression.

However, there are also some barriers: (1) Extra time and resources from various skilled professionals are needed in the early design stage. (2) Each member of the design team needs to understand the integration aspects. This requires that they have some knowledge/understanding of the whole range of professional fields.

Simulation tools can help the process. However, it is important to remember that tools and simulations do not generate better design – it is the interpretation of the simulation results that makes the difference. As argued in

the introduction chapter, the ideas of comfort, delight and well-being are extremely important and fundamental aspects of environmental quality in the built environment. While these aspects are absent in the simulation procedures of today, they form an integrated part of the extremely diverse cultures of architecture and engineering.

Research in energy optimization is not enough – we have to create quality and delight through energy savings. Quality and delight that can create good stories – because stories are what move our hearts and minds. Remember, *“Energy is about quality of life” (DeKay M. R., 2011).*

## Bibliography

Akin O. (1978), “*How do architects design?*” Latombe (ed.): Artificial Intelligence and Pattern Recognition in Computer-Aided Design, IFIP, New York, pp. 65-119

Archer B.L. (1965) “*Systematic methods for designers*”, in N. Cross (ed.): Developments in Design Methodology, Wiley, Chichester, 1984, pp. 57-82.

Asimov M. (1964), “*Introduction to Design*”, Englewood Cliffs, New Jersey, 1964

Baker N., Steemers K. (1996) “*LT Method 3.0 – a strategic energy-design tool for Southern Europe*”, Energy and Buildings, 23, 251-256.

Baker N., Steemers K. (1999) “*Energy and Environment in Architecture*”, 1st ed., Taylor & Francis.

Banham R. (1969) “*Architecture of the Well-tempered Environment*”, 1984 2nd Revised edition ed., Chicago University Press.

Bryan H., Moore J., Kwartler M., Jones T. (1981) “*The Utilization of Daylighting as an Urban Design Strategy*” Annual conference of the International Solar Energy Society, Philadelphia, PA, USA, 1371-1375

BR209, 1998 “*Site layout planning for daylight and sunlight – A guide to good practice*” P. Littlefair, ISBN: 978-1-86081-041-1

Compagnon R. (2004) “*Solar and daylight availability in the urban fabric*”, Energy and Buildings 36 (2004) Pages 321-328

Conzen, M.R.G. (1960) “*Alnwick, Northumberland: a study in town-plan analysis*”. Institute of British Geographers, Publication 27. London: George Philip

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

DeKay M., (2010) “*Daylighting and Urban Form: An Urban Fabric of Light*”, Journal of Architecture and Planning Research, 27:1 (Spring 2010)

DeKay M. R. (2011) “*Integral Sustainable Design – transformative perspectives*”, Earthscan Ltd, Dunstan House, 14a St Cross Street, London, UK

DNV Research & Innovation (2011). Technology Outlook 2020

Drexler A. (1977) “*The Architecture of the École des beaux arts*”. New York: Museum of Modern Art

*Encyclopaedia of modern architecture*, (1965) General editor: Gerd Hatje, Thames and Hudson London 1963, Second impression 1965

Erhvervs- og Byggestyrelsen, *Strategi for reduktion af energiforbruget i bygninger*, (n.d.).

Frampton K. (1992) “*Modern architecture – a critical history*”, Thames & Hudson Ltd, London, Third edition

Gehl J. (1986) “*Life Between Buildings – Using Public Space*” Van Nost. Reinhold, New York

Giedion S. (1941) “*Space, Time & Architecture: the growth of a new tradition*”, Harvard University Press, 5th edition, 2003

Golany G. (1995) “*Ethics and Urban Design: Culture, Form and Environment*” Wiley, New York

Haase, M. and Amato, A. (2005), “*Fundamentals for climate responsive envelopes*”, Paper at Glass in Buildings 2CWCT, Bath, UK.

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, 2002

Jones P., Patterson J., Lannon S. (2007) "*Modelling the built environment at an urban scale – Energy and health impacts in relation to housing*", Landscape and Urban Planning, vol. 83 pp. 39-49

Knowles R.L. (1985) "*Sun, Rhythm, Form*", New edition, MIT Press.

Knudstrup Mary-Ann (2004), "*Integrated Design Process in PBL*", article in The Aalborg PBL model red. Anette Kolmoes, Flemming K Fink and Lone Krogh. Aalborg University Press 2004. Denmark.

Koss. H. (2006) "*On differences and similarities of applied wind comfort criteria*", Journal of Wind Engineering and Industrial Aerodynamics, vol. 94, no. 11, pp. 781-797.

Lawson B. (1990) "*How Designers Think – The Design Process Demystified*", Architectural press, Oxford, MA

Littlefair P. (2001) "Daylight, sunlight and solar gain in the urban environment", Solar Energy. 70, 177-185.

Lynch K. (1960) "*The Image of the City*", The MIT Press, Massachusetts Institute of Technology and President and Fellows Harvard College

Lysen, E. H. (1996), "*The trias energetica: Solar energy strategies for Developing Countries*" Eurosun Conference, Freiburg, Germany.

Mänty T. A. (1988) "*Cities Designed for Winter*", Norman Pressman, Building Book Ltd, Helsinki

Newman, P. W. G., Kenworthy J. R. (1999) "*Sustainability and Cities: Overcoming Automobile Dependence*". Island Press.

Norman R.B. (1987) "*Intuitive design and computation*", in Y.E. Kalay (ed.): Principles of computer-aided design: Computability of Design, Wiley-Interscience, New York, pp. 295-301

Olgyay V., Olgyay A. (1963) "*Design with Climate*", Princeton University Press, Princeton

Pedersen P. B. (2009) "*Sustainable compact city*" Arkitektens Forlag

Ratti C., Raydan D., Steemers K., (2003) "*Building form and environmental performance: archetypes, analysis and an arid climate*", Energy and Buildings. 35 (2003) 49-59.

Ratti C., Baker N., Steemers K. (2005) "*Energy consumption and urban texture*", Energy and Buildings. 37, 762-776.

Rittel H.W. and Webber M.M. (1984) "*Planning problems are wicked problems*", N. Cross (ed.): Developments in Design Methodology, Wiley, New York, USA, pp. 135-144.

Robinson D., Campbell N., Gaiser W., Kabel K., Le-Mouel A., Morel, N., Page J., Stankovic S., Stone, A. (2007) "*SUNtool – A new modelling paradigm for simulating and optimising urban sustainability*" Solar Energy 81, 9, 1196-1211

Rocca A. (1998) "*Ian Ritchie: Technoecology*", Watson-Guptill Publisher, New York

Rowe P.G. (1987), "*Design Thinking*", MIT Press, Cambridge, MA

Santamouris M (2006), "*Environment Design of Urban Buildings*", ISBN-10 1-902916-42-5, published by Earthscan.

Sattrup P.A. (2009) "*Foster + Partners: interview med Stefan Behling og Gerard Evenden*", i K Kjeldsen & M Juul Holm (red), Fremtidens arkitektur er grøn, Arkitekturens grænser, nr. 2, Louisiana, Humlebæk, Louisiana, s. 49-55.

Sullivan L. H. (1896), "*The Tall Office Building Artistically Considered*" Lippincott's Magazine, 57, pp. 403-09

UNEP (2010) “*Sustainable Buildings & Climate Initiative*” Green Economy Report: Green Cities

United Nation Report (2009) “*World Urbanization Prospects: The 2009 Revision*” Department of Economic and Social Affairs, Population Division, UN

Whitehand J.W.R. (2001) “*British urban morphology: the Conzenian tradition*” Urban Morphology 5(2), 103-109

Whyte W. H. (1980) “*The Social Life of Small Urban Spaces*”, Project for Public Spaces, New York

# **Appended papers**



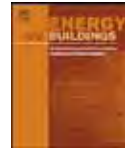


## **Paper I**

*“The urban canyon and building energy use: Urban density versus day-light and passive solar gains”*

J. Strømmand-Andersen<sup>a</sup>, P.A. Sattrup<sup>b</sup>

Published in: Energy and Buildings, 43, Issue 8, August (2011) 2011-2020



# The urban canyon and building energy use: Urban density versus daylight and passive solar gains

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## ARTICLE INFO

### Article history:

Received 8 September 2010

Received in revised form 30 March 2011

Accepted 10 April 2011

### Keywords:

Urban density

Energy use

Daylight

Solar radiation

Integrated design

## ABSTRACT

The link between urban density and building energy use is a complex balance between climatic factors and the spatial, material and use patterns of urban spaces and the buildings that constitute them. This study uses the concept of the urban canyon to investigate the ways that the energy performance of low-energy buildings in a north-European setting is affected by their context.

This study uses a comprehensive suite of climate-based dynamic thermal and daylight simulations to describe how these primary factors in the passive energy properties of buildings are affected by increases in urban density.

It was found that the geometry of urban canyons has an impact on total energy consumption in the range of up to +30% for offices and +19% for housing, which shows that the geometry of urban canyons is a key factor in energy use in buildings. It was demonstrated how the reflectivity of urban canyons plays an important, previously underestimated role, which needs to be taken into account when designing low-energy buildings in dense cities. Energy optimization of urban and building design requires a detailed understanding of the complex interplay between the temporal and spatial phenomena taking place, merging qualitative and quantitative considerations.

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## 1. Introduction

One of the most basic and fundamental questions in urban master planning and building regulations is how to secure common access to sun, light and fresh air, but for the owners of individual properties, it is often a question of getting the most of what is available. There is potential for repetitively recurring conflict between public and private interest. Solar access and the right to light remain contested territory in any society, vital as they are to health, comfort and pleasure.

Traditional urban planning has sought to control the proportions of the streets, because the basic geometry of building heights and distances between buildings regulates access to light and solar heat. Zoning laws and building regulations usually establish height-to-distance ratios that limit the overshadowing that buildings may cause for public spaces and other buildings. A similar geometric abstraction of urban space – the urban canyon [1] – has been used in urban climatology, to describe the way that urban spaces create special environmental conditions. It is a spatial archetype that allows us to integrate knowledge from several different specialized

fields of research. In geometric terms, the urban canyon is described as the height/width ratio of the space between adjacent buildings.

Cities develop over time, and the proportions of urban canyons have long lasting impacts on the future energy consumption for the heating, cooling and lighting of the buildings that define them and the environmental qualities of the streets, squares, courtyards or gardens that comprise them. Urban development is a rather slow process in most industrialized societies, but the impact of site conditions on building energy use multiply over the years – more than other processes that affect a buildings performance over its lifetime. So, considering that one of the main challenges to architects and engineers in the next decades will be how to improve the energy performance of our buildings and cities, we need to improve our knowledge of both urban and building design through research on the dynamic interplay between climate, context and building energy use. The passive properties of buildings are likely to play a much more important role in the total energy consumption, as winter heat losses are reduced with better insulation, glazing and air tightness.

Urban densification is one strategy for sustainable development, focusing on energy savings through efficient transport systems, shared infrastructures and minimizing heat gains and losses that dominate energy budgets. It has been established that densification is a balancing act between these opportunities on the one hand, and ensuring solar access for low-energy buildings and urban

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comfort on the other. Yet, the intricate connections between urban climate, urban form and energy use of buildings remain a subject that requires further research [2]. In the already built cities of northern Europe, urban density is of particular concern, because the high latitudes and the associated low solar inclinations mean that the urban geometry affects solar access much more here than in other urban centres around the world. Overshadowing is an obvious problem. The relative scarcity of light, particularly during the long winter season, is increased by the overcast skies that dominate the region throughout the year, creating special conditions for the region's architecture and planning to deal with.

Recent developments in computation, such as Geographic Information Systems (GIS), Building Information Models (BIM), and detailed climate-based thermal, shading and lighting simulation software, offer new insights into the dynamic relationship and specificities of climatic conditions and the individual building's use and properties, helping us identify the balancing points of solar gains and daylight conditions resulting from urban geometry. These insights can serve as an improved basis for energy-optimized urban planning and building design. The building design process often has the urban scale as one of its very first concerns, so knowledge of the relative impacts of urban geometry is an important asset for energy-optimized architecture, because energy savings from design choices on the urban scale are very long-term, and lessen the need for advanced technical measures, such as shading systems, ventilation systems and active systems like PVs on the building scale, that have high investment costs and short useful lifetimes. A serious deficiency in the energy calculations that are now mandatory in many countries is that they focus on the performance of the individual building, and neglect the interplay between the building and context due to overshadowing. As will be demonstrated in this paper, buildings in dense urban settings can not only make positive contributions to the energy and comfort performance of neighbouring buildings through their reflectance of daylight, but may gain qualities themselves in doing so.

The analysis focuses on north-European cities, with the climate of Copenhagen (55.40°N 12.35°E) used as reference, but both the methodology applied and the findings are relevant for urban development and building design globally. In Denmark, low-energy buildings will be the new standard by 2015. Primary energy use levels of  $\approx 35 \text{ kWh/m}^2/\text{year}$  for housing and  $\approx 50 \text{ kWh/m}^2/\text{year}$  for office buildings will be the minimum for compliance for new buildings, with further increases in energy efficiency being aimed at in the near future. Incentives and regulations to improve the performance of the existing building mass are being discussed for implementation [3].

The key questions of this study are:

- 1 How do the height/width ratios of urban canyons affect building energy use for lighting, heating and cooling?
- 2 How big is the relative impact of the height/width ratio on the total energy use compared to unobstructed solar access?

The first question aims at understanding the physical and temporal phenomena of energy exchanges, and their interdependencies. This requires an in-depth investigation of the urban canyon to study the differences in energy potential available to apartments or office subdivisions on the various levels of a building.

The second question allows for a quantitative comparison of the impact of the energy distribution of solar radiation and daylight in the urban canyon building requirements for heating, cooling and artificial lighting. The relative impact on these requirements is necessary and useful information when discussing, or indeed designing for, the energy optimization of buildings and urban spaces in the effort to improve cities and buildings.

## 2. Background

The urban canyon has been used in urban climatology as a principal concept for describing the basic pattern of urban space defined by two adjacent buildings and the ground plane. Apart from its metaphorical beauty, the key quality of the term is the simplicity it offers in describing a repeated pattern in the otherwise complex field of urban spaces and building forms. While the impact of urban geometry on the urban microclimate is well established, studies have tended to focus on problems of overheating in warm climates, the urban heat island effect, and urban comfort. The distribution of air movement and temperature in urban canyons and its potential for energy savings related to ventilation has been the subject of a number of studies [4,5], connecting urban canyons to the field of building energy use, but their impact on the full range of energy uses in buildings has not been thoroughly investigated.

At the other end of the building-urban space divide, energy models and simulation techniques have been developed to study and describe the energy performance of buildings in relation to the surrounding climate. However, these models are generally intended for use by building designers and tend to consider buildings as self-defined entities, either neglecting or grossly simplifying the importance of phenomena that occur on the urban scale. Nevertheless, there have been some investigations, e.g. Littlefair [6], of the link between the urban geometry and the individual building's energy performance. Ratti et al. [7] document an effect of almost 10% in the relationship between urban morphology and the annual per-metre energy consumption of non-domestic buildings. They demonstrate the effect using a calculation that compares the DEM (Digital Elevation Model) with the LT method (Lighting and Thermal) developed by Baker and Steemers [8]. The most detailed and complete investigations of urban obstruction affecting energy use are presented by Baker and Steemers [9]. Using the LT method, they derived a correction factor to modify the specific energy consumption for non-domestic buildings. The LT method is a tool for strategic energy design and it should not be regarded as a precision energy model. Li et al. [10], in their study of vertical daylight factor (VDF) calculations, demonstrate that daylight is significantly reduced in a heavily obstructed environment. A study of VDF predicted by RADIANCE simulation demonstrates that an upper obstruction ( $\alpha_U$ ) at  $60^\circ$  and a lower obstruction ( $\alpha_L$ ) at  $10^\circ$  reduce the daylight level by up to 85%. The results also indicate that the reflection of the obstructive buildings can be significant in heavily obstructed environments, such as rooms on lower floor levels facing high-rise buildings. Few, if any studies have investigated the results of a combined and fully integrated dynamic energy simulation. An earlier study by Sattrup and Strømman-Andersen showed how the precision of energy simulation for various types of building in context improves dramatically, when developed in a multilayered, climate-based, dynamic simulation [11]. New tools like IES-Virtual Environment 6.0.2/RADIANCE offer multilayered analysis of thermal and lighting performance integrated with Building Information Models (BIM), and they can handle the modelling and dynamic simulation of complex urban geometry.

## 3. Method

The research was done using a quantitative study of the simulated energy performance of digital models of buildings lining a series of variously proportioned urban canyons as the basis for a qualitative discussion. The research was conducted through the design of models based on types of urban space, building and user pattern. The type is a key concept to describe generic patterns associated with buildings. While generic models obviously lack a lot of the variation and diversity that could make them architecturally

**Table 1**  
Urban canyon and urban density guideline.

|   |          |      |      |      |      |       |     |
|---|----------|------|------|------|------|-------|-----|
| Street width  | $\infty$ | 30 m | 20 m | 15 m | 10 m | 7.5 m | 5 m |
| Height/width ratio (H/W)                            | $\infty$ | 0.5  | 0.75 | 1.0  | 1.5  | 2.0   | 3.0 |
| Plot ratio (%) guideline (5-storey uniform pattern) |          | 200  | 250  | 285  | 335  | 365   | 400 |



**Fig. 1.** Contemporary urban (re)developments. (A) Offices, Kampmannsgade, Copenhagen, H/W ratio 0.8. (B) Housing, Viborggade, Copenhagen, H/W ratio 1.25.

appealing, they have the abstract quality of identifying key parameters which can be varied and studied for their relative impact on overall performance.

Building types or typologies have been discussed throughout the history of architecture, and have influenced recent architectural thinking. As Eisenman notes in his introduction to Rossi [12], type refers to both object and process, and thus offers a basis for invention because it describes an essence of design to be investigated through research. Types are used in several studies of buildings, environment and energy. As Hawkes [13] says: “*Type offers the possibility of translating the results of technically-based research into a form that renders them accessible to designers*”.

In this study, types are used on three levels:

- The urban canyon is a type, which is itself an abstraction of other types; the street, the square, the courtyard, the garden, etc.
- The building is a type. In this instance the building is of the infill type, forming part of a larger array of buildings facing an urban canyon, as is usual in urban blocks, or building slabs. To achieve detail the building is subdivided in spatial units, such as apartments or office subdivisions, each unit facing in only one direction. This allows differentiated results for 4 orientations. The building type has two variations: housing and office linked to the types of user patterns for homes and workplaces.
- The use pattern is a type. The two user patterns studied are for homes and workplaces, the main difference being their complementary daily and weekly occupation patterns.

Since the aim in this study is to highlight the effects of urban density upon building energy consumption, default values are assigned to all variables except those that relate to urban geometry. Simulation was done on two levels: that of the radiative environment of the urban canyon itself, including the dispersion of daylight, and that of the energy performance of the buildings in the urban canyon.

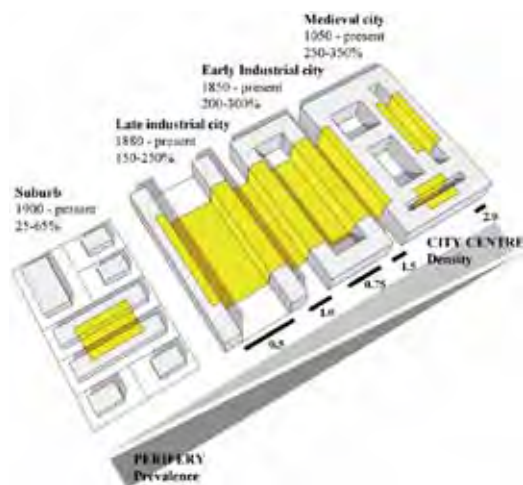
### 3.1. Urban canyon types, height/width ratios

The urban patterns of Copenhagen was taken as reference, and defined six different canyons by their height/width ratio (H/W) ranging from 3.0 to 0.5 (Table 1). The highest H/W ratio spaces are found mostly in the medieval parts of the city, such as passages and very narrow courtyards, and the lowest ratio reflects conditions found in urban squares, boulevards and more spatially generous courtyards (Fig. 1). The densities are closely associated with the

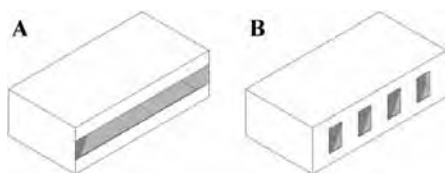
historical development of the city, and the societal and technological forces that guided it. Nevertheless, the patterns persist and are repeated in contemporary urban (re)developments (Fig. 2).

Each canyon was defined for a 5-storey building with a height of 15 m, allowing easy comparison and individuation of the resulting energy performance. Lower H/W ratios exist, of course, in the suburbs, but were not the subject of study here.

The relative ‘fit’ of the urban canyon concept to real urban patterns is scale-dependent. Because the urban canyon concept is an abstraction of the spatial complexities of real cities, its relation to density is somewhat simplified too. The extra solar access at street intersections and the lateral shading occurring at building angles are ignored. But if an ideal urban pattern consisting solely of uniformly distributed building slabs or terraced houses is presupposed, in which every second canyon is for access and traffic and the other a semiprivate communal space, like a courtyard or garden forming part of the building’s plot, density can be described using a rough plot ratio indicator (Table 1).



**Fig. 2.** Typical urban patterns and proportions of urban canyons in Copenhagen.



**Fig. 3.** Validated units. (A) Office unit (window-to-wall ratio 40%). (B) Housing unit (window-to-wall ratio 20%).

### 3.2. Urban-canyon simulation, radiative and daylight environment

The radiative environment was studied using Autodesk Ecotect Analysis 2010. Ecotect is a highly visual architectural design and analysis tool that links a comprehensive 3D modeller with a wide range of performance analysis functions [14]. For solar radiation calculations, ECOTECT uses hourly recorded direct and diffuse radiation data from the weather file (\*epw). In addition to standard graph and table-based reports, analysis results can be mapped over building surfaces or displayed directly in the spaces. This includes visualization of volumetric and spatial analysis results.

In this study, the RADIANCE-based simulation environment DAYSIM was used for all dynamic simulations of outdoor and indoor illuminance due to daylight. DAYSIM applies the Perez sky luminance model [15] to simulate indoor illuminance in arbitrary sky conditions. It merges the backward ray tracer RADIANCE (Ward and Shakespeare, 1998. G. Ward and R. Shakespeare *Rendering with RADIANCE. The Art and Science of Lighting Visualization*, Morgan Kaufmann Publishers (1998)) with a daylight coefficient approach and permits reliable and fast dynamic illuminance simulations [16]. DAYSIM allows the simulation of an annual illuminance data set for any specified point and orientation in a given environment. It uses data interpolation from the (\*epw) weather file. More detail on the underlying simulation algorithm of DAYSIM can be found in [17,18]. Daylight factors have been used in many previous studies as a simple method of predicting 'worst case' scenarios using CIE-standardized skies, but these ignore dynamic weather conditions since they do not incorporate actual climate data, which vary a lot depending on the real-world location. Advances in computing power now allow a detailed hourly analysis and relatively fast calculation of daylight levels using metrics, such as the Daylight Autonomy metric, in which available daylight is quantified combining both direct and diffuse radiation [19,20].

Street canyon surface reflectance variables are: Ground (Albedo)=0.20 and external wall=0.45/window=0.15. Surface reflectance thus depends on the glazing ratios of the adjacent buildings, 20% glazing for housing and 40% for offices.

### 3.3. Building and user pattern types for offices and housing

On either side of the canyons in our model, buildings are defined by 5 storeys of 50 m<sup>2</sup> spatial units, each with a 3 m floor to floor height, 5 m room depth and glazing ratios of 20% for housing and 40% for offices (Fig. 3). The proportions of the units are associated with apartments or office rental units commonly found in central Copenhagen. Taken together, 2 spatial units facing opposite directions would constitute a generic 100 m<sup>2</sup> apartment or office subdivision, a size that is commonly found, and close to the national average of 110 m<sup>2</sup> per dwelling [21]. The room depth falls well into the category of 'potentially passive' space [22] in which daylight and solar gains can play a significant role. The model, while generic, is thus linked to the most important geometric factors that regulate the development of the urban fabric over time.

**Table 2**

List of energy factors as stated in the Danish building regulation [25] and how they are used in the simulation.

| Energy source    | Factor | Simulation                           |
|------------------|--------|--------------------------------------|
| Gas and oil      | 1.0    | Heating and DHW                      |
| District heating | 0.8    | Heating and DHW                      |
| Electricity      | 2.5    | Cooling, Mech. Vent. and Art. Light. |

The user patterns are reflected in the different occupation hours and activity levels of the system settings, basically following the working week and the daily rhythm. The user patterns are designated so as to achieve the European standards of indoor environment [23] and reflect differences in requirements for housing and offices. These are not discussed as such (see Appendix A).

### 3.4. Building types energy simulation

The energy calculations were performed using the simulation tool IES-Virtual Environment 6.0.2, ApacheSim/RADIANCE, which creates a fully integrated thermal and daylight simulation with detailed hourly output of the electrical energy consumption for lighting, mechanical ventilation, heating load, cooling load, and indoor operative temperature. The IES-Virtual Environment is an integrated suite of applications linked by a common user interface and a single integrated data model. It qualifies as a dynamic model in the Chartered Institution of Building Services Engineers' [24] system of model classification. IES-Virtual Environment 6.0.2/ApacheCalc (thermal simulation) does not take the effect of the local microclimate into account. To accurately determine the local wind speed and thereby convective heat transfer on both internal and external boundary surfaces is extremely difficult and could only be done by means of careful measurements or advanced computer simulation. For these reasons, the variation of the surface heat transfer coefficient has been ignored.

The glazing ratios used are related to sizes typically found in traditional housing and modern office buildings. The model buildings are very well insulated heavy constructions. Wall *U*-values are 0.2 W/m<sup>2</sup> K. Glazing *U*-values are 1.5 W/m<sup>2</sup> K, *g*-values are 0.62. See Appendix A for details of default settings and generic user patterns for housing and offices.

The lighting system in the rooms is controlled by the illuminance at a reference point. Reference points are placed 0.85 m above the floor and 1 m from the back wall. In offices, lighting is dimmed between full power when no daylight is available and minimum power when the illuminance from daylight in the reference point is above 200 lx. A linear control is assumed. For housing, a manual on/off control is assumed, which means that the lighting is always at maximum power, when daylight in the reference point is under 200 lx. Since not every room in the house is always active, a switched-on-profile of 20% is added. As in the urban canyon simulation, the design simulation weather data is used for the full year simulation. The system settings for the model reflect a building that allows for a certain degree of user adaptation and control over the environment, so as to highlight the impact of geometries and material properties of both building and urban space, not the building technology as such.

Energy use is measured in primary energy using primary energy factors corresponding to the Danish building regulations [25] (Table 2). In principle, primary energy use is the total weighted energy. It can be calculated from the unit's estimated net consumption.

The total net energy consumption is divided into five primary needs: (1) Domestic Hot Water (DHW), (2) artificial lighting, (3) mechanical ventilation, (4) cooling load, and (5) heating load.

Energy use for electric appliances other than these is not considered in this study.

Of the five needs, three vary as a function of the urban density. DHW and mechanical ventilation are simulated as constant. In the simulation, it is assumed that the refrigeration system has a COP value (COP = Coefficient of Performance) of 2.5, which means that electricity consumption for cooling counted by a factor 1 to 1 (refrigeration kWh equals electricity kWh). Since the analysis operates in an urban context, it is assumed that the building is equipped with district heating. The heating supply is therefore regarded as having an efficiency of 1 to 0.8.

#### 4. Results and discussion

The analysis of the environments of the canyons is presented and discussed first in terms of radiation and daylight, comparing daylight factor and daylight autonomy metrics, and then in comparison with the energy consumption of electricity for artificial lighting in offices, because this is where the greatest impact and the widest diversity of results are found. The total energy consumption of offices is then presented and discussed, followed by an analysis of the energy consumption of housing.

##### 4.1. Urban canyon radiative environment and daylight

In Copenhagen, the solar inclination is rather low, particularly in winter,  $11^\circ$  at midday winter solstice,  $58^\circ$  in summer (compared to  $15^\circ/62^\circ$  in London), which means that direct solar radiation only grazes the top storeys and roofs of dense urban districts in winter. Overshadowing is an obvious problem.

Fig. 4 shows how the average daily distribution of radiation in urban canyons defined by north/south-facing buildings is calculated combining direct and diffuse radiation climate data on an annual basis. It is assumed that diffuse radiation is evenly distributed across the sky dome. The distribution of the radiation level curves is influenced by the sun angle, the climate-based mix of direct and diffuse radiation, and the reflectivity of the building surfaces.

When the radiation levels are converted to daylight levels and subjected to a daylight autonomy analysis, it can be seen how the asymmetry of the daylight distribution in the canyons varies greatly between high illuminance levels ( $>10,000$  lx) (Fig. 5) and low illuminance ( $<500$  lx) (Fig. 6). While the low level distribution is relatively even and resembles that of overcast skies, it is nevertheless slightly asymmetrical because it does include direct light that comes in at low angles at times of the day when the light is not intense. The high illuminance levels are pronouncedly asymmetrical, yet not more so than to include a significant proportion of diffuse and reflected light. An interesting point is to note how the intersection of the 10–15% daylight autonomy curve at the north-facing façade seems to follow the inclination of reflected light from the top of the opposing façade coming in at low angles.

The reflectance of the urban canyon affects the daylight distribution inside the spatial units significantly. Fig. 7 shows how the daylight distribution of an urban canyon with high wall reflectance (0.75), compared to one with low wall reflectance (0.45), is significantly better and more evenly distributed at the bottom of the canyon and deep inside the spatial units themselves. In the low reflectance canyon, the 80% daylight autonomy curve is almost identical to the sky-dome cut-off angles that are defined by the opposing building, making the daylight almost exclusively dependent on the view of the sky. In the high reflectance canyon, reflected light shows a remarkable capacity to penetrate laterally through multiple reflections and achieve reasonable daylight autonomy lev-

els of 50% even deep inside the spatial units at the bottom of narrow (10 m, H/W ratio 1.5) canyons. If we consider the light quality experienced by a person working away from the window on the ground floor, in the first case, the person might be almost totally dependent on artificial light, while in the second, the person might have much more of the variation and quality associated with daylight, even though filtered by the urban context.

It becomes clear that overshadowing is not the only way buildings affect the energy use of their neighbours. The reflectivity of their surfaces also significantly affects the availability and distribution of daylight, and the associated energy use for artificial lighting of their surroundings. This simple fact, which nevertheless holds enormous design potential for architects and engineers, should lead to design guideline developments in urban planning and zoning regulations, because the urban geometry can be considered a daylight and energy distributing armature proper. The light and energy of the sun, exploited and redistributed through a careful mediation of its temporal, spatial and atmospheric characteristics.

##### 4.2. Energy consumption for offices

Fig. 8 shows a general increase in energy consumption as a result of increased density as expressed by the H/W ratio. Because the results are balanced by a 2.5 primary energy conversion factor for electricity use compared to heating and cooling, artificial lighting becomes both the dominant factor in energy use at very high densities and the factor most susceptible to changes in density. Cooling demand decreases with density due to overshadowing, while the reduction in solar gains due to the very low solar altitude during the heating season results in increased use of energy for heating (Fig. 10). Artificial lighting has the largest variability of the individual energy needs. Energy use for artificial lighting is doubled even at the lowest density (H/W 1.0) compared to an unobstructed context, and increases more than six times at the highest density (H/W 3.0) (south  $2.8$ – $17.2$  kWh/m<sup>2</sup>/year).

Thus, comparing north/south-facing buildings to east/west-facing ones, it is interesting to note that an unobstructed context favours north/south-oriented office buildings while the opposite is true in dense urban canyons, with H/W ratios above 1.0. For east/west-facing buildings in unobstructed environments, the heat gains from the early morning and late afternoon sun would lead to overheating in summer, but this is partially blocked by the urban context and mostly affects just the upper levels. Instead, reflected light contributes positively to daylight in the lower levels of the buildings on the other side of the canyon. As the sun nears its maximum, its lateral angle towards the façade means that the area of east/west-facing windows towards the sun diminishes and receives less heat. At this point of the day, the direct radiation penetrates the length of the urban canyon at all times of the year, unless laterally obstructed, and contributes to raising the daylight levels at the bottom of the urban canyon through reflection.

Another interesting observation is that a north-facing building needs less energy for artificial lighting than a south-facing one at the highest density in this study (Fig. 11). It was found to be mainly due to the fact that the proportions of the urban canyon allows direct light to be reflected off the opposing façade and into the lower north-facing offices.

Fig. 9 shows the relative variation in the total energy consumption from free horizon to a height/width ratio of 3 varies from between +2.1% and +30.2% for offices depending on the geographic orientation. The greatest relative variation was found with the south/north building orientation. The south-oriented units in particular stand out by having a large relative influence even with large canyon widths. For example, the relative influence is +10% for a street width of 20 m (H/W 0.5). This means that the relative variation at is 2–3 times greater than with other orientations. The largest



Fig. 4. Average daily solar radiation in street canyon. Calculated in ECOTECT (working hours 08–17, contour range 500–2500 Wh in steps of 200 Wh). Weather data, Copenhagen (\*epw).



Fig. 5. Annual illuminance > 10,000 lx in street canyon. Calculated in RADIANCE/DAYSIM (working hours 08–17, contour range 0–50% in steps of 5%). Weather data, Copenhagen (\*epw).



Fig. 6. Annual illuminance > 500 lx in street canyon. Performed in RADIANCE/DAYSIM (working hours 08–17, contour range 85–95% in steps of 1%). Weather data, Copenhagen (\*epw).

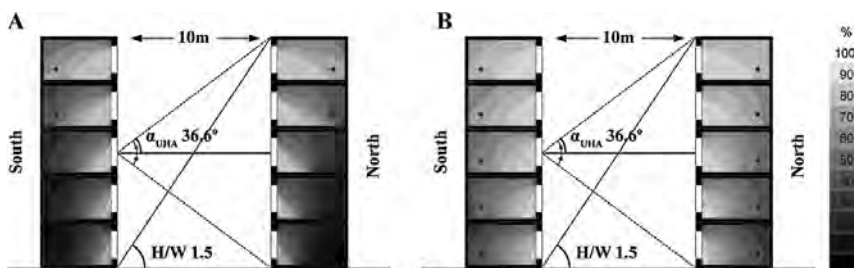


Fig. 7. Annual illuminance > 200 lx in street canyon with surface reflectance variables, Ground (Albedo)=0.20. Calculated in RADIANCE/DAYSIM, (working hours 08–17, contour range 0–100% in steps of 10%). Weather data, Copenhagen (\*epw). (A) Reflectance external wall = 0.45. (B) Reflectance external wall = 0.75.

relative variation is the need for cooling. Here the energy consumption is reduced almost exponentially with the increase in H/W ratio. For example, the need for cooling is reduced by an average of ~150% with a H/W ratio of 1.5 (canyon width 10 m) compared to free hori-

zon. With very narrow canyons, H/W higher than 1.5, the need for cooling is reduced to insignificant amounts.

Energy consumption not only varies as a function of the street width, but also for the individual building units. Each unit has a

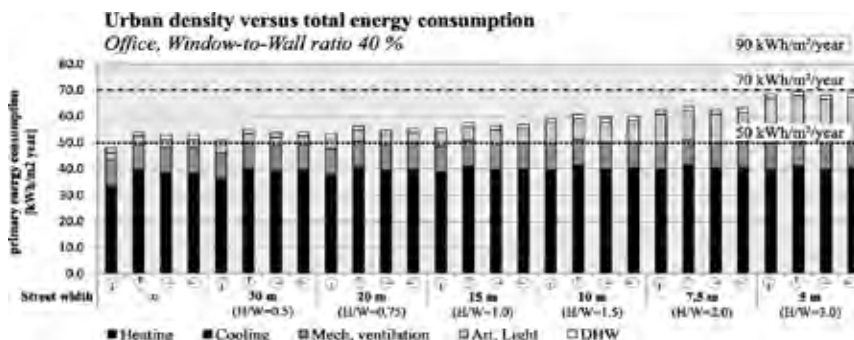


Fig. 8. Total primary energy consumption (kWh/m²/year) for a 5-storey office building as a function of urban density.



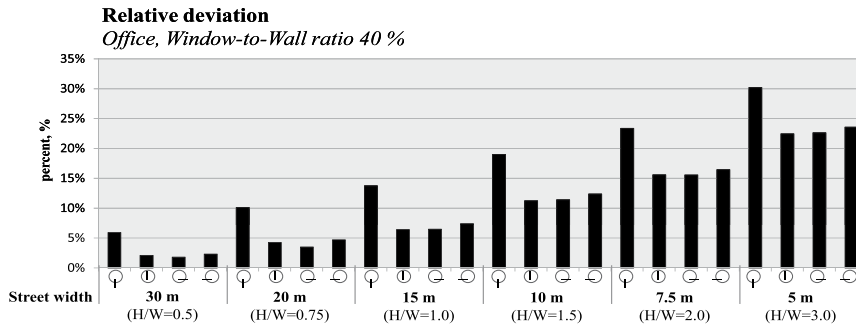


Fig. 9. Relative deviation (%) of energy consumption for a 5-storey office building as a function of urban density compared to free horizon.

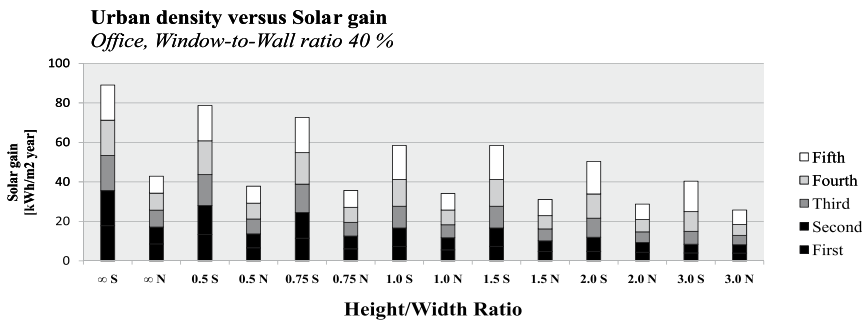


Fig. 10. Solar gain (kWh/m²/year) for a 5-storey office building (north/south) as a function of urban density.

specific energy consumption depending on the floor on which the unit is located. Generally the energy consumption increases the narrower the canyon and the closer the unit gets to the ground. However, the various orientations and canyon widths do not show the same distribution of the relative energy performance of the units. Within the overall pattern of higher energy use at the bottom of the narrowest canyons, north/south-facing buildings tend to favour the upper levels, which perform a lot better than the lower levels, to such a degree as to increase the overall performance significantly. East/west-facing buildings show a more evenly distributed increase in energy use along with increases in the H/W ratio and the position of the units closer to the bottom of the canyon.

The explanation is in the seasonal changes that happen through the year. If we take the south-facing units in the H/W 1.5 canyon

as an example, the whole building suffers summer overheating, which our model units deal with by increasing cooling, but only the top level units gain from the heat of direct radiation and enjoy most of the occasional savings for artificial light that comes with sunshine on a winter day. As winters are very often overcast with light levels well below 2000 lx, the sky dome does not contribute much, quantitatively, to establishing indoor lighting levels above 200 lx, which is the threshold value of this model.

#### 4.3. Energy consumption for housing

Figs. 12 and 13 show that the relative impact of increased density on energy consumption is more moderate for housing than for offices. The largest single need in housing is heating. This means

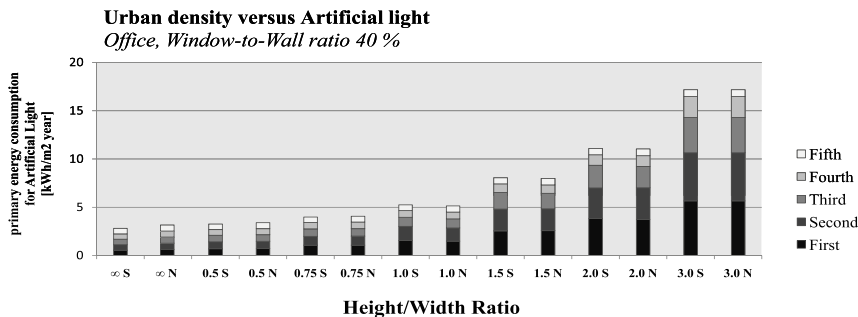
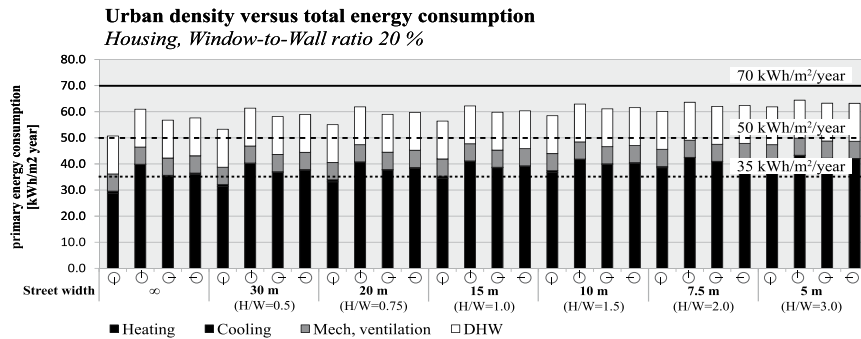


Fig. 11. Primary energy consumption for artificial light (kWh/m²/year) for a 5-storey office building (north/south) as a function of urban density.



**Fig. 12.** Total primary energy consumption (kWh/m<sup>2</sup>/year) for housing as a function of urban density (note: energy consumption for artificial light is not included in total primary energy consumption for housing [25]).

that the heating contribution from solar radiation is an essential element for housing – unlike for offices, in which illumination level is the most important parameter. For example, the energy consumption varies by 11.2 kWh/m<sup>2</sup>/year, from a north to a south orientation for a free horizon, due to variations in solar access (Fig. 12). However, the denser the city becomes the smaller the variation in passive solar gains.

The relative deviation of the total energy consumption from free horizon to a height/width ratio at 3 varies from between +2% and +19% for housing (Fig. 13). The relative development of individual needs for heating and cooling is approximately the same for housing as for offices.

The energy consumption for lighting is also more uniform across the city's density. This is due to the consumer pattern, where the number of hours with a need for lighting in housing falls in the periods with a global illuminance level less than 200 lx. During winter, the most active hours of a housing unit occur in the morning and evening while it is still dark and artificial light is turned on.

The energy variation over the individual floors is more uniform for housing than for offices. This is partly due to the relatively smaller variation in overall energy consumption. The north-oriented deviates from the other orientations by having a maximum variation of 4.5%. This rather low variation is due to the limited amount of solar radiation the units receive. Furthermore, the energy consumption for lighting is not part of the variation.

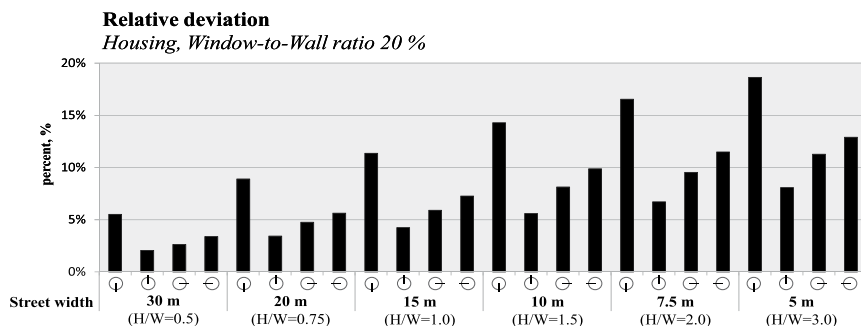
What becomes apparent is the way that consumption is more dependent on use patterns and material and geometrical patterns other than urban density. Since the model design for this study

reflects a '9 to 5' working life for the occupants, with apartments not being occupied in the daytime on weekdays, the hours where there is most activity are when the influence of solar radiation and daylight on the energy budget is minimal.

Because heating is the dominating parameter on the energy budget for housing, should future housing be developed using the passive strategy of large south-facing windows to make the most of solar gains? Should heating be the dominant object for design of housing in general?

At high latitudes as in northern Europe, solar gains are only available for the top storey in dense urban areas in the winter season, and even for the top storey it is drastically reduced compared to unobstructed solar access as shown in Fig. 10. This traditional passive solar design seems to have limited potential as a design strategy under these conditions, but because solar gains nevertheless play a discernible but minor role for lower storeys facing east, west and south, diffuse radiation reflected off opposing façades and the sky can be identified as the energy issue to design for. Overshadowing in dense cities is close to inevitable at these latitudes, but light redistribution through the reflectivity patterns of façades seems an interesting design possibility. One can imagine and indeed observe how temporal patterns of reflected light and heat can be redirected by façade sections at oblique angles to the sun.

Heating is easily produced and maintained at a quality that satisfies bodily needs regardless of the combination of radiation, convection and conduction measures used. There is plenty of design potential, both technically and metaphorically, in addressing the human need for thermal stimulation. Light is much more difficult to



**Fig. 13.** Relative deviation (%) of energy consumption for a 5-storey housing building as a function of urban density compared to free horizon.

reproduce in qualities and quantities that are anywhere near that of daylight, though artificial lighting offers interesting design opportunities. With this point in mind, and remembering that access to daylight and environmental variety affect human comfort and health in multiple ways, it is suggested that rich and varied daylight remains the main design priority in housing, though its direct contribution to the energy budget is smaller than heating.

## 5. Conclusions

The study has given a detailed analysis of the distribution of solar radiation and daylight in a range of urban canyons reflecting different urban densities and demonstrated how this distribution affects the total energy use for heating, cooling and artificial lighting on different storeys of low-energy buildings facing the urban canyon, depending on orientation.

It was found that the geometry of urban canyons has a relative impact on total energy consumption, compared to unobstructed sites, in the range of up to +30% for offices and +19% for housing, indicating that urban geometry is a key factor in energy use in buildings. From the given specifications of the building layout, it is possible on a free horizon to design a low-energy office building with an energy consumption of around 50 kWh/m<sup>2</sup>/year. If the context around the building over time transforms into a dense urban area, the energy consumption will increase proportionally to approximately 70 kWh/m<sup>2</sup>/year, resulting in a relative increase in energy consumption of up to 30% depending on orientation.

As a consequence any building project in the making, whether new-build or refurbishment, would be advised to integrate not only a detailed simulation of the energy impact of the context as it is, but also an estimate based on the maximum density allowed on neighbouring sites. In urban master planning, it becomes critical to define ways to control solar access as a common good, not least for the effect it has on the experiential qualities of public spaces. New developments should be carefully screened for their impacts on neighbouring buildings and the public spaces they participate in creating. As the relative impact of urban density varies with both height and width of the urban canyon, it can be argued that the design of future energy optimized façades should be able to respond in a differentiated way to the issues posed by the distribution patterns of radiation in the urban canyon.

Our investigation showed that reflected light makes an important contribution to the energy consumption of buildings, and is indeed the greatest fraction of daylight available to housing and offices on the lowest floors in high urban densities. The distribution of daylight in the urban canyon is more complex than previous studies have indicated, and the way that not only light, but also the heat carried with it, is distributed is very dependent on the reflectivity of building façades. What this highlights is that in northern Europe, building façades should not only be considered as selective devices so as to create optimum internal environments, but also in terms of their contribution to creating good and varied daylight conditions for neighbouring buildings.

As Oke [26] says, there are “almost infinite combinations of different climatic contexts, urban geometries, climate variables and design objectives. Obviously there is no single solution, i.e. no universally optimum geometry”. Nevertheless, there are optimum ranges of geometric conditions in urban design – if we want to design energy efficient cities, urban spaces, workplaces and dwellings that have an intimate connection to the qualities of the natural environment. The artificial environments generated by energy use are something else, not necessarily worse or without design appeal, but something else, and these environments become dominant with the increase in urban density, and the influence of the natural environment diminishes. But what is optimal, or just “what is good”, is at heart a qualitative question, a question of values.

## Appendix A.

|   | Office   | Housing                            |
|---|--|------------------------------------|
| <b>Construction</b>                         |  |                                    |
| Exterior walls                              |  |                                    |
| U-value                                     | 0.2 W/m <sup>2</sup> K   | 0.2 W/m <sup>2</sup> K             |
| Roof  |  |                                    |
| U-value                                     | 0.15 W/m <sup>2</sup> K  | 0.15 W/m <sup>2</sup> K            |
| Ground-contact/exposed floor                |  |                                    |
| U-value                                     | 0.15 W/m <sup>2</sup> K  | 0.15 W/m <sup>2</sup> K            |
| Internal walls                              |  |                                    |
| U-value                                     | 0.35 W/m <sup>2</sup> K  | 0.35 W/m <sup>2</sup> K            |
| Internal ceilings/floor                     |  |                                    |
| U-value                                     | 0.32 W/m <sup>2</sup> K  | 0.32 W/m <sup>2</sup> K            |
| Window                                      |  |                                    |
| U-value                                     | 1.5 W/m <sup>2</sup> K   | 1.5 W/m <sup>2</sup> K             |
| g-Value                                     | 0.62   | 0.62                               |
| Visible light normal properties             | 0.68   | 0.68                               |
| <b>Use of the building</b>                  |  |                                    |
| Service, occupants                          | 8 am–5 pm, M-F   | On continuously                    |
| <b>Internal gains</b>                       |  |                                    |
| People                                      |  |                                    |
| Internal heat gain                          | 4 W/m <sup>2</sup>   | 1.5 W/m <sup>2</sup>               |
| <b>Lighting</b>                             |  |                                    |
| Lighting level                              | 200 lx   | 200 lx                             |
| Maximum power                               | 4 W/m <sup>2</sup>   | 8 W/m <sup>2</sup>                 |
| Installed power density                     | 2 W/m <sup>2</sup> /100 lx                                     | 4 W/m <sup>2</sup> /100 lx         |
| Luminous efficacy                           | 50 lm/W  | 25 lm/W                            |
| Variation profile                           | 8 am–5 pm, M-F   | 6 am–9 am and 3 pm–10 pm           |
| Switched-on-percentage                      | 100%   | 20%                                |
| Dimming profile                             | Dimming, (200 lx)  | Manual/on-off (200 lx)             |
| <b>Miscellaneous</b>                        |  |                                    |
| Maximum sensible gain                       | 6 W/m <sup>2</sup>   | 3.5 W/m <sup>2</sup>               |
| Variation profile                           | 8 am–5 pm, M-F   | On continuously                    |
| <b>Air exchanges</b>                        |  |                                    |
| Infiltration                                |  |                                    |
| Min flow                                    | Day, 0.13 l/s m <sup>2</sup><br>Night, 0.09 l/s m <sup>2</sup> | 0.13 l/s m <sup>2</sup><br>–       |
| Variation profile                           | Day, am–5pm, M-F<br>Night, outside working hours               | –<br>–                             |
| <b>Mechanical ventilation</b>               |  |                                    |
| Min flow                                    | 0.9 l/(s m <sup>2</sup> )                                      | 0.3 l/(s m <sup>2</sup> )          |
| Variation Profile                           | 8 am–5 pm M-F  | On continuously                    |
| System specific fan power (SFP)             | 2.1 W/(l/s)  | 1.0 W/(l/s)                        |
| Vent. heat recovery effectiveness           | 65%  | –                                  |
| Cooling efficiency                          | COP = 2.5  | COP = 2.5                          |
| <b>Natural ventilation</b>                  |  |                                    |
| Max flow                                    | –  | 0.9 l/s m <sup>2</sup> , t > 25 °C |
| Variation profile                           | –  | Weeks 19–37                        |
| <b>Heating and cooling</b>                  |  |                                    |
| Winter season (timed, week 01–18 and 38–53) |  |                                    |
| Heating set point                           | 20 °C (working hours)<br>16 °C (outside working hours)         | 20 °C (on continuously)<br>–       |
| Cooling set point                           | 24 °C (working hours)<br>Off (outside working hours)           | 25 °C (on continuously)<br>–       |
| Summer season (timed, week 19–37)           |  |                                    |
| Heating set point                           | 23 °C (working hours)<br>16 °C (outside working hours)         | 23 °C (on continuously)<br>–       |
| Cooling set point                           | 25 °C (working hours)<br>Off (outside working hours)           | 26 °C (on continuously)<br>–       |
| <b>Hot water consumption</b>                |  |                                    |
|   | 100 l/m <sup>2</sup> /year                                     | 250 l/m <sup>2</sup> /year         |

## References

- [1] T.R. Oke, *Boundary Layer Climates*, Routledge, 1978.
- [2] K. Steemers, Energy and the city: density, buildings and transport, *Energy and Buildings* 35 (2003) 3–14.
- [3] Erhvervs- og Byggestyrelsen, Strategi for reduktion af energiforbruget i bygninger, (n.d.).
- [4] V. Geros, M. Santamouris, S. Karatasou, A. Tsangrassoulis, N. Papanikolaou, On the cooling potential of night ventilation techniques in the urban environment, *Energy and Buildings* 37 (2005) 243–257.
- [5] C. Georgakis, M. Santamouris, Experimental investigation of air flow and temperature distribution in deep urban canyons for natural ventilation purposes, *Energy and Buildings* 38 (2006) 367–376.
- [6] P. Littlefair, Daylight, sunlight and solar gain in the urban environment, *Solar Energy* 70 (2001) 177–185.
- [7] C. Ratti, N. Baker, K. Steemers, Energy consumption and urban texture, *Energy and Buildings* 37 (2005) 762–776.
- [8] N. Baker, K. Steemers, LI method 3.0 – a strategic energy-design tool for Southern Europe, *Energy and Buildings* 23 (1996) 251–256.
- [9] N. Baker, K. Steemers, *Energy and Environment in Architecture*, 1st ed., Taylor & Francis, 1999.
- [10] D.H. Li, G.H. Cheung, K. Cheung, J.C. Lam, Simple method for determining daylight illuminance in a heavily obstructed environment, *Building and Environment* 44 (2009) 1074–1080.
- [11] P.A. Satrup, J. Strømman-Andersen, Sustainable cities: density versus solar access? A study of digital design tools in architectural design, in: *ISES Solar World Congress 2009 Proceedings*, Johannesburg, South Africa, ISES, 2009.
- [12] A. Rossi, *The Architecture of the City*, The MIT Press, 1984.
- [13] D. Hawkes, *The Environmental Tradition: Studies in the Architecture of Environment*, 1st ed., Taylor & Francis, 1995.
- [14] D.B. Crawley, J.W. Hand, M. Kummert, B.T. Griffith, Contrasting the capabilities of building energy performance simulation programs, *Building and Environment* 43 (2008) 661–673.
- [15] G.W. Larson, R. Shakespeare, *Rendering with Radiance*, Morgan Kaufmann, 1998.
- [16] C. Reinhart, P.F. Breton, Experimental validation of Autodesk (R) 3ds Max (R) Design 2009 and Daysim 3.0, *Leukos* 2009 (2009) 7–35.
- [17] C.F. Reinhart, O. Walkenhorst, Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds, *Energy and Buildings* 33 (2001) 683–697.
- [18] C.F. Reinhart, S. Herkel, The simulation of annual daylight illuminance distributions – a state-of-the-art comparison of six RADIANCE-based methods, *Energy and Buildings* 32 (2000) 167–187.
- [19] A. Nabil, J. Mardaljevic, Useful daylight illuminances: a replacement for daylight factors, *Energy and Buildings* 38 (2006) 905–913.
- [20] C. Reinhart, J. Mardaljevic, Z. Rogers, Dynamic daylight performance metrics for sustainable building design, *Leukos* (2006).
- [21] Danmarks Statistik/Statistics Denmark, *Statistisk Årbog 2009*, 2009.
- [22] C. Ratti, D. Raydan, K. Steemers, Building form and environmental performance: archetypes, analysis and an arid climate, *Energy and Buildings* 35 (2003) 49–59.
- [23] EN 15251. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, 2007.
- [24] CIBSE Guide A, *Environmental Design*, 1999.
- [25] EBST, *Bygningsreglement for erhvervs- og etagebyggeri*, National Agency for Enterprise and Construction, Copenhagen, Denmark, 2010.
- [26] T. Oke, Street design and urban canopy layer climate, *Energy and Buildings* 11 (1988) 103–113.



## **Paper II**

*“Building Typologies in Northern European Cities – Daylight, Solar Access and Building Energy Use”*

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Accepted for publication: Journal of Architectural and Planning Research, 2011

## **“Building Typologies in Northern European Cities – Daylight, Solar Access and Building Energy Use”**

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#### **Abstract**

This study analyzes the potential of passive solar energy and daylight and their impact on the total energy performance of typical urban building patterns found in the climatic context of northern Europe with Copenhagen as a reference.

It is possible to calculate the total energy consumption and daylight autonomy of whole urban blocks and individual buildings and apartments, and identify the impact of critical planning parameters related to urban density, by using building typologies.

Analysis of urban typologies, from traditional patterns to very recent architectural projects, shows a relative deviation of total energy performance up to 19% and daylight autonomy up to 48% at similar densities, indicating that urban patterns and building typology are key factors affecting energy consumption and daylight levels.

A comprehensive suite of climate-based dynamic thermal and daylight simulations show how the passive energy properties of buildings are affected by increases in urban density and urban form design choices. The results are differentiated by typical descriptive algorithms used in planning and massing design, including plot ratio and surface-to-floor ratio.

*Keywords: Urban Design, Energy, Daylight, Building Typology, Urban Shearing Layers*

## Introduction

It is generally acknowledged that high density building optimizes the use of land, reduces the need for transportation, and creates cities with intense urban activity and increased social, cultural and economic interaction (Newman P. W. G, Kenworthy J. R. 1989, and Steemers K. 2003). But will optimization of urban density collide with future requirements for comfort and reduced energy consumption in housing? This study concludes with detailed suggestions for geometric design parameters for future sustainable cities in northern Europe.

Our knowledge of how to design buildings energy-efficient has improved considerably in recent decades, largely through improvements in building technology and energy calculation methods. But given how much we know about building design, we know surprisingly little about the effects of urban form and density on low-energy buildings.

Dense urban building patterns might be expected to increase heating requirements (Fig. 1) and decrease cooling requirements (Fig. 2) because of restricted solar access and reduced solar gains. With regard to artificial lighting, compact urban geometries restrict daylight too, though daylight is considerably more complex than solar access, see Fig. 3.



Figure 1: Energy required for space heating per m<sup>2</sup> of floor space

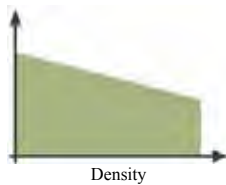


Figure 2: Energy required for space cooling per m<sup>2</sup> of floor space

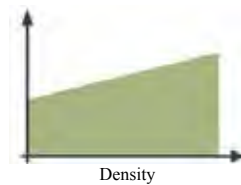


Figure 3: Energy required for artificial light per m<sup>2</sup> of floor space

But is it so simple? If we look at the factors again, we can state that more compact urban design should reduce heat losses due to reduced surface area and more shared wall space. Increased density and decreased surface-to-floor ratio can be expected to increase the need for cooling, as will any increase in the need for artificial lighting.

Urban density can be defined in different ways: the number of inhabitants per area unit, activity levels, etc. Since this study focuses on urban form, the plot ratio (total floor area / plot area) expressed as a percentage is used as the common denominator for the patterns studied.

But the question is: How does the morphological design of urban patterns affect the overall energy use through solar access and daylight conditions?

## Background

Although urban site conditions are critical for low-energy building design, very few studies have attempted to relate urban form to energy use or solar access and daylight conditions. Those that do, study regional climatic conditions, and are therefore not universally applicable, which they should not be, - an important point in environmental design supporting Frampton's early call for a regional, climatically conscious architecture. (Frampton, K. 1985). With the extreme global diversity of urban climatic conditions in mind, it is rather provoking that we know so little about the impact of urban form on buildings' environmental and energy performance.

A recent publication (DeKay M. 2010) asks the question: "*What would the form of the city be like if we were to take seriously the provision of daylight to all buildings?*" Using "Daylight Envelopes", (DeKay M. 2010) shows how an urban pattern of blocks and streets can be generated so that the limits of building boundaries provide lower floors of



neighboring buildings with sufficient light. DeKay concludes: *“There are still no basic massing rules... to ensure that the massing decisions intended to provide daylight are actually dimensioned within parameters that allow sufficient levels within the rooms of lower floors. This is clearly an unresolved subject for future research efforts”*. This indicates the need for more detailed investigation of the effect of urban form on the environmental performance of buildings.

(Cheng V. et al. 2006) investigated urban form in relation to solar potential in the context of Sao Paulo, Brazil at S23.5° latitude. In short, their results suggest that a random layout is preferable to uniform layout in improving ground-level exposure and that horizontal randomness is more effective than vertical randomness. The authors acknowledge that their results may be due to the sky conditions and high solar altitudes of their study’s location and may not be applicable under different conditions.

(Compagnon R. 2004) developed a method to determine the percentage of building façades in a given urban area receiving technically and commercially useful amounts of solar radiation over a selected period of time. Examination of five different layouts for a dense urban redevelopment project in Switzerland (Compagnon R. 2004) led to the conclusion that the best performing configuration was able to exceed the threshold for daylighting across 83% of the total façade area and for passive solar heating over 52% of the area.

(Ratti C et al. 2003) demonstrate in their study of building form and environmental performance that some urban configurations perform better than others. For instance, a courtyard configuration performs better in calculated environmental variables (surface-to-floor ratio, shadow density, daylight distribution and sky view factor) than pavilion types in the specific context of hot-arid climates.

A previous study by the authors (Strømman-Andersen J. & Sattrup P.A. 2011) investigated the impact of urban geometry - specifically the Height/Width ratio of urban canyons (streets and backyards) - on building energy use and daylight performance, finding that the urban space surrounding a building has considerable impact on energy use (up to 30% of the total). Daylight was found to have increased importance in the overall energy use, and the reflectivity of facades in the urban space was found to have a hitherto unnoticed impact on daylight distribution.

### *Urban Morphology - Northern European Cities*

Urban patterns develop over time, typically shaped by the climate and transport patterns, among many other parameters. They also reflect the technical possibilities of the periods in which they were developed. Northern European cities (Copenhagen, Stockholm, Oslo, Hamburg, etc.) are characterized by a relatively uniform urban scale, ranging from 5 to 6-story buildings in the city center to a widespread carpet of single-level family homes in the periphery. Their centers are characterized by the prevalence of the urban perimeter block pattern with remarkably similar sizes (Fig 4.), and the gradual dissolution of that pattern due to modern developments, and the introduction of new building types such as the building slab and the detached house. In the case of Copenhagen, this development was regulated according to the famous ‘Fingerplan’ of 1947. A sample of typical building patterns are shown in fig. 5

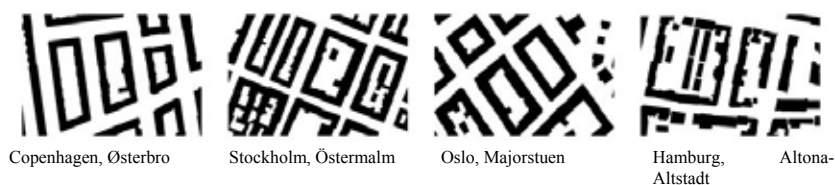


Figure 4: Local typologies from various northern European cities (Copenhagen, Stockholm, Oslo and Hamburg)

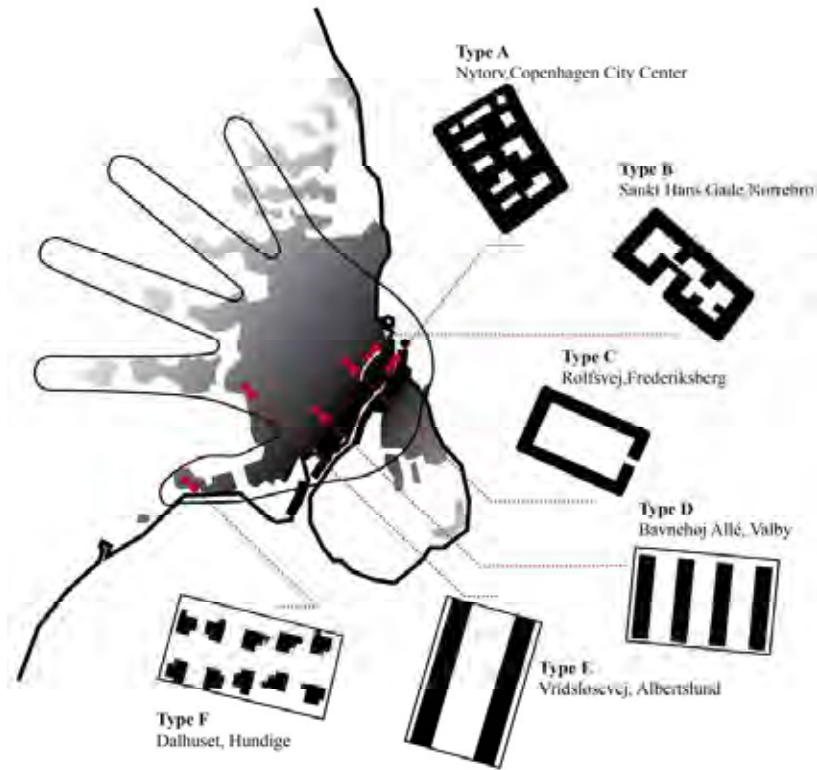


Figure 5: Samples of urban patterns and their location in Copenhagen superimposed on the 1947 “Finger plan”.

## Method

The study is parametric in approach. Six generic models representing a range of urban building type patterns were compared for energy and daylight performance. The six urban patterns correspond to different typologies in northern European cities, see Fig. 5. While generic, the models were structured to represent the most important geometric factors that regulate the development of the urban fabric over time.

First we analyzed the buildings as defined typologies: How do these traditional typologies perform? Then we looked at the master planning of new developments: If we were asked to design a new settlement with a density of 200%, low-energy consumption, and sufficient daylight levels, how would these typologies compare on daylight and energy use? Third, we reviewed two recent innovative projects where typologies have been redefined addressing solar access, asking what these developments may tell us about the future of urban patterns’ environmental performance.

### *Urban Shearing Layers*

The generic models for this simulation study were designed in accordance with an urban scale version of the shearing layers theory (Brand S. 1994). The shearing layers concept originated in ecology studies, and describes the way that short-lived processes in nature take place within the framework of processes with a longer lifespan, in a hierarchy of scale that is both spatial and temporal. The concept of shearing layers has been proved very useful in resource management for describing and differentiating the various rates of change that a building experiences over its lifetime. The concept is now used in designing for, calculating and discussing the lifecycle and metabolism of buildings (Berge 2009).

The shearing layers theory is here extended to encompass the urban scale. Six layers are proposed to describe the levels ranging from urban street grid to the interior organization of buildings in order of permanence and scale: **Grid, Block, Plot, Building, Apartment and Room.**

The layers proposed here are closely associated with, if not identical to the legal framework of planning and ownership that are effective in most liberal economies, with the added layer of rooms to describe spatial differentiation within the building. In contemporary urban development, the scale of operation is often so great that the differentiation is not entirely clear as it is in historical districts. Plots are often only individuated at block level, and individual buildings occupy the entire block. While focusing on the overall urban building pattern, this hierarchical organization of the model allows analysis and individuation of performance according to orientation, position, material properties and use patterns of rooms in subsequent studies.

The critical point in applying the urban shearing layers theory to a typological study is this: Since urban form is defined by the slowest changing layers (DISTRICT, GRID, BLOCK) it affects the performance of individual buildings throughout their lifetime. If an urban pattern has particular performance qualities (daylight, passive solar gains, energy savings etc.) the cumulative effect of these qualities will be considerable over the lifetime of the building.

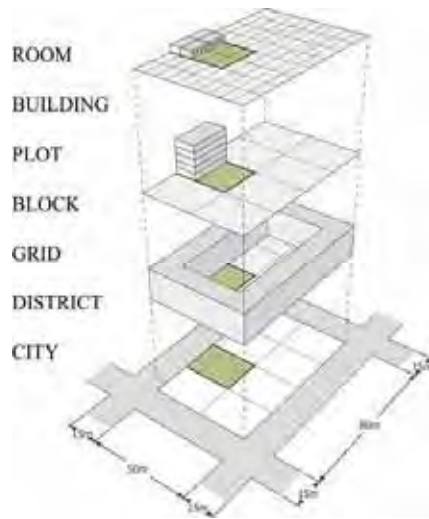


Figure 6: Urban Shearing Layers, and the differentiation of the generic models used in this study (50m<sup>2</sup> zone, 5 stories of 100m<sup>2</sup> apartments with 2 rooms each, 50x80m urban perimeter block)

**BLOCK** – The urban block is defined in this study as a rectangle 80 x 50 meters (262 x 164 feet) surrounded by streets 15m (49 feet) wide. Although European city centers are not usually ruled by uniform grids, the size was chosen so as to be representative of typical block dimensions, see Fig. 4. The street width is equivalent to a street composed of 2 traffic lanes with bicycle lanes and pedestrian sidewalks.

**PLOT** – The block is divided into land register plots with dimensions of 25 x 20 meters (82 x 66 feet). The plot size was chosen to simplify subsequent subdivisions, so that a number of urban patterns can be modeled using simple rooms that reflect existing apartment building typologies.

**BUILDINGS** – Buildings in this study are all five stories high, equal to a height of 15 meters (50 feet). These building heights are typical of inner city areas, but can also be seen in the periphery.

**ROOM** - Two rectangular rooms of 3 x 5 x 10 meters (10 x 16 x 32 feet) constitutes a simplified version of the apartments' inner lay-out for simulation purposes. The rooms allow the results to be differentiated according to position and orientation. Each room has a 3m floor-to-floor height and glazing ratios of 30%. Two such spatial units facing in opposite directions would constitute a generic 100 m<sup>2</sup> (1076 ft<sup>2</sup>) apartment, a common size close to the Danish national average of 110 m<sup>2</sup> (1184 ft<sup>2</sup>) per dwelling<sup>1</sup>. The room depth falls well into the category of 'potentially passive' space in which daylight and solar gains can play a significant role, (Ratti C et al. 2003).

### *Building Properties and User Pattern Types*

The model buildings are well-insulated heavy constructions. Wall U-values are 0.20 W/m<sup>2</sup> K (0.04 Btu/hr ft<sup>2</sup> °F). Window U-values (including frame) are 1.5 W/m<sup>2</sup> K (0.32 Btu/hr ft<sup>2</sup> °F); g-values are 0.62. These properties reflect minimum requirements under Danish building codes (2010 Danish building regulations), though the values are not in themselves a guarantee that a given apartment in the model complies with the current overall standard for energy efficiency.

The glazing ratio (30%) used is related to sizes typically found in residential buildings. The user patterns reflect a simple workday/weekend pattern. User patterns are designated to achieve the European standards for indoor environment (EN 15251, 2007) and reflect differences in requirements for residential buildings. These are not discussed as such (see Appendix).

### *Simulation Context*

Each simulation model was located in an analytical field in the center of a fictional context, composed of eight five-story blocks which cast shadow and reflect light on to it, see Fig. 7. This context has a density equal to a 275% plot ratio perimeter block pattern.

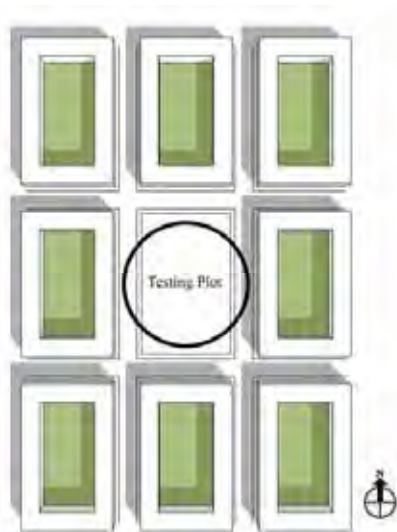


Figure 7: Analytical field: plot ratio 275% perimeter block

<sup>1</sup> Danmarks Statistik / Statistics Denmark, Statistisk Årbog 2009, (2009).

Urban Building Type Patterns

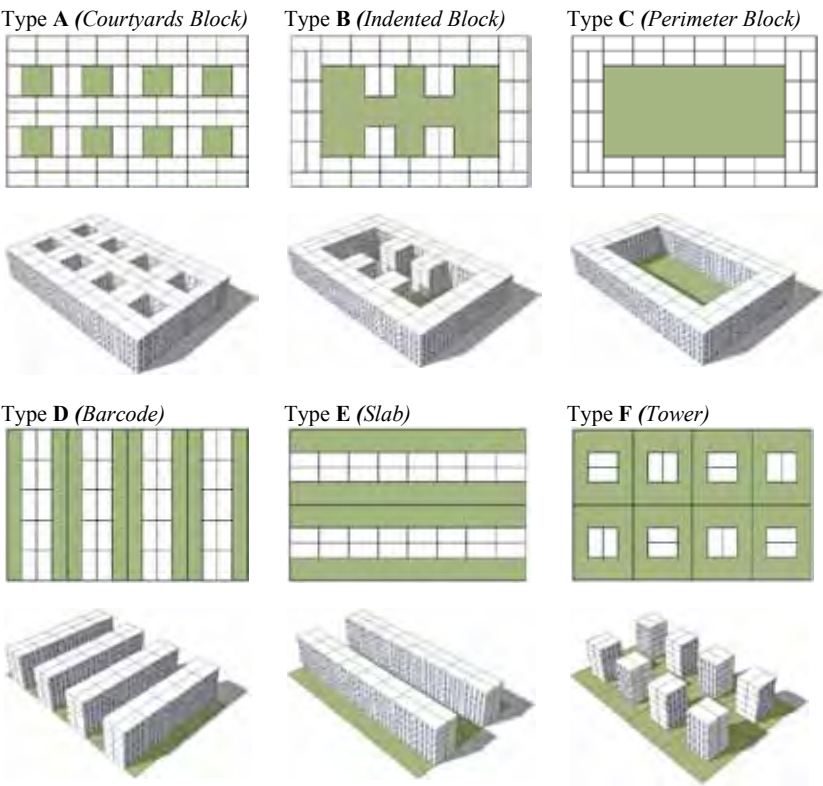


Figure 8: Six traditional urban building patterns

Plot Ratio

The plot ratio is an indicator of building type density. Type A has the highest plot ratio (400%) and Type F the lowest plot ratio (100%), see Table 1.

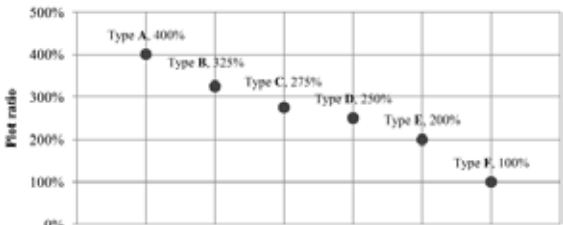


Table 1: Density: Plot ratio (area of built space per unit plot area)

Surface-to-Floor Ratio

The surface-to-floor ratio defines the amount of exposed building envelope per unit floor area. It is relevant to the energy consumption of buildings because it defines the balance

between passive gains and losses. Type A has the lowest surface-to-floor ratio (94%) and Type F has the highest surface-to-floor ratio (160%), see Table 2.

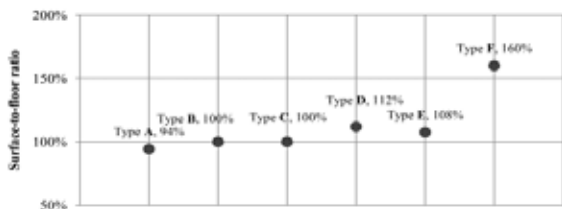


Table 2: Compactness: Surface-to-floor ratio (amount of exposed building envelope per unit floor area)

### Energy Simulation

The energy calculations were performed using the simulation tool IES-Virtual Environment 6.1.1, ApacheSim / RADIANCE. This program creates a fully integrated thermal and daylight simulation with detailed hourly output of the electrical energy consumption for lighting, mechanical ventilation, heating load, cooling load, and indoor operative temperature. The IES-Virtual Environment is an integrated suite of applications linked by a common user interface and a single integrated data model<sup>2</sup>.

Energy use is measured in primary energy. In principle, primary energy is the total weighted energy, see Appendix. It can be calculated from the unit's estimated net consumption. The total net energy consumption is divided into four primary needs: 1. Domestic Hot Water (DHW), 2. Mechanical ventilation, 3. Cooling load, and 4. Heating load.

Since we are dealing with an urban context, it was assumed that the building is equipped with district heating. The heating supply was therefore regarded as having an efficiency of 0.8. DHW and Mechanical Ventilation are simulated as constant, see Appendix.

### Evaluation criteria

Since the aim of this study was to analyze and compare urban patterns, the models were kept simple. What is of interest here is the relative performance of the urban building patterns, for two main reasons:

- Since urban patterns tend to last longer than individual buildings, the relative performance of a pattern is likely to affect any building within the pattern throughout its lifetime.
- The total calculated energy performance is of interest due to the weight that design choices related to urban pattern carry in the detailed design of buildings in later development phases.

### New Metrics: Dynamic climate-based simulation

Daylight factors have been used in many previous studies as simple tools for predicting 'worst case' scenarios using CIE-standardized skies. However, these scenarios ignore dynamic weather conditions since they do not incorporate actual climate data - which vary a lot depending on the real-world location. As (DeKay M. 2010) concludes, "*Generalizations about matching DF (daylight factor) recommendations to tasks or occupancies can be very misleading given wide variations in daylight availability under*

<sup>2</sup> IES-Virtual Environment qualified as a dynamic model in the Chartered Institution of Building Services Engineers system of model classification. CIBSE Guide A Environmental Design (1999).

*different sky conditions*” Advances in computing power now allow climate-based modeling and relatively fast calculation of daylight levels using metrics. One such system is the Daylight Autonomy Metric, in which available daylight is quantified combining both direct and diffuse radiation. (Reinhart C F et al., 2001). The important point is that now both daylight, thermal and energy performance can be analyzed based on the same climate data.

Daylight Autonomy (DA) uses work plane illuminance<sup>3</sup> as an indicator of whether there is sufficient daylight in a room so that an occupant can work by daylight alone. Daylight Autonomy is then defined as the percentage of the “occupied” times of the year when the minimum illuminance requirement at the sensor is met by daylight alone. In this study, the “occupied” time was set to 6 am – 6 pm (equivalent to sunrise to sunset at equinox) and the minimum illuminance to 200 lux.

## Results and Discussion

Energy and daylight results are presented below as independent subjects.

### Energy

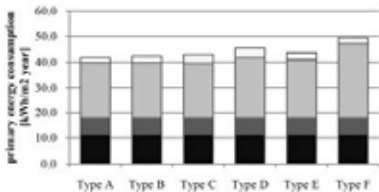


Table 3: Total primary energy consumption for Cooling, Heating, Mech. Ventilation and DHW (kWh/m² year)

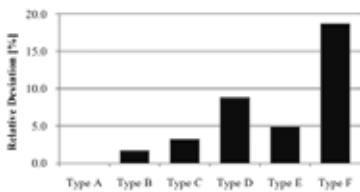


Table 4: Relative deviation (%) of energy consumption for each building type pattern. Courtyard type was used as reference.

Table 3 shows that the overall energy consumption varies from 41.5-49.5 kWh/m² year (13.2-15.7 kBtu/ ft²/year). Type A has the highest density and least energy use compared with the other types. For Types B, C, D and E, the energy consumption varies between +2 and +9%. Type F is the only type that has significantly higher energy consumption (19% higher than Type A). A general tendency is that energy consumption increases with decreasing urban pattern density, but the big jump in energy performance is achieved when using additive urban forms instead of detached building types.

The dominant factor in the total energy consumption is heating. This is partly due to Copenhagen’s low mean temperature at 8.2 °C (compared with London at 10.2 °C and New York City at 12.4 °C)<sup>4</sup>, which necessitates more energy for heating to achieve thermal comfort.

### Daylight Conditions

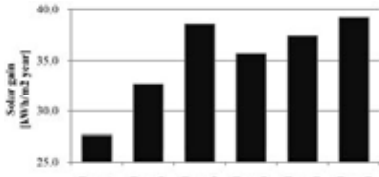


Table 5: Passive solar gain (kWh/m² year)

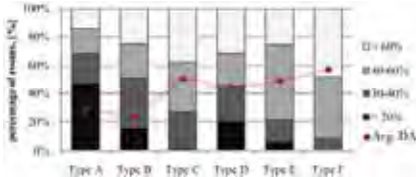


Table 6: Percentage of well-lit rooms as a function of Daylight Autonomy (DA)

Table 5 demonstrates a clear correlation between urban density and passive solar gain. Type A has the lowest passive solar gain. More surprising is the fact that the solar gain does

<sup>3</sup> Illuminance is the total luminous flux incident on a surface, per unit area

<sup>4</sup> Data from U.S. Department of Energy, Energy Efficiency & Renewable Energy



not fall proportionally with the density (plot ratio). Type C has a high building density (275%), but also a high level of passive solar gain. This shows that exposure to sunlight is not linearly connected with urban density, but depends to a high degree on the design of the individual typology. Daylight autonomy (DA) correlates quite precisely to the levels of passive solar gain. For Type A, it is notable that approximately 50% of all rooms have a DA of less than 20%. This signifies that 50% of all rooms require artificial lighting over 80% of the time. See table 6. (A room with no obstruction in front of it has a DA of 70% equal to maximum DA). In contrast, Type F has the optimal daylight performance. None of the rooms have a DA of less than 20%, and over 50% of all rooms have a DA of more than 60%. Type C differs by having a uniform daylight distribution with few dark rooms and simultaneously a high level of density.

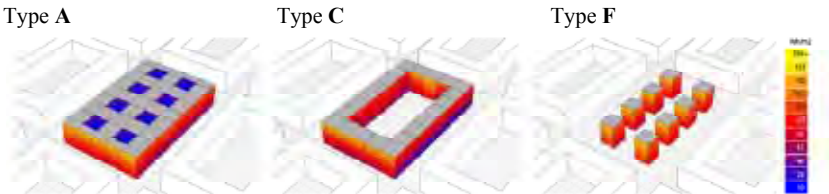


Figure 9: Illustration of incident solar radiation falling on Types A, C and F. Average hourly direct and diffuse solar radiation on different urban type patterns. Calculated in ECOTECT (hours in question 6 am–6 pm all year, Contour range 0–200 Wh/m2) Weather data, Copenhagen (\*epw).

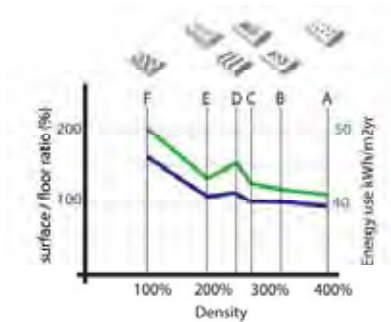


Table 7: Correlation: Density, Energy Use and Compactness

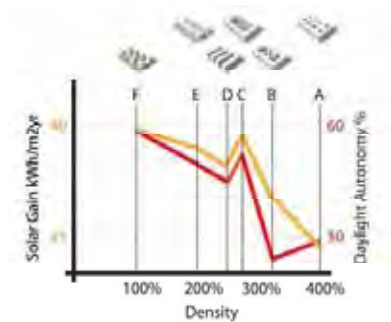


Table 8: Correlation: Density, Daylight Autonomy and Solar gains

Returning to the question of how urban density affects building energy use, it can be noted that high density generally leads to reduced energy use. But, as can be seen in table 7, the effect is mainly caused by the compactness of each typology (surface to floor area ratio) since the heating losses in winter remain the main cause for energy demand in Northern Europe, even with a well-insulated façade. But the effect fades out for developments denser than 250%. Parallel to the lessened energy demand, daylight and solar gains are severely compromised by the increase in density (fig. 8). But there is, very interestingly, a middle range between densities of 150 and 275% which are both energy efficient and have adequate daylight and solar access. The performance differences of types B, C, D and E suggest that there is plenty of opportunity to achieve better performance by designing with attention to orientation and solar access.

A relative variation of 19% in yearly energy performance by urban pattern design alone is very considerable over the perhaps 50-100 years lifetime of a building. This is clearly significant. But more interesting from a qualitative architectural point of view is that daylight and passive solar gains distribution vary even more, and is not linearly connected to urban density. This implies that there should be a strong case for architectural design at the interstice of urban and building design to improve these aspects of environmental performance.



Urban Type Patterns with Density at 200%

Urban density typically decreases with the distance from the center. In the central districts of Copenhagen, the average plot ratio is between 150-200%. What kind of typology should we choose if we are to design new districts with a plot ratio of 200% using traditional typologies?

If the typology is designed with a fixed plot ratio of 200%, we can directly compare the geometric performance of the different typologies independent of density.

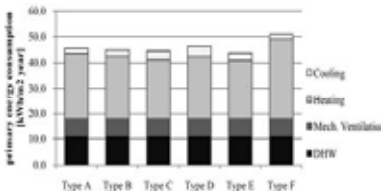


Table 9: Total primary energy consumption for Cooling, Heating, Mech. Ventilation and DHW (kWh/m² year)

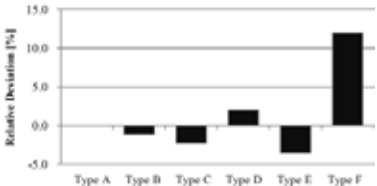


Table 10: Relative deviation (%) of energy consumption for each building type pattern. Courtyard type was used as reference.

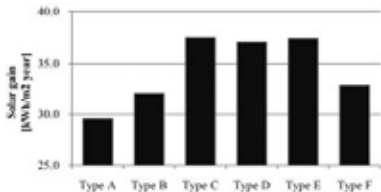


Table 11: Passive solar gain (kWh/m² year)

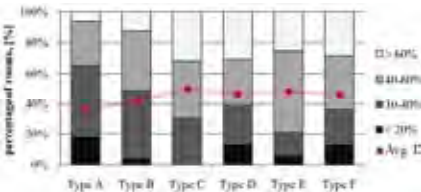


Table 7: Percentage of well-lit rooms as function of Daylight Autonomy (DA)

There is no great variation in energy consumption. Types C and E perform best with a relative saving of -2.2% and -3.5% in relation to Type A. A saving of 3.5% does not seem significant, but for an already energy-optimized building, 3% energy saving by urban design alone is considerable. It corresponds to an increase in the thickness of the insulation of the entire building façade from 125 mm (5 inches) to 170 mm (7inches). It should also be noted that the energy saving is passive, requiring no extra costs in the form of technical solutions.

Daylight autonomy (DA) varies more than energy consumption for the different typologies. Type C again outperforms other types in relation to minimizing the number of rooms with poor daylight (rooms requiring artificial lighting for more than 80% of the time). Types C and E provide the optimal average daylight autonomy (50%). It could be expected that Type F might be favored to outperform other types because it has the largest surface-to-floor ratio, but this is not so due to its high level of self-shadowing.

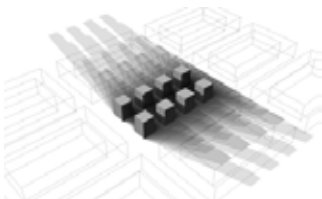


Figure 10: Type F, plot ratio 100%, Shadow range 6 am - 6 pm, 21st March

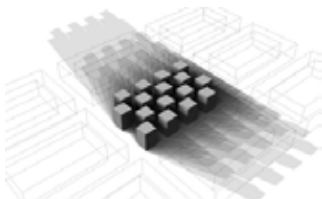


Figure 11: Type F, plot ratio 200%, Shadow range 6 am - 6 pm, 21st March

A summary of the results shows that energy consumption is primarily affected by density and compactness. Daylight autonomy and visual comfort depend more on the geometric design of the typology, i.e. its orientation and its construction in relation to the surrounding context. A final question emerges: Is it possible to qualify and optimize the design of a future city from this acquired knowledge?

### *New Urban Patterns?*

Recent years have witnessed architectural innovation at the scale of the urban block. We have chosen two projects that are formal reinterpretations of the traditional urban perimeter block (Type C):

1. “Twisted Block” - BIG House by BIG Bjarke Ingels Group
2. “Stepped Block” – De Landtong by Architekten CIE

The projects both have an overall sustainable urban vision behind their design and have been built as part of master plans for large-scale urban developments. In terms of this analysis, the projects have been modified, simplified and scaled down so as to fit into the same urban matrix as the previous studies with a 200% plot ratio. This consciously ignores some of the qualities of the real-world projects that affect their energy use, e.g. that both projects have unobstructed views of wide open areas to the south. Nevertheless, accepting this reduction and abstraction allows us to pinpoint the effect of a formal optimization of the urban block.

The question here is how these projects may, or may not, form the basis for new urban patterns and what can we learn from comparing these to the traditional patterns?

#### TWISTED BLOCK



Figure 12: BIG Bjarke Ingels Group, BIG House, Copenhagen, Denmark, 2008-2010

#### STEPPED BLOCK

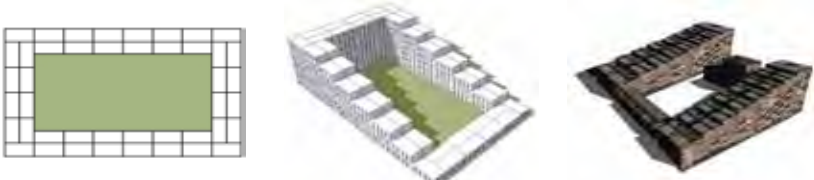


Figure 13: Architekten CIE, De Landtong, Rotterdam NL, 1994-1998

*"Twisted Block"* (Fig. 12) is designed with a focus on integrating the building's orientation and its use. The typology is twisted to create smaller and more intimate courtyards around a central core. The southwest corner is lowered and the typology slopes upwards to the northeast corner. The apartment's views and afternoon/evening sunlight are thereby optimized.

*"Stepped Block"* (Fig. 13) focuses on the optimal use of sunlight. The typology is characterized by a uniform slope towards the south. The slope provides the apartments with views and a maximized exploitation of sunlight.

Note: the alternative typologies were simulated with a plot ratio of 200% and using the same methodology as the previous analyses. The results are thus directly comparable with the other typologies.

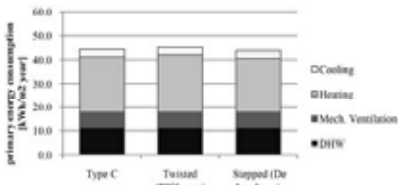


Table 8: Total primary energy consumption for Cooling, Heating, Mech. Ventilation and DHW (kWh/m<sup>2</sup> year)

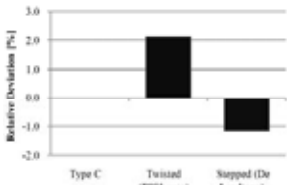


Table 9: Relative deviation (%) of energy consumption for each building type pattern. Perimeter type was used as reference.

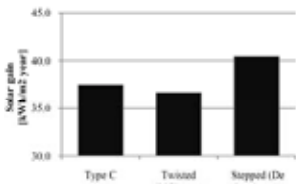


Table 10: Passive solar gain (kWh/m<sup>2</sup> year)

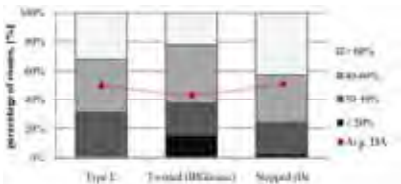


Table 11: Percentage of well-lit rooms as function of Daylight Autonomy (DA)

The results show that there is no great variation in energy consumption, but quite considerable variations in daylight performance, ranging from 42 to 50% average DA.

The ‘Twisted Block’ has an increased energy consumption of 2 kWh/m<sup>2</sup>/year (0.64 kBtu/ft<sup>2</sup>/year), compared to Type C. The daylight analysis shows that twisted block also have reduced overall daylight autonomy with 15% of individual spaces having daylight autonomies of less than 20%. The overall solar gains are also reduced.

The ‘Stepped Block’ shows small improved energy performance, which even comes with a better daylight performance than the perimeter block. 43% of all rooms have a DA above 60%, and the average DA for the Stepped Block is as high as 52%.

Both the projects mass the majority of apartments at the northern end of the block, following an imaginary sloping plane rising towards the north, which ensures that only a minority lie in the shadows of the surroundings or of the block itself. The stepped block shows that minimizing self-shading in this way has a noticeable effect on the energy use for heating. In contrast, in the Twisted Block, the ‘X’ in the middle actually increases the self-shading of the deep court at the northern end, dramatically lowering the daylight performance of rooms on the lower levels facing it. Yet, the twist itself also changes the orientation of all the apartments in the center of the block from South to South-East or South-West. This has the effect of increasing solar exposure during the heating season, particularly in the autumn and spring, since the sun comes in at a low altitude, thereby maximizing their exposed area and the radiation intensity. Over the course of a full year, this beneficial seasonal effect drowns in the overall balance of exposure and shading. It is thus the temporal and spatial dimensions of form and radiation intensity on the horizontal façades over the year that explains the peculiar performance of the twisted block.

Do these projects offer new model patterns for urban planning? When inserted in the 5-story urban matrix that has been used in all the comparative studies, the stepped block scheme performs remarkably well, and it does so by carefully differentiating urban form to provide optimal base conditions for daylight, sunlight and solar gains for a mixed use program. These base conditions can be further differentiated in the detailed design of a project, using glazing ratios, material properties, shading balconies, etc. but the lasting

impact of the urban form guarantees that the relative energy and daylight performance achieved at this strategic level is likely to outlast the detailed design and subsequent alterations to the building over its lifetime.

It is curious that both projects go against the grain of established solar access theory as defined by Ralph Knowles, who argued for the protection of solar access in public spaces and on neighboring façades (Knowles R. 2003). By massing the majority of the development at the northern end where it is likely to overshadow the neighboring block, both the twisted and the stepped block ‘privatize’ the solar potential of the neighboring buildings.

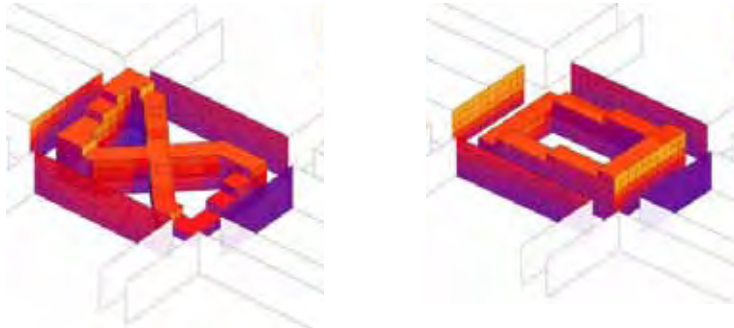


Figure 14: Average seasonal radiation in the heating season (Oct-Apr) on the ‘twisted block’ and a ‘stepped block’ inverted so as to protect the solar access of the buildings behind it. Density 250%. Range 0-200Wh/m2. View from solar position at equinox 15hrs.

The difference between massing at the sun-facing end of the block (as Knowles would suggest) or in the far end is illustrated in Fig. 14. The form of the block has clear impacts on the solar access of the surrounding urban context, but the results are more complex than traditional solar access theory would expect. While the twisted block overshadows its neighbours to the north, the triangular urban spaces on each side allow sunlight to penetrate deep into the streets and on the opposing façades. The block to the north does lose some solar radiation, but how much compared to what the neighbouring block to the west gains? In Fig.14 the total incident radiation on both the block and its immediate context is 9% higher on the twisted block than on the inverted stepped block, proving that there may in fact be considerable freedom in design to optimize the solar access of both a site and its surrounding context, though the changes to individual apartments may be considerable. This can be considered an issue of differentiation between public and private solar access at an urban level. Using a measuring matrix for the surrounding façades as is shown in fig. 14. may be a simple yet very useful tool to urban planners and policymakers in assessing the impact of densification developments for solar access, daylight and consequently energy use of neighboring buildings, instead of or supplementing the use of geometric constraints such as fixed eaves’ heights, solar or daylight envelopes.

## Conclusion

What are the consequences for urban developments in the future? The concise answer is that geometric design parameters become critical when planning for energy efficient cities and communities. Energy efficiency is however not the main issue of urban design – it remains a question of how to improve the experiential and environmental qualities of cities. Here it is demonstrated – focusing on daylight and passive solar gains – that urban form as expressed in building pattern and architectural typology have great impacts on the environmental performance and quality of buildings.

We find that differences in urban typologies have a relative impact on total energy consumption in the range of up to 19%, which correlates with the compactness of the different types’ surface to floor ratio. With well insulated building façades, increased urban

density and compactness will not necessarily lead to further energy use reductions. A certain balance in the energy performance emerges which depends on both regional climate, density and building technology, where daylight and solar access balances energy use in buildings. In the case of Copenhagen this is a range of densities from 100-300% (Table 17).

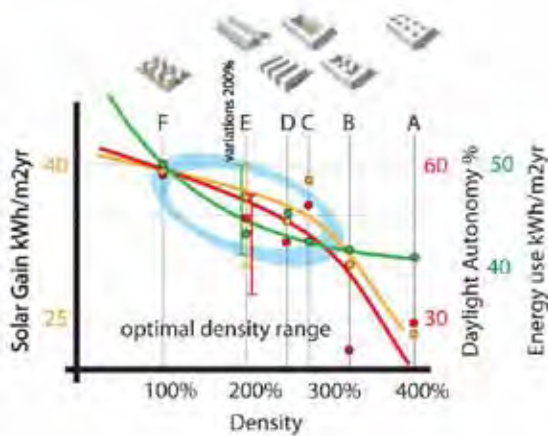


Table 17. Optimal density range for daylight, solar access and energy use, Copenhagen. The curves illustrate the tendencies from table 1-16. The variations at 200% are elaborated in table 18.

But the balance disguises the fact that the performance of these patterns is greatly differentiated. The daylight performances vary between 35% and 52% average daylight autonomy compared to a theoretical maximum of 70%, with the daylight performance of individual spaces within the typologies varying even more. This is a relative improvement of 48%. Daylight performance changes so dynamically compared to overall energy efficiency, that it may be helpful to shift technical performance criteria towards daylight and solar access metrics in urban design, as they have many direct implications on the experienced qualities of the built environment. Table 18 shows that there is ample opportunity to optimize environmental performance further by architectural design, given the optimal density range illustrated in table 17.

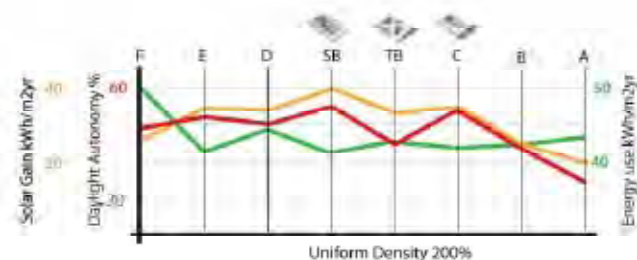


Table 15: Energy use, Daylight Autonomy and Solar gains compared for different typologies at 200% density. The graph sums up the data from tables 1-16. At this density the differences in energy use are quite precisely inversely correlated to solar access and daylight autonomy, indicating that a balance between urban density, building fabric and the climatic qualities of daylight and sun has been found.

These findings are strong evidence that architects and planners should design for daylight and solar access rather than focussing on energy use alone, while pursuing innovative solutions that are dense, compact and distribute daylight and sun in the urban fabric for both public and private benefit. While energy use may be reduced further by applying advanced building technology and integrated energy production, the results shown here indicate that basic typology design is able to reduce energy loads well below the relatively strict Danish standards (BR10) using urban design and building fabric as the main means of energy use reduction. Further optimization through building technology is typically

expensive and may have limited functional lifetimes, while daylight and solar access are decided at the interstice of urban and building design, and have long lasting impacts on the urban and indoor environmental qualities.

Using environmental simulation modeling, it is demonstrated that in the cool cloudy climate of Northern Europe the daylight performance derived from urban patterns is a critical concern which should be researched further, as it behaves in dynamic and complex ways which are not linearly connected to urban density.

(Oke T. 1988), says there are “*almost infinite combinations of different climatic contexts, urban geometries, climate variables and design objectives. Obviously there is no single solution, i.e. no universally optimum geometry.*” Nevertheless, there *are* optimum ranges of geometric conditions in urban design – *if* we want to design energy-efficient cities, urban spaces and homes with an intimate connection to the qualities of their natural environment.

## References

- Berge, B., 2009. *The ecology of building materials*, Architectural Press.
- Brand S., (1994), *How Buildings Learn: What Happens After They're Built*. New York Penguin Books
- Cheng V., Steemers K., Montavon M., Compagnon R., (2006) *Urban Form, Density and Solar Potential*, PLEA2006 – The 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland, 6-8 September 2006
- Compagnon R., (2004), *Solar and daylight availability in the urban fabric*. Energy and Buildings 36 (2004) Pages 321-328
- DeKay M., (2010), *Daylighting and Urban Form: An Urban Fabric of Light*, Journal of Architecture and Planning Research, 27:1 (Spring 2010)
- Frampton, K., (1985), *Towards a Critical Regionalism: Six Points for an Architecture of Resistance*. In Postmodern Culture. Pluto Press, pp. 16-30.
- Holl S. (1980), *The alphabetical city*, (Pamphlet architecture #5), New York: Princeton Architectural Press
- Knowles R., (2003) *The solar envelope: its meaning for urban growth and form*, Energy and Buildings 35 (1) (2003) 15–25.
- Newman P. W. G., Kenworthy J. R., (1989) *Gasoline Consumption and Cities*, Journal of the American Planning Association, 55: 1, 24–37
- Oke T., (1988), *Street design and urban canopy layer climate*, Energy and Buildings. 11 (1988) 103-113.
- Ratti C., Baker N., Steemers K., (2005), *Energy consumption and urban texture*, Energy and Buildings. 37 (2005) 762-776.
- Ratti C., Raydan D., Steemers K., (2003), *Building form and environmental performance: archetypes, analysis and an arid climate*, Energy and Buildings. 35 (2003) 49-59.
- Reinhart C. F., Walkenhorst O., (2001), *Dynamic RADIANCE-based Daylight Simulations for a full-scale Test Office with outer Venetian Blinds*. Energy & Buildings, 33(7), 683-697
- Reinhart C., Mardaljevic J., Rogers Z., (2006), *Dynamic Daylight Performance Metrics for Sustainable Building Design*, Leukos.
- Steemers K., (2003), *Energy and the city: density, buildings and transport*, Energy and Buildings, Volume 35, Issue 1, January 2003, Pages 3-14
- Strømmandersen, J., and P.A. Sattrup. 2011. “The urban canyon and building energy use: Urban density versus daylight and passive solar gains.” Energy and Buildings, Volume 43, Issue 8, August 2011, Pages 2011-2020.
- CIBSE Guide A Environmental Design., (1999).
- Danish building regulations BR10, (2010). *Bygningsreglement for erhvervs- og etagebyggeri*, National Agency for Enterprise and Construction, Copenhagen.
- EN 15251. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (2007).
- Danmarks Statistik / Statistics Denmark, Statistisk Årbog 2009, (2009).

## Appendix

### Calculation parameters, default values

|                                 |   |                        |
|---------------------------------|---|------------------------|
| Construction                    |   |                        |
| Exterior Walls                  |   |                        |
| U-value                         | 0.20 W/m² K (0.035 Btu/hr ft² °F)   |                        |
| Roofs                           |   |                        |
| U-value                         | 0.16 W/m² K (0.028 Btu/hr ft² °F)   |                        |
| Ground/Exposed Floors           |   |                        |
| U-value                         | 0.15 W/m² K (0.026 Btu/hr ft² °F)   |                        |
| Internal Walls                  |   |                        |
| U-value                         | 0.35 W/m² K (0.062 Btu/hr ft² °F)   |                        |
| Internal ceilings/floor         |   |                        |
| U-value                         | 0.32 W/m² K (0.056 Btu/hr ft² °F)   |                        |
| Window                          |   |                        |
| U-value                         | 1.5 W/m² K (0.026 Btu/hr ft² °F)  |                        |
| g-value                         | 0.62  |                        |
| Visible light normal properties | 0.68  |                        |
| Internal Gains                  |   |                        |
| People                          |   |                        |
| Internal heat gain              | 1.5 W/ m² (0.47 Btu/hr/ft²)<br>midnight–9 am & 3 pm–midnight (weekday)<br>on continuously (weekend) |                        |
| Lighting                        |   |                        |
| Lighting level                  | 200 lux   |                        |
| Maximum Power                   | 5 W/m² (1.58 Btu/hr/ft²)  |                        |
| Variation Profile               | 6 am–9 am & 3 pm–10 pm (weekday)<br>9 am–10 pm (weekend)  |                        |
| Switched-on-percentage          | 20%   |                        |
| Dimming profile                 | Manual/on-off, (200 lux)  |                        |
| Miscellaneous                   |   |                        |
| Maximum Sensible gain           | 3.5 W/m² (1.11 Btu/hr/ft²)  |                        |
| Variation Profile               | on continuously   |                        |
| Switched-on-percentage          | 50%   |                        |
| Air exchanges                   |   |                        |
| Infiltration                    |   |                        |
| Min Flow                        | 0.13 l/s m² (0.03 ft³/min/ft²)  |                        |
| Variation Profile               | on continuously   |                        |
| Mechanical ventilation          |   |                        |
| Min Flow                        | 0.30 l/s m² (0.06 ft³/min/ft²)  |                        |
| Variation Profile               | Occupants profile   |                        |
| System specific fan power (SFP) | 1.0 W/l/s   |                        |
| Vent. Heat recovery efficiency  | 65%   |                        |
| Cooling efficiency              | COP=2.5   |                        |
| Natural ventilation             |   |                        |
| Max Flow                        | 0.9 l/s m², t > 25 °C<br>(0.18 ft³/min/ft², t > 77 °F)  |                        |
| Variation Profile               | (weeks 19–37)   |                        |
| Heating and cooling             |   |                        |
| Heating set point winter        | 20 °C (68 °F)<br>(on continuously)  |                        |
| Cooling set point winter        | 25 °C (77 °F)<br>(on continuously)  |                        |
| Heating set point summer        | 23 °C (73.4 °F)<br>(on continuously)  |                        |
| Cooling set point summer        | 26 °C (78.8 °F)<br>(on continuously)  |                        |
| Hot water consumption           |   |                        |
|                                 | 250 l/m² pr. Year (0.82 ft³/ft² pr. year)   |                        |
| Surface reflectance variables   |   |                        |
| Ground (Albedo)                 | 0.20  |                        |
| External wall                   | 0.45  |                        |
| Windows                         | 0.15  |                        |
| Primary energy factors          |   |                        |
| Energy source                   | Factor  | Simulation             |
| Gas and oil                     | 1   | Heating and DHW        |
| District heating                | 0.8   | Heating and DHW        |
| Electricity                     | 2.5   | Cooling and Mech. Vent |





### **Paper III**

*“Urban Daylighting: the impact of urban geometry, façade reflectance  
and window to wall ratios on daylight availability inside buildings”*

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Submitted to: Building and Environment

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

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## **Abstract**

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

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

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

*Keywords: Urban Design, Daylight Strategies, Indoor Environment*

## 1 Introduction

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

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

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



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



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

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

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

## 2 Method

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

The hypothesis to be tested is:

- *In dense cities the orientation of the buildings has a minor importance on the daylight availability – it is the reflected light that plays the most important role.*
- *CBDM give a more precise and spatial understanding of the daylight availability compared to calculations performed under standard CIE overcast skies*

The hypothesis will be evaluated by challenging the urban density with different Height/Width ratios, orientations and fabrics (Window-to-Wall-Ratios (WWR) and reflectance). The simulations are per-

formed with the daylight simulation programme DAYSIM [9]. The DAYSIM/Radiance simulation parameters are given in Table 1.

Table 1: Radiance simulation parameters

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

## 2.1 Simulated rooms

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

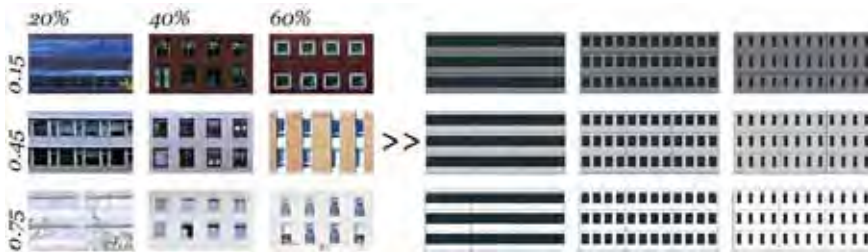


Figure 3: Simulation matrix of different WWR's (20%, 40% and 60%) and facade reflectances (0.15, 0.45 and 0.75)

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

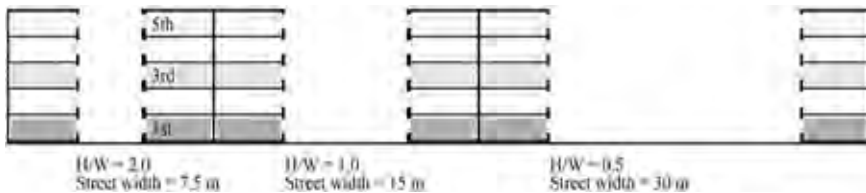


Figure 4: Urban street canyon, simulation setup

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

## **2.2 Evaluation methods**

### **2.1.1 Daylight availability within the room**

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

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

### **2.1.2 Daylight availability on the exterior vertical facade**

The daylight availability on the façade will be evaluated based on two metrics: 1) The Vertical Daylight Factor (VDF), and 2) a Vertical Daylight Autonomy (VDA). The Vertical Daylight Factor describes the amount of illuminance falling on a vertical surface of a building under overcast sky conditions [5,6]. The VDF is therefore limited and constricted by the same considerations as the daylight factor evaluation. Therefore a climate based metric, the Vertical Daylight Autonomy, has been proposed. The VDA describes the percentage of the occupied hours per year when a threshold illuminance on the façade can be maintained by daylight alone. For this study the threshold value is 10.000 lux, a threshold which in its magnitude equals to the empirically found irradiance of 50 W/m<sup>2</sup> at which blinds are retracted [18].

## **3 Results and Discussion**

### **3.1 Influence of moving vertically in the building**

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

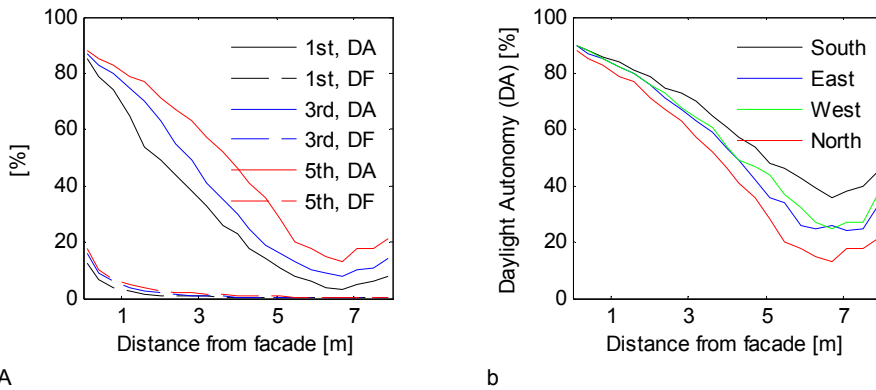


Figure 5: Northern orientation, street level of 1.5 m ( $H/W = 1$ ) and WWR of 40%. a) Daylight distribution through the room for different floor plans (1st, 3rd and 5th) for both Daylight Autonomy and Daylight Factor and b) orientations for the 5th floor.

The influence of orientation is depicted for the 5<sup>th</sup> floor, in Figure 5b, as expected the southern orientation has a higher DA, whereas the northern orientation is the lower bound. For the 1<sup>st</sup> and 3<sup>rd</sup> floor no real difference in daylight autonomy is observed, due to the buildings obstructing for the amount of sky visible, resulting in the lights entering the room primarily being diffuse and reflected light.

### 3.2 Influence of window-to-wall ratio

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



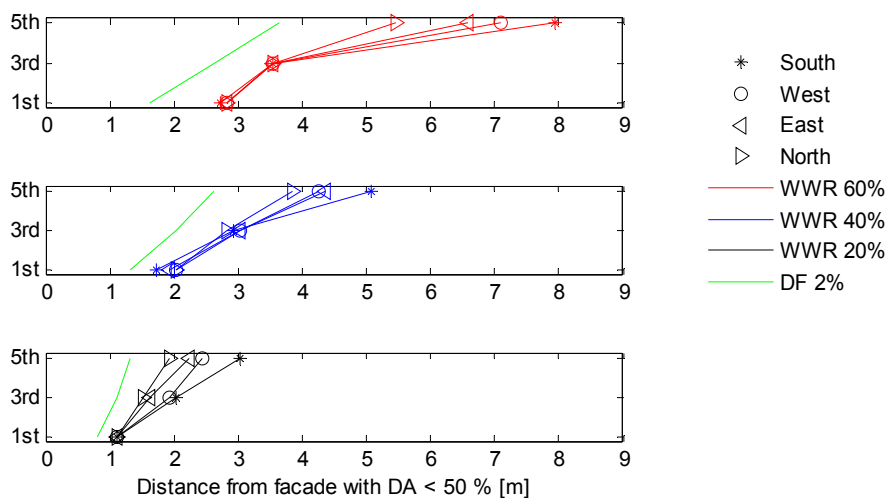


Figure 6: Distance from facade with DA below 50 % for street widths of 15 m, WWR varies from, 20 %, 40 % to 60 %. External reflectance 0.45.

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

### 3.3 Influence of opposing facade reflectance

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

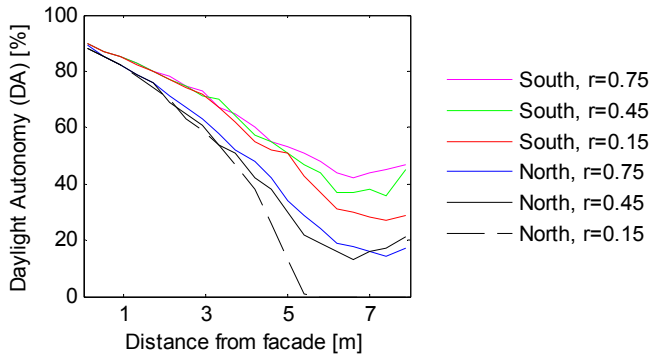


Figure 7: Daylight Autonomies on the 5th floor, through the room for north and south orientation and different reflectance's of the opposing building. H/W ratio of 1 and WWR of 40%.

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

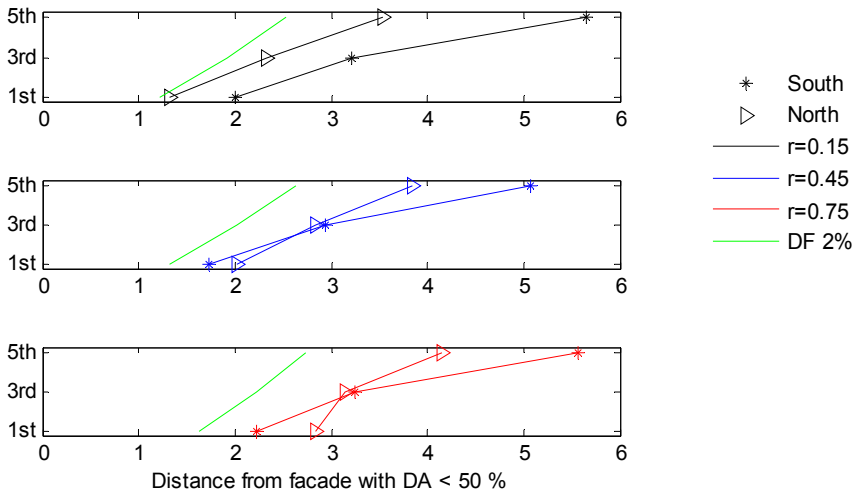


Figure 8: Distance from the facade with DA below 50 % as a function of floor level (1st, 3rd and 5th floor), H/W ratio of 1, WWR of 40%, and three different façade reflectance's. The green line show the distance from façade with DF of 2 %.

A very visible trend from

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

tion, which is what is seen in [8], where they found that south-facing buildings in urban context have higher energy consumption for artificial light compared to north-facing buildings.

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

### 3.4 Influence of changing Height/Width ratio

For large H/W-ratios the impinging on the variation in daylight availability on the facade from the different orientations is constant, see Figure , which suggests that for large H/W-ratios an orientation factor can be applied. However at a certain urban density threshold the inter-reflections between the buildings become important and the influence of orientations is no longer linear. When only evaluating the illuminance level on the facade from the VDF this behaviour cannot be seen, as the VDF in its nature is independent of orientation. Therefore only using the VDF will give a restricted result.

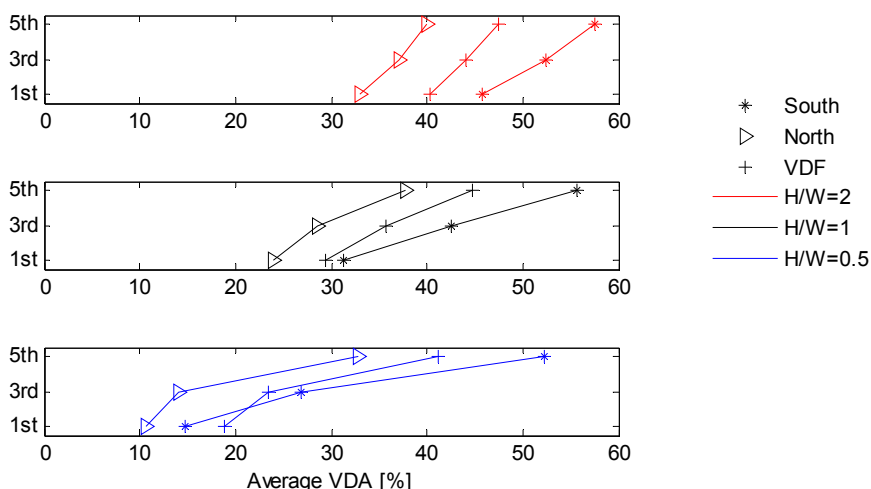


Figure 9: VDF and average VDA on the facade for northern and southern orientation. For WWR of 40% and different H/W-ratios.

In spite of the ratio between the VDA's is constant for the H/W ratio of 2, the daylight distribution within the room does not follow the same trend, see Figure . Here the DA lines for northern and southern orientation approximates each other the lower floor level. In dense cities the orientation of the buildings therefore has a minor importance on the difference in daylight availability. However, the results indicate that there is a preference for the northern orientations in terms of daylight availability at the lower floor plans. For H/W ratio of 1 and H/W ratio of 0.5 the light penetrates deeper into the room for the northern façade on the 1<sup>st</sup> floor and 3<sup>rd</sup> floor respectively. This is a consequence of the direct part of the daylight being reduced when the H/W ratio decreases, because a smaller amount of the sky is visible from the lower floor plans. For the dynamic simulations this has the effect that a higher proportion of the reflected light bounces of the southern façade, and then falls into the northern oriented rooms. Hereby the limit at which a DA threshold of 50 % is reached increases.

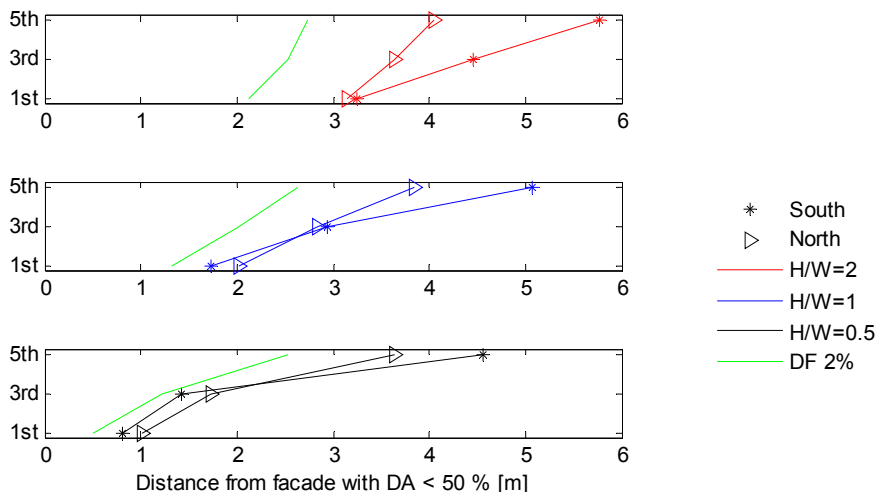


Figure 10: Penetration depth of DA 50 % within the space for southern and northern orientation and different H/W ratios, and daylight factor for the same room. WWR 40 %.

#### 4 Conclusions

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

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

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

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

## References

- [1] Bryan H., Moore J., Kwartler M., Jones T. 1981 "*The Utilization of Daylighting as an Urban De Strategy*" Annual conference of the International Solar Energy Society, Philadelphia, PA, USA, 1371-1375
- [2] Compagnon R: Solar and daylight availability in the urban fabric: *Energy Build* 2004;36: 321–328.
- [4] Käempf J, Robinson D: Optimisation of building form for solar energy utilisation using constrained evolutionary algorithms: *Energy and Buildingd* 2010;42:807–814.
- [5] Li D, Cheung G, Cheung K, Lam J: Simple method for determining daylight illuminance in heavily obstructed environment: *Build Environ* 2009;44:1074–1080.
- [6] Li D, Cheung G, Cheung K, Lam J: Evaluation of a simple method for determining the vertical daylight factor against full-scale measured data: *Indoor Built Environ* 2009;18(6):477–484.
- [7] Iversen A, Nielsen TR, Svendsen S. Illuminance level in the urban fabric and within the room: *Indoor and Built Environment*, 2011;20;4:456–463
- [8] Strømman-Andersen J., Sattrup P.A. 2011 "*The urban canyon and building energy use: Urban density versus daylight and passive solar gains*". *Energy & Buildings*, 43(2011), 2011-2020
- [9] Reinhart CF. Tutorial on the Use of Daysim Simulations for Sustainable Design. Harvard University Graduate School of Design, Cambridge, MA 02138, USA; 2010.
- [10] Perez P. R. Tregenza. Daylight coefficients. *Lighting Research and Technology*, 15(2):65{71, 1983.
- [11] Nabil A, Mardaljevic J. Useful daylight illuminance: a new paradigm to access daylight in buildings. *Lighting Research & Technology* 2005;37(1):41-59.
- [12] Reinhart C, Mardaljevic J, Rogers Z. Dynamic daylight performance metrics for sustainable building design. *Leukos* 2006;3(1):1-20.
- [13] DeKay M. 2010, "*Daylighting and Urban Form: An Urban Fabric of Light*", *Journal of Architecture and Planning Research*, 27:1, (Spring 2010)
- [14] BR10. Danish building regulation; Retrieved 30 June 2011, from <http://www.ebst.dk/bygningsreglementet.dk>.
- [15] BS8206-2:2008. Lighting for buildings - Part 2: Code of practice for daylighting; 2009.
- [16] Reinhart CF, Walkenhorst O. Dynamic radiance-based daylight simulations for a full-scale test office with outer venetian blinds. *Energy & Buildings* 2001; 33(7):683-697.

[17] Reinhart CF, Weissman DA: The daylit area - Correlating architectural student assessments with current and emerging daylight availability metrics, *Building and Environment* 50 (2012) 155-164

[18] Reinhart C. F. Daylight availability and manual lighting control in office buildings - simulation studies and analysis of measurements. PhD thesis, University of Karlsruhe, 2001.



## **Paper IV**

*“Urban design and pedestrian wind comfort – a case study of King Abdul-  
lah Financial District in Riyadh”*

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Accepted and in review process: Environment and Planning B: Planning and Design, 2011



**“Urban design and pedestrian wind comfort  
– a case study of the King Abdullah Financial District in Riyadh”**

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**Environment and Planning B-Planning & Design**

**Abstract**

This study reports progress made in using computational fluid dynamics (CFD) simulations for assessing wind comfort in very early phases of urban design and planning regulation. Wind is a microclimatic parameter that is often neglected by urban planners. However, high wind speed and turbulence (fluctuation of the wind) at pedestrian level is one of the most important environmental parameters determining user satisfaction in urban open spaces.

The aim is threefold: (1) to illustrate how technical scientific knowledge can be integrated in early urban planning and design decisions, (2) to indicate the need for the inclusion of pedestrian wind comfort studies in the design strategy, and (3) to show how planning regulation can ensure the climate comfort of urban spaces.

The computational capacity available nowadays allows us to calculate local microclimates inside the urban city. Relative wind speeds can be computed and the probability of their exceeding certain values can be calculated to evaluate the wind comfort for various pedestrian activities. In this study, numerical simulations were performed for two planned building layouts. The results show that the integration of technical knowledge can qualify the planning process and improve the overall outdoor comfort level – thus avoiding the need to introduce mitigating measures at later stages in the project.

*Keywords: Urban Design, Building Morphology, Wind Climate, Pedestrian Comfort, Microclimate, CFD.*

## Introduction

The industrial revolution started the transition from rural settlements to urban settlements. The urban fraction of the global population increased more or less linearly from about 13% in 1900 to 50% in 2010. The rapid urbanization of the world's population over the twentieth century is described in the 2009 Revision of the UN World Urbanization Prospects report (United Nation Report, 2009).

But what are the consequences of this dramatic urbanization and the intensive development of arable land to support it? Well, this is a complicated and multi-faceted question. From a global perspective, of most concern are the environmental consequences arising from the intense development of natural resources and increased pollution. From a local perspective, the high density of modern urban settlements affects the concentration of pollutants, socio-economics of cities, and people's life quality. Furthermore, adverse local climatic effects, such as a critical or dangerous wind environment, can affect the local economics of a new urban development or increase thermal discomfort through the creation of urban heat islands. The last few decades of rapid urbanization in Riyadh, Saudi Arabia, for instance, has been associated with large increases in local temperatures, which shows how important it is to understand the physics of introducing new urban areas.

It is generally agreed that the quality of outdoor urban spaces is important for social and economic life in cities. Urban spaces connect places, allow traffic to flow, make room for leisure and recreation, and give the city a face, shape and structure. A city can only be experienced from the space between the buildings and, as a consequence, the quality of urban space has a direct impact on the life quality of its people. Throughout history, urban space has always played a central role in the life of cities. However, modern cities have been strongly influenced by economic and technological values, which have led to a decline in the perceived significance of urban spaces (Madanipour, 1999; Gehl and Gemzøe, 1996).

We often think of people living their life inside buildings, but in fact we spend much of our time outside – between the buildings. It is there that much social interaction takes place (Gehl, 1986). Pedestrians passing in the street; people sitting on park benches, observing; business people gathering around the bus stop – waiting to get home to their families; a couple sipping coffee on a café terrace; children playing in a playground: all these scenes take place outside. The urban space in which these, and many other everyday activities take place, has a special social, cultural, and even economic significance. Gehl made an appeal to show concern for the people who were to move about between buildings, and urged an understanding of the subtle, almost indefinable – but definite – qualities of urban space, which have always been related to the interaction of people in cities, and pointed to the life between buildings as a dimension of planning and architecture that needs to be carefully treated.

The character of life between buildings changes from one social context to another, but architects, planners and engineers have defined a variety of criteria for the evaluation of the quality of urban space in the thinking of their professions. Urban climatology is one feature of the design of these spaces between buildings. Several studies have investigated how human beings negotiate urban space (Willis et al, 2004; Haklay et al 2001), but unfortunately, such urban design has not been combined with climate-responsive design to incorporate these two design elements into the planning regulatory of land-use development (Eliasson, 2000). Knowledge diffusion and case studies are critical for adopting and implementing urban planning policies that promote climate-responsive urban design (Ryser and Halseth, 2008).

The following sections review the progress that has been made in optimizing climate-responsive urban design, with a particular emphasis on the wind comfort of pedestrians as one key indicator of improved urban quality. The perception of urban space is partly cultural, partly social and partly physiological. So while this paper concentrates on the physical wind environment, this must be seen as part of a larger picture.

## **Background**

The design of outdoor spaces requires an understanding of the local environment. This has traditionally been the role of planners and architects, who have relied on intuition, personal experience, and the example of others. The ancient town planners of the Middle East have often been credited with superior understanding of the environment, which suggests that there are lessons to be learned for modern planners (Rahamimoff and Bornstein, 1981). For instance, a study of building archetypes shows how the traditional Arabic courtyard developed as a result of climate-responsive design (Ratti et al, 2003).

The importance of a comfortable and safe wind environment in the vicinity of buildings has also been emphasized by a large number of authors (Stathopoulos, 2006; Stathopoulos et al, 2004). Unfortunately, very few studies have attempted to integrate this know-how into the design process of a full-scale case study. Extensive studies have been conducted, but mainly in the Wind Engineering community, rather than in the Urban Design or Architectural community (Blocken et al, 2004). Indeed, wind studies of architectural and urban plans are rarely conducted, due to the high technical and scientific skills required for such analysis. Reiter further concludes “... *these tools are never used during the first phase of design, although the decisions taken at this first stage (volumes, implantation) are very important for wind distribution around buildings*” (Reiter, 2010). Experience shows that air flows around buildings can create uncomfortable or even dangerous wind speeds at street level. An understanding of air movement is vital for improving urban design and site planning. The layout, shape, mass and proximity of buildings can all have an effect on wind flow patterns. If potential problems, such as ‘funnelling’ or turbulence, are exposed, remedial action can be taken early on in the design process – for example, by changing the building’s position or designing topographical ‘wind break’ features.

Recognizing the importance of wind flow patterns, many urban authorities nowadays require studies of the pedestrian wind environment for large planning projects. In the past, most studies were conducted using wind tunnel modelling. Recently, Computational Fluid Dynamics (CFD) has become available as an optional tool. In the following, we will illustrate the use of CFD as a wind assessment and design tool for optimizing pedestrian wind comfort based on the case of the development of King Abdullah Financial District in Riyadh, Saudi Arabia.

## **King Abdullah Financial District in Riyadh (KAFD)**

The King Abdullah Financial District (KAFD), in Riyadh is set to become the leading financial centre of the Middle East, providing an attractive working environment for the growing workforce in the financial sector, see Figure 1.

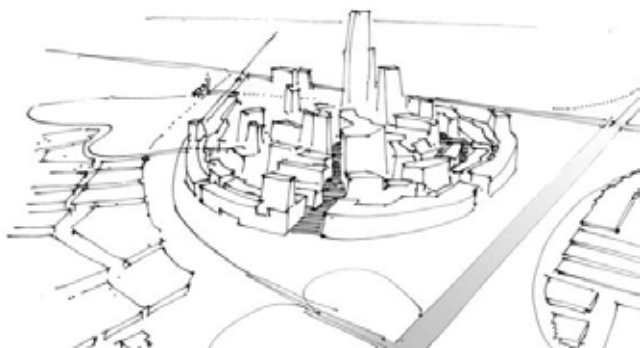


Figure 1: Conceptual sketch of the KAFD, Henning Larsen Architects

The plan for the KAFD was conceived as part of an overall programme of economic diversification. The site, located north of Riyadh (see Figure 2), is 1.6 million square metres and the development will have floor space of 3.5 million square metres, see Table 1. The KAFD will house the large community of professionals working in the financial sector and related industries, and host the headquarters of the Capital Market Authority, the Stock Exchange, banks, financial institutions, and other service providers, such as accountants, auditors, lawyers, analysts, rating agencies, consultants, and IT providers. Furthermore, leisure activity will be enhanced through the park area (the Wadi), shopping mall and sports arena. The master plan project won an international competition in January 2006.

|                     |  |
|---------------------|--|
| Location:           | Riyadh, Saudi Arabia                               |
| Client:             | Capital Market Authority of Public Pensions Agency |
| Site:               | 1,600,000 sq. m. (nearly 400 acres)                |
| Gross floor area:   | 3,500,000 sq. m.                                   |
| Year of design:     | 2008 – 2009  |
| Construction period | 2009 – 2011, Phase 1                               |
| Type of assignment: | First prize in international competition           |

Table 1: Basic information, KAFD

The vision for the KAFD was based on the site and the Arabian landscape. The main shape of a leaf forms a whole with the adjoining areas. Jacob Kurek, Architect MAA, the head of Henning Larsen Architects Middle East, explains the idea behind the KAFD: *“From our initial analysis and sketches, we were inspired to combine the Islamic traditions with modern technology. Focusing on the human scale and the climate, our work concentrated on the public realm. We wanted to create pedestrian-friendly open, green spaces that would become the heart of the KAFD and a destination in Riyadh”*.

The KAFD will contain a lot of outdoor activity areas. Among these are pedestrian areas for walking, apron areas, including open-air cafés and restaurants with outdoor serving, and recreational areas supporting general city life. These open spaces need shelter from the sun and wind – an aspect of great importance. The urban streetscapes are designed to achieve the optimum outdoor environment using the local potential. Mr Kurek explains: *“It was essential to create a master plan so robust and flexible that, in principle, it is independent of the qualities and design of the individual buildings within it”*. The new financial district for new ways of working would need a completely new city and building typology, which would emphasize the integration and diversity of the various elements and make the KAFD a city beacon.



Figure 2: Location of the KAFD in Riyadh, Saudi Arabia

The overall design of the KAFD is an “urban sand dune”, with a skyline where buildings towards the outskirts are lower with openings between them and the density and height increases as we move toward the central area, the Financial Plaza. The openings allow the wind to move into the district to ensure the removal of heat and pollutants. The KAFD covers a large area and contains a large number of building structures. Complex interactions between these structures will potentially affect the wind environment inside the district. The complexity of such interactions means it is not possible to predict the wind environment without performing either wind tunnel experiments or numerical simulations using the CFD method.

As is typical for many arid zones, the climate of the region is characterized by wide daily and seasonal thermal fluctuations. An average daily temperature range of 30–42° C in July is accompanied by low daytime relative humidity, intense solar radiation and strong late afternoon dusty winds, predominantly from the north. In winter, while minimum daily temperatures occasionally reach 10° C and winds are strong, clear skies and abundant solar radiation prevail in the daytime. (For meteorological data see Appendix).

### *A modern Wadi*

The heart of the district is “the Wadi”, cutting through the “urban sand dune” of the KAFD. The area is inspired by the Wadi Hanifa – a valley and riverbed – which traverses the whole present natural area at the site, see Figure 3.



Figure 3: The KAFD site, present of natural Wadi

The Wadi will be a grand landscape feature, with four branches, see Figure 4 – a pedestrian public space with attractive shops, cafès, restaurants, and cultural attractions. The Wadi will also connect the inner city with four major mosques.



Figure 4: Sketch of the KAFD with the Wadi defining the “veins” of the “leaf”

The design of the Wadi is as a dynamic shaded space with a rich landscape of trees, vegetation and water features. One of the definitions of the ‘oasis effect’ is the reduction of temperature at an isolated moisture source surrounded by an arid area. With inspiration from the old Arabian cities, the streetscapes are designed with diversity and a density to improve the microclimate. The building volumes are more intense (higher) around the Wadi to reduce the direct solar radiation.

## Objective and methodology

The overall objective of the design study was to generate a city layout that benefits from a good thermal and mechanical wind comfort. And we also wanted to show how technical scientific knowledge can be integrated in the early urban planning and design decisions.

A 3D computer model was constructed and 16 different wind directions were selected based on the available wind data. The computer model includes the district and some of the surrounding area. Outside the district, the modelling of roughness elements, such as building and terrain heights, is implicit and handled by applying an atmospheric boundary layer profile for the wind based on a distance of up to 10 km from the district. (The atmospheric boundary layer profile is a simple concept – when a fluid flows next to a fixed surface, friction slows down the molecules close to that surface. If you measure the speed of the air right at the ground, you will find the air is still; its velocity is zero. If you measure further away from the ground, you will see increasing speed until it reaches the maximum speed, which is called the free stream velocity.) Special focus areas inside the district are the Wadi and street levels. The simulation uses a selected reference wind velocity based on the available wind data together with a Weibull distribution of the wind speed, (Seguro and Lambert, 1999).

The interpretation of the computational results focused on the local acceleration of wind with respect to the reference wind velocity. Such local acceleration is the main way of identifying areas in the district that could have critical issues with regard to wind comfort. The results were related to comfort criteria for pedestrian activity in the district to evaluate possible areas which needed special attention. This information was coupled with the wind distribution (Weibull distribution of the wind speed) and directional frequency to compute the probability of exceeding the wind comfort level at various locations in terms of number of hours per year.

Two design schemes were assessed, named, the Base Scheme (Case 1) and the Revised Scheme (Case 2). The difference between the two schemes is the inclusion of a few buildings towards the eastern and southern sides of the main district.

## **Pedestrian Wind Comfort**

In contrast to the indoor environment, outdoor climatic parameters are quite variable and difficult to control. In the case of wind affecting pedestrians, the analysis is not straightforward. A clear separation between mechanical comfort and thermal comfort must be made. While mechanical comfort depends primarily on the wind speed and turbulence levels, thermal comfort is more subjective. Thermal comfort can be a result of wind speed, air temperature, relative humidity and solar radiation (Nikolopoulou and Steemers, 2003; Nikolopoulou and Lykoudis 2006; Stathopoulos et al, 2004).

### *Pedestrian Thermal Wind Comfort*

Many of the thermal parameters are strongly influenced by the individual physical and psychological conditions. Parameters such as exposure time, activity level, clothing insulation, age, gender, ethnicity, personal or psychological factors, e.g. different expectations and experience, affect the translation of a certain situation into a quality scale. And regional differences will introduce difficulties when treating wind environment in the Middle East and Europe with same guidelines or criteria. As a result of the wide variability of environmental impact factors and acceptance levels, the definition of guidelines and criteria for outdoor quality assessment is quite complex, as well as being the translation of particular perception information into a quality scale (Höppe, 2002).

There are, however, several thermal indices that describe the integrated effects of one or more of the climatic parameters on thermal perception or comfort of a person in indoor or outdoor urban space. In the 1970s and 1980s, the development of such indices, based on the heat balance models of the human body, and including wind speed, humidity, air and radiant temperature as well as clothing and activity level, came into focus. An important pioneer of these approaches was the thermal comfort index, Predicted Mean Vote (PMV), which predicts comfort votes on a seven-point scale (Fanger, 1972). The PMV equation rests on steady-state heat transfer – a state that hardly ever occurs in real life, particularly in an outdoor environment.

In recent years, a new index, the Universal Thermal Climate Index (UTCI), has been developed (Bröde et al, 2010). UTCI provides an assessment of the outdoor thermal environment based on the equivalence of the dynamic physiological response predicted by a model of human thermoregulation, which is coupled with a complex clothing model. The UTCI is defined as equivalent temperature for a given combination of wind, radiation, humidity and air temperature as the air temperature of a reference environment that produces the same strain index value. The operational procedure is available as software from the UTCI website ([www.utci.org](http://www.utci.org)).

If we consider the thermal challenge in the context of the KAFD, the most important issue is to keep the urban Wadi thermally comfortable. The Wadi acts as a link for the daily traffic between the offices and mosques. When it's time for the midday (Dhuhr) prayer, the people must travel from temperate office environments out into the natural environment. One scenario could be a hot sunny day with an outside air temperature of 40° Celsius ( $T_a$ ), a mean radiation temperature of 340° Kelvin ( $T_{mr}$ ), and a relative humidity of 10% (RH). How does the wind affect the thermal comfort in this case? In a windless environment (0.1 m/s) the UTCI physiological temperature is equivalent to 43.7° Celsius, but in a windy environment (10.0 m/s), it would be equivalent to 45.6° Celsius. The conclusion must be that, in the context of the KAFD, it will be beneficial to protect and minimize the wind in and around the Wadi. (Meteorological input, see Appendix).

### *Pedestrian Mechanical Wind Comfort*

The following section describes the assessment criterion which has been applied for evaluating mechanical wind comfort for the district.

Several criteria have been developed for evaluating simply the wind-induced mechanical forces on the human body, and the resulting pedestrian comfort and safety. It is also worth noting that there are significant differences between the criteria used by various countries and institutions to establish threshold values for tolerable or unacceptable wind conditions, even when a single parameter, such as the wind speed, is used as the criterion.

Wind effects do not necessarily imply wind discomfort. Bottema, (Bottema, 2000) states: “Pedestrian discomfort occurs when wind effects become so strong and occur so frequently that people experiencing those wind effects will start to feel annoyed and eventually will act in order to avoid these effects”. According to this definition, a suitable wind comfort criterion may consist of a discomfort threshold and an exceedance probability for that threshold. The perception of unacceptable or intolerable wind levels will thus vary depending on what activity people are engaged in – for example, wind comfort is much more of a factor when having an outdoor meal than when walking to work or parking the car.

It is worth mentioning that a new wind ordinance has been approved in the Netherlands just recently, after several years of intense effort by several experts, architects and engineers. Table 2 summarizes the code criteria in terms of hourly averaged wind speed at pedestrian level. As an indicator of wind comfort, the code uses a threshold wind speed of 5 m/s; the threshold for danger is 15 m/s. Grades of comfort are introduced related to the probability that a threshold wind speed will be exceeded (Willemsen and Wisse, 2007).

| Wind comfort                     |              |               |                           |              |          |            |          |
|----------------------------------|--------------|---------------|---------------------------|--------------|----------|------------|----------|
| P(U > 5m/s) in % hours per year  | Grade        | Activity area |                           |              |          |            |          |
|                                  |              | 1.Traversing  |                           | 2. Strolling |          | 3. Sitting |          |
| < 2.5                            | A            |               | Good                      |              | Good     |            | Good     |
| 2.5 – 5.0                        | B            |               | Good                      |              | Good     |            | Moderate |
| 5.0 – 10.0                       | C            |               | Good                      |              | Moderate |            | poor     |
| 10. – 20.0                       | D            |               | Moderate                  |              | poor     |            | poor     |
| > 20.0                           | E            |               | poor                      |              | poor     |            | poor     |
| Wind danger                      |              |               |                           |              |          |            |          |
| P(U > 15m/s) in % hours per year | Limited risk |               | 0.05-0.3 % hours per year |              |          |            |          |
|                                  | Dangerous    |               | > 0.3 % hours per year    |              |          |            |          |

Table 2: 1. Criteria for wind comfort and danger in NEN 8100, according to Willemsen and Wisse, 2007. 1. **Traversing**: business walking, brisk or fast walking (car park, street, pavement); 2. **Strolling**: pedestrian walking, leisurely walking, rambling, strolling (path, building entrance, shopping street, public park); 3. **Sitting** for a long period of time, lying down (terrace, street café or restaurant, swimming pool)

An exceedance probability of 5% indicates that in 5% of the hours in a year, i.e. 438 hours, the wind comfort for Grade B will be acceptable for traversing and strolling. However it also indicates the same area exhibits only moderate wind comfort for sitting.

Due to the lack of local criteria in Saudi Arabia, the threshold criteria selected for the evaluation of the wind comfort is mainly defined as for areas in Europe. This has to be acknowledged when interpreting the results of the wind comfort analysis for the warmer climate of Saudi Arabia.



## The CFD Method for Predicting Wind Environment

CFD (Computational Fluid Dynamics) is a powerful tool for analysing fluid flows. It is a computer-based simulation technique providing an approximate three-dimensional solution to the equations governing fluid motion. CFD builds a computational model that represents the system and applies fluid flow physics to this virtual prototype. It can handle both complex geometries and time-dependent flows.

The model divides the region of interest into a large number of smaller volumes referred to as mesh or grid cells. The solution consists of values of flow parameters, such as velocity, pressure, temperature, and gas concentration, calculated in each of the grid cells. In essence, it provides a complete three-dimensional picture of complex fluid flow. The CFD software used by RAMBØLL is ANSYS CFX v. 12.1. The software is a fully general-purpose 3D CFD program, capable of handling fluid flow, turbulence, heat transfer, multi-component flow, multiphase, chemical reaction, combustion and radiation.

### Geometry

The KAFD covers an area of roughly 1.8 km by 1 km, and includes a large number of buildings both inside and outside the ring road. For the purposes of wind comfort assessment, all buildings and structures in the area have to be included in the model because of the strong interaction between the buildings, see Figure 5. Moreover, buildings outside the assessment area up to 2H from the site, where H is the height of the tallest building inside the district, also need to be explicitly included.

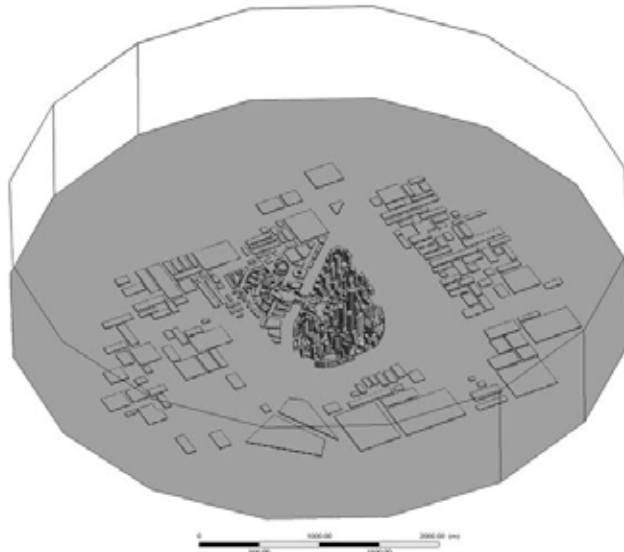


Figure 5: The complete calculation domain with a diameter of 5 km.

### Calculation mesh

The entire geometry is divided into a finite number of smaller volumes, which results in what is called a calculation mesh. The mesh consists of approximately 67.9 million tetrahedral volumes and 18.1 million prismatic volumes. This high number of mesh cells enables the resolution of low-speed features of the wind flow in the vicinity of the buildings, and makes it possible to capture small-scale flows within the built-up area and close to the pedestrian areas.

To minimize the overall number of elements in the model, the mesh has only been refined in the regions of interest, which can be seen on Figure 6. The regions of interest are close to ground and building structures.

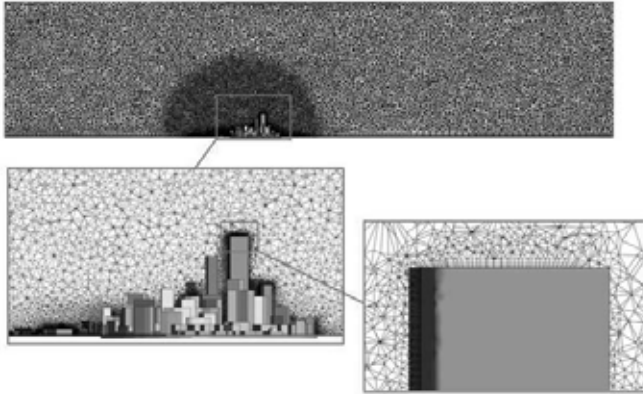


Figure 6: The mesh is shown on a plane slicing through the KAFD.

### *Wind Characteristics of the Site*

The KAFD is a special site for a wind microclimate assessment. The existing buildings are not particularly tall and are well-spaced around the planned district area. An analysis of the “open-site” wind conditions in different parts of the district is therefore very useful and pertinent for quantifying the relative windiness of various parts of the district. We consider the meteorological data adjusted to the site in what follows.

Knowing the prevailing wind direction allows us to focus on the likely impact of these winds on the site, except where the building mass or layout indicates that winds from other directions are likely to be important. This means that, taking account of other design constraints, it is desirable that the district is arranged so that the maximum acceleration of the wind due to the building mass occurs for the lightest and most infrequent wind speeds and directions, with due consideration given to ground roughness. This will optimize pedestrian comfort.

The wind data applied in the analysis was extracted from meso-scale MM5 meteorological simulation and daily averaged wind data for Riyadh at a reference height of 10 meters above ground level. Detailed high-resolution measurements could have improved the analysis, but unfortunately were not available.

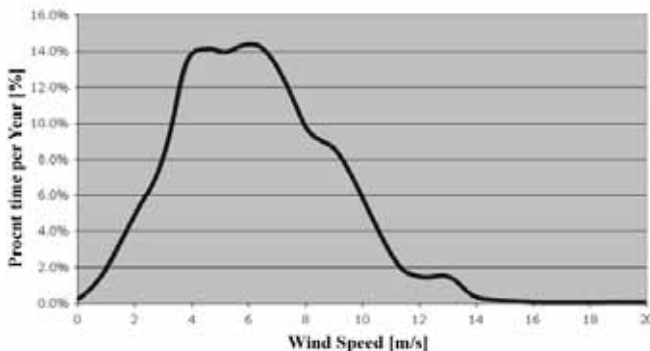


Figure 7: Wind speed frequency at a reference height of 10 meters above ground level averaged over 5 years (from 2001 to 2005)

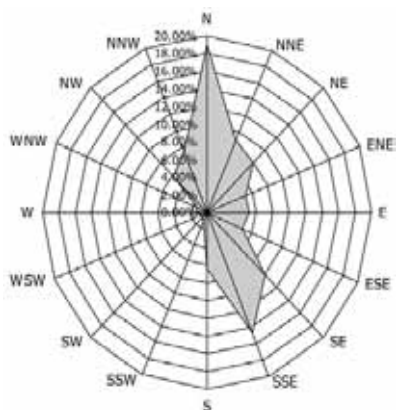


Figure 8: Wind direction frequency at a reference height of 10 meters above ground level averaged over 5 years (from 2001 to 2005)

The wind environment around the district is mainly dominated by wind from the north and south. Winds from the west are rare.

Both the speed frequency and the direction frequency wind availability data are applied in the numerical simulation for the wind comfort. Local wind acceleration between the buildings must be limited because it can affect pedestrian comfort even when wind speeds are relatively low, and downbursts in the vicinity of high-rise buildings are also important.

## Results and Discussion

To evaluate wind comfort inside the district, 16 different wind directions were simulated for two cases: Case 1 (Base Scheme) and Case 2 (Revised Scheme), see Figure 9.

### Case 1 - Base Scheme



### Case 2 - Revised Scheme

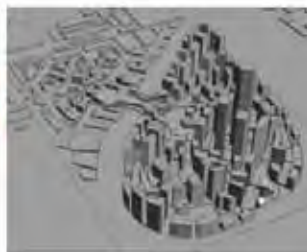


Figure 9: Site isometric view of the CFD model: Left Case 1 – the Wadi is not shielded; Right: Case2 – change in building layout towards the south, east and north

In the following section, the exceedance probability for the threshold criteria throughout the Wadi is illustrated. This is a sum for all wind directions during the year. The results were computed from the wind data using the wind profile and the reference wind velocity at 10 meters above ground level. Furthermore, to evaluate the pedestrian wind comfort, wind distribution frequency was applied to compute the exceedance probability using the critical threshold wind velocity of 5 m/s, see Table 3.

### Wind comfort

The irregular layout of the buildings in the district creates a general sheltering effect at street level and the level of the Wadi. Local wind accelerations occur mostly in the areas facing directly into the wind, and areas facing away from the wind are effectively shielded. Below are the wind discomfort plots for Case 1 and Case 2 around the Wadi level, see Figure 10 and Figure 11.

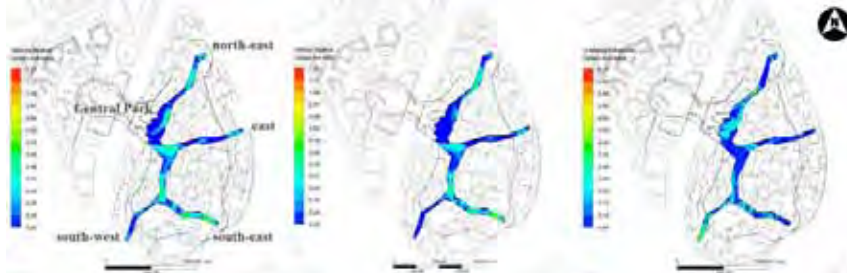
**Case 1 - Base Scheme****Case 2 - Revised Scheme****Difference**

Figure 10: Contour plot showing the relative wind velocity at 2m above the Wadi level for Case 1, Case 2 and the differences.

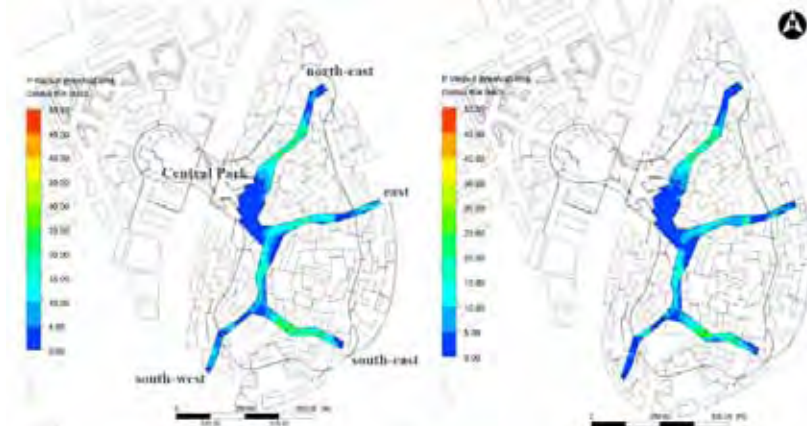
**Case 1 - Base Scheme****Case 2 - Revised Scheme**

Figure 11: Contour plot showing the probability of exceedance of the critical velocity at 2m above the Wadi level for Case 1 and Case 2. The critical velocity is defined as:  $U_{critical} = 5 \text{ m/s}$ .

The Wadi covers a large area with its four branches, and although it is located below ground level, there is a risk of wind being forced down into this sub-terrain channel, especially when the wind direction is aligned with one of the branches. Generally, the wind comfort at Wadi level is good, which promotes traversing and strolling. Especially the areas around the entrance to the Wadi from the central park show very good levels of wind comfort, enabling all types of activity.

In Case 1, channelling effect occurs predominantly for the north-east and south-west branches, see Figure 11. A reason for this is found in the building topology at the ends of the north and the south east branches. Here the Wadi terminates and is not shielded from the outer terrain, which creates a large gap to the nearest buildings, see Figure 12. This gap traps the wind into the district, and from there, the air propagates into the district, creating local wind accelerations. In these zones, the wind gets accelerated into the alleys, thereby creating wind velocity levels above the threshold criteria for wind comfort. The conditions are acceptable for traversing, but strolling or sitting would be adversely affected by the wind speed.

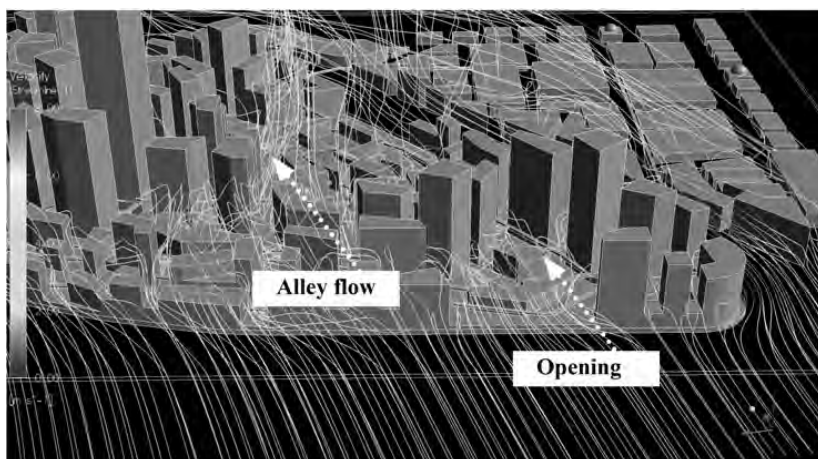


Figure 12: Problem area for entrance flow to the Wadi

In contrast, the branches of Case 2 are shielded behind a row of buildings, and although there is a risk of high wind speeds in the north-east and south-east branches, the overall wind environment for the Wadi with respect to pedestrian comfort is more moderate.

### *Comparisons and evaluation*

In the revised scheme (Case 2), the overall wind environment ranges from good to moderate, but there are still a number of concerns within the district. Some of these problem areas can be handled by implementing local measures to control the local wind environment. However, such measures will not solve all problems, and the pedestrians could be affected to a considerable extent. This is also the case for pedestrian thermal comfort, where there are a few critical areas in the district. Threshold levels for the wind criteria are more diffuse because they have been developed for areas in Europe. The KAFD will have less sensitivity with regard to strolling and traversing, since the local climate has an increased thermal profile compared to Europe. Small increases in wind speed can actually improve thermal comfort. This is reinforced by the need to bring air into the district to dilute pollutants and the remove of heat gains from the sun and the buildings. These needs act somewhat in contradiction to the wind comfort criteria. However, a balance can be found at an early stage of the project design by combining the different assessment tools for wind comfort, air quality and local air ventilation needed for the urban area to obtain an overall improved design scheme and thus avoid the creation of urban heat island problems.

Both schemes result in a reasonable wind environment. However, direct comparison between the two shows that the inclusion of a few buildings in the building perimeter in Case 2 gives a better wind environment and thereby an overall better wind comfort level.

### **Conclusion**

If the soul of urban design is to provide a pleasing and protective environment, then microclimate considerations become the central part of urban planning. The quality of life of millions of people living in cities can be improved if the factors that affect the urban microclimate are understood and if the cities are designed and planned accordingly. If we use the opportunities and constraints of the local climate in the design of spaces between buildings, the comfort of pedestrians and others will be enhanced, encouraging people to conduct more activity outdoors, and in turn to moderate their dependence on air-conditioned buildings and private vehicles. Integrated design on an urban scale will also

enable individual buildings to make better use of “natural” energy, improving the comfort of occupants and lessening their reliance on fossil fuels for heating and cooling.

As part of an overall integrated design, our study shows that optimizing the urban layout can improve the overall wind comfort level. The technical wind analyses have also had an essential impact on the KAFD’s visual appearance. The KAFD will be characterized by its clear line of demarcation and the dynamic variation of curved streets that differ from the orthogonal grid of Riyadh, creating a counterpart to the old city of Riyadh.



*Figure 13: A, the KAFD site in April 2008; B, the KAFD development in November 2010*



*Figure 14: the KAFD construction site in March 2011*



Figure 15: Visualization of the KAFD Wadi in January 2013

The hope is that the KAFD's residents will experience the morning sun of Riyadh in the way Gehl put it: *"It's really wonderful to wake up in a city where every day you realize that today the city is a little bit better than yesterday"* (Gehl, 2009).

### Acknowledgement

We would like to express our sincere appreciation to Christian Nørgaard, Project Manager at Rambøll and the KAFD design team at Henning Larsen Architects A/S. Special thanks to Jacob Kurek, Associate, Architect MAA, for supporting the research and publication.

### Appendix

| Month  | Jan  | Feb  | Mar  | Apr  | May  | Jun  | Jul  | Aug  | Sep  | Oct  | Nov  | Dec  |
|--|------|------|------|------|------|------|------|------|------|------|------|------|
| Dry Bulb temperatures (°C)                   | 14.0 | 16.7 | 20.3 | 25.9 | 32.1 | 35.2 | 36.2 | 36.4 | 33.0 | 27.6 | 21.6 | 14.9 |
| Relative Humidity (%)                        | 43   | 34   | 30   | 24   | 15   | 12   | 8    | 11   | 16   | 21   | 24   | 57   |
| Wind Speed (m/s)                             | 3.0  | 3.0  | 3.6  | 3.6  | 3.6  | 3.7  | 4.3  | 3.5  | 2.5  | 2.2  | 1.1  | 2.8  |
| Direct Solar Radiation (Wh/m <sup>2</sup> )  | 5652 | 5601 | 5502 | 5428 | 6330 | 7613 | 7049 | 6879 | 6970 | 7264 | 5595 | 4592 |
| Diffuse Solar Radiation (Wh/m <sup>2</sup> ) | 1314 | 1711 | 1982 | 2362 | 2378 | 1962 | 2164 | 2017 | 1719 | 1249 | 1357 | 1236 |

Table 3: Meteorological input data from Riyadh, Daily Avg. values, U.S. Department of energy (<http://www.eere.energy.gov/>)

## References

- Blocken B, Carmeliet J, 2004, "Pedestrian Wind Environment around Buildings: Literature Review and Practical Examples" *Thermal Envelope and Building Science* **28**, No 2
- Bottema M, 2000, "A Method for Optimisation of Wind Discomfort Criteria", *Building and Environment* **35** 1-18
- Bröde P, Jendritzky G, Fiala D, Havenith G, 2010 "The Universal Thermal Climate Index UTCI in Operational Use", Proceedings, Adapting to Change: New Thinking on Comfort, Windsor, London
- Eliasson I, 2000, "The use of climate knowledge in urban planning" *Landscape and Urban Planning* **48** 31-44
- Erell E, Pearlmuter D, Williamson, 2011, "Urban Microclimate – Designing the Spaces between Buildings" 1<sup>st</sup> ed. *Earthscan Ltd, Dunstan House, 14a St Cross Street*, London, UK
- Fanger P O, 1972, "Thermal Comfort", McGraw-Hill Book Company, New York
- Gehl J, 1986, "Life Between Buildings – Using Public Space" *Van Nost. Reinhold*, New York
- Gehl J, Gemzøe L., 1996, "Public Spaces – Public Life" *The Danish Architectural Press & The Royal Danish Academy of Fine Arts, School of Architecture*, Philip de Langes Allé 10, DK-1435 Copenhagen K, Denmark
- Gehl J, 2009, "Contested Streets" – a Transportation Alternatives documentary *127 West 26<sup>th</sup> Street, Suite 1002, New York, NY 10001*
- Golany G S, 1995, "Urban Design Morphology and Thermal Performance", *Atmospheric Environment* **30** 455-465
- Haklay M, O'Sullivan D, Thurstain-Goodwin M, Schelhorn T, 2001, "So go downtown: simulating pedestrian movement in town centres" *Environment and Planning B: Planning and Design* **28** 343-359
- Höppe P, 2002 "Different aspect of assessing indoor and outdoor thermal comfort", *Energy and Buildings* **34** 661-665
- Madanipour A, 1999, "Why are the design and development of public spaces significant for cities?" *Environment and Planning B: Planning and Design* **26** 879-891
- Nikolopoulou M, Steemers K, 2003, "Thermal comfort and psychological adaptation as a guide for designing urban spaces" *Energy and Buildings* **35**, No. 1, 95-101
- Nikolopoulou M, Lykoudis S, 2006, "Thermal comfort in outdoor urban spaces: Analysis across different European countries" *Building and Environment* **41**, No. 11, 1455-1470
- Rahamimoff A, Bornstein N, 1981, "Edge conditions – climatic considerations in the design of buildings and settlements", *Energy and Buildings* **4** 43-49
- Ratti C, Raydan D, Steemers K, 2003, "Building form and environmental performance: archetypes, analysis and an arid climate", *Energy and Buildings* **35** 49-59
- Reiter B, 2010, "Assessing wind comfort in urban planning" *Environment and Planning B: Planning & Design* **37** 857-873



Ryser L, Halseth G, 2008, "Institutional barriers to incorporating climate responsive design in commercial redevelopment" *Environment and Planning B: Planning and Design* **35** 34-55

Seguro J V, Lambert T W, "Modern estimation of the parameters of the Weibull wind speed distribution for wind energy analysis", *Journal of Wind Engineering and Industrial Aerodynamics* **85** 75-84

Stathopoulos T, Wu H., Zacharias J., 2004, "Outdoor human comfort in an urban climate" *Building and Environment* **39** 297-305

Stathopoulos T, 2006, "Pedestrian level winds and outdoor human comfort" *Journal of Wind Engineering and Industrial Aerodynamics* **94** 769-780

United Nation Report, 2009, "World Urbanization Prospects: The 2009 Revision" *Department of Economic and Social Affairs*, Population Division, UN.

Walton D, Dravitzki V, Donn M, 2007, "The relative influence of wind, sunlight and temperature on user comfort in urban outdoor spaces" *Building and Environment* **42**, No. 9, 3166-3175

Willemsen E, Wisse J A, 2007, "Design for wind comfort in The Netherlands: Procedures, criteria and open research Issues", *Journal of Wind Engineering and Industrial Aerodynamics* **95** 1541-1550

Willis A, Gjersoe N, Havard C, Kerridge J, Kukla R, 2004 "Human movement behaviour in urban spaces: implications for the design and modelling of effective pedestrian environments" *Environment and Planning B: Planning and Design* **31** 805-828

Whyte W H, 1980 "The Social Life of Small Urban Spaces" *Project for Public Spaces*, New York





## **Paper V**

*“Integrated Design – paradigm for the design of low-energy  
office buildings”*

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Published in proceedings: ASHRAE Winter Conference, 2011, Las Vegas, Nevada

# 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.

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## THE CASE

This case revolves around the design of a 6-storey (15,000 m<sup>2</sup>) 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<sup>2</sup>/year, but a wish for 70 kWh/m<sup>2</sup>/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/m²K                |                       |
| Heat transfer coefficient of glazing (U-value)                    |                        | 1.19 W/m²K                |                       |
| 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/m²K                 |                       |
| 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 <sup>-1</sup>      | 0.17 h <sup>-1</sup>  |
| Mechanical ventilation <sup>a)</sup>                              |                        | 1.4 l/s m <sup>2</sup>    | 0.0 l/sm <sup>2</sup> |
| Heat exchanger efficiency of mechanical ventilation <sup>b)</sup> |                        | 0.8                       | -                     |
| Specific fan power, SFP   |                        | 2.5 KJ/m <sup>3</sup>     | -                     |
| Venting rate (maximum) <sup>c)</sup>                              |                        | -                         | -                     |
| Mechanical cooling, efficiency (COP)                              |                        | 2.5                       | -                     |
| Internal loads from persons and equipment                         |                        | 10 W/m <sup>2</sup>       | 0 W/m <sup>2</sup>    |
| General lighting  |                        |                           |                       |
|   | Illuminance set point  | 200 lux                   | -                     |
|   | Max. power             | 6 W/m <sup>2</sup>        | 0 W/m <sup>2</sup>    |
|   | Min. power (stand-by)  | 0.5 W/m <sup>2</sup>      | 0 W/m <sup>2</sup>    |
| Task lighting   |                        |                           |                       |
|   | Illuminance set point  | 500 lux                   | -                     |
|   | Max. power             | 1 W/m <sup>2</sup>        | 0 W/m <sup>2</sup>    |
|   | Min. power             | 0 W/m <sup>2</sup>        | 0 W/m <sup>2</sup>    |

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).

## IDENTIFYING 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.

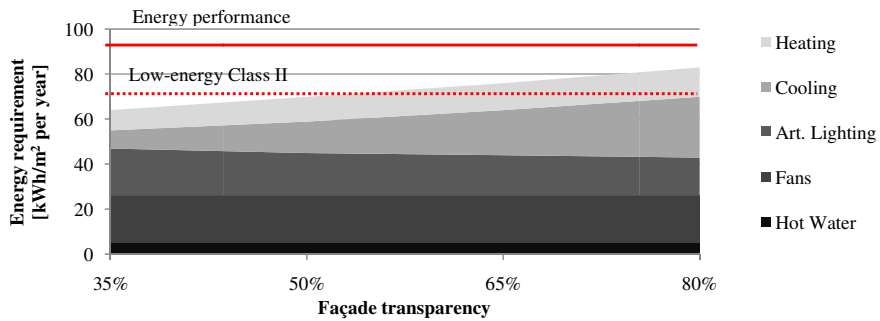
**Table 3. Energy performance was simulated in accordance with the European Directive EPBD as defined in (DS/EN 15251:2007). All energy demands are stated in kWh/m<sup>2</sup> per year and daylight factors were simulated for the third row of tables from the façade.**

|                     | 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

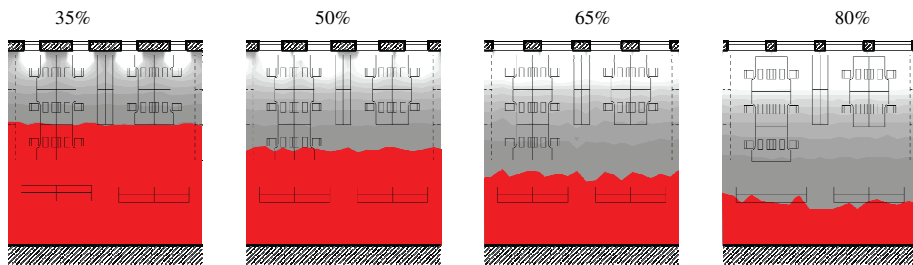
When presenting the results, it was important that they would help facilitate the design development. By showing the effect of the façade transparencies on the total energy demand and its components, coupled with visualisations of the daylight availability and pictures of reference projects with corresponding 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**

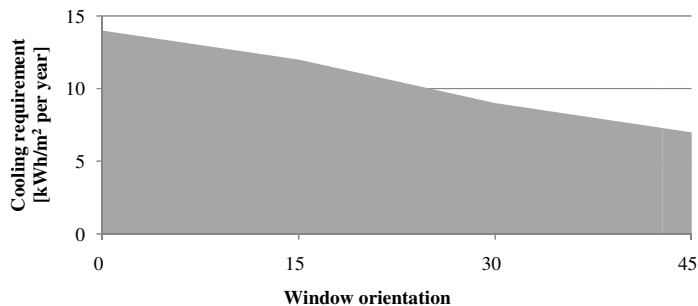
Thermal and daylight simulations were carried out for a section of the building with a façade transparency of 50% and window orientations ranging from 0° (east) to 45° (northeast). Default values were assigned to all variables except those that related to the orientation of the window.

**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<sup>2</sup> per year and daylight factors were simulated for the third row of tables from the façade.**

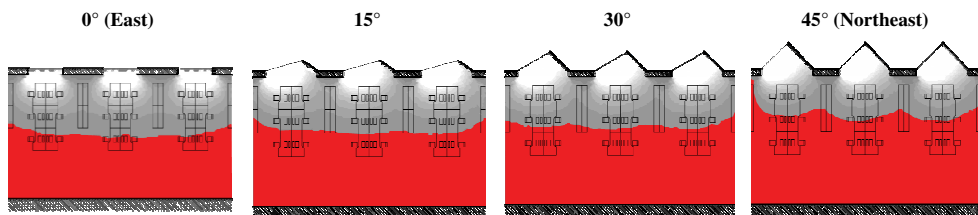
| Energy performance  | Window orientation |     |     |                 |
|---------------------|--------------------|-----|-----|-----------------|
|                     | 0° (East)          | 15° | 30° | 45° (Northeast) |
| Heating             | 11                 | 12  | 13  | 14              |
| 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.



**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 15° to 30°, and since no major deterioration in daylight levels was registered, a 30° 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

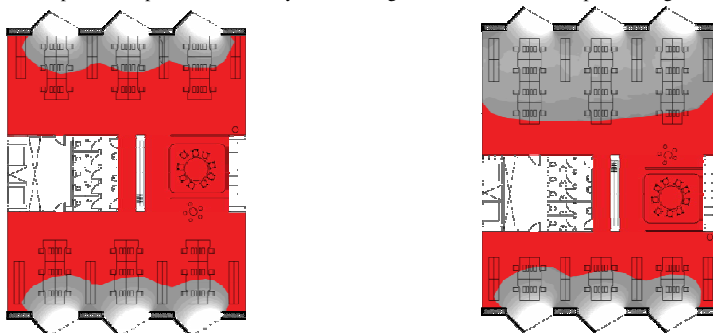
Thermal and daylight simulations were carried out for a characteristic section of the building with double room height towards the east and the asymmetrically placed core towards the west. Default values were assigned to all variables.

**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<sup>2</sup> 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<sup>2</sup>/year well below the requirements stated in the competition brief.

## ACKNOWLEDGMENTS

The authors wish to thank Henning Larsen Architects A/S and the external collaborators for their support and the opportunity to be part of the design process.

## 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 VI**

*"A methodological study of environmental simulation in architecture and engineering - Integrating daylight and thermal performance across the urban and building scales"*

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In proceedings: Symposium on Simulation for Architecture and Urban Design, 2011,

Boston, MA, USA



# A methodological study of environmental simulation in architecture and engineering.

## Integrating daylight and thermal performance across the urban and building scales.

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**Keywords:** Integrated design methodology, holistic design, architectural theory, design process, energy optimization, environmental simulation

### Abstract

This study presents a methodological and conceptual framework that allows for the integration and creation of knowledge across professional borders in the field of environmental simulation. The framework has been developed on the basis of interviews with leading international practitioners, key theories of environmental performance in architecture and engineering, and a range of simulation experiments by the authors. The framework is an open structure, which can continuously be renewed and contributed to by any author.

The value of the framework is demonstrated, using it to map a series of simulation studies, emphasising the multidimensionality of environmental performance optimization. Clarifying the conceptual interconnectivity between architecture and engineering, - agency and physics, - not only enhances communicative power and the dissemination of knowledge, but becomes instrumental in pointing out the need for improving metrics, software and not least the performance of the built environment itself.

### 1. INTRODUCTION

Though environmental simulation software has been around for decades, developed and used mainly by engineers, it has only recently become widely available to

architects without an extreme specialization in physics and computation. Following this introduction of technology into the field of architecture, comes a stimulating shift of attention in terms of the aims of simulation research: that of studying the relations between different spatial scales, exploring form and material organization as means to produce desirable human environments, rather than the singular optimization of specific technical subsystems. Architecture can in itself be considered an open system of environmental technology that is not just technical but informational, social and cultural too.

A problem in current energy optimization in architecture and engineering is a certain blindness towards the multiple facets of performance of each part of the complex systems of built environments. Buildings failing to use form and materials to direct nature's forces for the benefit of the occupants get wrapped up in sub-optimized comfort and energy delivery systems to compensate for their lack of environmental qualities. Technical systems, that is, that have high embodied energy and a much shorter lifespan than the building structure and its skin, and as a consequence a higher detrimental impact on the environment.

There is a need for a holistic view and an integrated approach that emphasizes that the layers, scales, components, materials, uses etc. of a building or a built environment plays multiple roles, and must be understood in temporal dimensions that include the day to day, seasonal,

yearly and lifetime dimensions. This holistic view should embrace the multidisciplinary of the design professions, and establish a common conceptual framework.

The research questions behind this paper are:

How can a conceptual framework be devised, that allows for the synthesis and integration of environmental performance information in the built environment across the architecture/engineering professions? How can the dual aspects of operational and embodied energy in architecture be linked? How can the spatial and temporal dynamics of the performance of the built environment be highlighted, to improve communication, software and metrics in environmental simulation?

To answer these questions, 3 principal approaches are used, including interviews with leading practitioners in architecture and engineering, a literature review and the simulation experience of the authors – an architect and an engineer. The framework devised can potentially be used to guide future research, mapping the impact of design variables on environmental performance, and act as a support when establishing the decision hierarchies necessary in any design project regardless of scale, to meet the demands of rapid decision making and efficiency of solutions required today.

## 2. METHODS AND METHODOLOGY

A distinction between methods and methodology needs to be made. Methods are ways of using tools or techniques using a prescribed procedure towards a certain aim. Following a tutorial of how to do a daylight analysis could be an example. Methodology instead considers multiple methods, critically examining the assumptions behind them and examines the interrelationships between output from different methods. Though architects rarely claim to follow specific design methodologies, a new attention to design methods and processes is emerging in order to deal efficiently with the realization that even the first sketches potentially carries a strong impact on the energy and environmental performance of the design. In particular engineers have begun to promote 'integrated design processes' in which the architect-engineer collaboration is shifted forward into the initial design phases, instead of the traditional process of engineers following up on designs already elaborated by architects. This could possibly result in some rivalry for position and influence on design among

the professions, but the view taken in this paper is that collaboration is necessary and beneficial for the overall good of the built environment. The paper is a result of a collaboration of an architect and an engineer, and the methodological framework proposed here is intended to clarify the basis for the use of environmental simulation in the early design phases as a common platform across the professions.

The methodological framework presented in this paper, is in itself the outcome of different research methods: The hypothesis that architectural scale is a key factor in energy efficient design, connecting both integrated design processes, operational efficiency and lifecycle analysis, was derived from interviews with leading practitioners in architecture and engineering from the offices of Foster and Partners (Behling and Evenden 2009), Baumschlager & Eberle Architekten (Eberle 2008) and Transsolar (Schuler 2008). The theory behind the hypothesis was developed through a literature review. A series of simulation studies using Copenhagen as a reference were carried out by the authors to test the hypothesis in regards to solar access, daylight, thermal and energy performance in urban and basic building design, some of which are presented in the demonstration case below.

## 3. ARCHITECTURAL PRACTICE

While their architectural interests and formal expression differ significantly, the architect offices of Foster and Partners and Baumschlager and Eberle share the notion based on their experience in design and built work, that the greatest environmental impacts come with design decisions taken at the scale of the city, and that impacts decrease with minor scale decisions. Argued this way, optimization of the basic formal and material properties of a design, takes priority compared to the optimization of technical service systems, - conveniently weighting the influence of the architect's design responsibilities over those of the engineers. Both offices employ specialists working with simulation, and have developed tailor-made software applications to suit the offices' workflows. Fig. 2 shows a diagram by Foster and Partners presented with the Masdar project, expressing the notion that design decisions taken at the largest scales of a project impact the environment the most, and are inverse proportional to the costs of the solutions. While 'environmental gain' includes other factors than energy, - it could be interpreted aesthetically, - energy plays the dominant role in the diagram's highlighting of

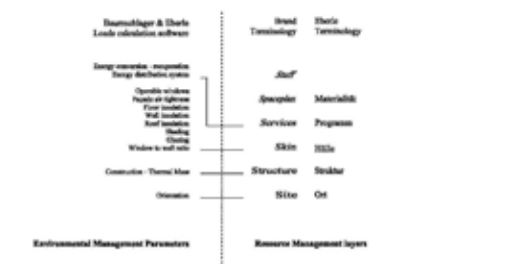
passive and active measures and the implementation of renewable energy systems.



**Figure 1:** Foster and Partners: Scale, systems, costs and environmental gain diagram.

In the design approach of Dietmar Eberle attention towards the durability of the different layers that constitute a building govern a hierarchy of design decisions. Each layer: place, load bearing structure, envelope, programme and materiality carry weight in the design process according to their relative permanence, so as to preserve the resources invested in them. Where Foster and partners employ advanced form to harness the benefits of nature’s forces, Baumschlager and Eberles approach highlights architecture’s generality and its adaptivity over time as a sustainable strategy. Eberle explicitly states the need for design methodology to integrate knowledge in the design process (Simmendinger and Schröer 2006).

But what lies behind these assumptions and notions?



**Figure 2:** Comparison of design variables in environmental management to shearing layers and the layers of the design theory by Dietmar Eberle of Baumschlager & Eberle Architekten.

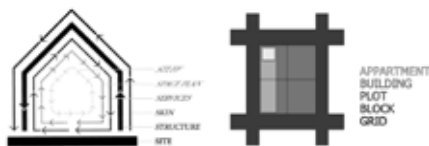
#### 4. ARCHITECTURAL THEORY – RESOURCE AND ENVIRONMENTAL MANAGEMENT

Two key references seem to have spawned several subsequent architectural research enquiries. While research

has developed since then, it is nevertheless the original concepts that remain fundamental to sustainability in architecture. Taking a step back does not ignore the progress of knowledge since then, rather it allows us to identify design issues at the macro level of sustainable design that must be addressed simultaneously and coherently by designers, including specialists working with environmental simulation.

In the book ‘The Architecture of the Well-tempered Environment’ (Banham 1984) ‘structure’ and ‘power’ solutions are defined as the two fundamental ways to mediate the environment through the use of resources. Structure solutions are resources invested in built space that is able to ‘conserve’ energy (eg. heat). Power solutions are energy resources used to ‘regenerate’ environmental condition artificially, as when burning a timber resource to provide heat rather than burning it. The ‘selective’ mode in between, is the building features that allows the occupant to choose among environmental stimuli, natural or artificial. The distinctions are not exclusive, - many building components perform and can be used in different modes. Banham was able to set the stage for later introduction of the technical distinctions between embodied and operational energy, and the environmental performance associated with the building fabric, user behaviour and energy use through service systems.

The second key reference is ‘How Buildings Learn’ (Brand 1997). Drawing on the theory of the shearing layers, originally developed in forestry and ecology studies, Brand establishes the idea that buildings have metabolism, and that the rate of metabolism is connected to layers of scale and activities that change a building over its lifetime. The layers that Brand identify are Site, Structure, Skin, Services, Spaceplan and Stuff, - their sequence referring to their durability and expected lifetimes, - Site being the most durable, almost permanent condition governing a building and Stuff, - furnitures and the like - being the most ephemeral with the highest metabolic rate (Fig. 3). It is perfectly possible for parts of buildings to fulfil more purposes, though it should preferably be avoided to allow better adaptability in the long term. Similarly at the urban scale spatial, legislative, regulative and ownership layers with different permanence can be identified that frame the evolution of the city. (Fig. 4)



**Figure 3:** Brand: Shearing Layers. Organizing a building according to the permanence of its different functional layers becomes instrumental in the resource management of buildings' material lifecycle.

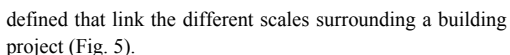
**Figure 4:** Sattstrup: At the urban scale, regulatory layers can be identified on the basis of the spatial, property and planning framework that governs the development of cities over time.

Brand identifies two ways of ensuring that a building achieves a long life – thus ensuring the maximum benefit of the resources and energy invested in its construction and maintenance – the ‘high’ way of investing a high cultural value in a building, and the ‘low’ way of ensuring the practicality of adapting the building to changing uses, by consciously using the shearing layers as a way to organize the building functionally and tectonically. This has spawned subsequent research enquiries in architecture aimed at minimizing the environmental impact of waste associated with buildings’ materials and the embodied energy invested in them, through ecologically and lifecycle oriented approaches (Berge 2009), (Braungart and McDonough 2009).

## 5. A METHODOLOGICAL FRAMEWORK FOR ENVIRONMENTAL SIMULATION

What does Banham's Environmental Management and Brand's Shearing Layers have in common, how are they differentiated, - and how can they be linked?

Brand's *Shearing Layers* primarily addresses the long term use of resources – what Banham terms solutions of Structure. But the layers also differentiate between different building scales, and the uses associated with them, opening up a connection to Banham's secondary concepts of the conservative, selective and regenerative modes of environmental management. Shifting Banham's definition of the selective mode slightly, so as to specifically describe the selective behaviour of the occupant rather than the properties of building components, Brand's layers: Site, Structure and Skin can be specifically linked to the Conservative mode, and the Selective mode used to describe the occupants' behaviour regarding the operation of the Skin and the Services layers. Now several frameworks can be

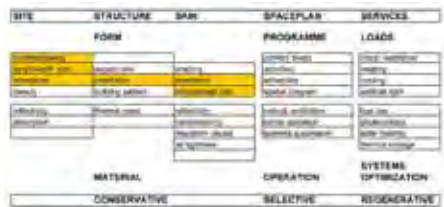


**Figure 5:** Connection of frameworks: Urban, Building, Operation, Time and Energy. The relative position of layers imply their relatedness.

Within the regulatory layers of the Urban Framework, we can use Brand's layers to describe the Building Framework, which again frames the Operational Framework, which we can describe using Banham's terms. Each of these operate at different time scales, so the Time Framework indicates the rate of change of the others: from the Urban Framework that can potentially last for centuries, to the daily rhythms of people in the Operational Framework. The Energy framework describes how embodied energy is stored in the fabric, solar energy potential for heating and lighting is mediated through the urban and building layers, and how operational energy is dispersed through the service systems. By organizing these visually it is made clear how the Frameworks influence each other, so as to create an awareness of the multiple aspects of the built environment that designers need to navigate to create truly environmentally and culturally sustainable buildings. The Spaceplan layer involves the organization of the building's programme, and is connected to the patterns of occupation and operation. The Services layer is associated with the energy loads for heating, cooling and lighting and the process of optimizing the plant and distribution systems. This categorization allows us to identify six domains of performance optimization: *Form*, *Material*, *Programme*, *Operation*, *Loads* and *Service Systems*. Each has different design variables that interact as complex systems and sometimes overlap between domains (Fig 6 & 7).



**Figure 6:** Design domains in between the Building and Operational framework. The domains can be described using specific design variables



**Figure 7:** Design domains with detailed design variables. Variables can be added according to design or simulation interest.

## 6. DEMONSTRATION CASE – INTEGRATING DAYLIGHT AND THERMAL PERFORMANCE ACROSS THE URBAN AND BUILDING SCALES

In the following demonstration case Site, Structure and Skin layers are investigated for the impact of Form on energy use, differentiating thermal performance according to Conservative, Selective and Regenerative modes of operation. The framework is used to map and interrelate a series of simulation studies undertaken by the authors. The aim of the studies is to clarify the following:

- 1) The impact of Form on the energy performance, investigating orientation and window size design variables of the Site, Structure and Skin layers.
- 2) Using the Conservative, Selective and Regenerative modes as conceptual and analytical tools to pinpoint the influence of Form and Material properties on the daylight and thermal performance related to Building Skin.

The studies focus on the integration of daylight and thermal performance tracing the impact of generic formal design decisions from the urban to the building scale, investigating how the temporal and spatial dimensions of solar access in the urban environment affect thermal and daylighting performance of apartments with different window to wall ratios. The climatic context of the study is Copenhagen (N56,E12) in Northern Europe, a climate that is marked by the relative scarcity of sunlight due to high latitudes, a predominance of overcast skies and the low solar altitude in the winter months. Sketch-up was used to create the models, which were exported to IES-VE for thermal, artificial light and energy analysis. Ecotect was used to analyse and visualize the spatial and temporal distribution of

solar radiation in the urban environment exporting the model for daylight autonomy analysis using DAYSIM. In all studies a design reference year (DRY) weather file for the city of Copenhagen was used. The material specifications are equal to the minimum current requirements in Danish Building regulations. See appendix.

### 6.1. SITE, STRUCTURE and SKIN

A first step in understanding the conditions of the Site was an analysis of the temporal and orientational distribution of radiation. A 'solar rose' was invented to visualize the yearly and seasonal radiation on vertical surfaces compared to the global radiation on a horizontal surface, as passive solar energy usually is distributed through vertical facades. Using the solar rose both seasonal and daily variations can be grasped at a glance, as the intensities are also connected to the time of the day. As can be seen, the intensity differs greatly, but due to the angle of incidence, some surprising facts are found: the solar potential on facades in spring is equal to that of summer, and offers a potential to shorten the heating season as temperatures have not risen yet. In Autumn and winter the low inclination of the sun means that the intensity of radiation on south facades can rival those of the yearly average though the exposure times are shorter, and the sensitivity to overshadowing in urban contexts increases greatly.



**Figure 8:** SITE: Solar roses, Copenhagen. From left to right: average hourly radiation on vertical (red) and horizontal (yellow) surfaces, - yearly, winter, spring, summer and autumn averages. Range 0-300wh/m<sup>2</sup>.

Previous studies by the authors examining solar envelopes (Knowles 1985) for the city of Copenhagen suggest that a maximum eaves height at 5 stories is advisable in dense urban districts at the same latitude, - a fact that corresponds very precisely to the actual densities of the inner city of Copenhagen. Above these densities, solar and daylight access are so restricted that denser urban patterns risk becoming unattractive, unless other attractions are associated with them.

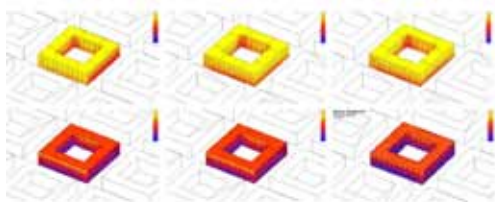
To find out the seasonal intensity variations, the solar potential of the facades of a 5 story 50x50m perimeter

block was calculated. As can be seen (fig. 11) the patterns of overshadowing by the surrounding buildings are gradients of intensities with great directional and temporal variations.



**Figure 9 SITE+STRUCTURE & TIME:** solar exposure on 5 story 50x50m perimeter block. Top to bottom: SE view, W, N, E & S facades. Left to right: winter, spring, summer and autumn exposure. Range 0-200wh/m2.

As the urban grid and planning regulations often limit the formal exploration on a given site, geometry and orientation can still be used by designers to increase or decrease the radiation intensity through working at the building Structure and Skin scales. Orientation is investigated as a design variable through either rotating the block 45 degrees or folding its skin, so as to increase solar intensity hitting glazed areas of the façade in the winter season /Fig. 10).

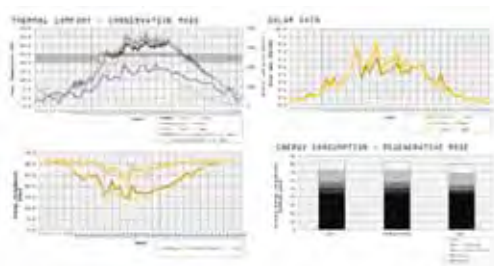


**Figure 10: SITE+STRUCTURE+SKIN & TIME:**

North/south, rotated 45degrees and North/South faceted façade block. Radiation levels during warm season April-Oct and cold season Oct-April. Radiation levels 0-200wh/m2.

The radiation levels are so low due to the high latitude and low sun angles in Copenhagen which cause overshadowing in winter, that only the top 3 stories can

pursue solar strategies for low-energy consumption with interesting local differences: South facing apartments have higher solar exposure in winter, but lower in summer than the others, due to the changing inclination of the sun-path. East-West facing apartments have high exposure in the summer and very little in the winter, which can be mediated using faceted facades, shifting the gains towards the season where they are needed. The rotated block has medium-high solar gains throughout the year when compared to the others. But changes to orientation carry very little weight on the overall energy demand, even given today's standard of construction. Heating demand for a 100m2 apartment with a window to wall ratio of 40% changes insignificantly when averaged over all 5 levels of the model, stabilizing at 44kwh/m2yr as the 3 bottom levels are totally overshadowed during winter at the urban density studied in this model. The 45 degree rotated block has a more even spread of the solar potential, more apartments benefit from the heat gains and a greater diversity of climatic situations and sunshine hours than in a north/south facing block, faceted or not.



**Figure 11 Thermal comfort, daylight, solar gains and Energy.** North/south, rotated 45degrees and East/West facing buildings.

Surprisingly the rotated block does not get the energy savings for daylight that the high radiation levels would make one think, it performs much worse than the north/south and east/west oriented buildings. A careful examination using a sunpath tool reveals why: As the buildings are used for housing, the occupants are not at home during weekdays at the hours where the sun delivers its energy. In the morning and afternoon the sun-angles are so low that the main bulk of the building lies in shadows.

Linking the energy use calculation for artificial light to climate based daylighting metrics such as the Daylight Autonomy is not so straight-forward. Using IES-VE

radiance to set up an artificial light control system that switches on light when natural light levels fall below 200lux in the occupied hours applying a 30% switched-on percentage, is not quite the same, though it is climate based, as it is linked to the climate file's radiation data, converted to lighting. IES-VE automatically places the sensor point in the middle of the zone, (if one uses the thermal engine's control system for switching as is done here) when generic models such as the ones presented here are studied.

The true benefit from working with the orientation lies in the temporal dimension of the solar exposure seen in accordance with the building's rhythms of occupation. But as minimum insulation values will increase over the next decade, even the small increases in average radiation observed in this simulation are likely to carry a larger weight on comfort levels and energy use in future construction. Returning to the Urban Framework, it may well be worth opting for an optimization of solar potential through orientation though it carries little weight in the energy budget today. In the long term perspective of the Site, a 10% better solar potential which is more evenly shared among neighbours can prove a valuable asset as cities develop, building technologies are upgraded and social patterns change.

## 6.2. CONSERVATIVE, SELECTIVE and REGENERATIVE mode analysis.

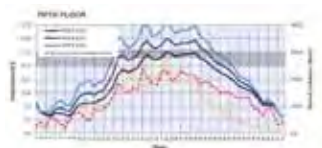
Further investigating the performance of the Building Skin, the influence of different Window to Wall ratios was defined, using the same model properties as in the previous study. To be able to identify precisely the influence of the building fabric, the behaviour associated conditions and the systems energy loads on the thermal performance, the settings of the model were varied using the Conservative, Selective and Regenerative mode:

In the **Conservative** mode the empty building envelope is simulated. This allows a very accurate analysis of the influence of the Form and Material design domains on the thermal performance, as the influence of user patterns is excluded.

In the **Selective** mode the building is basically free-running, including internal gains from occupants and equipment and natural ventilation in summer. This adds the probabilistic user patterns of the Programme and Operation design domains to the model. No climatization is included.

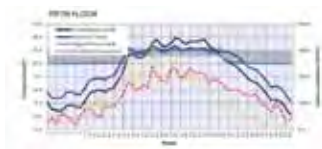
In the **Regenerative** mode the building is fully conditioned, adding the influence of all three modes. Total primary energy use is calculated using fully dynamic IES-VE radiance climate based thermal and lighting simulation.

The practically unobstructed apartments at the 5<sup>th</sup> floor were subjected to a comparative study using the conservative, selective and regenerative modes to analyze their thermal performance. Some interesting facts emerge: The building fabric alone (conservative) is able to shorten the heating season by 6 weeks in spring and delaying it in autumn by 4 weeks totalling 2½ months when comparing the 20% window to wall ratio with 80%, though this comes with the risk of serious overheating unless measures are taken to limit summertime heat gains, as natural ventilation (Selective mode) is not sufficient, or cooling (Regenerative mode) will be necessary (Fig. 11).



**Figure 11** CONSERVATIVE: 5<sup>th</sup> floor apartment types with 20, 40 and 80% window to wall ratio. Thermal performance of the empty building envelope.

During winter, the average temperature performance favours large windows, showing that the higher conductive losses from larger windows can be balanced by the heat gains from the solar radiation, even though it should be noted that daily temperature swings are much more pronounced the larger the glass areas, a fact that is masked by the weekly averages shown by the graphs. The 40% wwr apartment is better balanced, and the selective mode shows, that the heating season can be shortened equally to 80% wwr, when the internal gains from the occupants are included in the energy balance (fig. 12).



**Figure12** CONSERVATIVE+SELECTIVE+REGENERATIVE: 5<sup>th</sup> floor apartment with 40% window to wall area. Thermal analysis

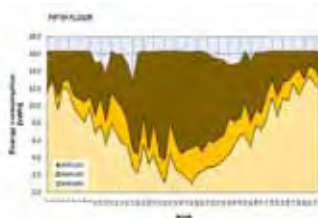


The daylight autonomy metric (Reinhart, Mardaljevic, and Rogers 2006), - that could be considered a 'selective' mode analysis in this context, - can be rendered using DAYSIM. It shows the yearly percentages of time where the light distribution levels are above a certain threshold deemed adequate for given tasks (fig. 13).



**Figure13** SELECTIVE: DAYSIM Daylight autonomy renderings of the yearly percentage of time where daylight levels exceed 200lux during occupancy hours 6-18.

When compared to a likewise temporal analysis of the energy use for lighting, the connection between the two figures is hard to see. Though each method uses radiance to calculate the time that light levels are above 200lux in a sensor point, the spatial imagery of DAYSIM is more visually communicative of the spatial qualities of the light. Though the new climate-based daylight metrics are greatly superior to the daylight factor, the analytical control of light's temporal dimensions should be improved in simulation so as to be able to grasp and communicate more of this variation. (fig. 13).



**Figure13** REGENERATIVE: graph showing the temporal dimension of energy use for artificial lighting dependent on window to wall ratio.

## 7. CONCLUSION

A methodological framework was developed, derived from interviews with leading practitioners and key references from architectural theory. The framework establishes a holistic view and an integrated approach that emphasizes that the layers, scales, components, materials uses etc. of a building or a built environment plays multiple roles, and must be understood in temporal dimensions that

include the day to day, seasonal, yearly and lifetime dimensions. The framework is structured according to a reinterpretation and expansion of Brand's and Banham's original concepts to differentiate and connect building performance analysis of the built environment, the influence of occupants behaviour and the optimization of service systems, showing ways to connect the areas of operational and embodied energy, environmental management and resource management.

The framework is used to map a series of studies ranging from the urban scale to the facades, integrating thermal and daylighting performance dynamically, while tracing the impact of the urban context on building performance. The mapping of this particular study, points out the need for future research in the 'blank' spaces of the framework: Specific studies across the boundaries of the operational/embodied energy fields, further investigations of the temporal potentials in climatebased daylighting metrics, and a continual evolution of conceptual clarifications that allows knowledge to be integrated and disseminated across professional borders.

## References

- BANHAM, R. 1984. *Architecture of the Well-tempered Environment*. 2nd ed. Chicago University Press.
- BEHLING, STEFAN, AND EVENDEN. 2009. *Foster and Partners Interview by P. A. Sattrup. Green Architecture for the Future*.
- BERGE, BJØRN. 2009. *The ecology of building materials*. Architectural Press.
- BRAND, STEWART. 1997. *How Buildings Learn: What Happens After They're Built*. New edition. Weidenfeld & Nicolson.
- BRAUNGART, MICHAEL, AND WILLIAM McDONOUGH. 2009. *Cradle to Cradle*. Vintage.
- EBERLE, DIETMAR. 2008. *Arkitekt, Arkitektur og Ressourcer Interview by P. A. Sattrup. Arkitekten 11*.
- KNOWLES, R. L. 1985. *Sun, Rhythm, Form*. New edition. MIT Press.
- REINHART, CHRISTOPH F., JOHN MARDALJEVIC, AND ZACK ROGERS. *Dynamic daylight performance metrics for sustainable building design*. Leukos 2006, no. 3. Leukos (July): 1-25.
- SCHULER, MATTHIAS. 2008. *Paven af Integreret Design Interview by P. A. Sattrup. Arkitekten 12*.
- SIMMENDINGER, PIA, AND ULRIKE SCHRÖER. 2006. *'City and House – a Strategy Of Teaching Design'*. In *The Complexity of the Ordinary*. Copenhagen: Royal Danish Academy of Fine Arts





## **Paper VII**

*“Sustainable Cities – Density versus solar Access; A Study of Digital Design tools in Architectural Design”*

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In proceedings: ISES Solar World Congress, 2009, Johannesburg, South Africa

**SUSTAINABLE CITIES:  
DENSITY VERSUS SOLAR ACCESS?  
A Study of Digital Design tools in Architectural Design**

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**Presented and published at ISES Solar World Congress 2009, Johannesburg, South Africa**

**Abstract**

Increased urban density is promoted in city centres and around transport nodes as a sustainable strategy to promote social interaction and to reduce the energy use for personal transportation. However, increased density affects solar access. In the already built-up cities of Northern Europe, the problem of overshadowing has consequences for both comfort and the solar energy potential of sites, and may even lead to disputes over solar access in a near future where buildings are dependent on passive and active solar energy contributions to comply with energy regulations.

The study aims to clarify and improve a design methodology for architects and engineers working with integrated design processes for energy optimization, by testing the relative precision of simulation tools and building information modelling on the calculated energy performance in relation to different stages in the design process.

This study examines how urban density as defined by building height and built form relates to energy use in the Copenhagen climatic context, and how passive solar energy contributions are affected by urban density for typical building patterns based on architectural archetypes common in Copenhagen and familiar to many cities in Northern Europe. It traces how increased (or decreased) density affects the lowest level of an office building which is the most susceptible to changes in solar access.



## 1. BACKGROUND

With the present renewed focus on energy optimization as a means to lessen the dependency on fossil fuels for supply security and climate change reasons, now is perhaps the time to take a renewed look at the energy performance of buildings as the result of the form of the urban structure, with a focus on how to improve the design and performance of urban buildings, and the design process itself. Energy optimization plays an important role in sustainable architecture, but only as part of a much larger picture that engages the values and ideals of our societies as expressed in built form.

### Energy optimized architecture

Energy optimization in architecture has two main focal points, - that of optimizing built form, orientation and selection of materials in relation the building's use, to achieve comfort with a minimum of energy use for its operation, - and that of optimizing the energy embodied in the building's fabric in relation to their performance and eventual recycling. Seen over a 100 years lifetime of a building, the energy used for operation is much greater than the embodied energy, but if we put this in the dynamic perspective of future low-energy buildings that will be upgradeable for better performance, the relationship will change. Fig.1.

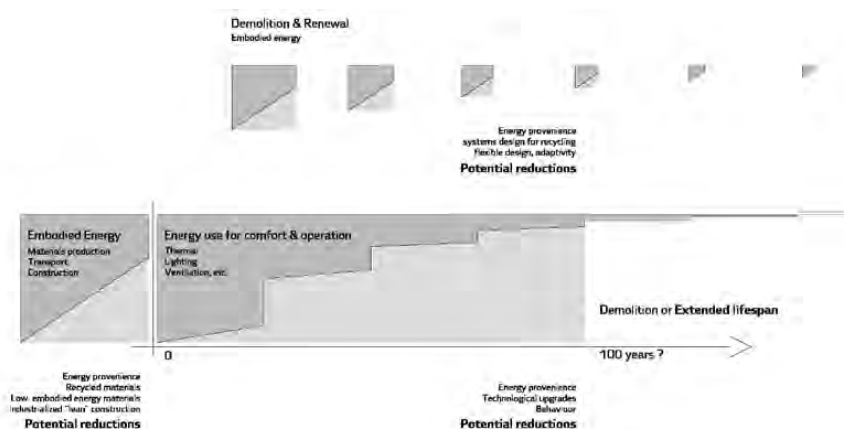


Fig.1 Sattup: Embodied energy and energy used for operation in a buildings lifetime

### Shearing Layers – Metabolism and Life Cycle Assessment

While embodied energy is not discussed in any detail in this paper it is important to keep in mind, as it is needed as part of a holistic design approach. The “Shearing layers” theory elaborated by Brand (1994) traces how buildings evolve over time at different paces according to scale. The bigger scale, the longer lifespan it has, the smaller the scale, the more often will it be altered or replaced. One could call this the metabolism of a building. Fig 2. The shearing layers theory even tends to become a design imperative in sustainable architecture as it is able to establish a rough spatial hierarchy that can guide decisions concerning Life Cycle Assessments (LCA) of materials and activities. Its fundamental ethos is: “Don’t fix a 5 minute problem with a 50 year solution” It is essential when discussing the industrial or biological ecology of architecture as defined by Braungart and McDonough. (2006).

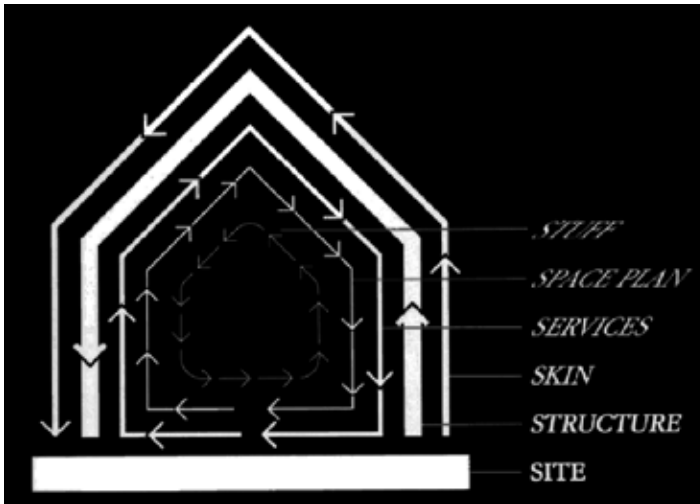


Fig. 2. Brand: Shearing Layers of a building. The relative speed of change at different spatial scales.

## Building Information Modelling (BIM)

Another interesting quality of the Shearing Layers theory is that it can be used to structure the design process as proposed by Eberle & Simmendinger (2007). Building Information Modelling (BIM) tools can be used to keep track of resource use through the different stages of a design process.

The promise of BIM is that it combines 3D computer modelling with an extensive database, thus controlling geometry, quantities, qualities, time aspects and costs, giving the designers unprecedented control of the process from conception to manufactured product. Linking the Life Cycle Assessment data of materials to the BIM model, it is possible to have a very detailed description of the environmental impact of design decisions relating to materials. BIM is typically stratified according to stages of a design process in which a particular Level Of Definition (LOD) is achieved, the project gaining complexity and interdependent information. A design process progresses through various iteration stages and is summed up by documentation, drawings, models, prints, images e.a. at the end of each stage.

## Simulation Modelling

Energy calculation have until recently been a matter of formulas presented in charts and figures, worked out by engineers with meticulous attention to detail in spreadsheets describing very simple geometries, material properties and activities. The newest generation of software has now 3D modelling interfaces that connect directly to architects software and even offers templates and default values for typical construction and material types, which architects can work with and create simple simulations. The results can even be visualized spatially and temporally so as to get an impression of how the building physics and climate conditions work together in space and time. There is a great architectural potential in exploring these interrelationships for formal and conceptual design ideas.

The challenge of simulation modelling is that it can be very time consuming to do properly, as the devil is very much in the detail. Simulations can therefore be run at increasingly complex levels as time permits. Ultimately what is simulated is something as erratic as human behaviour which gives it a certain slippage compared to the actual energy performance of the finished building. And there is ample room for the discussion of what comfort is and how it is achieved, as understood by both architects and engineers.

## **Design Processes for Integrated Energy Design**

It is common knowledge that the impact of design decisions is biggest in the initial design phases where the knowledge of how they work is lowest. As the design process progresses, changes become considerably more difficult and costly to implement, which is even more true once the building is finished. The value of knowledge generation by building information modeling and simulation to aid design decisions in the earliest stages is therefore obvious.

But how reliable are these tools? Do they change the professional boundaries between architects and engineers? Is there a risk of creating misleading results taking decisions on imprecise simulations?

How can the design process between architects and engineers be improved?

These are the underlying questions behind the following study of how density affects solar access and energy use in Copenhagen's coastal cool humid climate. In the study the IESVE suite of software was used in such a way as to reflect an exchange between architects and engineers. (The authors are an architect and an engineer respectively).

The study looks at the base levels of the shearing layers theory, - site and building shape in an urban context, and tests how it affects energy use as a result of passive solar heat and daylight.

The results are then checked for the way they correspond to two very basic Levels of Definition according to a BIM design process progression.

These are again checked to see how they correspond to a simulation process progression of increased complexity:

- basic thermal based energy calculation (Apache)
- thermal based simulation with shadow casting context (Apache + Suncast)
- thermal simulation with context and daylighting simulation (Apache + Suncast + Radiance).

## **2. ANALYSIS: ENERGY AND DENSITY**

### **Method**

A generic “Copenhagen Block” of 50x100 meters (½ hectare) is modelled. It is subdivided in 10 plots of 20x25 meters and surrounded by 15 meter wide streets. While the block is very generic, its plot dimensions are commonly found in Copenhagen, to such an extent that it can be used as a framework to compare different urban patterns of the city.

Three building archetypes are introduced – the courtyard building, the terrace building and the pavilion. These archetypes are common to most urban cultures of the world if not all, and have been subject of performance studies particularly at Cambridge University (Ratti, Steemers, Baker and others) This study changes the focus towards the design process instead of mapping relative values, since the tools and processes explored will quite probably be mainstream in architects and engineers office within a short time span.

Energy performance is calculated for each type, at ground level for a south facing office in the middle of the street. This is the position most susceptible to changes in the density of its surroundings. The block is surrounded by similar blocks with the same building type, and simulations are run at 1, 3, 5 and seven story scenarios. Each story is 3 meters high.

The material properties are predefined construction sets made available by the software developer. The values chosen come as close to current Danish minimum standards as possible, with U-values of 0,2 for facades. No heat loss is assumed to neighbouring buildings. The buildings are ventilated mechanically, and cooled to eliminate excess temperatures. See appendix for specifications.

### **Urban morphology**

In the context of Copenhagen the types reflect the urban morphology as a result of its modern development stages:

The walled city until the 1850’ies had the courtyard as a dominant type, since the only expansion was upwards, maximizing the built area in relation to the plot size.

The industrial city expanded beyond the fortifications, still very dense, the most common pattern being the perimeter block since transport was still mostly by foot.

The early modern city saw a widespread expansion along the main lines of public and private traffic at a low density according to the famous “Fingerplan” of 1947. The center too experienced decreased density, mainly because of traffic breakthroughs, and demolition and renewal of derelict buildings.

At the present the post industrial city sees redevelopment of former industrial areas, and one of the big questions is what to do with the existing building stock that has a poor energy performance. Is increased density a feasible option in Copenhagen? And if so, at what densities?

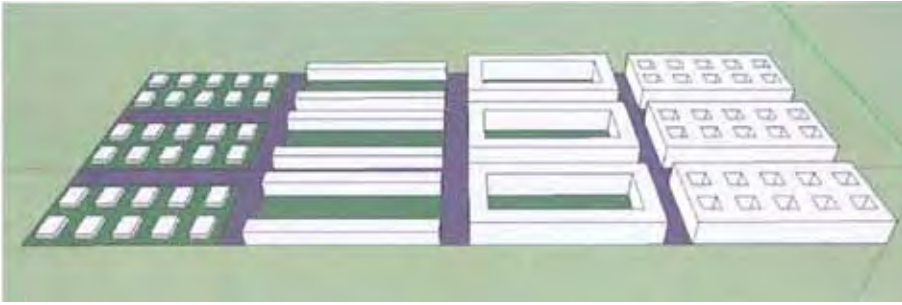


Fig. 3. Urban morphology. Generic urban patterns reflecting Copenhagen evolution from walled city to dispersed metropolis

### 3. RESULTS

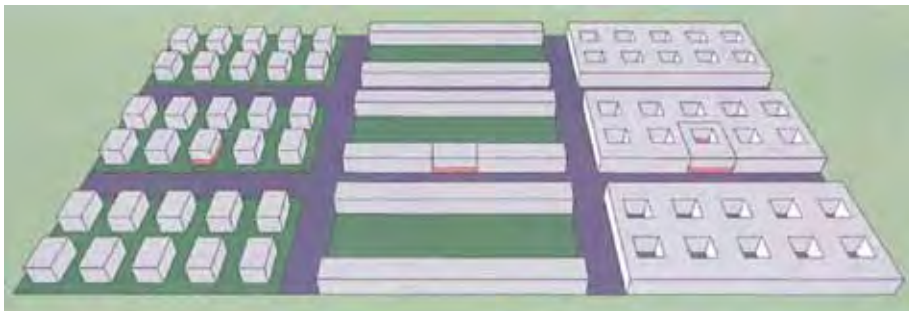


Fig. 4. Overview of energy performance calculation results from pavilion, terrace and courtyard urban patterns.

#### Courtyard

The courtyard type performs quite well thermally as a result of its limited surface. It is however very sensitive to loss of daylight as density increases. The contribution of passive solar energy to heating stabilizes at app. 2kWh/m<sup>2</sup>year at 3 stories. Cooling loads decrease with increased density, but not enough to compensate for the additional energy use for artificial lighting. Daylighting is reduced to such a degree at the ground floor that lights will be switched on most of the time throughout the year which should be considered a serious comfort loss, as access to daylight is connected to health, wellbeing and productivity. (Fig. 5)



Fig. 5. Courtyard type energy performance with increased urban density.



**Terrace**

The overall energy use is higher than for the courtyard type, since it has more exposed surface, and the building across the street block solar gains for building height higher than 3 stories. It is not nearly as susceptible to daylight losses, as the rear side has a greater distance to obstructions than the street facing side.



Fig. 6. Terrace type energy performance with increased urban density.

**Pavilion**

The pavilion has the lowest energy use since its relatively open context allows solar gains from more directions and longer time. This results in the most use of energy for cooling to get rid of excess temperatures during summer. As this type has the lowest density of floor area to plot size, it represents a more widespread city, which has implications for energy use for transport.



Fig. 7. Pavillion type energy performance with increased urban density.

**4. DESIGN PROCESS – TOOL EVALUATION**

Evaluating the simulation as a step by step process with increasing sophistication of simulation levels interesting results appear: First of all is it interesting to see that the inclusion of the context results in a 25% better performance, particularly as the predicted daylighting performance is improved. Cooling too is affected considerably as the effect of shading from the urban context makes its mark. As the simulation with no context is the result of the freeware version of the software, it makes for considerable doubt of the validity of the results at this extremely low level of definition.

Simulation precision improves considerably with the levels of definition even at this very basis stage. (Fig. 8) The difference becomes even more pronounced when calculated for primary energy consumption, as electricity is used for both cooling and artificial lighting.

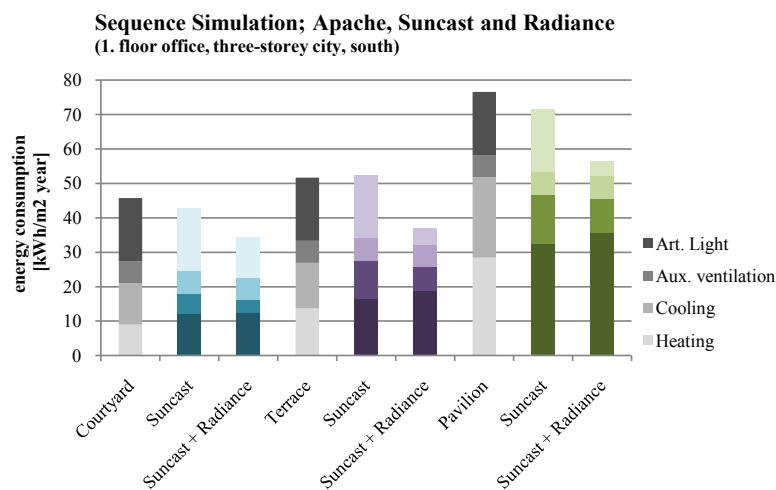


Fig. 8. Comparative results with increased level of definition of simulation modeling.

While it is not very time-consuming to set up a basis daylighting simulation at this level, it does require considerable knowledge of building physics that is not typical for architects without a specialization in the subject. The default values that is very easy to set up and “play” with, constitute a source of insecurity that can be misleading if not controlled carefully.

The software is no substitute for a qualified team of architects and engineers collaborating through the initial design stages. As a platform for integrated energy design, smoothly and allowing the exchange of information from BIM to SIM software the prospects are very promising. The software facilitates the communication of basic design ideas, and can probably positively aid the learning process of any project, and the possibly the education of future architects and engineers too.

### 5. CONCLUSIONS

Building information modelling and simulation modelling are merging, to provide common software platforms for architects and engineers. The ease with which one can produce “results” based on default values, masks the complexity of the way in which geometry, building physics and use have to be considered together. This can lead to faulty conclusions if not controlled properly.

The tools cannot replace an experienced team of designers working together across their professional boundaries in the initial design phases, but can aid communication within the team and speed up the process.

Simulation modelling can provide provisional data based on thermal modelling in the very beginning of the design phase, but precision improves dramatically with the level of detail,

particularly when daylight simulation is added, - to such a degree that daylight simulation should be considered the lowest level of definition in simulation modelling. Context plays an import role for both solar gains and daylight and should as a minimum be included in any simulation.

## REFERENCES

Brand, S. (1994) *“How Buildings Learn”*

Braungart M. and McDonough W. (2006) *“Cradle to Cradle”*

Eberle, D. and Simmendinger, P. (2007) *“From City to House – a Design Theory”*

Ratti, C., Raydan D., and Steemers, K. (2003) “Building form and environmental performance: Archetypes, analysis and an arid climate” *Energy and Buildings 35*, Elsevier Science B.V.





## **Paper VIII**

*“Energy Design: Message to Staff on Spaceship Earth”*

J. Strømmand-Andersen

Published in: ArkitekturM , Vol 1, No 5, 2009, Arkitektens Forlag



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ArkitekturMagasinet Vol. 1 Nr. 5 2006

# arkitekturM



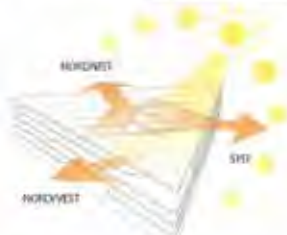
## HLA: Kolding Campus



Kolding Campus, Syddansk Universitet, er et eksempel på, hvordan overordnet geometrivalg og en faktuel betragtning af lyset, landskabet og klimaet har bragt energiforbruget helt i bund. Institutions- og erhvervsbygninger har ofte problemer med at kontrollere varmetilskuddet, bl.a. pga. utilsigtet solindfaldet. Øst- og vestorienterede facader er de værste af afskærmne pga. den lavtstående morgen- og eftermiddagsol. Sydfacaden er derimod lettere at afskærme, fordi solen står højt på himlen og derved rammer facaden med en højere vinkel.

Campusen er med sin trekantede grundform optimeret ud fra disse forudsætninger. Trekanten er orienteret syd-nord omkring dens akse. Dvs. bygningens ene facade er orienteret direkte mod syd, mens de to andre facader er orienteret mod nord/øst og nord/vest. Derved opnåes en struktur, hvor nord/øst- og nord/vestfacaden har meget lav solpåvirkning, mens sydfacaden kan kontrolleres med den effektive solafskærmning.

Jakob Skovmand Andersen er arkitekt



Ved en højere vinkel falder solen i rummet, hvilket for en bygning med et lavt energiforbrug og gode klimatiske forhold. HLA: Henning Larsen Architects

## HLA: FIH Bank, konkurrenceforslag



FIH Bank, Langeliniekaj, arbejder med en beredt stillingtagen til lyset. Ud over de æstetiske og oplevelsesmæssige kvaliteter, som lyset kan give os, er det også blevet en vigtig faktor i beslutningerne på at reducere elforbruget til belysning. Elforbruget til belysning udgør op imod 30 % af det samlede energiforbrug både i den offentlige sektor og i privat-, kontor- og erhvervsbygget.

Lyset eller solstrålingen, som rammer jordens overflade, kan opdeles i den direkte solstråling fra solen og den diffuse himmelstråling. Det direkte sollys kan give anledning til generende blænding og overophedning, mens bidraget fra den diffuse himmelstråling giver et jævnt daglysniveau.

I FIH Bank var målet at minimere det direkte sollys og optimere det diffuse daglys - for derigennem at begrænse energiforbruget til kunstig belysning og køling. Konceptet er en facetteret facade, der åbner sig mod nord og lukker sig mod syd.

Jakob Skovmand Andersen er arkitekt



Generations af facadekoncepter der illustrerer effekten af direkte solstråling i rummet. Den facetterede facade med bevægbare vinduesflader åbner sig mod nord og lukker sig mod syd, hvilket reducerer det diffuse daglys. HLA: Henning Larsen Architects





## Energidesign meddelelse til personalet på Spaceship Earth Af Jakob Stromann-Andersen

"We are all passengers on Spaceship Earth." Richard Buckminster Fullers vision af de globale ressourcers begrænsning dateres tilbage til hans notat fra 1920'erne. Men det var først i 1973, med kraftigt stigende oliepriser, at energibesparende strategier for alvor kom på den arkitektoniske agenda.

Interessen for at spare energi er steget kraftigt inden for de senere år som et resultat af vores generelle bekymring for klimaforandringer. Det er nu bredt accepteret, at forbrænding af fossile brændstoffer, med den resulterende udledning af drivhusgasser til atmosfæren, påvirker de etablerede klimatiske mønstre. Ingen i samfundet kan flygte fra det akutte behov for at reducere energiforbruget, men bygningssektoren er specielt under pres. I Danmark spænder vi omkring 40 % af samfundets samlede energiforbrug til at drive vores bygninger. Med drift mens energiforbruget til opvarmning, køling, ventilation, varmt brugsvand og belysning. Men klimaforandringerne og de sparsomme ressourcer kan også være en forættelse til arkitekturen. God arkitektur gør oftest et uundværligt og begrænsning.

### Arkitektens ansvar

Det første skridt i forbedringen af bygningens energimæssige ydeevne starter ved arkitektens første skitse på papiret. Det er her rammerne og forudsættelserne for bygningens ydeevne bliver sat. Det kræver en bevidsthed omkring formgivningens (højde, bredde, orientering mv.) indflydelse på bygningens energiforbrug.

Hvis arkitekten går ind i formgivningsprocessen uden den bevidsthed og erkendelse af, at der er en sammenhæng mellem formgivning og energiforbrug, er der stor risiko for, at det senere i processen vil blive nødvendigt at indføre tekniske løsninger til at kompensere for grundlæggende dårlige valg. Det kan betyde, at potentialet for energibesparelser begrænses. Er bygningen designet "rigtigt tænkt", giver det optimale muligheder for at udnytte bygningens passive egenskaber i forhold til indklima og optimerer mulighederne for lavenergi inden for varme, køling, ventilation, dagslys m.m. Bygningen kan naturligvis altid senere optimeres med den til enhver tid bedste teknik, men en fra starten rigtigt tænkt bygning vil altid være bedre end de bygninger, der har brug for tekniske som kompensation - simpelthen fordi udgangspunktet for passivløsninger er bedre. (Passivløsninger er løsninger, der ikke benytter energi til at opretholde et ønsket komfortniveau, men i stedet betjener sig af naturlig ventilation, solfaktermønstre, isolering og lav varmestakkuleringsskema).

Fremtidige byggeprojekter skal godkendes efter det danske bygningsreglement samt EU's nye krav for energiforbrug og indklima (Energy Performance Building Directive).

Det er allerede lagt op til, at de danske krav for bygningens energiforbrug bliver skærpet med 25 % til næste år, i 2010, og med yderligere 25 % i 2015. Med kombinationen af de skærpede krav og den nuværende teknik er der ingen vej udenom - klimastyringen kan ikke løses med ren teknik. Det kræver ganske enkelt for meget energi at drive traditionelle, mekaniske anlæg. Vi er derfor nødt til at arbejde med *energidesign* som en fast del af den kreative proces. Energidesign betyder, at viden om de forhold, der påvirker bygningens energiforbrug, bliver en vigtig designparameter. En viden som må tænkes ind i starten af ethvert projekt.

Det er ikke begrænsende for den kreative og intuitive udfoldelse. Problematikken må vendes på hovedet og udfordringerne ses som muligheder for at gentænke arkitekternes rolle ud fra nye mål og værdier. Et sted, man kan starte, er f.eks. at arkitektoniske referencer og principper analyseres videnskabeligt i forhold til klima- og energipotentialer for at opnå en synsryk mellem arkitektens sædvanlige intention og den faktiske energimæssige effekt.

### Erfaringer fra en tegnestue

Tverrfaglighed og integration mellem lagene byder enkelt og let - men det er det ikke altid. Grundlæggende er det vanskeligt for arkitekter og ingeniører at arbejde sammen.

En traditionel ingeniør er skolet i rationelt at løse opgaver fra A til B til C, mens arkitek-



## **ENERGY DESIGN: MESSAGE TO STAFF ON SPACESHIP EARTH**

**Up to 50% of a building's energy consumption is determined in the architects' first sketch<sup>i</sup>. So it is important for the architect to acknowledge her or his impact on future resources.**

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**Published in ArkitekturM 2009; Vol 1, No. 5, Arkitektens Forlag**

*"We are all passengers on Spaceship Earth"*.<sup>ii</sup> Richard Buckminster Fuller's vision of global resource limitation dates back to his memo in the 1920s. But it was not until 1973's sharply rising oil prices that energy-saving strategies really came on the architectural agenda.

Interest in energy conservation has increased further in recent years due to general concerns about climate change. It is now widely accepted that the combustion of fossil fuels, with its resulting release of greenhouse gases to the atmosphere, is affecting the established climate patterns.<sup>iii</sup>

No member of society can escape from the pressing need to reduce energy consumption, but the building sector is under particular pressure: approximately 40% of Denmark's total energy consumption takes place in buildings – for heating, cooling, ventilation, hot water and lighting.<sup>iv</sup>

But climate change and scarce resources can first and foremost be a gift to architecture. Good architecture is often the product of necessity and limitation.

### **The architect's responsibility**

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 building's performance will be set. It requires an awareness of how the design (height, width, orientation, etc. of a building) will affect the building's energy consumption.

If the architect goes into the design process without the awareness and recognition that there is a correlation between design and energy consumption, there is a considerable risk

that later in the process it will be necessary to introduce technical solutions to compensate for fundamentally bad choices. This can lead to limited potential for energy savings. On the other hand, if these points are borne in mind, the architect has the very best opportunities for using passive solutions in relation to the indoor climate, low energy-heating, cooling, ventilation, daylight, etc. A building can, of course, always be optimized later using the latest techniques, but a building that is designed with energy-saving in mind right from the very beginning will always be better than a building that needs later adjustment in compensation for poor design – simply because the starting point for passive-solutions is better. (Passive-solutions are solutions that do not use energy to maintain a desired comfort level, but instead use natural ventilation, solar screens, insulation and high heat accumulation capacity).

Future projects must be approved in accordance with the Danish Building Regulations as well as the EU's new requirements for energy consumption and indoor climate (Energy Performance Building Directive).<sup>v</sup> There are already plans for the Danish requirements for building energy consumption to be tightened by 25% this year 2010 and by a further 25% in 2015. The combination of stricter requirements and current technique means there is no way around it – the technical solutions available will not be adequate. Quite simply it takes too much energy to run traditional mechanical installations. So we need to use energy-design as an integral part of the creative process. Energy-design means that knowledge of the factors that affect the building's energy consumption will be an important design parameter – knowledge which must be taken into account at the beginning of every project.

This way of thinking need not restrict creative and intuitive expression. On the contrary, the challenges must be seen as opportunities to rethink the architectural role on the basis of new goals and opinions.

One place we can start is to analyze architectural references and principles scientifically in relation to climate and energy-potentials with the aim of achieving synergy between the architect's aesthetic intention and the actual energy effect.

### **Experience from a drawing office**

Multidisciplinary integration between different professions sounds simple and easy – but is not always so. Basically, it is difficult for architects and engineers to work together.

A traditional engineer is trained to work rationally from A to B to C, while an architect works on multiple potential solutions at the same time. So problems often occur in the 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.

Multidisciplinary integration is not something that comes from sitting around the same table. It's a matter of being able to tell a common story. The architect is the storyteller and the engineer's role is to enrich the architect's story and add new facets to it. To be able to do this, the engineer needs architects who are prepared to let technical knowledge into the process early on and who are also critical and inquisitive in relation to technical

challenges. And the engineer needs to be better at actively communicating her or his knowledge and be able to contribute with multiple solutions that can challenge and inform the architect's design.

To be concrete, the engineer must learn from how the architect reads and understands the context. A solution in one place is not necessarily the same good solution somewhere else — which actually fits in very well with knowledge gained in a technical scientific way. However, it would be a great help if the architect were more explicit in the reading of the context. The subjective feeling and understanding of the context is often difficult to translate because it is implicit in the way architects work.

### **The Danish tradition – a fantastic starting point**

We have long looked towards Austria, Switzerland and Germany with regard to sustainable construction. These are by no means bad examples, but the time has come to define our own tradition in modern energy-efficient architecture.

The Danish architectural tradition is a great starting point. It is a tradition based on an instinctive reading and understanding of the context and natural world that surrounds us. Light, landscape and climate are important elements here. These are exactly the same elements which are essential in the design of energy-efficient architecture. It is not the presence of some new element that is revolutionary. It is the sum of all the elements, and the way we use them, that makes the difference between traditional and energy-efficient architecture.

The complexity may seem scary, but basically energy-efficient architecture is just about using basic pragmatic common sense in the way we design buildings. We must all take part in the challenge, as the philosopher Marshall McLuhan put it: *"There are no passengers on Spaceship Earth. We are all crew"*.<sup>vi</sup>

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<sup>i</sup> Jørgensen, Michael., Strømmand-Andersen, Jakob.: "Anvendelse og videreudvikling af metode til integreret design af større bygninger" DTU Byg, februar 2008

<sup>ii</sup> Fuller, Buckminster R.: "Operating Manual for Spaceship Earth". New York: E.P. Dutton & Co., 1963.

<sup>iii</sup> Geneva 1995, Intergovernmental Panel on Climate Change, Second Assessment Report: Climate Change, Geneva 1995, IPCC web site: [www.ipcc.ch](http://www.ipcc.ch)

<sup>iv</sup> Energistyrelsen: "Energistatistik 2007". Energistyrelsen, Amaliegade 44, 1156 København K, september 2008

<sup>v</sup>

[www.buildingsplatform.org](http://www.buildingsplatform.org)

<sup>vi</sup> Marshall McLuhan.: Statement of 1965, in reference to Operating Manual for Spaceship Earth by Buckminster Fuller





## **Paper IX**

*“Climatic Diversity in the City”*

J. Strømman-Andersen

Published in: Byplan, No. 3 september 2010/62 årgang







form, aktivitet og klima. Form i relation til aktivitet og indretning, aktivitet, i form af funktionel diversitet, kulturelle tilbud og rekreative områder. Og klima, i forbindelse med muligheder og begrænsninger i forhold til lys, skygge, sø og vind. Hvor samspillet mellem form og aktivitet længe har været et studeret og dokumenteret område<sup>1</sup>, er effekten af det lokale mikroklima i relation til byens liv dækket stadigvæk af forskellene, over- og underordnet områder.

Der er dog foretaget en hel del forskning med specielt fokus på temperaturvaringer gennem byen, den såkaldte "urban heat island" effekt. Undersøgelser viser ikke bare, at temperaturen er højest i bymidten og reduceres mere eller mindre kantende ud mod forstæderne, men også at der er temperaturforskelle internt og lokalt i byen. Variationerne er særlig udtalte i nærheden af pladser og parker, hvor temperaturen i varme tilfælde reduceres med op til 2°C, alene på grund af vegetationen<sup>2</sup>.

I teorien kan vi forestille os store mangfoldigheder, når man ser ændringerne på byens form. Nogle byer kan blive udsat for direkte sollys en stor del af dagen, mens andre ligger i skygge eller er overdækkede. For at illustrere betydningen af sollys vil en variation på  $ca. 70 \text{ W/m}^2$  i horisontal indstråling ændre lufttemperaturen med 1°C<sup>3</sup>. I det danske klima er det ikke ualmindeligt, at solindstråling i et byrum kan variere med op til  $1.000 \text{ W/m}^2$ , svarende til en temperatursvingning på 14°C.

Første skridt i forståelsen af mikroklimaet er at studere og simulere måden det fungerer på, og

hvordan det påvirker os. Fysiologisk, kan mennesker udvise sig til at opleve forandringer, når i det visuelle (syn) miljø, men også gennem lydige (følel), taktil (føle) og olfaktoriske (lugt) sensorer. Den indgroede erfaring er forbundet med psykologiske opfattelser af sikkerhed, komfort og velvære i og omkring i fare, spænding og ubehag. Uppået fysiske/klimatologiske parametre kan individuelle faktorer som aktivitetstilstand og påklædning også indflyde på oplevelsen af byrummet.

- **Det visuelle klima**  
Lys- og synsindvirkninger som f.eks. blænding, kontraster, farvegenkendelighed, dagslys, fortolkning - det som vi oplever med vores øjne.
- **Det akustiske klima**  
Lyd- og støjindvirkninger som f.eks. trafiklarm, det som vi kan høre med vores ører.
- **Det atmosfæriske klima**  
Lugt-, duft- og forureningspåvirkninger som f.eks. pollen, lugt, kvalitetstoffer, partikler mv. der som påvirker luftkvaliteten gennem vores næse.
- **Det termiske klima**  
Temperaturpåvirkninger som f.eks. solindstråling, vindretning og luftfugtighed - det vi også alle de påvirkninger, som vi oplever ved hjælp af vores hud og temperatursensorer.

Det samme byrum kan således have en bred vifte af klimatiske forhold, som har relation til, op-

levelse af byrummet. De centrale spørgsmål er, hvad der er årsag og påvirkning af denne mangfoldighed, og hvordan samspillet er til byrummets form og aktivitet?

# Forskningsprojekt

I dag er den mest anvendte metode til at forstå, reagerer og forstå byrum på, empirisk og subjektiv. De empiriske opfattelser af, f.eks. menneskeliv er umiddelbart lette at afkode, men de giver også svære at afkode. Hvorfor bevæger vi os som vi gør? Det er ofte en individuel og subjektiv vurdering, der er svært at overvinde, da den ligger dybt i personens kulturelle baggrund. Resultatet kan være en metode, der giver en overblik og størst blik på byrummets faktuelle dynamiske livsløb.

På Danmarks Tekniske Universitet (DTU) Syg forskning der i øjeblikket i et samarbejde mere objektiv og målbare metoder til at registrere mikroklimaet indflyde på folks adfærd i byrummet. Forskningen er inddelt i tre faser:

- Den første fase af forskningen er rettet mod det urbane mikroklima med en særlig henvisning til dens mangfoldighed og de forskellige betingelser. Her indgår et især vigtigt samarbejde med videnskaber med erfaringer i byrumregistrering og design.
- Den anden fase ligger på, hvordan brugere af byrummet reagerer på mikroklimaet, som de er udsat for gennem en kombination af empiriske forsøg og målinger.



Eksempel på kategori A - Børn Park, Østerbro  
Foto: Jakob Skovgaard Andersen



Eksempel på kategori B - Skovhøj Park, Sønderborg  
Foto: Jakob Skovgaard Andersen



Eksempel på kategori C - Langelinie ved "Kvar", Frederiksberg  
Foto: Jakob Skovgaard Andersen



### Kategorisering af aktivitet i byrummet

- A** Ophold af længere varighed; rolig ophold; stående eller siddende.  
Terrasse, gådecafé eller restaurant, bootcamp, etc.
- B** Ophold af kort varighed; aktivitet; ophold i kortvarig position.  
Ophold på plads, ekspedition, aktivitet, etc.
- C** Aktiv ophold; nysgerrig og nemt gang; aktivitet; ophold.  
Gæder, indgangspart, indkøbsgade, etc.
- D** Ophold, aktivitet; gang, aktivitet; gang.  
Indkøbsgade, boulevard, etc.

### Vindmiljøet i byrummet bør udformes ud fra følgende komfortkriterier

|          | Acceptabelt | Ubehageligt |
|----------|-------------|-------------|
| <b>A</b> | 0,1 %       | 3 %         |
| <b>B</b> | 6 %         | 15 %        |
| <b>C</b> | 23 %        | 34 %        |
| <b>D</b> | 43 %        | 50 %        |

Eksempel: Andelen af vindmiljøet i byrummet, der er acceptabelt, ifølge gennemsnitligt vindhastighed (4,5 m/s) i 2010 i København (10-15 m/s).

► Den sidste fase i analysen er ikke blot at måle forskelle, men at få et indblik i hykkan for at forklare principperne til den mangfoldighed, som er blevet målt.

Det er i tværsnittet af forskellige komfort som en funktion af klimatiske parametre, f.eks. temperatur, luftfugtighed og strålingsvarme og personlige variable, såsom beklædning og aktivitet. Fanger\* varmebalance model, der beskrives ved "Predicted Mean Vote" (PMV) og "Predicted Percentage of Dissatisfied" (PPD) sammenholder f.eks. aktivitetsniveauet, hvor varmt tøj man har på, lufttemperaturen, middelstrålingstemperaturen og middelluftfugtigheden med brugerens tilfredshed. PPD er således et udtryk for en matematisk model, der angiver den forventede procentvis andel af personer, der vil føle sig for kolde eller varme i et givent indklima.

Men som her omsat vides erfaring, at komfort er relateret til både fysiologiske og psykologiske fænomener. Der vil derfor være diskutabelt at opfatte byrumskomfort som en rent matematisk og objektivt parameter. Det er således vigtigt, at projektet og metoden kombinerer teoretiske modeller og beregninger med efterfølgende sammenligning med folks oplevelser og adfærd. Derfor bygger forskningen også på et tæt samarbejde mellem forskellige fagkompetencer (ingeniør, arkitekt, plantegger, sociologer mv.).

Altmed projektet er at skabe spædende byrum, hvor voldsamer stimulering i forhold til rummets design og funktion. Stimuleret af forskningsprojektet skal skabes forudsigt til et mere

kvantificeret (objektiv) forståelse og analyse af byrumsmiljøet og dens fysiologiske og psykologiske effekt på mennesker.

#### Det målbare byrum

Indledende resultater viser, at det er muligt at udføre simuleringer af mikroklima, der kan fungere som spilleregler for designet af nye byrum. Det er f.eks. muligt at kvantificere og kategorisere betydende vindmiljøet vil forekomme ubehageligt i forhold til den aktuelle aktivitet. Aktiviteten kategoriseres i fire niveauer, der ud fra et fysiologisk hierarki beskriver byrummets funktion.

Hvis kategorierne sammenholdes med f.eks. de ovenstående analyser af Aalborg, kan det konkluderes, at pladens funktioner ikke er optimale i forhold til vindmiljøet. Cafeområdet langs Søla har f.eks. et vindmiljø, der kan kategoriseres som niveau C eller D. Det, et komfortniveau der ikke indbyder til længerevarende ophold. Hvis til gengæld vil være klimatiske (bælt til parkeringsareal). Konsekvensen er, at en stor del af året vil cafegesterne på pladten været generet af kulde og høje vindhastigheder. Det kan dog afhjælpes eller helt undgå. F.eks. via etablering af den rette beplantning eller læskærme.

Studier fra Norge har konstateret, at med den rette planlægning af mikroklimaet kan komforten optimeres og udsættelsestiden forlænges med op til seks uger i løbet af de mere kolde perioder i året og efteråret. Det betyder, at alle steder som beskyttes mod vinden, maksimering af eksponering, minimering af skyggeområder, anvendelse af varmeabsorberende og varmeeffekt



Begrebskoden på Aalborg KBN (Klimakortet) 1. april 18, 17, 20 min (temperatur). Aalborg KBN (Klimakortet) med vind. Illustration: Jakob Steenhusen-Arbores



Simulering af vinden og luftens retning på Aalborg KBN (KBN, Aalborg Kommunes Klimakort). Illustration: Jakob Steenhusen-Arbores



Vindretningen (C/D) simulering af Aalborg KBN (KBN, Aalborg Kommunes Klimakort). Illustration: Jakob Steenhusen-Arbores

terændr. materialer, m. ikke alene kan have en positiv effekt på brugerens komfort, men også på coffeejernes pædagogik.

Kategoriseringen kan udover en viderføring af eksisterende byrum anvendes i designet af nye byområder og byrum. Der vil f.eks. være muligt for kommuner at opstille krav til ulemiljøet i lokalplanen ligesom byghererne nu stiller krav til indeklimaet i byggeprogrammet. Der vil således være en målbart indikator for, hvordan byrummet løbende performer.

Det er dog vigtigt at være opmærksom på, at kategorierne skal anvendes med en vis stillings. Det giver f.eks. ingen mening at sige en Udsigt(A) for et effektivt byrum i byen, hvis der ikke er en modsvarende til byrummet rum for en større mangfoldighed og diversitet af aktiviteter. Som eksempel kan peges på byrummet langs Låneds Brygge, der anvendes til en bred vifte af forskellige aktiviteter med dertil forskellige komfortforhold. Der anvendes solbæde, skatebaner og pynt i et vindst.

Konklusionen er, at der er en begrænset værdi i at opdele eller definere et "optimalt" komfortniveau i byrummet. Vigtigere for at opnå et vellykket lands byrum er, at byrummet vurderes i forhold til den klimatiske mangfoldighed, både rumligt og dynamisk. Her kan tekniske analyser af mikroklimaet være en målbart designindikator for udviklingen af byrummet. Målet er at skabe flere klimatiske

nisander i byrummet og give os mulighed for at vælge mere præcist når vi designer byrum i forhold til klima, aktivitet og brugerens ønsker.

Der har ikke været muligt at offentliggøre enkelte resultater fra forskningsprojektet, da de forventes publiceret i teknisk videnskabelige journaler. En løbende opdateringer vil bl.a. finde sted på DTU Netnews: [www.casolin.byg.dtu.dk](http://www.casolin.byg.dtu.dk).

#### Ph.D. projekt

##### "Integreret energidesign (masterplanning"

Civilingeniør Jakob Strømme-Andersen forsker i udfordringer af fremtidige master- og byplansplaner og deres påvirkninger på byens energiforbrug og mikroklimatiske betingelser. Parametrene er: naturens, byens og landskabets struktur, geometri og indflydelse forhold samt muligheder og begrænsninger i forhold til lys, skygge, sol og vind.

Ph.D. projektet er igennemført af Henning Larsen Architects, Forsknings- og Innovationsstyrelsen og Realitama Fonden.

Jakob Strømme-Andersen

Cand. Polyt., Erhvervs Ph.D. Stipendiat  
DTU Byg, Institut for Byggeri og Anlæg  
HENNING LARSEN ARCHITECTS A/S

#### Litteratur

- (1) Gehl, J. 2002. *Level mellem mennesker og byrum*. Copenhagen: Arkitektens Forlag, København.
- (2) Serrenouin, M. 2001. *Energy and Climate in the Urban Environment*. London: James & James.
- (3) Sasaki, S. 1990. *Environmental Science Handbook for Architects and Builders*. Larsen: The Construction Press.
- (4) Fanger, P.D. 1979. *Thermal Comfort*. McGraw-Hill, New York.
- (5) Holger Kutz, H. 2002. "On the feasibility of applying wind-solar criteria", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 94, no. 11, pp. 781-787.
- (6) B. Guljet, K. Enslin. 1998. *Climate-responsive urban space: A Scandinavian perspective*, in: J. Manly, N. Plessner (Eds.), *Office Designed for Winter*. Building Book Ltd, Helsinki.
- (7) Nikolopoulos, M. & Vassiliou, S. 2003. "Thermal comfort in outdoor urban spaces: Analysis across different European countries", *Building and Environment*, vol. 41, no. 11, pp. 1453-1470.
- (8) Nikolopoulos, M. & Steemers, K. 2003. "Thermal comfort and psychophysiological adaptation as a guide for designing urban spaces", *Energy and Buildings*, vol. 35, no. 1, pp. 95-101.
- (9) Walker, G., Dawkins, V. & Davis, M. 2007. "The relative influence of wind, sunlight and temperature on user comfort in urban outdoor spaces", *Building and Environment*, vol. 42, no. 8, pp. 2566-2575.
- (10) Mayhew, H., Höpfer, P. 1995. "Thermal Comfort of Man in Different Urban Environments", *Theoretical and Applied Climatology*, Vol. 38, pp. 43-48.



## **CLIMATIC DIVERSITY IN THE CITY**

**New research from DTU shows, that there is a dynamic link between urban life and the local microclimate.**

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**Published in BYPLAN**

We have to rethink and get the “climate” back into the urban space. In recent years there has been an emphasis on the visual and aesthetics’ of the urban space. Just look at many of the squares in Ørestaden and by the metro stations - wind-swept, sterile and lifeless. We should ask ourselves; how do we get activity, quality of life and diversity back into the design of the urban space?

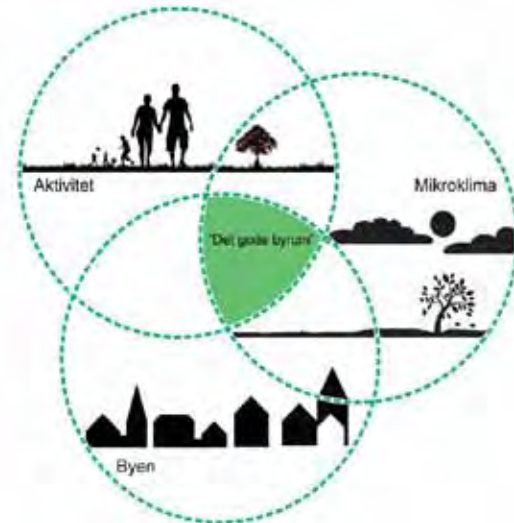
For most people the word “urban space” invokes associations of heaviness and firmness. But experience shows that the perception of the urban space is dynamic over time. The perception changes as a result of either movement through the urban space or because of a change in the climatic comfort conditions. It is the dynamic quality of movement, sequence and activity which stimulates our senses both visually, thermal and acoustic. But too rarely are these qualities included in the design of urban space.

We all know the feeling that there is a headwind on the bicycle path – regardless of our direction or that it’s always raining at the bus stop. But everyone also knows the hidden alcove in the park, yard or square, where there is sunlight, shelter and a comfortable temperature. These are examples of how the climate stimulates our senses and the way in which we use and recall the city. An understanding and evaluation of the senses impressions (the comfort) is therefore necessary since it has a great impact on the development of cities and urban spaces. By knowing and “controlling” the sources of discomfort, we will be able to make it so, that living and going about in the city becomes more attractive.

### Microclimate – the unknown factor

Successful urban spaces attract large numbers of people, which in turn, attracts businesses, employees and residents. The area becomes attractive and economically viable. But what defines a good urban space?

There exist lots of good examples of well-functioning urban spaces. They are characterized by often having a defined and integrated interaction, between the form of the urban space, activity and climate; form in relation to architecture and arrangement; activity by functional diversity, cultural offerings and recreational areas; climate in terms of opportunities and limitations in regards to light, shadows, sun light and wind.



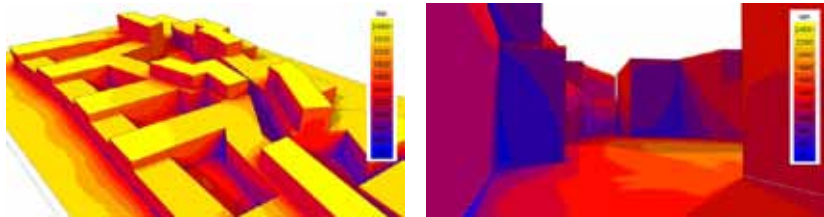
*Illustration: Interactions between activities in urban spaces and microclimate.*

While the interaction between the shape of the urban space and activities is a well studied and documented field [1], the effect of the local microclimate in relation to the urban life, still remains a fairly overlooked and understudied field.

However, a great deal of research has been done with focus on temperature fluctuations through cities, the so-called urban heat island effect. Investigations not only indicate that the temperature is highest in the city center and that it is more or less reduced in a concentric fashion towards the suburbs, but also that there is temperature differences both internal and locally within the city. The variations in temperature are particularly evident in the vicinity of parks and squares, where the temperature in certain cases is reduced by as much as 3°C solely because of the vegetation [2]. We can in theory expect greater diversity when taking a closer look at the city's shape. Some urban spaces can be exposed to direct sunlight for a majority of the day, while other areas are in the shade or roofed. In order to illustrate the significance of sunlight, consider that a variation of ca. 70 W/m<sup>2</sup> horizontal solar radiation changes the air tem-



perature by 1°C [3]. For the Danish climate it is not unusual that the solar radiation in an urban space can vary up to 1,000 W/m<sup>2</sup> or what equals a temperature change of 14°C.



*Illustration: Variations within the city of incident (direct + diffuse) solar radiation, daily average values. Competitive proposal for Carlsby, a new city area in Hillerød (Henning Larsen Architects A/S)*

The first step in understanding the microclimate is to study and simulate the way in which it works and the way it affects us. From a physiologically perspective man has evolved an affinity for perceiving changes, especially the visual (sight) environment but also the aural (hearing), tactile (touch) and the olfactory (smell). The ingrained experience is associated with psychological perceptions of safety, comfort and well being - and vice versa - danger, excitement and discomfort. Besides the physical climatological parameters, individual factors such as activity and clothing also influence the experience of urban space.



*Illustration: Climatological parameters that affect our sensory experiences.*

- **The visual environment**  
Lighting and visual effects e.g. glare, contrast, color recognition, daylight conditions, etc. - sensations we perceive with our eyes.
- **The acoustic climate**  
Sound and noise e.g. traffic noise - sensations which we hear with our ears.

- **The atmospheric climate**

Smell, scent and pollution e.g. pollen, moisture, nitrogen oxides, particulates, etc. - That which affects the respiratory system through our nose.

- **The thermal climate**

Temperature e.g. solar radiation, wind speed and humidity - All the sensory impressions that we perceive through our skin and thermal receptors.

The individual urban area can thus have wide range of climatic conditions, which in turn relates to the experience of the urban space. The key questions are then, what is the nature and extent of the diversity and how is the interaction in relation to the urban form and activity?

### **Research project**

Today the most common method for understanding, documenting and mapping spaces, is empirical and subjective. The empirical counts of e.g. human traffic flow are immediately easy to read, but then hard to decode. Why do we move as we do? It is often an individual and subjective assessment, which is difficult to translate because it is implicit, in the person's cultural background. The result can be a method that provides a diverse and blurred image of urban space factual dynamic quality.

At the Technical University of Denmark (DTU.Byg) research is under way, in setting up a more objective and quantifiable method to detect microclimatic influences on people's behavior in urban space. The research is divided into three phases:

- The first phase of research has focused on the urban microclimate, with a particular reference to its diversity rather than its absolute terms. This is done via an integrated collaboration with companies with experience in urban space surveying and design.
- The second phase looks at how users of urban space respond to the microclimate in which they are exposed, through a combination of empirical experiments and measurements.
- The final stage of the analysis is not only to measure the differences, but also to get an insight into the physics, in order to explain the principles of the diversity, which has been measured.



*Photo: DTU students record the micro-climate (noise, wind, humidity, etc.). At Trinity Church Square*



*Photo: Students test the wind environment of an urban design at DTU Byg's wind tunnel.*



*Photo: Work area by the wind tunnel.*



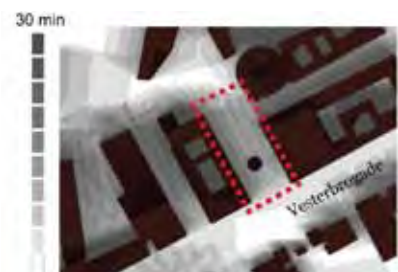
*Photo: Wind tunnel test section with a setup of flow visualization.*



*Photo: Erosion testing of urban environment in the wind tunnel (Axel-square Copenhagen).*

It is theoretically possible to predict comfort as a function of climatic parameters, e.g. temperature, air velocity and radiant heat and personal variables, such as clothing and activity. Fanger's [4] heat balance model which is described by "Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD)", compares e.g. the level of activities, how warm clothes are, air temperature, mean radiant temperature and mean air velocity, with the user satisfaction. PPD is thus an expression of a mathematical model that indicates the expected percentage of people who will feel too cold or too warm, in a given indoor environment. But as mentioned before, experience shows that comfort is related to both physiological and psychological phenomena. It is therefore questionable to perceive urban comfort as a pure mathematical and objective parameter. It is therefore important that the project and the method combine theoretical models, calculations and subsequent comparisons with people's perceptions and behavior. Thus the research is based on a close collaboration

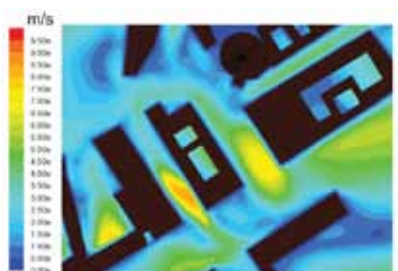
between different specialists (Engineers, Architects, Planners, Sociologists, etc.).



*Illustration: Shadow analysis on Axel Torv, Copenhagen (Shadow hour on April 1<sup>st</sup>. at. 8 am- 5 pm, 30 min interval). Note: Axel torv are marked in red.*



*Illustration: Simulation of direct and diffuse solar radiation on Axel Torv, Copenhagen (Wh, daily averages).*



*Illustration: Wind analysis (CFD simulation) of westerly winds on Axel Torv, Copenhagen (m / s)*

The project aims to create exciting urban spaces, where our senses are stimulated in proportion to the form of the urban space's design and function. The end result of the research project should contribute to a more quantifiable (objective) understanding and analysis of urban environment and its physiological and psychological effect on humans.

### **The measurable spaces**

Preliminary results show that it is possible to perform simulations of microclimates that can serve as ground rules for the design of new urban spaces. For an example it is possible to quantify and categorize when wind environment will occur uncomfortable compared to the current activity [5]. Activity is categorized into four levels by a physiological hierarchy that describes the function of an urban space.

## Categorization of activity in urban space

|          |   |
|----------|---|
| <b>A</b> | Stay of longer duration, quiet position, sitting or lying, terrace, street café or restaurant, pool, amphitheater, etc. |
| <b>B</b> | Stays of short duration, standing / sitting in the short term, public parks, playgrounds, shopping streets etc.         |
| <b>C</b> | Actively stay, comfortable and normal walking pace, strolling, walkway, entrance, shopping street, etc.                 |
| <b>D</b> | In transit; objective walk; rapid or quick pace, parking lot, boulevard; sidewalk, etc.                                 |



Example of a Category A - Bopa Plads, Østerbro. Photo: JSA



Example of a Category B - Islands Brygge Sports Park, Islands Brygge. Photo: JSA



Example of a Category C - Landscape by "The Wedge"(Kilen), Frederiksberg. Photo: JSA



Example of a Category D – Parking lot at DTU, Kgs. Lyndby. Photo: JSA

Wind Environment in urban spaces should be designed based on the following comfort criteria:

|          | Acceptable | Uncomfortable |
|----------|------------|---------------|
| <b>A</b> | 0,1 %      | 3 %           |
| <b>B</b> | 6 %        | 15 %          |
| <b>C</b> | 23 %       | 34 %          |
| <b>D</b> | 43 %       | 50 %          |

The criteria describes the maximum likelihood of an exceeded average wind speed of 5 m / s (18 km / h), equivalent to a mild breeze.

If the categories are compared with, e.g. the above analysis of Axel Torv, it can be concluded that the site's features are not optimal in relation to the wind environment. The café area at Axel Torv has a wind environment, which can be categorized as Level C or D. That means that it's com-

fort environment, is not ideal for stays of longer duration, but will in turn, be climatically ideal for parking. A consequence is that for a larger part of the year, café guests at Axel Torv will have been bothered by turbulence and high speed winds. This can however be mitigated or eliminated e.g. through the establishment of the proper planting or wind shelters. Studies from Norway have found that with the proper planning of the microclimate the comfort levels can be optimized and the outdoor season can be extended by up to six weeks, during the most critical periods in the spring and autumn [6]. This means that elements such as, protection against the wind, maximizing solar exposure, minimization of shadow formation, use of heat-and heat-reflective materials, etc. not only can have a positive effect on user comfort, but also on the café owners' wallets.

Taking categorization beyond the assessment of existing open spaces, it can also be used in the design of new urban areas and urban spaces. It would, for an example, be possible for municipalities to establish requirements for the outdoor environment, much like entrepreneurs who nowadays requires an indoor climate classification in the construction program. There will therefore be a continuously measurable indicator of how the urban space performs.

It is however important to note that the categories should be used with some degree of wisdom. It gives, for an example, no sense to search for a category A. site for every urban space in the city. The city provides, as opposed to buildings, a space for a greater abundance and diversity of activities. One example highlighted is the cityscape along Islands Brygge, which is used for a wide range of different activities associated with different comfort needs - swimming, sunbathing, skateboarding and joggers in a jumble.

The conclusion is that there is a limited value in obtaining or defining an "optimum" level of comfort in the urban space. It is more important to achieve a well-functioning urban space, and that the urban space is being considered in relation to the climatic diversity, both spatially and dynamically. Here technical analysis of the microclimate can deliver a measurable design indicator for the development of urban spaces.

The goal is to create more climatic nuances of urban space, which in turn allows us to be more precise when we select a design of urban space, in relation to climate, activity and user wishes.

(Note: It has not been possible to publish the exact results from the research project because they are expected to be published in technical scientific journals. Ongoing updates will be posted at DTU's home page: <http://www.cesdyn.byg.dtu.dk>)

## References:

- [1] Gehl, J. 2003 *Livet mellem husene, udeaktiviteter og udemiljøer*, Arkitektens Forlag, København
- [2] Samtamouris, M. 2001 *Energy and Climate in the Urban Environment*, London: James & James
- [3] Szokolay, S. V. 1980 *Environmental Science Handbook for Architects and Builders*, Lancaster: The Construction Press
- [4] Fanger, P.O. 1970 *Thermal Comfort*: McGraw-Hill, New York
- [5] Holger Koss, H. 2006, "On differences and similarities of applied wind comfort criteria", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 94, no. 11, pp. 781-797.
- [6] B. Culjat, R. Erskine. 1988, Climate-responsive social space: a Scandinavian perspective, in: J. Mänty, N. Pressman (Eds.), *Cities Designed for Winter*, Building Book Ltd., Helsinki
- [7] Nikolopoulou, M. & Lykoudis, S. 2006, "Thermal comfort in outdoor urban spaces: Analysis across different European countries", *Building and Environment*, vol. 41, no. 11, pp. 1455-1470.
- [8] Nikolopoulou, M. & Steemers, K. 2003, "Thermal comfort and psychological adaptation as a guide for designing urban spaces", *Energy and Buildings*, vol. 35, no. 1, pp. 95-101.
- [9] Walton, D., Dravitzki, V. & Donn, M. 2007, "The relative influence of wind, sunlight and temperature on user comfort in urban outdoor spaces", *Building and Environment*, vol. 42, no. 9, pp. 3166-3175.
- [10] Mayer, H., Höppe P. 1986, "Thermal Comfort of Man in Different Urban Environments", *Theoretical and Applied Climatology*, Vol. 38, pp. 43-49

Ph.D.Project:

### **"INTEGRATED ENERGY DESIGN IN MASTERPLANNING"**

MSc Jakob Strømman-Andersen researches the design of future masters and district plans, their impacts on the city's energy consumption and microclimatic conditions. The parameters are: nature, city and landscape structure, geometry and internal relations as well as opportunities and constraints related to light, shadow, sun and wind.

The Ph.D. project is sponsored by Henning Larsen Architects, Research and Innovation Board and Realdania foundation.







## **Design Experiment**

*“Thermal Observatory - Installation proposal”*

P.A. Sattrup<sup>a</sup>, J. Strømman-Andersen<sup>b</sup>

Proposal for: Charlottenborg, Spring Exhibition 2010 and 24/7

## THERMAL OBSERVATORY

Installation proposal for the Spring Exhibition 2010 and 24/7 (Charlottenborg)

**P.A. Sattrup<sup>1</sup> and J. B. Strømman-Andersen<sup>2</sup>**

<sup>1</sup>Institute of Building Technology  
Royal Danish Academy of Fine Arts School of Architecture  
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### Description

In the middle of the room to the right of the entrance hall facing Charlottenborg's courtyard to the northwest a curtain is hung defining a cylindrical space within the space.

The fabric of the curtain registers the temperature of the space, the flow of air and the movement of people. Its temperature range changes with the rhythms of the day, with the unstable weather conditions of spring in Copenhagen. It changes with the influence of people and building climate technology.

It sways gently with the movement of people and the thermodynamic movement of air. It muffles the sound of the exterior slightly.

Its temperature is continuously measured by thermal cameras whose iron-glow coloured images are projected onto the curtain - transfiguring the invisible realm of the tactile, of the skin's sensations of heat and air, - into the visible and measurable. The imagery is present in the Charlottenborg gallery in real time. It is collected and presented on the web gallery, continuously adding and compressing layers of time.

The curtain allows the visitor to interact with the microclimate of the space, experiencing how their sensations change with its thermal properties.

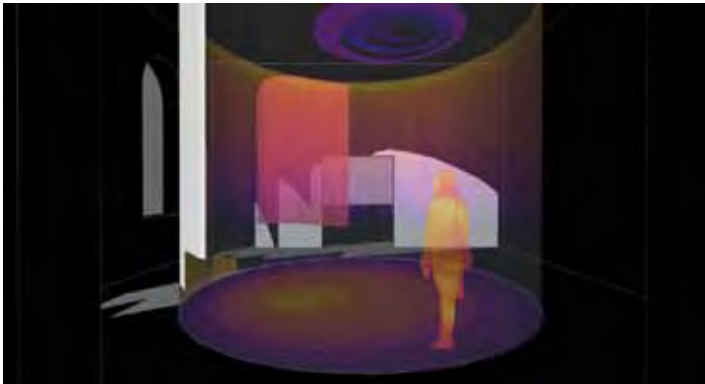


Figure 1: 3D visualization of the installation

## Specification

The gallery is blacked out by paint and black fabric, absorbing and converting the incoming daylight to heat, through eliminating reflections.

The curtain is hung from a rail offset from the ceiling. The fabric is slightly translucent. People can enter the cylindrical space defined by the curtain, and change its surface properties tightening or loosening its folds.

Thermal cameras are suspended from the ceiling recording the temperatures of the curtain, the floor and people moving across the floor. Projectors suspended from the ceiling projects the images of the cameras onto the curtain and floor.

The images are collected and compressed into 5 min sequences, which are displayed on the 24/7 web.

On clear days sunlight will temporarily leave a trace of direct light and heat on the curtain in the afternoon. On cloudy days the light of the sky will interact dynamically with the projections on the curtain.

A thermal coil on the floor and a ventilator suspended from the ceiling in a north-south orientation are programmed to occasionally artificially enhance the climatic conditions of the space in rhythmic patterns of heat or cold.

A heat exchanger producing heating and cooling is placed visibly in the gallery outside the curtain.

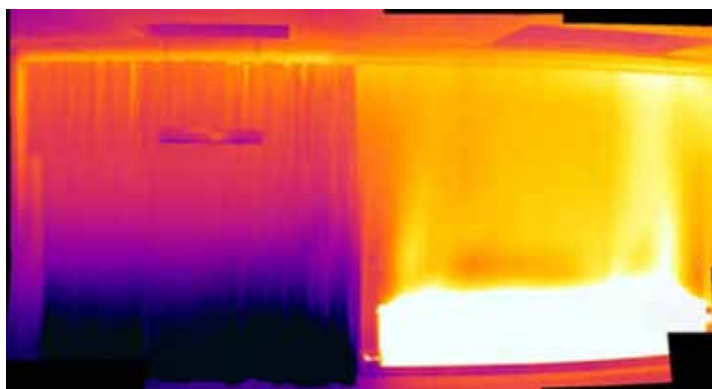


Figure 2: Thermographic photo of the test installation

## Agenda

The installation forms part of a research in the relations of space, climate, human behaviour and energy through a collaboration between an architect and an engineer.

The research investigates how the physical properties of light and heat can be considered as proper building materials in their own right, widening the aesthetic and functional possibilities of architectural imagination, thinking and making.

While architects and engineers have traditionally collaborated on the production of buildings, their research traditions and philosophies are worlds apart.

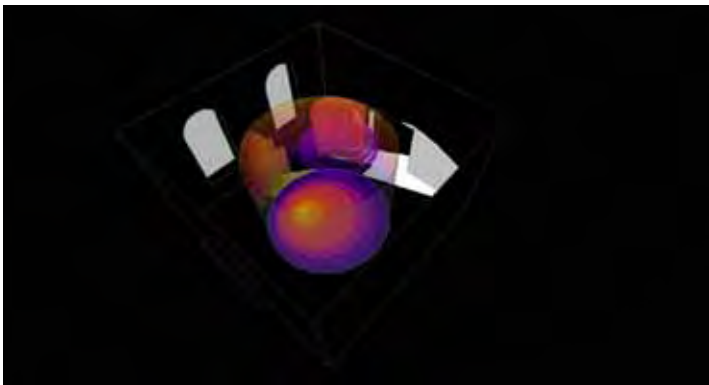
For instance *comfort* in engineering terms is a technical term of climate control. It is defined by the statistical absence of discomfort in a normalized group of people. It is the cornerstone of theoretical calculations of energy consumption.

In architecture it could be considered one of the deepest levels of meaning, perhaps one of the primary aspirations of architecture through time? It is not just a functional term, but a multifaceted question of aesthetics and meaning.

The installation is an attempt to bridge this gap rendering the invisible into the visible, the measurable into the imaginable, the functional into the aesthetic.



**Figure 3: 3D visualization of the installation**



**Figure 4: 3D visualization of the installation**



Figure 5: Thermographic photo of the test installation

Note: The proposal came through the second round of three, but was not included in the final exhibition.





## **Background information**

Author's Curriculum vitae and list of supervision in connection with the  
PhD project, (master and bachelor thesis)



The intention with this PhD thesis is to contribute to the creation of a breakthrough in the effectiveness of the Integrated Energy Design method such that it is transformed into something with relevance, meaning and positive effect for people and nature in the built environment.

This thesis is not a continuation of the tradition of theses about Integrated Energy Design (IED). The vast majority of discourse on integrated design takes a technical view of sustainable design in which performance is the primary value. The thesis presented here looks at sustainable urban design not with the eyes of an engineer (How does it work?) or of an architect (How does it look like?), but rather with the eyes of an Architectural Engineer (How is it perceived? What is wonderful about it? How is it part of a greater whole?)

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**ISBN: 9788-778773364**  
**ISSN: 1601-2917**